Patellar Kinematics, Part I: The Influence of Vastus Muscle Activity in Subjects With and Without Patellofemoral Pain
Christopher M Powers
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Patellar Kinematics, Part I: The Influence of Vastus Muscle Activity in Subjects With and Without Patellofemoral Pain

Background and Purpose. Reduced motor unit activity of the vastus medialis muscle relative to the vastus lateralis muscle has been implicated as a cause of lateral patellar subluxation. The purpose of this study was to assess the influence of vastus muscle motor unit activity on patellar kinematics. Subjects. Twenty-three women (mean age = 26.8 years, SD = 8.5, range = 14–46) with a diagnosis of patellofemoral pain and 12 women (mean age = 29.1 years, SD = 5.0, range = 24–38) without patellofemoral pain participated. Only female subjects were studied because of potential biomechanical differences between sexes. Methods. Patellar kinematics (kinematic magnetic resonance imaging) and vastus muscle electromyographic (EMG) activity using indwelling electrodes were measured during resisted knee extension. Measurements of medial and lateral patellar displacement and tilt obtained from magnetic resonance images were correlated with normalized vastus lateralis:vastus medialis oblique muscle and vastus lateralis:vastus medialis longus muscle EMG ratios at 45, 36, 27, 18, 9, and 0 degrees of knee flexion using a stepwise regression procedure. Results. The vastus lateralis:vastus medialis longus muscle EMG ratio contributed to the prediction of lateral patellar displacement at 27 degrees of knee flexion ($r = -0.48$), with increased vastus medialis longus muscle activity being associated with greater lateral patellar displacement. A similar inverse relationship was evident with lateral patellar tilt at 36, 27, 18, and 9 degrees of knee flexion. Conclusion and Discussion. These results suggest that increased motor unit activity of the vastus medialis muscle appears to be associated with abnormal patellar kinematics in women, but it is not necessarily a cause of abnormal patellar kinematics. [Powers CM. Patellar kinematics, part I: the influence of vastus muscle activity in subjects with and without patellofemoral pain. Phys Ther. 2000;80:956–964.]

Key Words: Electromyography, Magnetic resonance imaging, Patellar kinematics, Patellofemoral joint, Quadriceps femoris muscle.

Christopher M Powers
Patellar instability is commonly thought to be the result of unequal activity of the various components of the quadriceps femoris muscle. More specifically, lateral patellar subluxation has been attributed to reduced motor unit activity of the vastus medialis muscle. Lieb and Perry separated the vastus medialis muscle of cadavers into 2 functional components based on fiber orientation, with the proximal longitudinal fibers being termed the vastus medialis longus muscle (VML) and the distal oblique fibers being designated the vastus medialis oblique muscle (VMO). As a result of its more horizontal fiber orientation, they considered the VMO to be the primary medial stabilizer of the patella. This premise has formed the theoretical basis for exercises for patellofemoral pain (PFP) because improving VMO force is thought by some authors to be essential in overcoming the lateral pull of the much larger vastus lateralis muscle (VL).

Despite the large emphasis on the VMO in the treatment of PFP, assessment of VMO force production in vivo is not possible. In lieu of this limitation, electromyography (EMG) has been used to establish the activity patterns of the vastus muscles with the rationale that decreased activity of the VMO relative to the VL is indicative of compromised medial patellar stability. Numerous researchers have compared the EMG activity of the VMO with that of the VL. There is no general consensus, however, as to whether reduced motor unit activity of the VMO exists in people with PFP or, more importantly, whether it is predictive of abnormal patellofemoral joint function.

With the advent of kinematic magnetic resonance imaging (KMRI), quantification of patellar kinematics throughout an arc of resisted knee extension is possible. This diagnostic technique has a distinct advantage over imaging procedures that do not allow for knee movement because contributions of the extensor mechanism to patellofemoral joint kinematics can be assessed.

The purpose of this investigation was to assess the influence of vastus muscle activity (as determined through EMG) on patellar tracking patterns in subjects with and without PFP. I hypothesized that lateral displacement and lateral tilting of the patella would be associated decreased vastus medialis muscle activity relative to the VL.

