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Dynamic In Vivo 3-Dimensional Moment Arms of the Individual Quadriceps Components

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Abstract

The purpose of this study was to provide the first *in vivo* 3-dimensional measures of knee extensor moment arms, measured during dynamic volitional activity. The hypothesis was that the vastus lateralis (VL) and vastus medialis (VM) have significant off-axis moment arms compared to the central quadriceps components. After obtaining informed consent, three 3D dynamic cine-Phase Contrast (PC) MRI sets (x,y,z velocity and anatomic images) were acquired from 20 subjects during active knee flexion and extension. Using a sagittal-oblique and two coronal-oblique imaging planes, the origins and insertions of each quadriceps muscle were identified and tracked through each timeframe by integrating the cine-PC velocity data. The moment arm (MA) and relative moment (**RM**, 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) were calculated for each quadriceps component. The tendencies of the VM and VL to produce patellar tilt were evenly balanced. Interestingly, the magnitude of **RM-P_{Spin}** for the VM and VL is approximately four times greater than the magnitude of **RM-P_{Tilt}** for the same muscles suggesting that patellar spin may play a more important role in patellofemoral kinematics than previously thought. Thus, a force imbalance that leads to excessive lateral tilt, such as VM weakness in patellofemoral pain syndrome, would produce excessive negative spin (positive spin: superior patellar pole rotates laterally) and to a much greater degree. This would explain the increased negative spin found in recent studies of patellar maltracking. Assessing the contribution of each quadriceps component in three-dimensions provides a more complete understanding of muscle functionality.

Introduction

In the musculoskeletal system, moments generated by muscle are transmitted through the tendon to the skeleton. The magnitude of this moment, typically referred to as a joint moment, depends on the magnitude of the muscle-tendon force and the moment arm length. The moment arm is defined as the perpendicular distance between the musculotendon line of action and the point about which moments are summed (Boyd and Ronsky, 1998; Spoor et. al., 1990). Accurate values of musculotendon moment arms are essential for modeling applications (Maganaris et. al., 2001), determination of musculotendon material properties (Wilson; 2007), and the study of pathology (Gage and Novacheck, 2001; Sheehan et. al., 2008c).

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CONFLICT OF INTEREST STATEMENT

The authors report no potential conflicts.

Experimentally measured joint torques cannot be transformed to muscle forces, nor can the material properties of musculotendon structures be calculated, without knowledge of the moment arms. In addition, there are often both mechanical and biological changes associated with joint pathology (Buford, Jr. et. al., 1997). Without understanding the normal joint geometry, these changes cannot be identified or simulated. For example, current literature suggests that the etiology of patellofemoral pain is multifactorial (Csintalan et. al., 2002; Schepesis and Watson, 2005) and associated with abnormal patellar alignment and patellar maltracking (Fitzgerald and McClure, 1995; Fulkerson, 2002; Grelsamer and Stein, 2005; Schepesis and Watson, 2005; Sheehan et. al., 2008a; Wilson et. al., 2009). However, the factors that initiate the shift from healthy to pathological knee biomechanics have yet to be determined. A disruption in the balance of moments from the quadriceps muscles at the patellofemoral joint could lead to patellar maltracking and pain.

Previous investigations of the knee extensor moment arms have either reduced the quadriceps muscles to a single tendon (Herzog and Read, 1993; Imran et. al., 2000; Kellis and Baltzopoulos, 1999; Nisell and Ekholm, 1985; Smidt, 1973; Tsaopoulos et. al., 2007; Wretenberg et. al., 1996) or have relied on cadaver-based (Fick, 1879) and modeling approaches. To date, only three studies have investigated the moment arms of the individual quadriceps components (Table 1). Two were cadaver-based investigations and used the tendon excursion method (Buford, Jr. et. al., 1997; Visser et. al., 1990). This method has limited application because the required assumptions rarely hold in a true dynamic situation (Sheehan, 2007). In the tendon excursion method, the moment arm is calculated with respect to a point on the finite helical axis. However, summing moments about a point integral to the tibiofemoral joint, rather than the patellofemoral joint, implies that the patella and patellar tendon do not dissipate force from the quadriceps. This in turn, assumes that the quadriceps muscles directly impart a moment on the tibia (Yamaguchi and Zajac, 1989). The only 3-D dynamic study to investigate the moments arms of the individual quadriceps components was a modeling study, based on previously published data (Pal et. al., 2007). Other studies, primarily 2-D and static, have calculated the moment arm of the single quadriceps tendon using the direct load method (Draganich et. al., 1987; Grood et. al., 1984; Hsu et. al., 1993; Spoor and van Leeuwen, 1992; Yamaguchi and Zajac, 1989). Although the direct load method can be used to derive a direct relationship between the quadriceps force and the moment imparted on the tibia, it provides no information regarding how these moments affect the patella. In addition, it is not currently feasible to perform direct load calculations on individual muscle components *in vivo*. Thus, to date, no study has quantified the *in vivo* 3-D moment arms of the individual quadriceps components during volitional activity, relative to the patella.

