In vivo and Noninvasive Three-Dimensional Patellar Tracking Induced by Individual Heads of Quadriceps

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ABSTRACT

LIN, F., G. WANG, J. L. KOH, R. W. HENDRIX, and L.-Q. ZHANG. *In vivo* and Noninvasive Three-Dimensional Patellar Tracking Induced by Individual Heads of Quadriceps. *Med. Sci. Sports Exerc.*, Vol. 36, No. 1, pp. 93–101, 2004. **Purpose:** Unbalanced actions of the quadriceps components are closely linked to patellar mal-tracking and patellofemoral pain syndrome. However, it is not clear how individual quadriceps components pull and rotate the patella three dimensionally. The purpose of this study was to investigate *in vivo* and noninvasively patellar tracking induced by individual quadriceps components. **Methods:** Individual quadriceps component was activated selectively through electrical stimulation at the muscle motor point, and the resulting patellar tracking was measured *in vivo* and noninvasively in 18 knees of 12 subjects. The *in vivo* and noninvasively patellar tracking was corroborated with *in vivo* fluoroscopy and *in vitro* cadaver measurements. **Results:** Vastus medialis (VM) mainly pulled the patella first in the medial and second in the proximal directions and vastus lateralis (VL) pulled first in the proximal and second in the lateral directions. The oblique portion (VMO) of the VM pulled the patella mainly medially and the longus portion (VML) more proximally. Medial tilt was the major patellar rotation induced by VMO contraction at full knee extension. With the knee at the more flexed positions, the amplitude of patellar movement induced by comparable quadriceps contractions was reduced significantly compared to that at full knee extension, and VMO changed its main action from extending to flexing the patella. **Conclusions:** The medial and lateral quadriceps components moved the patella in rather different directions, and rotated the patella differently about the mediolateral tilt and mediolateral rotation axes but similarly in extension. The approach can be used to investigate patellar tracking *in vivo* and noninvasively in both healthy subjects and patients with patellofemoral disorder and patellar malalignment. **Key Words:** PATELLA, KINEMATICS, PATELLAR MALALIGNMENT, KNEE

Patellofemoral pain (PFP) syndrome is one of the most commonly observed physical abnormalities involving the knee in sports medicine clinics. Although PFP is a fairly broad definition of a set of symptoms involving pain around the patella, its etiology is still not very clear and its clinical treatment is often not satisfactory (12,9). PFP is considered to be associated with patellar malalignment and abnormal patellar tracking. In clinics, patellar alignment and subluxation are generally evaluated by physical examination and measurement of the Q angle and tightness of parapatella soft tissues. Patellar alignment and tracking has been evaluated with radiographic x-ray imaging, computed tomography, and magnetic resonance imaging at different knee flexion angles (6,9,26,18), which, however, does not provide quantitative information on the actions of individual quadriceps components on the patella.

Appropriate patellar tracking is dependent on balanced actions of the different quadriceps components. Reduced action of the medial stabilizers, especially the vastus medialis oblique (VMO), is thought to be an important factor in patellofemoral malalignment and abnormal patellar tracking (3,14,15,24). Therefore, it is important to understand patellar movement induced by different quadriceps components. However, although patellar tracking has been investigated in several cadaver-based studies (28,8,19,3), there has been a lack of information on patellar tracking induced by individual quadriceps components, especially under *in vivo* and noninvasive conditions.

The purpose of this study was to investigate six degrees-of-freedom (DOF) patellar tracking induced by *individual*

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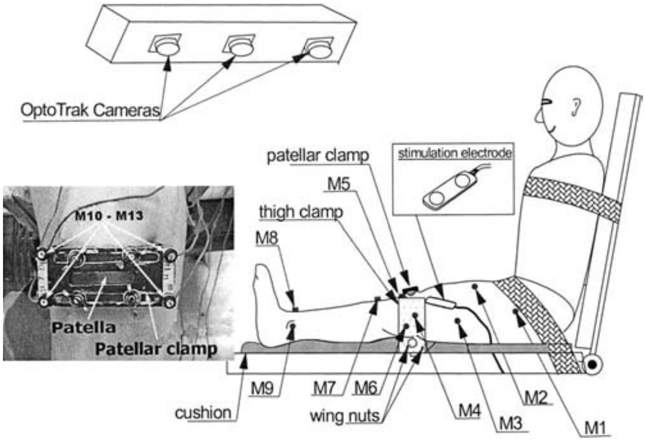

FIGURE 1—Experiment setup for *in vivo* and noninvasive patellar tracking. The subject was seated with the thigh and trunk strapped to the seat and backrest, respectively. The femoral condyles were fixed from the medial and lateral sides with a thigh clamp. Two pairs of wing nuts were tightened from the medial and lateral sides to fix the femoral condyles. Markers 1–3 were placed on the thigh. Markers 4–6 were attached to the thigh clamp with marker 4 placed on the knee flexion axis and lateral to the lateral epicondyle. Markers 7–9 were mounted to the leg. Markers 10–13 were fixed to the four corners of the patellar clamp. M1, M2, ..., M13 stand for marker 1, marker 2, ..., marker 13, respectively.