**Method**

**Subjects**

Twenty-three women with a diagnosis of PFP and 12 women without PFP participated in this study. Only female subjects were studied because of potential biomechanical differences between sexes. Both groups were similar in age, height, and weight (Tab. 1). Age, height, and weight were found to be normally distributed within each group and when data from both groups were

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Dr Powers provided concept/research design, writing, data collection and analysis, subjects, project management, and fund procurement.

This study was approved for human subjects by the Los Amigos Research and Education Institute Inc of Rancho Los Amigos Medical Center, Downey, Calif.

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combined. No attempt was made to match each subject specifically for age, height, and weight, as there is no evidence in the literature to suggest that individuals of different ages, heights, and weights will demonstrate differences in patellar kinematics.

The subjects with PFP were patients of the Southern California Orthopaedic Institute who were deemed to be appropriate candidates by the treating physician. Prior to participation, all subjects with PFP were screened to rule out ligamentous instability, internal derangement, and patellar tendinitis. Each subject’s pain originated from the patellofemoral joint, and only patients with histories relating to nontraumatic events were accepted. In addition, pain had to be readily reproducible with at least 2 of the following activities: stair ascent or descent, squatting, kneeling, prolonged sitting, or isometric quadriceps femoris muscle contraction.2,19 Subjects were excluded from the study if they reported previous knee surgery or a history compatible with acute traumatic patellar dislocation.

Individuals comprising the comparison group were recruited by word of mouth and were either employees of Rancho Los Amigos Medical Center (Downey, Calif) or students from the University of Southern California. Subjects had to have no history or diagnosis of knee pathology or trauma and they had to be free of any current knee pain. In addition, these subjects did not report pain with any of the activities listed earlier.

**Instrumentation**

**Kinematic magnetic resonance imaging.** Kinematic magnetic resonance imaging (KMRI) of the patellofemoral joint was assessed with the transmit and receive quadrature body coil of a 1.5T magnetic resonance system* using a fast-spoiled GRASS pulse sequence.16 Axial-plane imaging was performed using the following parameters: time to repeat=6.5 milliseconds, time to echo=2.1 milliseconds, number of excitations=1.0, matrix size=256×128, field of view=38 cm, flip angle=30 degrees, and a 7-mm section thickness with an interslice spacing of 0.5 mm.16 Acquisition time was 6 seconds to obtain 6 images (ie, 1 image per second).

All imaging was performed using a specially constructed, nonferromagnetic positioning device† that permitted bilateral knee extension against resistance (in the prone position) from 45 degrees of flexion to full extension (Fig. 1). The device was designed to allow uninhibited movement of the patellofemoral joint and natural rotation of the lower extremities. I believe that these design features are important because patellar tracking may be influenced by tibial rotation.20

Resistance was provided through a pulley system with a constant 30.5-cm lever arm. The design of the device was such that the application of the force was always perpendicular to the tibia to ensure a constant (isotonic) torque throughout the entire range of motion.16 Weights constructed of nonmagnetic, 316L series stainless steel‡ supplied the resistive force for this maneuver. These plates were placed on a movable carriage that was attached to the pulley apparatus (Fig. 1).

**Electromyography.** Indwelling, fine-wire electrodes were used to record the intensity of vastus muscle activity. The electrodes were bipolar in configuration and were made of nylon-insulated 50-μm wire (nickel-chromium alloy). The wires were passed through the cannula of a 25-gauge hypodermic needle with the distal ends staggered and folded over the needle tip as described by Basmajian and DeLuca.21 After insertion into the muscle, the wires were secured to a plate that also contained a ground electrode and the signals were fed directly into a differential amplifier/FM radio transmitter unit.§ The differential amplifier had a common mode rejection ratio of 60 dB. The EMG signals were then telemetered from the transmitter to the receiver unit where the signal was band-pass filtered.