The long-term goal of this work is to explore how pathology (e.g., patellofemoral pain syndrome, cerebral palsy, and stroke) alters muscular moment arms and whether interventions (e.g., anteromedialization of the tibial tubercle) re-establish the mechanical advantage of these structures. As a part of this overall goal, the primary purpose of this study is to provide the first *in vivo* 3-D measures of the moment arms of the individual quadriceps components, measured during dynamic volitional activity. A secondary aim was to compare the relative moments for each quadriceps component in order to evaluate their primary moment directions with respect to the patella.

Methods

Twenty two healthy subjects volunteered to participate in this study. All participants gave informed consent upon entering this IRB approved study. Subjects were excluded if they had any contraindications to having an MRI scan or if they had any current or past history of knee pain, regardless of etiology. 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) (Seisler and Sheehan, 2007). Statistical analysis of results obtained from each scanner determined that kinematics obtained from the two imaging systems were not significantly different (Appendix 1).

Subjects were positioned laying supine on the bed with their hip flexed to approximately 20° (from horizontal) with a cushioned wedge placed under the knee such that full extension of the leg was attainable within the bore of the magnet. They were then asked to cyclically flex/extend their knee, guided by an auditory metronome, from maximum attainable flexion (~50°) to full extension (0°) while an optical trigger synchronized the data collection to the motion cycle. No additional load was applied to the leg. Prior to data collection, subjects practiced the task until they could comfortably repeat the motion. Using a sagittal or sagittal-oblique imaging plane (bisecting the patella and perpendicular to the femoral epicondylar line), a 3D dynamic cine phase contrast (PC) MR image set (x,y,z velocity and anatomic images over 24 time frames) was acquired. Using a coronal-oblique imaging plane (parallel to the quadriceps tendon), two additional cine-PC MR image sets were acquired for tracking the insertion of the four quadriceps muscle components into the quadriceps tendon (Figure 1b). In addition, dynamic cine images (anatomic only) were acquired in three axial planes during the cyclic movement. These images were used to establish anatomical coordinate systems.

The change in the 3-D rigid body rotation and translation (kinematics) of the femur, tibia, and patella were quantified through integration of the cine-PC velocity data. Although the cine-PC acquisition was based on a single imaging plane (Figure 1a), the velocity data allowed the kinematics of the bones to be accurately tracked in three dimensions throughout the movement. Kinematics were defined relative to an anatomical coordinate system embedded in each bone. The patellar coordinate system was based on a previously published system (Seisler and Sheehan, 2007), with the exception that the patellar medial/lateral axis was defined as the vector connecting the most medial and lateral points on the patella at the level of the mid-patella (Figure 1c: Points E and F). Identification of these anatomical coordinate systems was completed for a single time frame only and the cine-PC data were used to track kinematic changes through the entire motion cycle (Sheehan et. al., 1998). In a similar manner, all bony points of interest were identified in the full extension time frame and tracked through the motion cycle based on each bone's kinematics. All bony points were identified in one of two dynamic images, the sagittal reference plane or the axial reference plane; both taken through mid-patella (Figure 1). For example, the patellar tendon (PT) line-of-action was defined by the insertion of the tendon into the patella and tibia from the sagittal reference plane (Sheehan and Drace, 2000) (Points A, B, Figure 1a).

As the quadriceps muscles have myotendinous junctions which approach the quadriceps tendons through a range of angles (Buford, Jr. et. al., 1997), the tendon origins were chosen as the center point of each myotendinous junction in the first frame of the coronal cine-PC images (Points C–E, Figure 1b). For each muscle the entire curvilinear myotendinous junction was manually outlined and the tendon origin (center point of the outline) was determined using ImageJ (National Institutes of Health, Bethesda, MD). The tendon origin was then tracked through each timeframe by integrating the coronal-oblique cine-PC velocity data.