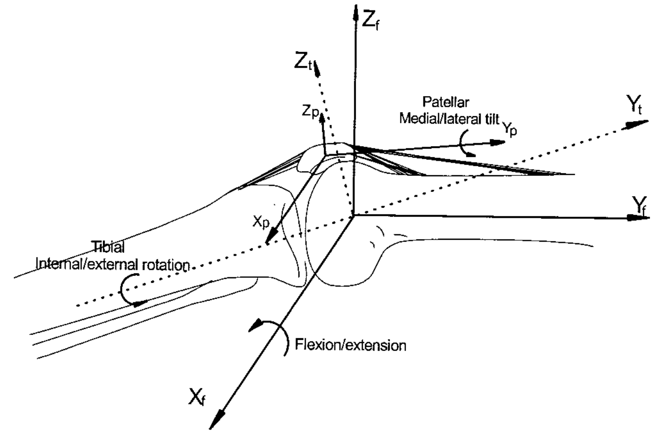

FIGURE 2—The femoral, tibial, and patellar coordinate systems (medial view of a right knee). The joint coordinate system convention was used to describe rotations of the patella and tibia relative to the femur. For the right patellofemoral joint, the positive directions of the three rotations about the JCS axes were flexion about the femoral transepicondylar line X_f, medial tilt about the patellar Y_p axis, and patellar medial rotation about the third floating axis perpendicular to both the X_f and Y_p axes. For the right tibiofemoral joint, the positive directions of the three rotations about the JCS axes were flexion about the femoral transepicondylar line X_f, internal rotation about the tibial long axis Y_t, and adduction about the third floating axis perpendicular to both the X_f and Y_t axes.

quadriceps components *in vivo* and noninvasively. It was hypothesized that VMO, vastus medialis longus (VML), and vastus lateralis (VL) pull and rotate and pull the patella differently in three-dimensional space. Quantitative evaluation of the roles of individual quadriceps components in patellar tracking will help us better understand the knee extensor mechanism, gain insight into the mechanisms underlying patellofemoral disorder, and evaluate pathological changes accurately. Relevant six-DOF patellar tracking during voluntary knee flexion and extension has been reported recently (17).

MATERIALS AND METHODS

Eighteen knees from 12 subjects with no prior history of knee injuries were investigated in this study. The subjects were 32.8 ± 10.0 yr old (mean ± standard deviation), and their height and weight were 171.0 ± 8.3 cm and 71.5 ± 18.9 kg, respectively. Five of the subjects (seven knees) were female and their age, height, weight, and Q-angles were 27.6 ± 7.1 yr, 165.8 ± 5.8 cm, 66.1 ± 16.2 kg, and 16.2 ± 1.5°, respectively. For the remaining seven male subjects (11 knees), their age, height, weight, and Q-angles were 36.7 ± 9.2 yr, 174.7 ± 7.5 cm, 75.4 ± 16.2 kg, and 13.5 ± 1.3°, respectively. All subjects gave written informed consent before the experiment, and the study was approved by the Institutional Review Board of Northwestern University.

Experimental setup. The subject sat upright with the back and leg supported (Fig. 1). The femur was clamped at the medial and lateral condyles, and remained stationary during the experiment. The heel was rested on a table that was adjusted to achieve knee flexion angle of 20° and 0° (Fig. 1). Three-dimensional tibial and patellar movements relative to the femur were measured by an optoelectronic motion capture system (OPTOTRAK™ 3020, Northern Digital, Inc., Waterloo, Canada). Active infrared markers were placed on the thigh and leg (at least three markers on each limb segment). Markers 1–3 were placed at the greater trochanter, mid-, and distal thigh, respectively. Markers 4–6 were mounted on the thigh clamp with marker 4 located lateral to the lateral femoral epicondyle on the knee flexion axis (Fig. 1). Markers 7–9 were placed on the tibial tubercle, mid-tibia, and lateral malleolus, respectively.

A lightweight patellar clamp was mounted to the patella to follow its movement in three-dimensional space (Fig. 1). Four Teflon strips were mounted inside of the medial and lateral plates of the clamp. The distal ends of the Teflon strips had a groove matching the edges of the patella and the strips could be pushed from behind individually by screws to grasp the medial and lateral edges of the patella like four "fingers" on each side. Four markers (markers 10–13) mounted on four corners on top of the clamp were used to capture the patellar movement in six DOF (29,17).

Knee coordinate systems. A joint coordinate system (JCS) (5) was used to characterize three-dimensional patellar tracking, which was described in detail previously (17). Briefly, for both the tibiofemoral and patellofemoral joints, the X_f axis of the femur was the flexion-extension axis, coinciding with the transepicondylar line. For the patellofemoral joint, the origin of the patellar coordinate system was located at the centroid of the patella, determined by markers 10–13. For a right patella, the X_p, Y_p, and Z_p axes pointed medially, proximally, and anteriorly, respectively (Fig. 2). The positive directions of patellar rotations about the three JCS axes for a right knee were flexion, medial tilt, and medial rotation, respectively. The positive rotations about the three JCS axes of the tibiofemoral joint for a right knee were flexion, internal rotation, and adduction, respectively. Linear shifts of the tibia and patella relative to the femur were described by translations along the axes of the femoral coordinate system and the positive directions of the X_f, Y_f, and Z_f axes were medial, proximal, and anterior, respectively (Fig. 2).