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Table 1. 
Subject Characteristics

<table>
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<th>Subjects With Patellofemoral Pain (n=23)</th>
<th>Subjects Without Patellofemoral Pain (n=12)</th>
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<tr>
<td>X</td>
<td>SD</td>
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<tr>
<td>Age (y)</td>
<td>26.8</td>
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<tr>
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<tr>
<td>Weight (kg)</td>
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* Probability values based on independent t tests.

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1 Captain Plastic, PO Box 27493, Seattle, WA 98125. 
2 Esco Corp, 6415 E Corvette St, Los Angeles, CA 90242. 
3 Biosentry Telemetry Inc, 20270 Earl St, Torrance, CA 90503.

* General Electric Medical Systems, 3200 N Grandview Ave, Waukesha, WI 53186.
(150–1,000 Hz) and amplified to a gain of 1,000. The raw signal was sampled and digitized by a DEC 11/23 data acquisition computer. Each analog channel was sampled at 2,500 Hz.

Procedure

This study involved 2 different testing sessions: KMRI to determine patellar kinematics and EMG evaluation to assess the vastus muscle activity pattern. The EMG and KMRI data could not be collected simultaneously in our study due to magnetic interference. Prior to testing, all procedures were explained to each subject and written informed consent was obtained.

Kinematic magnetic resonance imaging. All imaging was performed at Tower Imaging Center in west Los Angeles, Calif. Subjects were placed prone on the positioning device with care taken to allow for natural lower-extremity rotation. After this position was achieved, Velcro straps were used to secure the subject’s thigh and tibia to the apparatus. Resistance on the device was then set at 15% of body weight.

After familiarization with the knee extension apparatus, subjects were instructed to practice extending their knees at a rate of approximately 9°/s. This rate ensured 6 evenly spaced images throughout the 45-degree arc of motion (including the 45° position) and permitted imaging at 45, 36, 27, 18, 9, and 0 degrees of knee flexion. Approximation of this rate was made by the principal investigator (CMP) with the use of a stopwatch.

Once the subject was able to reproduce the desired rate of motion in a smooth and even manner, imaging commenced. Subjects were instructed to initiate extension upon verbal command and continue until full extension had been reached. Imaging was done at 3 different image planes to assess the entire excursion of the patella in relation to the trochlear groove (ie, 3 slices were obtained for each angle of knee flexion). These procedures were repeated if the rate of knee extension was too fast or too slow, or not performed in a smooth manner. In addition, assessment was repeated if 6 adequate images were not obtained. An adequate image was one in which the medial and lateral borders of the midsection of the patella, the trochlear groove, and the posterior femoral condyles were well defined. Visualization of these landmarks was necessary for subsequent analysis.

Electromyography. Following KMRI, all subjects underwent EMG analysis at the Pathokinesiology Laboratory, Rancho Los Amigos Medical Center. This analysis typically occurred within 24 hours of the KMRI evaluation.

Sterilized, fine-wire electrodes were inserted into the mid-belly of the VMO, VML, and VL, with electrode placement being confirmed by mild electrical stimulation. To allow for comparison of EMG intensity between subjects and muscles and to control for the variability of electrode placement, EMG data were normalized to the EMG data acquired during a maximal isometric knee extension effort. This was done on a LIDO dynamometer with the subject seated and the knee flexed to 60 degrees. This position was used because women without musculoskeletal impairment are thought to generate the greatest extensor torque in this position and because this position is supposed to provide greater patellar stabilization within the trochlear groove.2,19 It would appear, therefore, that positioning subjects in 60 degrees of knee flexion would minimize quadriceps femoris muscle inhibition resulting from the pain associated with patellar instability.

Vastus muscle activity then was recorded during active knee extension using the positioning device described previously for the KMRI. Procedures for subject positioning, setting of the device resistance, and familiarization practice were identical to those reported earlier. To ensure the same rate of knee extension during KMRI, signals from an electric goniometer positioned at the axis of rotation of the knee were fed into an oscilloscope.
to provide visual feedback (Fig. 2). Once the requested rate of knee extension could be consistently achieved, 6 seconds of EMG activity was recorded while performing this maneuver. Data were collected during 5 trials.

Following the knee extension trials, the maximal isometric muscle test on the LIDO dynamometer was repeated, with the maximal EMG activity being recorded. This was done in an effort to ensure that the intramuscular electrodes had not been displaced during the testing procedure. At no time during the course of this study was electrode displacement observed.

**Data Management**

**Kinematic magnetic resonance imaging.** Prior to analysis, all images were screened to ascertain the midsection of the patella (maximum patellar width) at each angle of knee flexion. Once this was determined, measurements for these images were obtained. Only images containing a midpatella slice were analyzed.

To accurately assess patellofemoral joint relationships at the various degrees of knee flexion, measures that were independent of the shape of the patella and the anterior femoral condyles were used.16 This was done to avoid measurement variability resulting from the continually changing contour of these structures when viewed at different angles of knee flexion and to allow assessment of patellar orientation when the intercondylar groove was not well visualized. All measurements were made with a custom-made, computer-assisted program and included assessment of medial and lateral patellar displacement, medial and lateral patellar tilt, and the sulcus angle.

Medial and lateral patellar displacement were determined by the “bisect offset” measurement as described by Stanford et al22 and modified by Brossmann et al.23 The bisect offset was measured by drawing a line connecting the posterior femoral condyles and then projecting a perpendicular line anteriorly through the deepest point (apex) of the trochlear groove (Fig. 3). This line
interacted with the patellar width line, which connected the widest points of the patella. The perpendicular line was projected anteriorly from the bisection of the posterior condylar line to obtain data when the trochlear groove was flattened (Fig. 3). All bisect offset data represented the extent of the patella lying lateral to the projected perpendicular line and were expressed as a percentage of patellar width.

Medial and lateral patellar tilt were measured using a modification of the technique described by Sasaki and Yagi. The patellar tilt angle was reported as the angle formed by the lines joining the maximum width of the patella and the line joining the posterior femoral condyles (Fig. 4). All tilt measurements were reported in degrees.

**Electromyography.** Digitally acquired EMG data were full-wave rectified and integrated over 0.25-second intervals. Intensities were reported as a percentage of the EMG data collected during the maximum isometric muscle test.

Intensity of VL, VMO, and VML contraction was assessed at points in the range of motion that corresponded to the angular position at which the magnetic resonance images were obtained. These data were further analyzed to obtain VL:VMO and VL:VML ratios.

**Reliability of KMRI and EMG data.** Because MRI and EMG data were not collected simultaneously, I believed that it was particularly important to assess reliability of these measures in order to compare data between testing sessions. In addition, determination of the number of trials to be averaged for consistent data was necessary. To assess the reproducibility of the measurements, 7 subjects without PFP underwent repeated testing. All repeat testing took place within 24 hours of the initial testing session, using the same procedures outlined earlier. The day-to-day reliability of KMRI data, assessed using the procedures and measurements described earlier, was previously reported to have intraclass correlation coefficients (ICCs) ranging from .79 to .85. Intraobserver measurement error was determined to be 3.4% for the bisect offset measurement and 2.9 degrees for patellar tilt.

**Data Analysis**

All statistical procedures were performed with BMDP statistical software. Prior to analysis, descriptive statistics were calculated for all variables, and normality of distribution was assessed using the Wilk-Shapiro test. Based on the analysis of distribution, all data were analyzed using parametric tests. All significance levels were set at $P < .05$.

<table>
<thead>
<tr>
<th>No. of Averaged Measurements</th>
<th>VL:VMO</th>
<th>VL:VML</th>
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<tr>
<td>1</td>
<td>.47</td>
<td>.54</td>
</tr>
<tr>
<td>2</td>
<td>.48</td>
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<td>.62</td>
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<td>5</td>
<td>.59</td>
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*VL=vastus lateralis muscle, VMO=vastus medialis oblique muscle, VML=vastus medialis longus muscle.*