For each quadriceps muscle, the insertion was selected to capture the central tendency of each musculotendon unit. The quadriceps tendon inserts on the entire superior edge and portions of the medial and lateral edges of the patella, wraps around the anterior patellar surface and converges distally to form the patellar tendon. However, it has been shown that each head of the quadriceps muscle can be associated with a distinct portion of the trilaminar quadriceps tendon (Farahmand et. al., 1998). The tendons associated with the rectus femoris (RF) and vastus intermedius (VI) both insert on the superior pole of the patella (Farahmand et. al., 1998). In contrast, the portions of the quadriceps tendon associated with the vastus lateralis

(VL) and vastus medialis (VM) insert on the superior edge of the patella and wrap around to the lateral and medial patellar margins, respectively (Farahmand et. al., 1998). Therefore, the insertions of the RF and VI were chosen as the midpoint of the most proximal edge of the patella (Point F, Figure 1b), whereas, the insertion of the VL and VM muscles were chosen as the most lateral and most medial points on the patella, respectively (Points G, H, Figure 1c). All insertions were chosen by a single investigator in the full extension time frame and tracked throughout the movement, based on the 3D patellar kinematics. The line-of-action of each tendon (RF, VI, VL, and VM) was defined as the unit vector between the respective myotendinous junction and the tendon insertion point on the patella. Therefore, the results represent the moment arm of the muscle line of action through the central muscle fibers (Buford, Jr. et. al., 1997).

The scalar moment arm (MA) was quantified relative to two points. It was first calculated relative to the patellar geometric center (MA-P), assumed to be the patellar center of mass. In an axial mid-patellar imaging plane (cine), the patella was manually outlined and the centroid of the cross-section was calculated using ImageJ. To facilitate comparison with literature values, the scalar moment arm was also calculated relative to the midpoint of the tibiofemoral flexion/extension axis (MA-F) (Pandy, 1999), assumed to be the line connecting the medial and lateral femoral epicondyles. The epicondyle points were chosen from an axial imaging plane of the femoral epicondylar width at full extension.

The relative moment (**RM**, 3D vector quantity) represents the coefficients of the muscles in moment equilibrium equations (An et. al., 1984). **RM** was calculated as the cross product of the tendon line-of-action and a line connecting the tendon line-of-action to the point about which moments were summed (Krevolin et. al., 2004). The **RM** was used to assess the relative contribution of each muscle component in the three planes of motion and was composed of three components, flexion/extension (**RM-P_{F/E}**), tilt (**RM-P_{Tilt}**), and spin (**RM-P_{Spin}**). Positive spin results in the superior patellar pole rotating laterally. These components transform the tendon force into moments acting on the patella in the medial, superior, and anterior directions, respectively. Thus, **RM-P_{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**. These moment arms were calculated with respect to the patellar center, relative to the patellar coordinate system. All moment variables (MA-P, MA-F, and **RM-P**) were tested for correlation with subject height and epicondylar width. No correlations were demonstrated, therefore the moment variables were not normalized.

Data were collected in even temporal, rather than even knee angle increments. In order to create population averages, each kinematic and moment variable was interpolated to single-degree knee angle increments. An individual subject's range of motion varied depending on their leg length. Therefore, not all subjects were represented at the extremes of the range of knee flexion. Data points representing five or fewer subjects were eliminated from the total group average. Statistical analysis showed no differences between the flexion and extension portions of the movement. Therefore, only the extension (concentric quadriceps contraction) portion of the movement was used for further analysis. Statistical comparisons were made between the RF, VI, VM, VL, and PT at single knee flexion angle increments (0–45°) using 2-way ANOVA with repeated measures and Bonferroni post hoc comparisons ($\alpha=0.05$). Although origin and insertion points could be selected with sub-pixel accuracy, the sensitivity of moment arm calculations to small errors in choosing the appropriate reference point location (i.e. the type of error one might expect based on intraobserver variations) was investigated. For each tendon, the origin and insertion points were altered by a single pixel in each cardinal direction, resulting in 18 altered moment arms. At each knee angle, the average absolute difference between the original MA and each of the 18 altered MAs was calculated. Finally, a mean absolute difference was calculated across all knee angles and all subjects.

Results

The MA-P was similar for the central quadriceps (VI and RF) and the PT and changed little throughout knee flexion (Figure 2a, