clinical review

Neuromechanics of the patellofemoral joint

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ABSTRACT

GRABINER, M. D., T. J. KOH, and L. F. DRAGANICH. Neuromechanics of the patellofemoral joint. *Med. Sci. Sports Exerc.*, Vol. 26, No. 1, pp. 10–21, 1994. Patellofemoral joint pain is one of the most common ailments associated with visits to sports medicine clinics and can be disabling, although conservative clinical treatment has a reportedly very high success rate. Patellofemoral joint pain is often associated with improper tracking of the patella within the femoral trochlear notch. Improper tracking of the patella can be associated with increased patellofemoral contact pressures that may be a mechanical stimulus underlying patellar cartilage degeneration. In those cases in which anatomic anomalies and trauma may be excluded as the basis for improper tracking, attention is directed toward possible disruptions to the central nervous system control and contractile potential of the knee joint extensor musculature that underlies proper patellofemoral mechanics. This paper presents a review of three seminal components related to the neuromechanics of patellofemoral function; patellofemoral tracking, patellofemoral contact pressures, and neuromotor control of patellofemoral agonists. It is the intent of the authors to illuminate areas requiring further basic and clinical research and provide a point of departure for this work.

KNEE, MECHANICS, NEUROMOTOR, PATELLA, PATELLOFEMORAL, TRACKING

The patella was at one time considered to be trivial relative to knee joint function. The present view is much different. The patella serves to increase knee extension moment by as much as 50%, guides the forces of quadriceps femoris components to the patellar ligament, protects deeper knee joint anatomy, protects the quadriceps tendon from frictional forces, and increases the compressive forces to which the extensor mechanisms can be subjected. Sports medicine practitioners, especially those who emphasize the lower extremities, are acutely aware of the dominance of knee disorders over all other musculoskeletal problems. Further, Dehaven and Lintner (10) reported that, of the knee disorders presenting over a period of 7 yr, 18.1% of males and 33.2% of females were associated with patellofemoral pain. The purpose of this paper is to review the present state of knowledge relative to the neuromechanics of patellofemoral function, and in doing so, illuminate areas requiring further basic and clinical research. The term neuromechanics has been used for 20 yr but has been recently repopularized by Enoka (12), who describes the area of neuromechanics as "... consideration of the principles of mechanics ... various components of the [neuro]musculoskeletal system ... and an examination of the interaction of the biological model with its surroundings."

An important mechanical factor thought to contribute to patellofemoral pain is the manner in which the patella articulates with the femoral trochlear groove, referred to as "tracking." The tracking of the patella will tend to influence a second key element thought to be related to patellofemoral pain, which is the magnitude of the forces acting at the patellofemoral joint. Related to both the tracking of the patella and the patellofemoral forces are patellofemoral pressures. The tracking and kinetics of the patellofemoral joint are influenced by a number of factors including active forces, generated by reflexive and voluntary contraction of knee joint musculature. The neuromotor control of this musculature is essential to proper patellofemoral joint function. Each of these three factors, tracking, pressures and forces, and control of the skeletal muscles acting on the patellofemoral joint will be treated sequentially.

Quantitative *in Vivo* Measurement of Patellar Tracking

Although many disorders of the patellofemoral joint are assumed to be related to abnormal tracking of the

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patella relative to the femoral trochlear groove (22), this relationship is not well understood. Further study is required to characterize and understand normal and abnormal patellar tracking, and to understand the possible relationships between abnormal patellar tracking and patellofemoral disorders.

To fulfill the need for further study, accurate and reliable methods of measuring patellar tracking are needed. Current quantitative methods include both noninvasive and invasive techniques. So far, the noninvasive methods of measuring patellar tracking have involved only two-dimensional analyses of this three-dimensional event (e.g., 27,34,59), although three-dimensional methods are available (66). Invasive methods have provided data on three-dimensional patellar tracking (30,33,35,44). Measures obtained with both the noninvasive and invasive techniques as well as the advantages and disadvantages of theses techniques will be discussed in the following paragraphs.

Most frequently, the noninvasive techniques involve two-dimensional imaging of the patellofemoral joint during nonweight-bearing, static conditions with knee joint muscles relaxed (27,34,36,45,59). Conventional radiographic (x-ray) imaging involves a tangential view of the patellofemoral joint with the knee flexed between 20° and 45° (36,45). It is considered desirable to obtain images with the knee flexed as little as possible, because some patellae that appear lateralized at full knee extension become "centered" in the trochlear groove as the knee flexes (27,34,59). However, it is technically difficult to obtain a high-quality image with a conventional x-ray and a small knee flexion angle (59). Computed tomography (CT) and magnetic resonance (MR) imaging provide such high-quality imaging (27,34,59,61). Thus, despite prohibitive costs for routine clinical use, these latter techniques are considered valuable in obtaining information on subtle cases of maltracking.

The position and orientation of the patella relative to the femoral trochlear groove are commonly described with the congruence angle, CA (45), the lateral patellofemoral angle, LPA (47), and the patellar tilt angle, PTA (59). The CA is a measure of the medial/lateral position of the patella within the trochlear groove, and the LPA and PTA are measures of the medial/lateral tilt of the plane of the patella relative to the femur (Fig. 1).

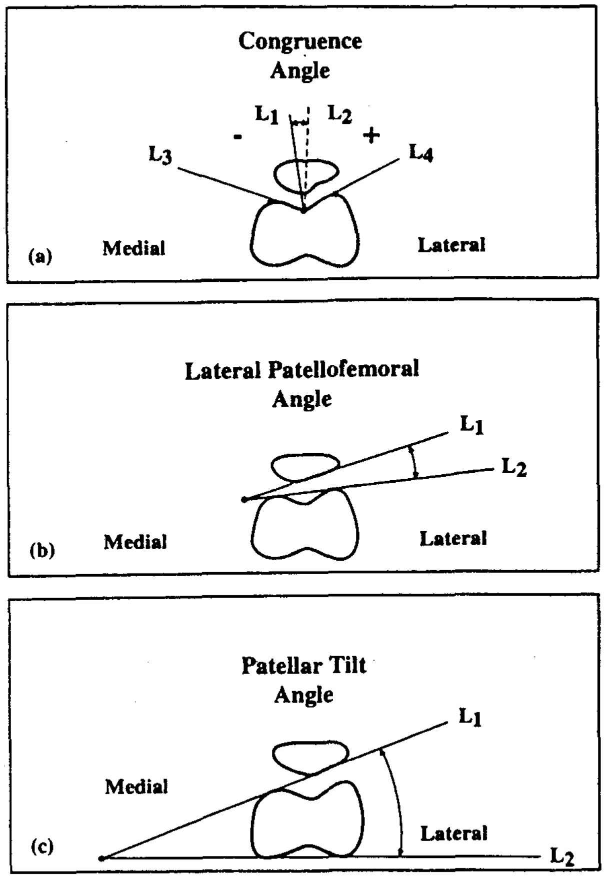

Figure 1—Depictions of (*a*) the congruence angle, (*b*) the lateral patellofemoral angle, and (*c*) the patellar tilt angle, measured from tangential view images of the patellofemoral joint. Each is depicted as the angle between L_1 and L_2. For (*a*) L_1 is drawn through the lowest point of the patella and of the femoral groove, and L_2 bisects the angle formed by L_3 and L_4, which are drawn through the lowest point of the femoral groove and the highest point of each femoral condyle (anterior). For (*b*) L_1 is drawn through the lateral patellar facet and L_2 is drawn through the highest point of each femoral condyle (anterior). For (*c*) L_1 is drawn through the lateral patellar facet and L_2 is drawn through the lowest point of each femoral condyle (posterior).

Normal two-dimensional patellar tracking has been characterized noninvasively using the techniques discussed above. Schutzer et al. (59) reported that the mean CA and PTA determined from CT images ($N = 10$ subjects) showed no statistical change when the knee flexed from 0° (full extension) to 30°. The results suggested that, through this range of motion, the patella was centered in the trochlear groove and did not tilt. Inoue et al. (27) analyzed conventional x-rays and CT images ($N = 30$) and reported that the mean LPA increased slightly during the initial 45° of knee flexion. These results suggest that the patella tilted medially a small amount with knee flexion. Kujala et al. (34) reported that the CA determined from MR images ($N = 10$) decreased and the LPA increased as the knee flexed from 0–30°. These findings suggest a medial patellar tilt and shift. In summary, the results of these imaging studies suggest that, for the normal patellofemoral joint, there is little change in the position and orientation of the patella in the transverse plane with knee flexion. The changes present suggest slight medial tilt and shift during knee flexion.

In contrast, patellar tracking patterns involving patellae tilted and/or shifted laterally relative to normal have been reported for patients with certain patellofemoral disorders. For 54 patients, Schutzer et al. (59) reported three patterns of malalignment characterized by the CA and PTA: lateral subluxation without lateral tilt, subluxation with tilt, and tilt without subluxation. Inoue et al. (27) reported that the LPA was smaller than normal values throughout knee flexion from 0–45° in 50 patients with laterally subluxing patellae. This suggests that the patella was tilted laterally relative to normal. The LPA moved toward control values as the knee flexed. Kujala et al. (34) reported that, throughout knee flexion, the CA was larger and the LPA was smaller, for 11 patients with laterally dislocating patellae than for normals, suggesting a lateral shift and tilt of the patella relative to normal. Both angles tended to move toward control values with knee flexion. Although tracking associated with medial subluxation has been described qualitatively (63), no quantitative data appear to have been reported.

Two-dimensional imaging of the true three-dimensional position and orientation of the patella relative to the femoral trochlear groove offers important but limited information. The relationships between the two-dimensional parameters and their three-dimensional counterparts are unknown. Generally, imaging has also been limited to static conditions, although some MR images have been obtained during active flexion (61). Another limitation of the imaging techniques is an absence of clearly defined and constant reference points upon which accurate and reliable spatial measurements can be made. A review of the literature revealed no reports of the accuracy or intertest reliability of image measurements. In an MR imaging study, the means and standard deviations for interobserver differences in the LPA and CA were 2.56 ± 3.26 and 2.50 ± 8.60°, respectively (34). [NB: In the same study, the mean LPA increased from 4–8°, and the mean CA decreased from 15° to –15°, as normal knees flexed from 0–30°.] The large variability indicates a need for further study of the accuracy and reliability of measurements made with imaging techniques.

Invasive techniques artificially place clearly defined and constant reference points into the patella and femur to enhance the accuracy and reliability of the measurements. One such invasive technique involves inserting at least three small (1-mm diameter) tantalum beads into the patella and femur (three points are the minimum necessary to determine the position and orientation of a rigid body in three dimensions). Photogrammetrical techniques are then used with biplanar conventional x-rays to determine the three-dimensional locations of the beads in various static knee joint configurations. The error associated with this technique has been reported to be less than 0.05 mm and 0.10° for linear and angular positions, respectively (30). Veress et al. (70) used this technique to describe patellar tracking in four patients with degenerative knee joint disease for whom high tibial osteotomies had been performed. Conventional biplanar x-rays were obtained with the knee held at 0, 30, 60, and 90° of flexion with unknown isometric quadriceps loads. Complete three-dimensional results were not reported, but the results presented showed that, in general, the patella tilted and shifted laterally with knee flexion. van Kampen and Huiskes (30) used this x-ray technique to study three-dimensional patellar tracking in four normal cadaver knees with simulated quadriceps loading. Their results showed that the patella flexed with knee flexion, but that patellar flexion lagged behind knee flexion. The patella also showed medial rotation, inconsistent medial/lateral tilt, and lateral shift with knee flexion (cf. Fig. 2 for definitions of motions).