Reliability of the EMG measurements (VL:VMO and VL:VML ratios) and MRI measurements (bisect offset and patellar tilt) was assessed using ICCs. Multiple one-way analyses of variance (ANOVAs) for repeated measures were used to compare EMG ratios between sessions at each designated angle of knee flexion. The mean squares between subjects and the mean squares within subjects were substituted into the ICC~1 equation described by Bartko. This analysis was repeated for each measurement to obtain correlation coefficients for each of the number of averaged values (ie, ICCs were calculated for the data obtained by averaging 2 measurements for both sessions and were compared with ICCs calculated for data obtained by averaging 3, 4, and 5 measurements). I determined that averaging data obtained from 3 EMG trials produced the most consistent results (Tab. 2). Overall, moderate reliability in obtaining the VL:VMO and VL:VML ratios was evident across all angles of knee flexion (ICC values of .61 and .64, respectively).

To determine whether EMG ratios varied between groups or angles of knee flexion, a $2 \times 6$ (group $\times$ angle) ANOVA for repeated measures on one variable (angle) was performed. This analysis was performed for each EMG ratio. Main effects were reported if there were no interactions. If an interaction was found, the individual main effects were analyzed separately.

A regression analysis was performed to determine whether the VL:VMO ratio or the VL:VML ratio was predictive of patellar tilt or displacement. This analysis was repeated for patellar tilt and displacement at each angle of knee flexion. Because the presence of PFP could potentially influence the relationship between the variables, I deemed it necessary to account for this factor by including the grouping variable in all regression equations. This type of analysis was used in an effort to ensure that an overall relationship between the EMG ratios and patellar kinematics could be ascertained regardless of a diagnosis of PFP.
Results

Electromyography

There was no difference in the VL:VMO ratio between the subjects with PFP and the subjects without PFP (no group effect or interaction) (Fig. 5). When averaged across all knee flexion angles, the mean VL:VMO ratio was 1.85 for the subjects with PFP compared with 1.17 for the subjects without PFP. Similarly, there was no difference in the VL:VML ratio between the subjects with PFP and the subjects without PFP (no group effect or interaction) (Fig. 6). When averaged across all angles of knee flexion, the mean VL:VML ratio for the subjects with PFP was 0.78 compared with 0.94 for the subjects without PFP.

Patellar Kinematics

For results and discussion concerning the comparison of patellar kinematic data between groups, the reader is referred to the article by Powers titled “Patellar Kinematics, Part II: The Influence of the Depth of the Trochlear Groove in Subjects With and Without Patellofemoral Pain” in this issue.

Relationship Between EMG Ratios and Patellar Kinematics

In general, the Pearson correlation coefficients ranged from –0.48 to 0.37 for both bisect offset (Tab. 3) and patellar tilt (Tab. 4). The VL:VML ratio was found to be the only predictor of patellar tilt at 36 degrees (r = –0.40, R² = 0.16), 27 degrees (r = –0.48, R² = 0.24; Fig. 7), 18 degrees (r = –0.42, R² = 0.18), and 9 degrees of flexion (r = –0.45, R² = 0.20). Similarly, the only EMG predictor of the bisect offset measurement was the VL:VML ratio at 27 degrees of flexion (r = –0.48), which accounted for 24% (R²) of the variability (Fig. 8).

Discussion

The EMG data obtained from the comparison group were relatively consistent, with the VL:VMO and VL:VML ratios averaging 1.17 and 0.94, respectively, across all knee flexion angles. This finding is consistent with those of previous studies.[7,19,26] In which the activity of the VMO relative to the VL in subjects without pain is approximately 1:1. The EMG data obtained from the subjects with PFP, however, showed much greater variability. The lack of statistical significance in the VL:VMO and VL:VML EMG ratios between groups may have been.
the result of a type II statistical error due to the high variability of the subjects with PFP throughout the range of motion, variability that was 2 to 3 times greater than for the comparison group. A post hoc power analysis revealed that the number of subjects in each group was adequate to test the null hypothesis (no group effect), as the statistical power to detect a 60% change was found to be greater than 0.90.

