Quantification of Dynamic In Vivo 3-D Muscle Moment Arms Using Cine-PC MRI

N. A. Wilson[1], A. J. Behnam[1], and F. T. Sheehan[1]

[1]Rehabilitation Medicine, National Institutes of Health, Bethesda, Maryland, United States

INTRODUCTION

A number of structures, both passive and active, contribute to the force balance on the patella. 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 investigated the moment arm of the patellar tendon and the quadriceps muscle as a whole and have relied on static *in vitro* methods or modeling. However, no study has characterized the moment arms of the individual quadriceps components *in vivo*. Assessing the contribution of each quadriceps component in 3D provides a more complete understanding of muscle functionality, and will allow exploration of whether pathology alters muscular moment arms. For example, patellofemoral pain (PFP) syndrome is closely related to patellar maltracking. Patellar maltracking and pain could result from a disruption in the balance of moments from the quadriceps muscles at the patellofemoral joint. Thus, the primary purpose of this study was to advance the use of phase contrast (PC) MR imaging in the quantification of musculoskeletal properties in order to provide the first *in vivo* 3D measures of knee extensor moment arms, measured during dynamic volitional activity. As a test of the utility of the developed methodologies, the quadriceps moment arms were compared in two different populations (asymptomatic and patients diagnosed with PFP).

METHODS

Nineteen asymptomatic subjects with no prior history of knee problems or pain, and 11 subjects with clinically diagnosed PFP and maltracking participated in this study. Subjects were placed supine in a MR imager (1.5 T, GE Medical Systems, Milwaukee, WI, USA or 3.0 T, Philips Medical Systems, Best, NL) [1]. Kinematics obtained from the two imaging systems were not significantly different. During cyclic flexion/extension and using a 2D sagittal-oblique imaging plane (bisecting the patella and perpendicular to the femoral epicondyles), a 3D dynamic cine-PC MR image set (x,y,z velocity and anatomic images over 24 time frames) was acquired [2]. Two additional PC sets (Figure 1a) were acquired using coronal-oblique imaging planes (parallel to the quadriceps tendon). Dynamic cine images were also acquired in three axial planes to establish anatomical coordinate systems (Figure 1b). The kinematics of the femur, tibia and patella were quantified through integration of the velocity data [2]. All bony points of interest were visually identified in the full extension time frame of the dynamic images (Figure 1) and tracked through the motion cycle based on each bone's kinematics. For each component of the quadriceps muscle, the myotendinous junctions (MTJs) were identified in the first frame of the coronal PC series and tracked in a similar manner. The tendon insertion onto the patella was chosen as the midpoint of the most proximal edge of the patella (Point D, Figure 1a) for the rectus femoris (RF) and vastus intermedius (VI), and the most lateral and medial points on patella (Points E,F, Figure 1b) for the VL and VM, respectively. Each tendon's line-of-action was defined as the unit vector between the respective MTJ and the tendon insertion on the patella.

The relative moment (**RM**, 3D vector) was calculated to assess the contribution of each muscle component in the three planes of motion. **RM** was defined as the cross product of the tendon line of action and a line connecting the line of action with the patellar center of mass and was composed of: flexion/extension ($\mathbf{RM}_{F/E}$), tilt ($\mathbf{RM}_{Tilt}$) and spin ($\mathbf{RM}_{Spin}$). These **RM**s transform the tendon force into moments acting on the patella in the medial, superior and anterior directions, respectively. Thus, $\mathbf{RM}_{F/E}$ results in a medially directed moment, causing patellar flexion. The moment of each muscle could then be calculated by multiplying its scalar force by its **RM**. Statistical comparisons were made between populations for each quadriceps muscle using 2-way ANOVA with a Bonferroni post-hoc test (α=0.05).

RESULTS

In asymptomatic knees, the VM had a tendency to produce patellar flexion, medial tilt, and positive spin (Table 1). The largest tendency of the VM was to produce positive spin, followed by medial tilt. The VL had a tendency to produce patellar flexion, lateral tilt, and negative spin with the largest tendency to produce negative spin, followed by lateral tilt. The central quadriceps components (VI and RF) produced patellar extension, medial tilt, and positive spin. Results for PFP subjects were similar to asymptomatic subjects (Table 1), except for the patellar spin component (Figure 2). In PFP subjects, the magnitude of $\mathbf{RM}_{Spin}$ was decreased for both the VM and VL muscles. In addition, both the RF and VI showed an increase in the tendency to produce positive spin.