Another invasive technique involves placing intracortical pins into the patella, tibia, and femur and attaching at least three markers to each intracortical pin. The markers are assumed to be rigid extensions of the underlying bone, and thus motions of the markers reflect motions of the bones. The three-dimensional motions of these external markers may then be determined using standard motion analysis methods. The error associated with this technique has been reported to be less than 1 mm and 1° for linear and angular positions, respectively (33). Koh et al. (33) used this technique to describe patellar tracking patterns for one normal male subject. During knee flexion while the subject was seated, the patella flexed (with a lag similar to that of van Kampen and Huiskes' study), tilted laterally, and shifted laterally (cf. Fig. 2). The patellar tracking pattern for seated knee flexion was very similar to that during a squatting exercise despite measured differences in tibial rotations and assumed differences in quadriceps activation. The small differences observed occurred in the first few degrees of knee flexion, probably before the patella had become well seated in the trochlear groove of the femur.

The intracortical pin technique has also been used to investigate patellar tracking during locomotion. Lafortune (35) used the intracortical pin technique to describe the patellar tracking patterns of three normal subjects during walking. McClay et al. (44) used similar methods to determine the tracking patterns for two normal subjects and two patellofemoral pain patients during running. Both studies reported consistent relationships between patellar flexion (cf. Fig. 2) and knee flexion, with patellar flexion lagging behind knee flexion. Both also reported a tendency for the patella to laterally rotate (abduct in their terminology) with knee flexion. Little consistency was found in medial/lateral tilt (internal/external rotation in their terminology) of the patella with respect to knee flexion and in intersubject comparisons. Finally, Lafortune found a trend of lateral shift with knee flexion, while McClay reported a general pattern of medial shift with knee flexion with patellofemoral pain patients showing greater medial-lateral excursions than the normal subjects.

Limitations of the tantalum bead and intracortical pin techniques include the usual risks associated with invasive techniques, and reluctance of subjects to participate in such studies. It is notable, however, that subjects have reported only minor discomfort during and after one study (33) and no complications have been reported in any of the studies (33,35,44,70). Another possible limi-

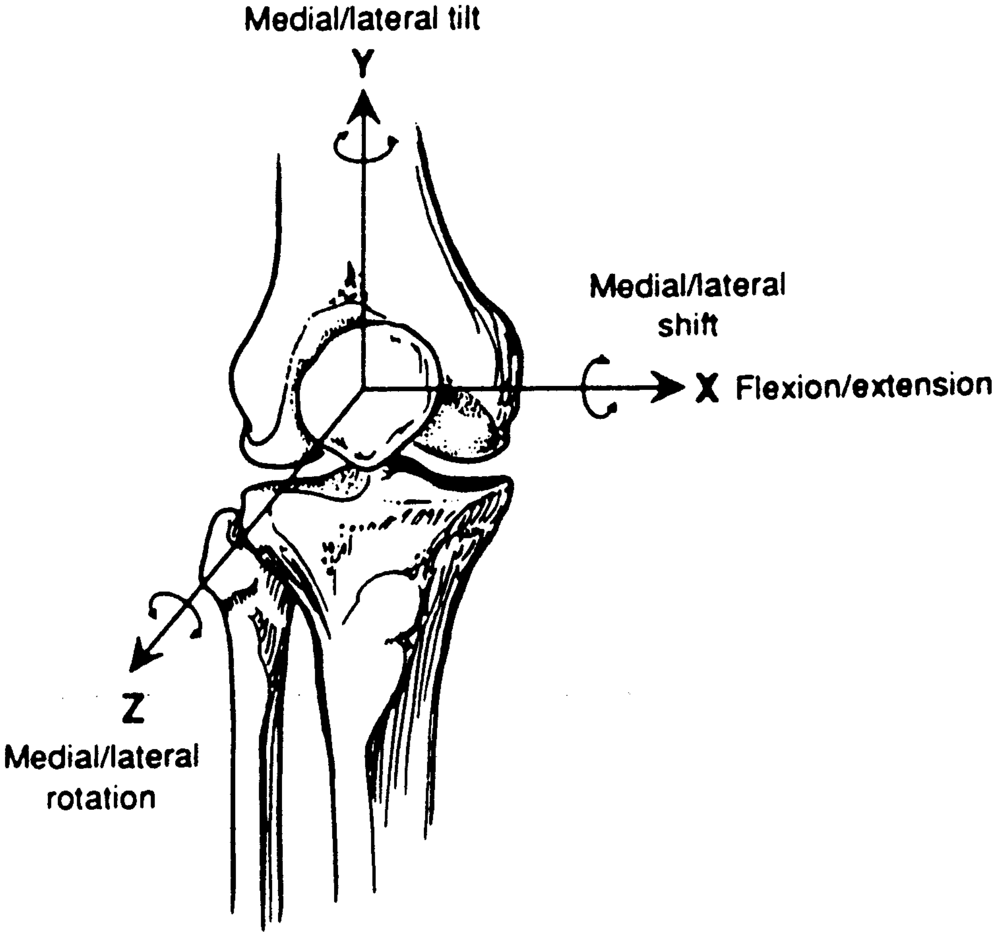

Figure 2—Reference system for the patella and associated motions. The X-axis is directed medially, from lateral to medial femoral condyle, the Y-axis directed superiorly along the long axis of the femur, and the Z-axis anteriorly. Rotations about the X-, Y-, and Z-axes were termed flexion/extension, medial/lateral tilt, and medial/lateral rotation, respectively. Translation along the X-axis was termed medial/lateral shift. The terms before the slashes indicate motions with positive values, and those after, motions with negative values.

tation especially for the intracortical pin technique is that the technique itself may influence patellar tracking. However, soft tissue incisions were made to minimize possible pin impingement (33,35,44). For at least one study (33), the mass characteristics of the pin/marker system (8.5 g effectively located approximately 6 cm from the bone) were considered negligible for the motions investigated. An important limitation of both invasive techniques is that, although motions of the markers accurately represent motions of the underlying bones, additional information is needed to infer the proximity of the articular surfaces of the patella and femur from the positions of the markers. This additional information is likely to be obtained using an imaging technique in which the articular surfaces are defined relative to the markers.

A variety of patellar tracking patterns have been described for subjects without symptoms and for patients with patellofemoral pain. For normal subjects, noninvasive studies tended to show a small amount of medial tilt and translation of the patella with knee flexion whereas the invasive studies tended to show a small amount of lateral tilt and shift. These differences may reflect differences in the testing conditions. For noninvasive studies, the conditions were generally static with the knee joint muscles relaxed and the subject lying down. For invasive studies, the conditions were generally dynamic with quadriceps loading. The differences in results may also reflect differences in the parameters used to characterize patellar orientation and position—the precise relationships between the parameters used in the two-dimensional noninvasive and the three-dimensional invasive studies is unknown. One factor influencing this relationship is the reference system used for each study. A limitation of the noninvasive studies is that a slightly different reference system is used for each image in a series of flexion steps of the patellofemoral joint.

Choosing a reproducible and intuitive reference system is perhaps the most important task for patellar tracking and other joint kinematics studies. Shellock et al. (62) have noted a number of difficulties in producing quantitative data for patellar tracking and have advocated a qualitative approach. These authors have noted that bony structure irregularities (abnormally shaped trochlear grooves and patellae) can be problematic for defining consistent and meaningful reference systems for the femur and patella. However, the qualitative criteria described by these authors depend implicitly on a reference system. For instance, lateral subluxation is indicated when “the apex of the patella is laterally displaced relative to the femoral trochlea groove or the centermost part of the femoral trochlea.” In this case, the position of the patella is subjectively determined relative to a reference system implicitly defined for the trochlear groove. Although subjective analysis may be useful for diagnosing patients, explicitly defined reference systems and quantitative measures would seem essential for scientific investigation. Quantitative three-dimensional assessment of femoral and patellar shapes from CT or MR images should help in determining reliable reference systems and provide meaningful information on articular approximation and relative movements.

The accuracy and reliability of the invasive techniques make them desirable for use in further scientific study of patellar tracking. Future study could include a rigorous verification of the accuracy and reliability of measurements made with CT and MR imaging techniques. In addition, precise evaluations of the effects of conservative and surgical interventions for maltracking patellae on patellar tracking seem warranted. If accurate three-dimensional noninvasive techniques can be developed, perhaps with the aid of the invasive techniques, then the limitations associated with the invasive procedures can be avoided. Although quantitative three-dimensional MR imaging has been reported (e.g., 66), application to patellar tracking has not yet appeared in the literature.

Future directions might thus include developing a subject-specific mathematical surface model of the patellofemoral joint using MR images and photogrammetrical techniques. The kinematic MR imaging technique (61) could then be used in conjunction with this model to determine the three-dimensional tracking pattern of the patella relative to the femur, including information on the proximity of the articular surfaces. The next step could be to include muscle and soft tissue forces into the model, and attempt to predict patellofemoral joint motions and forces for different simulated loading conditions. Such a model might contribute to the characterization of the relationship between patellar tracking and patellofemoral disorders and to predict the outcomes of interventions for maltracking patellae.

PATELLOFEMORAL PRESSURE

Studies have indicated that the normally occurring patellofemoral joint reaction force (PFJR) can be several times that of body weight during certain functional activities (26,43,50,56,69). This led to the assumption that malalignment of the patellofemoral force system could be associated with an increase in patellofemoral contact force, a decrease in patellofemoral contact area, or both. The result, increased patellofemoral contact pressure could be the mechanical stimulus triggering damage to the cartilage (14,53). Many cadaver studies have been directed at determining patellofemoral contact pressures in the normal knee (1,2,13,24,55,60) and following some clinically relevant alteration in the biomechanics of the patellofemoral joint (1,9,13,24,25).

Bandi (2) may have been the first to perform an *in vitro* study of patellofemoral contact pressures. He measured the PFJR in both a metal model of the patellofemoral joint and in a cadaver knee using a piezoelectric force transducer. Patellofemoral pressures were calculated based on the assumption that contact occurred over the entire articular region of the patella. Perry et al. (55) reported a similar technique, whereby they sandwiched two pressure transducers into the patella of a single cadaver knee to measure the patellar compressive force and carbon paper to measure the patellofemoral contact area. The measured contact areas were not reported, but patellofemoral compressive forces, reported as indicative of the patellofemoral contact pressures, increased from 0.1 times body weight at 5° of flexion to 2.1 times body weight at 60°. These earliest *in vitro* studies had limitations, especially with regard to contact area measurements, but addressed the problem of measuring patellofemoral contact pressures and provided some insight into their magnitude.

