INTRODUCTION: Patellofemoral pain (PFP) is closely related to static patellar malalignment and patellar maltracking. The etiology of patellar maltracking is multifactorial; relating to femoral shape, passive soft-tissue restraints; and/or an imbalance of forces on the patella. A number of structures, both passive and active, contribute to the force balance on the patella. Previous studies have investigated the moment arm of the patellar tendon and the quadriceps muscle as a whole. However, the presence of increased patellar spin (positive spin or varus results in the superior patellar pole moving laterally) in PFP [1,2] suggests that the relative moment contributions of the individual quadriceps components play an important role in stabilizing the patella.

Therefore, in order to understand the relative contribution of each quadriceps component to the balance of forces on the patella, the individual moment arms of the quadriceps tendons must be known. Previous studies have relied on in vitro methods at static knee flexion angles or modeling. No study has characterized the moment arms of the individual quadriceps components in vivo. Thus, the purpose of this study was to quantify the moment arms of the quadriceps tendons in vivo and noninvasively during dynamic flexion/extension of the knee. The hypothesis of this study was that the tendons associated with the medial and lateral quadriceps components will have significant off-axis moment arms (resulting in patellar spin) compared to the central quadriceps components. A secondary purpose was to determine if increasing the magnitude of quadriceps contraction influences the dynamic moment arms of the quadriceps components.

METHODS: Thirty-two healthy subjects with no prior history of knee problems or pain participated in this IRB-approved study. After obtaining informed consent, subjects were placed supine in a MR imager (1.5 T, GE Medical Systems, Milwaukee, WI, USA or 3.0 T, Philips Electronics, Eindhoven, NL) [1]. Preliminary work determined that kinematics obtained from the two imaging systems were not significantly different.

A cushioned wedge was placed under the knee such that full knee extension was attainable. Subjects were randomized into two groups (non-weight, n=18 and weight, n=14). Both groups lifted the weight of their leg during cyclical flexion/extension, but subjects in the weight group had an additional 0.5-kg weight secured to the ankle.

Using a sagittal-oblique imaging plane (bisecting the patella and perpendicular to the femoral epicondyles), a fast full-PC image set (x,y,z velocity and anatomic images over 24 time frames) was acquired during active knee flexion/extension [1]. Using coronal-oblique imaging planes (parallel to the quadriceps tendon), two additional fast-PC image sets were acquired during the movement. For each component of the quadriceps muscle, the myotendinous junction [3] was identified in the coronal fast-PC series. The insertion of the tendon onto the patella was chosen as the midpoint of the most proximal edge of the patella, and the most lateral and most medial points on patella, for the rectus femoris (RF) and vastus intermedius (VI), vastus lateralis (VL) and vastus medialis (VM) muscles, respectively. Patellar insertions of the quadriceps tendons were tracked using the 3D displacement of points on the patella by integrating the fast-PC velocity data [1].

The moment arm (MA, scalar) was defined as the perpendicular distance between the line of action of the tendon, and the point about which moments were summed. The latter was assumed to be the midpoint between the medial and lateral femoral epicondyles. The relative moment (RM, 3D vector) was calculated to assess the contribution of each muscle component in each of the three planes of motion and was the cross product of the tendon line of action (LOA) and the distance between the LOA and the point about which moments were summed. The moment of each muscle could then be calculated by multiplying its scalar force by its RM. The MA and RM were scaled by the ratio of the average subject height from the able-bodied population (169.46 cm) and the subject height for each individual knee to account for skeletal size variations across subjects. Next, they were compared between the weight and non-weight group and between each quadriceps component and the patellar tendon (PT) at single knee flexion angle increments using 2-way ANOVA with repeated measures (α=0.05).

RESULTS: The VM and VL produced significant moments about the anterior axis (patellar spin, Figure 1). The VM spin RM was significantly different compared to the other quadriceps components and the PT (p<0.01). The VL spin RM was also different compared to the other three quadriceps muscles and the PT (p<0.01). The scalar MAs of all four quadriceps components were similar and matched with previously published values (Table 1). There were no differences except when the four quads components were compared to the PT (p<0.01). All 4 quadriceps components have similar extension RM, which are opposite in direction, but similar in magnitude, to the PT flexion RM. There were no significant differences in extension RM when the VM was compared to the other quads components. The extension RM of the VL was significantly smaller than both the VI and RF (p<0.01). All tendons produced small RMVs about the superior axis (positive results in medial patellar tilt), but no significant differences were found among any of the quadriceps components or compared to the PT. Increased quadriceps contraction significantly increased the MA in all tendons. In addition, increased load resulted in increased flexion RM for all quadriceps tendons, increased (decreased) tilt RM in the VL and PT (RF, VI), and decreased (increased) spin RM in the PT (VM).

DISCUSSION: This is the first study to characterize the moment arms of the individual quadriceps components in vivo during dynamic volitional activity. While the scalar MAs of the quadriceps components are similar, it is important to assess the contribution of each component in 3D. The VL and VM have significant off-axis RMs, particularly about the anterior axis (patellar spin). The VL spin RM is the largest of all the quads components. Therefore, any weakening of the VL could be exacerbated by the fact that not only is it a smaller force contributor than the VL, but is at a mechanical disadvantage to offset the spin moment of the VL. This could explain the finding of increased patellar spin in subjects with PFP. The VM lateral tilt RM is an artifact of summing moments about a point posterior to the patella. If moments are summed about the patellar centroid, VM RMx (4.6±2) produces medial tilt, VL (-5.3±2) lateral tilt, and RMx of the VL/RF/PT are small (<1) at 10°.

Further, increasing the level of quadriceps contraction has a significant effect on MAs associated with each component, reinforcing the importance of developing in vivo, noninvasive methods to assess the structure and function relationships of the musculoskeletal system.