DISCUSSION

This is the first study to characterize the relative moments of the individual quadriceps components *in vivo* during dynamic volitional activity. Accurate values of musculotendon moment arms are essential for modeling applications, determination of musculotendon material properties, and the study of pathology. The current study advances the use of phase contrast MRI for full 6 degree-of-freedom tracking of bone, tendon, and muscular structures during a single experiment.

A disruption in the balance of moments from the quadriceps muscles at the patellofemoral joint could lead to patellar maltracking and pain. For example, patellar maltracking is often thought to be caused by a weakening of the VM [3], but could also be due to a relative moment imbalance. Weakening is likely the cause of the lateral patellar subluxation commonly seen in PFP as it is a force-displacement issue. On the other hand, two recent studies have demonstrated the presence of increased patellar spin in PFP [4,5]. The results from the current study suggest increased spin may result from a moment imbalance due to the presence of lateral patellar subluxation. A lateral shift of the patella (due to a force imbalance) creates a moment imbalance in which the central quadriceps components increase their tendencies to produce anteriorly directed moments, resulting in a positive change in patellar spin. This study serves as a basis to begin to explore how pathologies, such as patellofemoral pain, effect and are affected by the moment arms and relative moments of the knee joint.

REFERENCES

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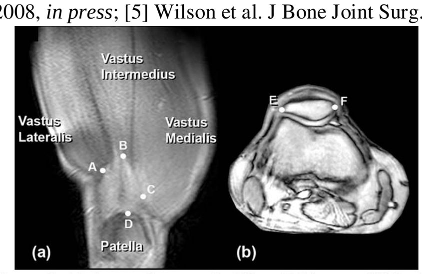

Figure 1: (a) Anatomic coronal-oblique PC image. White dots show the myotendinous junctions of the (A) VL; (B) VI; and (C) VM. (D) Represents the insertion of the tendon on the patella. **(b)** Mid-patellar axial dynamic image at full extension. Insertions of lateral (E) and medial (F) quads tendon on patella.

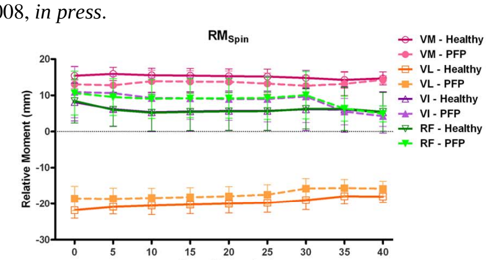

Figure 2: Mean **Relative Moment** - $\mathbf{RM}_{Spin}$ (positive, superior pole rotates laterally) from full extension (0º) to 40º of knee flexion. Mean of healthy knees represented with open symbols and solid lines. Mean of PFP knees, filled symbols and dashed lines. Error bars represent standard deviation.

	Group	$RM_{F/E}$ (mm)	RM_{Tilt} (mm)	RM_{Spin} (mm)
VM	Healthy	0.4 (0.9)	4.6 (2.1)	15.6 (1.9)*
	PFP	-0.2 (1.3)	5.4 (2.5)	13.7 (2.7)*
VL	Healthy	0.5 (0.9)	-5.2 (1.9)	-20.5 (2.5)*
	PFP	-0.2 (1.4)	-6.1 (2.1)	-18.4 (2.7)*
VI	Healthy	-4.9 (2.8)	0.7 (2.0)	5.3 (5.4)*
	PFP	-5.0 (1.8)	2.0 (1.7)	9.5 (5.3)*
RF	Healthy	-2.1 (2.6)	0.5 (1.2)	5.2 (5.1)*
	PFP	-1.8 (1.8)	1.3 (1.1)	9.3 (5.1)*

Table 1: The mean (SD) relative moments **(RM)** of the quadriceps tendons at 10° of knee flexion.
* indicates a significant difference ($p<0.05$) between healthy and patellofemoral pain groups.