Two studies reported in 1977 provided more accurate measures of patellofemoral contact area and provided quantitative information on patellofemoral contact pressures. Seedhom and Tsubuku (60) reported a casting technique for measuring patellofemoral contact area. The deformation of the femoral cartilage at the patellofemoral interface during dynamic loading of the quadriceps of a cadaver knee was measured. Oscillating quadriceps loads of 20–1200 N were applied over time periods of 0.1–0.5 s for a given knee flexion angle. Quadriceps loads necessary to maintain the deformation corresponding to a specific load were then applied while obtaining a casting of the space surrounding the patellofemoral joint. The casting was then photographed and the contact area, represented by the void in the casting, was measured using polar planimetry. Although the method used to determine the PFJR, necessary for the computation of pressure, was not described, they reported average patellofemoral contact pressures ranging from 1.4–2.0 MPa for flexion angles from 45–90° (Table 1).

Matthews et al. (43) developed a methylene blue contact print technique to measure PFJR contact area. The patella was painted with methylene blue, a 250-N quadriceps load was applied, and the area of the resulting imprint on the femur was measured using photography and planimetry. A trigonometric equation to compute the PFJR for a given quadriceps force based on the geometry of the extensor mechanism, and on the assumption that the patellar mechanism acts as a frictionless pulley was developed. The knee extensor mechanism geometry was measured using x-ray images to identify the locations of metallic markers inserted in the quadriceps tension and patellar ligament of cadaveric specimens during the manual application of unspecified magnitudes of quadriceps forces. This methodology, performed on 15 knees, enabled the prediction of PF contact pressures using their

TABLE 1. Comparison of published patellofemoral pressure data.

Study	Knee Flexion Angle (deg)	Quadriceps Force (N)	Patellofemoral Contact Pressure (MPa)
Seedhom et al. (60)	45	565	1.5
	60	601	1.4
	90	1172	2.0
Matthews et al.[a] (43)	15	647	1.9
	30	785	2.5
	45	1923	5.3
	60	1687	4.5
Matthews et al.[b] (43)	15	1776	5.0
	30	2168	6.6
	60	2530	6.8
	90	2717	9.4
Ahmed et al.[c] (1)	Level walking	734	1.5–1.9
	Walking up ramp	734	2.1–2.3
	Walking down ramp	734	3.3–3.6
	Ascending stairs	734	3.5–4.1
	Descending stairs	734	3.3–3.4
Huberti and Hayes (25)	20	NR[d]	2.0
	30	NR	2.3
	60	NR	4.0
	90	NR	4.1
D'Agata et al. (9)	20	500	2.2
	30	700	3.0
	60	750	2.5
	80	700	2.5

[a] Using Morrison's (50) quadriceps force predictions.
[b] Using Smidt's (65) quadriceps force predictions.
[c] The values correspond to maximum patellofemoral pressures found.
[d] NR = not reported.

measurements of patellofemoral contact area and using their equation in conjunction with those of Morrison's (49) and Smidt's (65) for predicting quadriceps forces. They reported average patellofemoral contact pressures ranging from 1.9–9.4 MPa for flexion angles from 5–90° (Table 1).

The aforementioned studies were primarily focused upon the development of techniques by which patellofemoral pressures could be estimated. From a clinical vantage, it was of great interest to quantify the changes in patellofemoral mechanics and patellofemoral pressures subsequent to surgical interventions. This interest was paralleled by improvements in pressure sensing technology. Ferguson et al. (13) reported on the use of miniature (0.5-mm thick and 2-mm diameter) pressure transducers to measure the effects of elevating the patellar tendon (by displacing the tibial tubercle by 0.5, 1, and 1.5 inches) on patellofemoral pressures. The piezoelectric transducers were implanted in six different locations on the patella, flush with the retropatellar surface. Isometric quadriceps loads, simulated using an Instron, cycled between 10 and 220 N for flexion angles of 0, 45, and 90°. The study demonstrated that elevation of the patellar tendon provided relief of contact pressures at all angles of flexion tested with the most pronounced effects on local pressures occurring at 90°. The first 0.5-inch of tendon elevation resulted in average reductions in contact pressures of 83.3% at 90°, 57% at 45°, and 91% at 0° of knee flexion.

Ahmed et al. (1) evaluated the sensitivity of the patellofemoral contact pressures to variations in the loads applied to the four heads of the quadriceps femoris. Patellofemoral contact pressures were measured in 24 cadaveric knee specimens using a plastic indentation transducer for knee flexion angles ranging from 0–130° while loads of 734 N were applied to each of the four heads of the quadriceps. By implementing the quadriceps loads reported by Morrison (49,50) in conjunction with the patellofemoral joint reaction force computed by Matthews et al. (54), Ahmed et al. were able to report patellofemoral contact pressures for daily living activities. The contact pressures in the normal knee were reported to range from approximately 1.5–1.9 MPa for level walking to 3.5–4.1 MPa for climbing stairs (Table 1). Relative to the sensitivity of the contact pressures to quadriceps forces, it was found that the removal of tension from either the vastus medialis oblique or the vastus lateralis considerably altered the pressure distributions; when tension in the vastus medialis oblique was removed, the pressure zone moved mostly to the lateral facet, and when the tension in the vastus lateralis was removed the pressure zone moved mostly to the medial facet. Alterations in the lines of action of these two muscles also had strongly marked effects on the location and orientation of the pressure zone. The results suggest that the popular lateral capsular release may alter both the magnitude and distribution of patellofemoral pressure among the facets of the patella.