Selective activation of individual quadriceps components. To activate an individual head of the quadriceps selectively, a pair of surface electrodes was placed on the skin above the targeted individual muscle (VML, VMO, and VL) and constant-current electrical stimulation was delivered through the electrodes. "Motor point" of the targeted muscle was located by carefully moving the electrodes to achieve the strongest muscle contraction with the lowest electrical stimulation current, which would minimize current overflow to neighboring muscles and reduce possible pain associated with the stimulation.

A train of constant current stimulation pulses was used to activate the muscle at a 3-s interval. The pulse width was 0.3 ms repeated at 25 pulses$\cdot s^{-1}$. The pulse train duration was 600 ms. The current amplitude was adjusted for each quadriceps component so that moderate contraction of the target muscle was elicited without significant current overflow to the surrounding muscles (checked by palpating the quadriceps tendon and visual inspection). Between the two stimulation current polarities, the one that elicited stronger contraction (by the subject's sensation and experimenter's palpation) at the sample current amplitude was used to activate the muscle. In three subjects, M-wave (compound muscular action potential) was recorded at the VMO, VML, and VL components during electrical stimulation of each of them. M-waves at the targeted and neighboring muscles were used to evaluate the stimulation-elicited contraction at the former and current overflow to the latter, respectively.

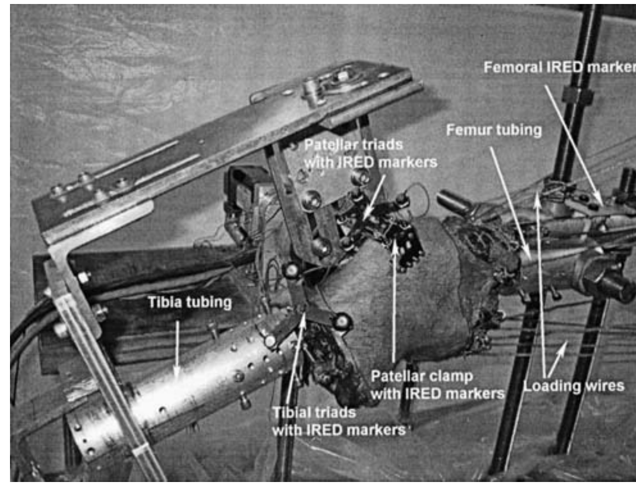

FIGURE 4—Cadaver experiment used to corroborate the *in vivo* patellar tracking measured by the patellar clamp. Patellar, tibial, and femoral movements were measured by triads of markers attached to each of the bones, using an Optotrak system. Patellar clamp movement was measured by markers attached to the clamp. A slot in the patellar clamp allowed potential relative movement between the patellar clamp and the patellar triads. Muscles across the knee joint were loaded by dead weights according to their PCSA. Dynamic loading of the individual muscle head of the quadriceps was applied by manually pulling the rope attached to it.

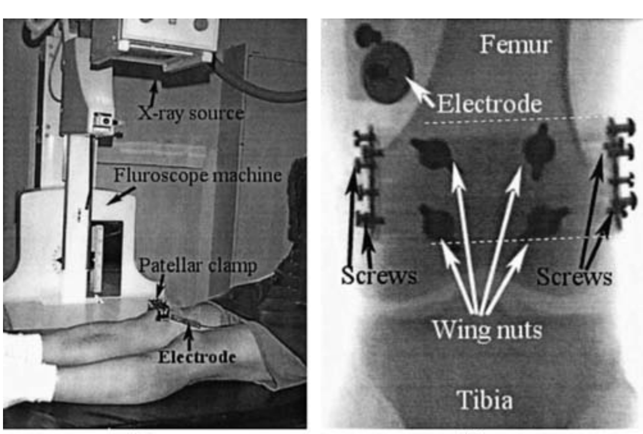

FIGURE 3—Fluoroscopic imaging experimental setup used to check the consistency between the patella and patellar clamp in patellar tracking induced by electrical stimulation of an individual quadriceps component. a. Setup; b. a corresponding posterior view of the right knee, mounted patellar clamp, and stimulation electrode. The *dotted line* shows the approximate position of the patellar clamp, which was made of aluminum and was not clearly shown under x-ray.

Protocol. Each individual quadriceps component was stimulated at the motor point with the knee at the full extension and 20° flexion. Patellar tracking was measured by the markers mounted on the patellar clamp and recorded at 100 Hz. Four trials were repeated for each quadriceps component at each knee position.

Data analysis. Translations and rotations of the patella and tibia relative to the femur were calculated from the measured infrared marker coordinates in three-dimensional space. For left knees, appropriate sign changes were made to convert the patellofemoral and tibiofemoral translations and rotations to the right-knee conventions (Fig. 2). In order to compare patellar tracking at different knee positions and across different subjects, normalized direction of translation (DOT) and direction of rotation (DOR) were used to characterize different components of three-dimensional patellar movement as follows (31):

$$DOTx = Tx/T, DOTy = Ty/T, DOTz = Tz/T, T = \sqrt{T_x^2 + T_y^2 + T_z^2} \quad [1]$$

$$DOR_1 = R_1/R, DOR_2 = R_2/R, DOR_3 = R_3/R, R = \sqrt{R_1^2 + R_2^2 + R_3^2} \quad [2]$$

where T_x, T_y, and T_z were translations along the femoral X, Y, and Z axes, respectively. R_1, R_2, and R_3 were rotations about the three JCS axes of the patellofemoral or tibiofemoral movements, respectively. Normalized patellofemoral and tibiofemoral movements from multiple trials were averaged across multiple trials for each subject.