The EMG ratio data obtained from the subjects with PFP suggests that the motor unit activity of the VML and that of the VMO were different during the knee extension maneuver. This difference was reflected by the observation that the VL:VML ratio remained consistent throughout knee extension, whereas the activity of the VMO (with respect to the VL) became more pronounced at terminal knee extension. This pattern of EMG activity may be related to the fact that the VML is primarily a knee extensor (as a result of a more longitudinal fiber orientation), whereas the VMO is much less efficient in this role because of its oblique fiber arrangement.9 Because knee extension was the primary movement performed, I believe it is logical that the VML would be recruited more readily to accomplish this task. However, the fact that the EMG activity of the VMO became more pronounced at the end-range of extension emphasizes the function of this structure in providing medial patellar stability, as it is at this point in the range of movement where maximum lateral displacement typically occurs.2 Differences in the observed EMG activity of these 2 portions of the vastus medialis muscle compared with the VL suggests that this muscle may have varied roles with respect to patellofemoral joint mechanics.

Regression analysis of the EMG and KMRI variables revealed that the VL:VMO EMG ratio was not predictive of patellar motion at any point in the range of knee flexion. In contrast, the VL:VML ratio was a predictor of patellar tilt at 36, 27, 18, and 9 degrees of flexion, as well as of bisect offset at 27 degrees of flexion. All correlations involving the VL:VML ratios were negative, however, indicating an inverse relationship between EMG activity and patellar motion. For example, subjects with lower VL:VML ratios (increased VML activity relative to the VL) were found to have greater degrees of lateral patellar displacement and tilt, whereas subjects with higher VL:VML ratios (decreased VML activity relative to the VL) had less severe abnormalities. These results do not support the original hypothesis that decreased activity of the vastus medialis muscle is a cause of patellar malalignment. To the contrary, increased motor unit activity of the vastus medialis muscle appeared to be in response to meeting the increased demand of providing patellar stability. The fact that VML activity was increasing as the patella demonstrated greater malalignment was suggestive of an active, but inadequate, effort to center the patella within the trochlear groove.

A premise behind the use of EMG biofeedback to evaluate VMO activity is, in my opinion, that diminished VMO EMG activity is indicative of abnormal patellofemoral joint function. The finding that VMO activity could not be shown to be predictive of patellar kinematics illustrates the limitations associated with the use of EMG ratios as indicators of patellofemoral joint pathomechanics. Although normalized EMG data are useful in measuring relative levels of activity between muscles (ie, intensity of effort), such information is not indicative of muscular strength or “muscular balance,” as is commonly assumed.27 Without considering factors such as muscle length, cross-sectional area, and angle of insertion of the various muscle fibers, it would appear that EMG has limited use in determining the effective muscle force.27
The correlation coefficients in this study had $R^2$ values that were small (ranging from .16 to .24), indicating that only a small percentage of the variance in patellar kinematics could be explained by the EMG ratios. Although the inherent variability in EMG data combined with inability to precisely control the speed of knee extension could have contributed to the low $r$ values, further research should be directed toward identifying additional factors that can improve the predictability of patellofemoral joint kinematics.

As a result of the limitations imposed by the size of the MRI bore, the loading condition used in this study (non–weight bearing) was not consistent with the loading condition that would be evident with running or climbing stairs or with our inability to take all of our measurements simultaneously (EMG and KMRI). Although there have been no studies that have examined the differences in patellar tracking patterns between weight-bearing and non–weight-bearing activities, an argument can be made that the non–weight-bearing knee extension maneuver does not simulate most functional tasks. Therefore, care must be taken in interpreting the results of this study until differences in patellar kinematics can be established between various loading conditions.

Conclusion
The results of this study showed an inverse relationship between the VL:VML EMG ratio and lateral patellar tilt at 36, 27, 18, and 9 degrees of knee flexion and lateral patellar displacement at 27 degrees of knee flexion. Although increased activity of the vastus medialis muscle relative to the VL may be a response to patellar malalignment, decreased activity does not appear to be associated with abnormal patellar tracking. The premise that lateral patellar displacement and tilt are the result of diminished activity of the vastus medialis muscle is not supported by this study.

References
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