Huberti and Hayes (24) reported on the PF contact pressures in 12 cadaveric knees using pressure sensitive (Fuji Prescale) film. Their methodology enabled the application of bending moments to the knee joints through a loading fixture that allowed them to vary both the Q-angle of the patellar ligament and the knee flexion angle. Applied flexion moments to the knee were based on one-third the maximum voluntary isometric extension moments reported in the literature. Linearly extrapolating their patellofemoral contact pressures at 90° of knee flexion from one-third of the maximum moment to maximum *in vivo* moments resulted in pressures of approximately 12 MPa (Table 1), which is close to that predicted by Matthews et al. (43) using the isometric quadriceps force levels predicted by Smidt (65). They also found that both increases and decreases in Q-angle resulted in less uniform pressure patterns than observed in the normal knee, with increased peak pressures in some areas and reduced pressures in others. Two different contact patterns were discovered with both variations in Q-angle that could not be predicted from the morphology of the patella alone. They concluded that these findings contraindicated the use of reconstruction procedures aimed at reducing Q-angle in patients with chondromalacia and a normal Q-angle. The results also suggested that both increased and decreased Q-angles may play a role in the pathogenesis of chondromalacia.

Huberti and Hayes (25) later used previously developed techniques to measure contact pressures in 10 patellofemoral joints with degenerative lesions to determine the effects on those pressures of four different capsular reconstructions. They found that for the intact, normal capsule, localized lesions of grade I–II demonstrated a 50% reduction in pressure directly over the lesion, while lesions of grade III–IV demonstrated reductions in pressure greater than 90%. Furthermore, capsular reconstruction procedures (medial plication, lateral plication, lateral release, and bilateral release) did not demonstrate consistent reductions in pressure, nor did they demonstrate more uniform pressure patterns. Moreover, the more popular lateral capsular release resulted in no change in three knees and four different pressure distributions in the other seven knees.

Most recently, D'Agata et al. (9) investigated the effect on patellofemoral contact pressures following removal of the central one-third of the patellar tendon, before and after closing the resulting defect with suture. The motivation for this study arose from reports of patellofemoral pain subsequent to reconstruction of the anterior cruciate ligament deficient knee (58,69,72). In particular, some authors have attributed patellofemoral pain to contracture of the patellar tendon (53,54,59). Thus, D'Agata et al. investigated if closure of the defect, resulting from removal of the central one-third of the patellar tendon, would lead to enough contracture of the patellar tendon that an alteration in patellofemoral contact pressure might occur. They found that neither removing the central one-third of the patellar tendon, nor closing the resulting gap significantly altered average patellofemoral contact pressures (Table 1). The investigators indicated that their model, however, did not assess the effects that postoperative biological processes, such as a pathological contracting cicatricial response of the patellar tendon, might have on the patellar mechanism and, hence, on the patellofemoral contact pressures.

The foregoing *in vitro* studies have begun to provide baseline data on normal patellofemoral contact pressures and have begun to provide data on the effects of clinically relevant changes in the biomechanics of the patellofemoral joint on patellofemoral contact pressures. Because of the inherent limitations of the cadaver model, such *in vitro* studies cannot assess the effects that postoperative biological processes and physical activities might have on patellofemoral pressures. Nevertheless, these *in vitro* studies demonstrate that alterations in the normal biomechanics of the patellofemoral joint can lead to substantial changes in the magnitude, distribution, and pattern of patellofemoral contact pressures. However, it is also apparent that much more research in this area needs to be performed.

NEUROMOTOR CONTROL OF PATELLOFEMORAL AGONISTS

Perhaps the least understood of the factors thought to be associated with patellofemoral pain are the relationships among the neuromotor control of the knee joint musculature, the onset/recurrence of symptoms, and rehabilitation. Neuromotor control is assumed to be disturbed in the presence of patellofemoral pain and the restoration of normal control is, at least implicitly, one of primary goals of conservative treatment of patellofemoral pain. Conservative treatment has been reported to be successful in over 75% of patients (10), although Devereaux and Lachman (11) have reported that 70% of conservatively treated patients are symptomatic 12 months following the intervention. Two components of conservative treatment of patellofemoral pain are the modification of the patient's activity profile and the use of anti-inflamatant and pain medications. A third component, short-arc, or limited range of motion, quadriceps strengthening exercises are generally performed through the initial 20–30° of knee flexion. These exercises are almost universally prescribed and are considered the cornerstone of conservative treatment. The underlying rationale for the clinical acceptance of the short-arc quadriceps exercise is founded first, and perhaps most defensibly, on cadaveric studies that have supported the contention that through this range of knee joint flexion the patellofemoral joint contact forces and pressures are small relative to other joint angles. The effect of these reduced forces and pressures is decreased pain during knee joint exercise and, thus, increased patient compliance during rehabilitation.

A common clinical opinion is that in the presence of knee trauma or injury "the VMO [vastus medialis oblique] is the first to atrophy and the last to be rehabilitated" (22). The data of Gerber et al. (18) offered partial support for this opinion. In anterior cruciate ligament deficient subjects, the VMO demonstrated greater atrophy than other quadriceps components. However, although the atrophy level was statistically significant, the relative decrease in VMO cross sectional area was only 2.7% greater than the relative decrease in the total cross-sectional area of the quadriceps.

The perceived need to selectively rehabilitate the VMO may be related to the conviction that the VMO is selectively atrophied, and that the VMO is crucial to normal patellofemoral joint function. Short-arc quadriceps exercise is often promoted as a vehicle through which *selective strengthening* of the VMO can be achieved. The selective strengthening of the VMO is thought to improve an assumed disruption of the mechanical balance of medially and laterally directed forces exerted on the patella that influences patellar tracking patterns and patellofemoral contact forces and pressures. Thus, restoration of the balance of this force system is thought to result in an appropriately positioned patella within the trochlear groove, decreased patellofemoral forces and pressures, and improved quadriceps efficiency.