The MIXED procedure in the SAS statistical software package was used to test the hypotheses that there was no difference among the three patellar rotations and among the three translations during selective contraction of an individ-

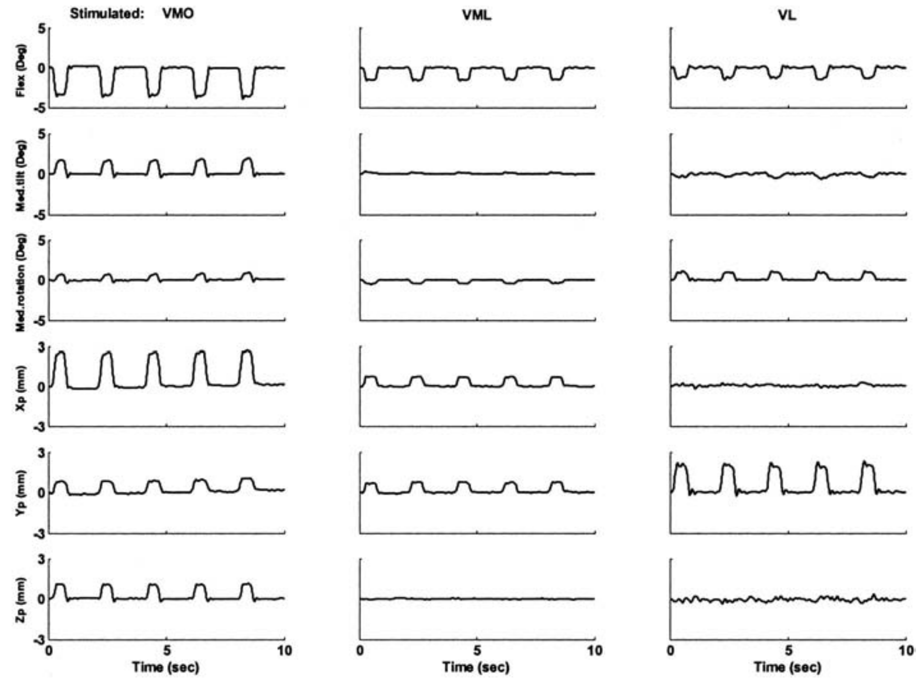

FIGURE 5—Representative results of the six DOF patellar tracking induced by activating a quadriceps component selectively through electrical stimulation. The stimulation train (and thus the contraction) was repeated at an interval of 2 s. From top to bottom, the six rows correspond to patellar flexion, medial tilt, medial rotation, medial shift, proximal shift, and anterior shift, respectively. The positive direction of each DOF is given for the ordinates. The zero position corresponded to patellar position before stimulation. The knee was at full extension and neutral rotation and abduction. This data came from one subject.

ual quadriceps component (SAS Institute, Cary, NC). The significance level was set at 0.05.

Corroborations of *in vivo* patellar tracking measured by the patellar clamp. Two methods were used to corroborate the above *in vivo* patellar tracking based on the small patellar clamp. First, fluoroscopic imaging of the patellofemoral joint was conducted on two subjects to evaluate patellar tracking induced by selective stimulation of individual quadriceps components (Fig. 3). With the small clamp mounted on the patella, anterior and medial views of fluoroscopic imaging were used to monitor movements of both the patella and patellar clamp. Dynamic images displayed on a fluoroscopic monitor were inspected to compare the movements of the patella and patellar clamp (Fig. 3).

Second, a cadaver specimen was used to corroborate *in vivo* patellar tracking by measuring patellar movement with both the patellar clamp and markers rigidly fixed to the patella (Fig. 4). In addition to the clamp mounted onto the patella, metal screws were inserted into the patella, tibia, and femur. A small Y-shaped frame with a marker on each of the three arms was fixed to the metal screw (Fig. 4). The metal screw was inserted into the patella through a slot in the top-plate of the patellar clamp, which allowed potential relative movement between the screw and clamp if the two did not move together during patellar tracking (Fig. 4). Patellar tracking was induced by pulling individual quadriceps components along their lines of action through a rope-pulley system. Patellar movements measured by markers attached to the metal screw and by the patellar clamp were compared in six DOF.

RESULTS

Electrical stimulation at the motor point induced consistent contractions of the targeted individual quadriceps components and the resulting patellar movement (Fig. 5). Selective contraction of the VMO generated consistent patellar rotation of extension, medial tilt, and medial rotation, and patellar linear translation of medial, proximal, and anterior shifts. Activation of VML induced mainly patellar extension and proximal shift, and VL generated mainly patellar extension, medial rotation, and proximal shift (Fig. 5). Across the subjects, quantitative results on the DOT and DOR of the individual quadriceps muscles are summarized in Table 1. Because statistical analysis showed that there was no gender difference in either the DOT ($P = 0.2289$) or DOR ($P = 0.4010$) among subjects in this study, the relevant results from male and female subjects are therefore reported together (Table 1).

Across the knees, the medial and lateral quadriceps components shifted the patella in rather different directions (Fig. 6). At full knee extension, contraction of the VMO mainly pulled the patella medially with the corresponding $DOT_x = 0.860 \pm 0.098$ (mean $\pm$ standard error (SE)) significantly greater than $DOT_y = 0.460 \pm 0.178$ (proximal shift, $P < 0.002$) and $DOT_z = 0.222 \pm 0.192$ (anterior shift, $P < 0.001$) (Fig. 6). With the knee flexed at 20°, VMO contraction still mainly pulled the patella medially, but the minor shifts changed to the posterior and distal directions.

Different from the VMO that pulled the patella medially, the VML pulled the patella more in the proximal ($P <$

TABLE 1. Patellar DOT and DOR generated by selective activation of the VMO, VML, and VL at full knee extension and 20° knee flexion.

Knee Angle (°)	0			20		
Muscle	VMO	VML	VL	VMO	VML	VL
DOT						
Medial	0.860 ± 0.098	0.427 ± 0.126	−0.337 ± 0.089	0.854 ± 0.179	0.708 ± 0.167	0.293 ± 0.163
Posterior	0.460 ± 0.178	0.904 ± 0.081	0.938 ± 0.055	−0.305 ± 0.318	0.701 ± 0.210	0.612 ± 0.194
Anterior	0.222 ± 0.192	−0.008 ± 0.206	−0.081 ± 0.161	−0.420 ± 0.264	−0.085 ± 0.245	−0.735 ± 0.176
DOR						
Flexion	−0.534 ± 0.237	−0.768 ± 0.332	−0.590 ± 0.288	0.846 ± 0.554	−0.688 ± 0.289	−0.035 ± 0.295
Medial tilt	0.814 ± 0.208	0.467 ± 0.310	−0.281 ± 0.273	0.274 ± 0.413	0.568 ± 0.340	−0.089 ± 0.374
Medial rotation	−0.228 ± 0.154	−0.438 ± 0.217	0.757 ± 0.214	−0.457 ± 0.331	−0.455 ± 0.240	0.995 ± 0.308

Data are given in mean ± SE.
Results were obtained at tibial neutral rotation.

0.005) and anterior ($P < 0.0001$) directions than in the medial direction. At full knee extension, DOT for the VML were $DOT_x = 0.427 \pm 0.126$ (medial shift), $DOT_y = 0.904 \pm 0.081$ (proximal shift), and $DOT_z = -0.008 \pm 0.206$ (Fig. 6). With the knee flexed to 20°, medial and proximal shifts were the major motion induced by VML, with $DOT_x = 0.708 \pm 0.167$, $DOT_y = 0.701 \pm 0.210$, and $DOT_z = -0.085 \pm 0.245$ (Fig. 6).

Selective contraction of the VL mainly moved the patella proximally, plus moderate lateral pull with $DOT_x = -0.337 \pm 0.089$, $DOT_y = 0.938 \pm 0.055$, $DOT_z = -0.081 \pm 0.161$ at full knee extension (Fig. 6). Among the three linear translations, the quadriceps components generated little patellar movement in the anterior-posterior direction, except for the VL at 20° knee flexion, in which the patella was pulled by the VL posteriorly with $DOT_x = 0.293 \pm 0.163$, $DOT_y = 0.612 \pm 0.194$ and $DOT_z = -0.735 \pm 0.176$ (Fig. 6).

The medial and lateral quadriceps components rotated the patella rather differently about the mediolateral tilt and mediolateral rotation axes but similarly in extension (Fig. 7). The extension component was significantly larger than the medial rotation component for both VMO ($P < 0.005$) and VML ($P < 0.02$).

Medial tilt was the major patellar rotation induced by VMO contraction at full knee extension and the corresponding DOR_2 at the neutral tibial rotation was 0.814 ± 0.208 (Fig. 7), which was significantly larger than $DOR_3 = -0.228 \pm 0.154$ (corresponding to lateral rotation, $P < 0.0005$). On the other hand, the VL generated little lateral tilt with $DOR_2 = -0.281 \pm 0.273$ at full knee extension.

The VMO generated little patellar mediolateral rotation, whereas medial rotation was the major motion generated by the VL (Fig. 7). The corresponding DOR_3 at full knee

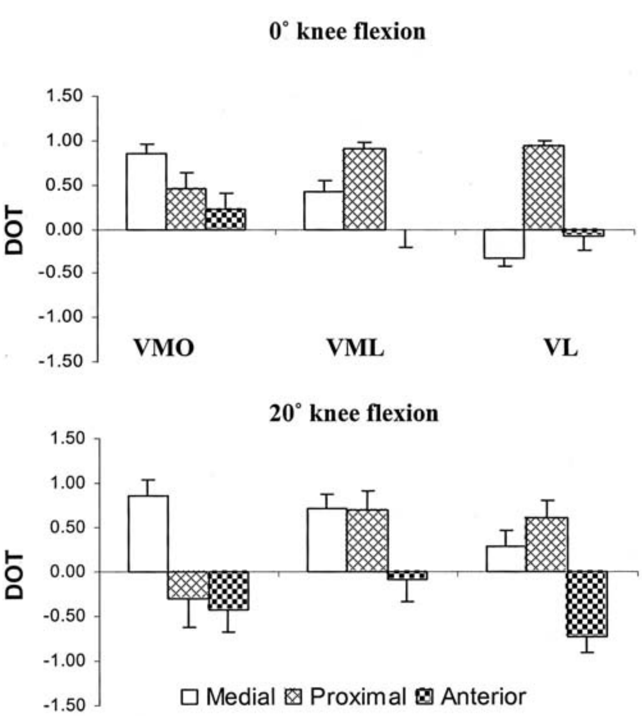

FIGURE 6—Patellar DOT generated by selective activation of the VMO (left column), VML (middle column), and VL (right column) at full knee extension (first row) and 20° knee flexion (second row), respectively. Results shown here were taken at tibial neutral rotation. The vertical bars represent standard error of means across multiple knees. For clarity, the SE was shown in only one direction.