Although selectively strengthening the VMO may be desirable, the question of whether it can occur has been debated clinically and scientifically for many years. The debate may have its roots in a paper by Lieb and Perry (37) that identified the anatomic distinction between the VMO and its more vertically oriented partner, the vastus medialis longus. Two notable observations included the fact that the VMO is not capable of contributing to knee extension moment, and that the efficiency of the vastus lateralis in generating knee extension moment is decreased if the patella becomes lateralized in the femoral trochlear groove. These findings, plus the pennation angle of the VMO relative to the vertical axis of the patella (approximately 45°) lend much credibility to the proposition of a singular functional role for the VMO: to medially track the patella.

There is abundant evidence in the clinical literature of the belief that selective VMO strengthening is possible. Shelton and Thigpen (64) refer to "good VMO control," "VMO facilitation," and in a statement suggesting that the VMO is separate from the quadriceps femoris, refer to "VMO and quadriceps strengthening." The reference to "selective VMO strengthening" is also quite common (3,16,17,28). However, the quantification of *in vivo* selective strengthening in humans is simply not possible. Thus, the issue of selective strengthening of the VMO is somewhat contentious. Generally, a solution to the question of whether *selective activation* of the VMO occurs has been sought. The underlying assumption of this course of reasoning is that if a muscle can be selectively activated, it may be possible to produce a selective training effect.

Selective activation can refer to individual motor units as well as individual muscles within a synergistic group. There is a convincing body of published literature suggesting that selective activation does occur during reflexive and voluntary conditions. Some examples of conditions in which selective activation include rapid automatic motions such as bicycling at high rates, maximum effort hopping, and eccentric muscle contractions in humans (6,48,51,52), paw-shaking in cats (15,67), and rapid breathing in rabbits (7,8). The evidence related to selective activation of the VMO is less compelling. Various authors have reported that it is possible to activate the VMO to a significantly greater extent than the VL during some types of knee extension activities (23,26,31,40,68). However, other authors have reported that there are no differences in relative activation of these two muscles (5,32,38,39,42,46,47,57,74). Careful review of the individual articles on both sides of the argument reveals many aspects that may be criticized, including data collection or analysis methods. These criticisms are often important enough to cast some suspicion on the conclusions. In some papers, for example, the incorrect aspect of the vastus medialis muscle (the longus fibers) was monitored. In some cases, electromyographic analyses were implemented that have subsequently been demonstrated to be less than sensitive. Other studies, although more recently reported, can be seriously challenged for making fundamental analytical mistakes such as directly comparing absolute EMG values from different muscles. Biofeedback has been reported as having limited success at increasing relative activation of VMO compared with VL. However, these studies, by necessity, used muscle contractions of generally relatively low-tension levels. The minimum stimulus for strength gains in a muscle or muscle group is generally accepted as 60% of maximum force (41); a value that exceeds those used in biofeedback studies. Thus, the question of whether there is a significant carryover effect to more challenging motor tasks is largely unanswered.

The difficulty in resolving the issue of whether or not relative differences in VMO and VL activation can be achieved by reviewing the literature is compounded because for the most part the published work is that of numerous individuals and teams, each employing different methods of collection and analysis. At this point, the results from a series of investigations performed in the laboratory of one of the authors will be presented. The characteristics of reports from the same laboratory is one of consistency, for better or worse, with regard to some of the methodologically influential characteristics such as dynamometers, EMG instrumentation, and EMG analysis.

Although selective strengthening cannot be measured, it is possible to measure, indirectly, selective fatigue. Grabiner et al. (19) hypothesized that short-arc quadriceps exercise would not result in a selective fatigue of the VMO relative to the VL. The hypothesis was based upon (a) the larger cross-sectional area of the VL (73) and (b) the larger proportion of Type II muscle fibers in the VL (29). The first factor, larger cross-sectional area, translates to a larger absolute maximum force for a given fraction of maximum contraction force. As muscle force increases, there are concomitant increases in intramuscular pressure and occlusion of blood flow. Thus, for a specific level of activation, the absolute muscle force, intramuscular pressure, and diminution of blood flow of the VL is expected to be larger than that of the VMO. Second, the larger proportion of Type II muscle fibers in VL suggests that at large knee extension forces, the accumulation of glycolytic metabolites in the VL should be larger than in the VMO thus contributing to a greater rate of fatigue. Relative fatigue of the VMO and VL was quantified using the median frequency of the power density spectrum of the EMG, which reflects the changes to muscle action potential propagation velocity associated with the metabolic processes of muscular fatigue. Two conditions of isometric knee extension force (30 and 60% MVE) and a condition of dynamic concentric-eccentric short-arc knee extension contractions were studied. The study concluded that the difference between fatigability (which qualitatively tended to be larger in the VL) was not significant.

Grabiner et al. (20) investigated the effect of patellofemoral pain on VMO and VL activation patterns. VMO and VL activation, quantified using normalized integrated EMG, was studied in a normal group and a group being clinically treated for patellofemoral pain. Three conditions of knee extension force generation were studied, constant force isometric knee extension at 20, 50, and 80% MVE, maximum effort knee extension performed as fast as possible (in a step fashion), and maximum effort knee extension developed over 3 s (in a ramp fashion). As expected, no intergroup activation differences were found during the constant force conditions. The hypothesis that patellofemoral pain subjects would demonstrate significantly different VMO and VL activation patterns during ramp and step contractions was partially borne out. It was hypothesized that patellofemoral pain subjects would demonstrate significantly different activation from normal subjects during dynamic (ramp and step) conditions. Although there were no intergroup differences in the ramp force condition, the activation of both the VMO and VL were significantly lower than that of the normal subjects in the step force condition.