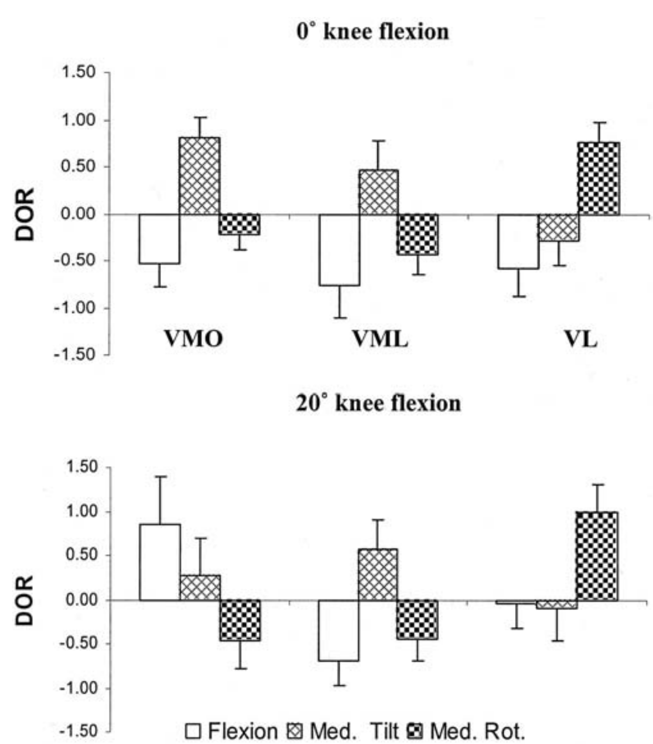

FIGURE 7—Patellar DOR generated by selective activation of the VMO (left column), VML (middle column), and VL (right column) at full knee extension (first row) and 20° knee flexion (second row), respectively. Results shown here were taken at tibial neutral rotation. The *vertical bars* represent standard error of means across multiple knees. For clarity, the SE was shown in only one direction.

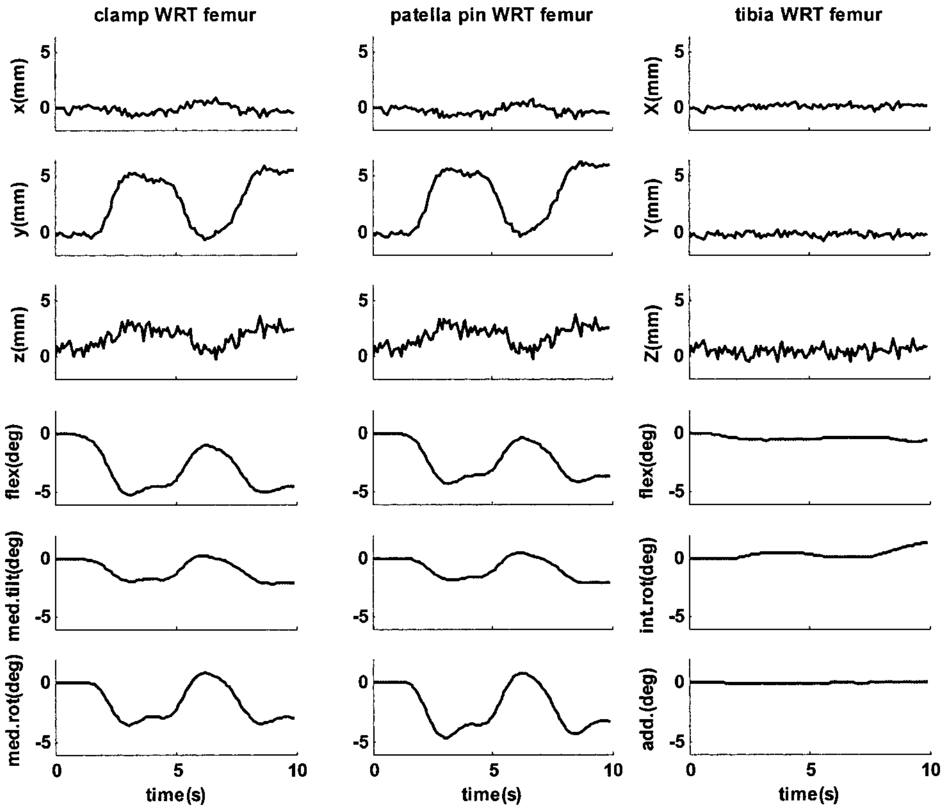

FIGURE 8—Patellar tracking produced by loading the VL along its line of action using a rope-pulley system and a deadweight of 2.3 kg. The initial knee flexion was 15°, and the corresponding patellar position was taken as zero. The knee was extended 0.5° during the VL loading. The first and second columns give patellar movement with respect to (WRT) the femur measured by markers mounted on the patellar clamp and on the metal screw inserted into the patella, respectively. The third column gives tibial movement with respect to the femur.

extension was −0.228 ± 0.154, −0.438 ± 0.217, and 0.757 ± 0.214 for the VMO, VML, and VL, respectively (Fig. 7).

The amplitude of patellar movement induced by comparable quadriceps contractions was generally reduced from full knee extension to the flexed position, with significant decrease in medial tilt, medial and proximal shifts of VMO ($P < 0.05$), proximal shift of VL ($P < 0.0002$), and all the DOFs of VML ($P < 0.05$). On the other hand, the DOR and DOT might change as the knee flexed, dependent on the specific quadriceps components. When the knee position was changed from full extension to 20° flexion, only the VMO changed its main rotation component from patellar extension ($DOR_1 = -0.534 \pm 0.237$) to flexion ($DOR_1 = 0.846 \pm 0.554$). The major patellar movement induced by VML and VL contraction at flexed knee did not change from that at full knee extension (Figs. 6 and 7). VML kept its main actions of patellar extension, medial tilt ($DOR_1 = -0.686 \pm 0.289$, $DOR_2 = 0.568 \pm 0.340$, $DOR_3 = -0.455 \pm 0.240$, Fig. 7), and proximal and medial shifts ($DOT_x = 0.708 \pm 0.167$, $DOT_y = 0.701 \pm 0.210$, $DOT_z = -0.085 \pm 0.245$, Fig. 6). With the knee flexed, VL maintained the main function of medially rotating and proximally shifting the patella, and generated less patellar extension/flexion and less proximal but more posterior shifts with $DOR_1 = -0.035 \pm 0.295$, $DOR_2 = 0.088 \pm 0.374$, $DOR_3 = 0.995 \pm 0.308$, $DOT_x = 0.293 \pm 0.163$, $DOT_y = 0.612 \pm 0.194$, and $DOT_z = -0.735 \pm 0.176$ (Figs. 6 and 7). With the knee flexed, VMO generated less medial rotation than VML ($P < 0.005$) and VL ($P < 0.02$).

Corroboration of the *in vivo* and noninvasive patellar tracking. First, in the cadaver model, patellar tracking measured using markers attached to the patellar clamp and to metal screws inserted into the patella, tibia, and femur in a triad formation matched closely, especially in patellar translations (Fig. 8). Over six trials, compared with the measurements with the pin inserted into patella, the patellar movements measured with the patellar clamp gave errors of −0.38 ± 0.14°, 0.05 ± 0.08°, −0.03 ± 0.32°, 0.02 ± 0.04 mm, −0.26 ± 0.04 mm, and −0.01 ± 0.05 mm (mean ± SE) for flexion, medial tilt, medial rotation, medial shift, proximal shift, and anterior shift, respectively. Second, fluoroscopic imaging on human subjects also showed that the patellar clamp closely followed the patellar movement under selectively activation of individual heads of the quadriceps.

DISCUSSION

Although patellar tracking is involved in most knee functional activities and abnormal patellar tracking may be involved in various pathological conditions, there is a lack of information on three-dimensional patellar tracking induced by individual quadriceps components, especially under *in vivo* and noninvasive conditions. The present study provided

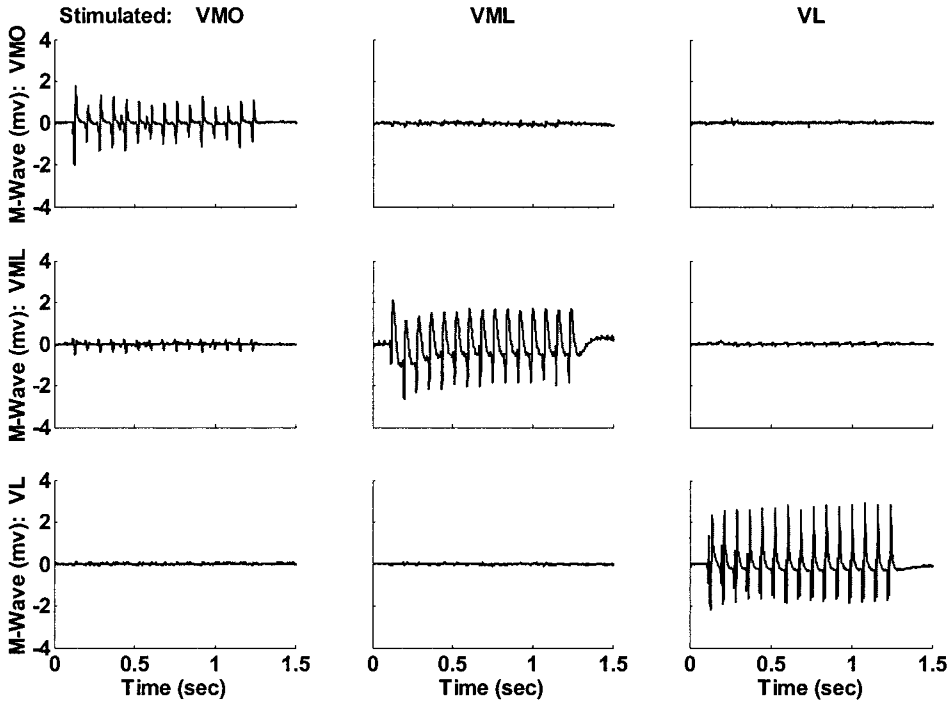

FIGURE 9—Surface M-wave recorded from individual quadriceps component during the selective electrical stimulation. The knee was at full extension and neutral rotation and abduction.