The study also tested the hypothesis of a feedforward activation (larger relative initial VMO activation compared to that of VL) during step force conditions in which it was expected that the initial VMO activation would exceed that of VL. This hypothesis was not supported statistically and, thus, the results of the study argued against the feedforward activation of VMO during maximum effort contractions as measured by activation amplitude. However, temporal- or amplitude-related feedforward activation to the VMO compared to the VL remains a reasonable expectation from a neuromechanical standpoint. Despite the mechanical advantage offered by the direction of its muscle fibers, without some activation-related advantage the smaller force and velocity-generating capabilities of the VMO compared with the VL would be predicted to be associated with dominance of patellar motion by the laterally directed forces. This laterally directed dominance could be reduced (a) if VMO activation was initiated prior to that of the VL, and/or (b) if the relative activation of the VMO was larger than that of the VL. Either, or both, of these mechanisms could result in a change in the ratio of absolute medial to lateral forces that could ensure appropriate tracking.

In support of a feedforward activation, Voight and Wieder (71) reported that when subjected to patellar tendon taps, the reflex time of the VMO was significantly faster than that of the VL. Notably, this pattern was reversed in patients with extensor mechanism dysfunction. Based upon the failure of maximum isometric (step) conditions to yield *statistical* evidence of feedforward, Grabiner and Koh (unpublished observations) hypothesized that feedforward activation characteristics might become evident during voluntary contraction conditions known to be associated with activation levels larger than "normal" maximum efforts. The desired conditions of supramaximum voluntary activation was achieved by preceding knee extension contraction with isometric activation of the hamstrings. The influence of four levels of hamstrings preactivation (25, 50, 75, and 100% maximum) on maximum effort isokinetic ($250°\cdot s^{-1}$) knee extension and the relative timing and amplitudes (normalized integrated EMG) of VMO and VL activation was investigated. Temporally, the VMO was observed to become activated earlier (mean = 5.6 ms) than the VL across all conditions. Although the difference was statistically significant, the functional significance of this earlier activation may be challenged. The activation level of the VMO and VL was measured from the onset of activation to the instant of peak knee extension force. Hamstrings precontraction did increase the activation levels of both the VMO and VL ($P < 0.05$) and the level of increased activation was observed to be a function of the intensity of hamstrings activation. However, the difference between the levels of VMO activation and those of VL were not significant. Thus, based upon the failure of functionally meaningful differences in the timing of VMO and VL activation to become evident and the failure of the activiation amplitudes of the muscles to demonstrate significant differences, these data tend to contest the feedforward activation hypothesis.

If CNS exploitation of muscle architecture and properties occurs then it is likely that other related-tissues would be called upon for their contribution. Bose et al. (4) reported a connective tissue link between the origin of the VMO and the adductor magnus and longus. Brownstein et al. (5) interpreted these observations to suggest that hip adduction exercises could provide a vehicle to selectively strengthen the VMO. The addition of hip adduction, or in some cases tibial rotation to knee extension exercise, has often been promoted and some evidence has been reported to support these contentions. For example, Hanten and Schulties (23) reported that isolated hip adduction exercise was associated with a significantly greater VMO activation compared with that of the VL. Maximum effort hip adduction conditions were reported as having been associated with VMO and VL activation of approximately 62% and 46%, respectively, of the activation levels observed during isolated maximum knee extension. Their conclusions were challenged by Grabiner et al. (21) on methodological issues. In the study by Grabiner et al., the purpose of which was to determine the effect of concomitant hip adduction and knee extension forces on the relative activation profiles of VMO and VL, those factors in the Hanten and Schulties paper that had been criticized were carefully controlled. Grabiner et al. reported that the addition of a 50% MVE hip adduction contraction to isometric knee extension of 25, 50, 75, and 100% MVE failed to effect the activation of either the VMO or VL as measured by normalized integrated EMG. Based upon the previous work of this group it was not surprising that there was no difference between the activation levels of the VMO and VL.

In view of the broad distribution of findings in the literature on the topic of selective VMO activation, one may be tempted to conclude that the issue remains unresolved. Careful evaluation of those studies that either support or refute the notion, however, may lead to a different conclusion. The series of experiments performed in a single laboratory perhaps offer the strongest evidence against selective VMO activation and strengthening within the framework of the limitations associated with the measurement and quantification of muscle activation data. If selective activation and strengthening do not occur, then exercise intervention simply causes the quadriceps femoris muscle to experience a general strengthening effect. If VMO force is crucial to maintain a symptom-free patellar tracking system, there may be a threshold VMO strength required for proper tracking. If atrophy causes a general reduction in quadriceps strength and a specific VMO reduction below the threshold, then maltracking may result. Exercise, in this scenario, would simply act to restore the required force potential in the VMO but not in a selective manner.

There are questions related to knee joint muscle activation and its relationship to patellofemoral pain that remain unanswered. The exercise interventions used for patients with patellofemoral pain have not, and probably cannot, all be individually investigated; more so in view of the fact that variations on themes seem to surface on a regular basis. Questions remain with regard to (a) the basic control strategies used by the central nervous system to control knee joint musculature, (b) changes to the strategies that may occur in the presence of pain, (c) the relationship of these strategies to the onset and duration of, and recovery from patellofemoral pain, and (d) the relationships between the control strategies, changes in the control strategies and patellar tracking and subsequent patellofemoral forces and pressures. The technologies that have been used thus far to address these and related questions may prove to lack the sensitivity needed. An example of a new approach to test the hypothesis of the eccentric role of the VMO is the emerging methods of magnetic resonance spectroscopy for distinguishing muscles that contract concentrically and eccentrically. Solutions to the above questions will have a significant influence on orthopaedic and sports physical therapy rehabilitation methods.

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