us an *in vivo* and noninvasive tool to evaluate three-dimensional patellar tracking induced by selective activation of an individual quadriceps component. Experimentally, the *in vivo* approach used in this study was corroborated with *in vitro* and fluoroscopic methods. It was found that each quadriceps component moved the patella in its unique way, which was different among the different quadriceps components. It was found that the medial and lateral quadriceps components moved the patella in rather different directions with the VM mainly pulled the patella in the medial and proximal direction and VL pulling more proximally than laterally. Within the VM, the VMO pulled patella more medially and the VML more proximally. The medial and lateral quadriceps components rotated the patella rather differently about the mediolateral tilt and mediolateral rotation axes but similarly in patellar extension. Medial tilt was the major patellar rotation induced by VMO contraction at full knee extension. With the knee at the more flexed positions, the amplitude of patellar movement induced by the same quadriceps contractions was reduced from those at full knee extension, and VMO changed its major action from extending to flexing the patella.

In comparable cases, patellar tracking presented in this study was in general consistent with previous *in vitro* and *in vivo* studies. Little information has been provided for the contribution to the patellar movement by the individual head of quadriceps except for the VMO, largely because of the belief of its important role in preventing patellar mal-tracking (3,8,13,24). Our results showed VMO actions (pulling and tilting the patella medially) similar to that reported in the literature (3,22,24). These major actions change with knee flexion angle substantially, mainly in patellar extension and medial tilt. It was shown in our study that when knee flexion was changed from 20° to full extension, patellar medial tilt became the major function of VMO, whereas it was the smallest rotation in the more flexed knee. It implies that the VMO's major role, especially during the last stage of knee extension when the patellar has little bony constraint by the trochlear grove, was to counterbalance the pull of the lateral component of the quadriceps, probably attributed to its large insertion angle onto the patella (1,16,27). At the same time, VMO also changed its role from flexing to extending the patella. This was consistent with what Koh et al. (13) found in their *in vivo* patellar tracking measurement when the VMO was activated by electrical stimulation. In several studies focused on the anatomy of VMO (10,20,21,30), it was reported that the two portions of the vastus medialis have marked difference in fiber alignment, with VMO generally directs much more medially (45–65° from the femoral axis) and VML only has about a 15–25°angle with the femoral axis. Besides, Raimondo et al. (21) suggested that the insertion angle of VMO onto the patella may be related to patellar location which is related to knee flexion. When the knee is in a more extended position, the patella seats on the superior part of trochlear grove of femur and thus results a larger insertion angle of VMO onto the patella. As a result, contraction of the VMO pulls the patella more in the direction of medial tilt and medial shift. On the other hand, VMO contributed the least to the patellar medial rotation among all three muscle heads, indicating the line of action of the muscle is very close to the rotation center of the patella.

Although there are different opinions about whether VMO should anatomically be defined as a separated muscle itself, it is generally agreed that the two portions of the vastus medialis function differently. As shown above, the main actions of the VML was to extend and proximally shift the patella. Furthermore, unlike the actions of the VMO, VML was not influenced much by knee flexion. This may be attributed to its small insertion angle onto the patella, which makes it pull along the axis of the femur, despite the change of knee flexion angle.

The interesting result that the VL rotated the patella medially in some of the subjects was corroborated in our experiment by visual inspection and videotaping. There were anatomical findings (7,30) suggested different portions of VL inserted on different parts of the patella with different insertion angle, creating variations in the force applied to the patella. Sakai et al. (23) also briefly demonstrated the possibility that the VL might exert medial rotation moment around the center of patella.

Most patellar tracking studies were done *in vitro* using cadaver knees; much less research has been done *in vivo*. Koh et al. (13) evaluated patellar tracking on one human subject with reflective markers placed on intracortical pins inserted into the patellar and femur. Their finding that VMO contraction induced patellar extension at fully extended knee but generated patellar flexion in more flexed knee (13) was confirmed by our results in this study (Fig. 7).

To evaluate the selective activation of individual quadriceps components through surface stimulation, patellar tracking was also measured in selected subjects together with the compound muscle action potential (M-wave) in the several quadriceps components. M-wave was only observed in the quadriceps component that was stimulated, indicating selective activation of the stimulated component and negligible co-contraction of other quadriceps components (Fig. 9).

A limitation of the present noninvasive study was that the patellar clamp could only be used at a small range of motion, approximately from 20° flexion to full knee extension. If more flexed knee positions need to be investigated, other approaches need to be used. Fortunately, the more extended knee positions happen to be the range where the patellar malalignment and abnormal tracking tend to be more severe. Furthermore, the more extended knee positions are also in the range where it becomes difficult to obtain the standard tangential (axial) view patellar radiograph because it is technically difficult to see the patella on the radiograph at the more extended knee positions (2,4,11,25).

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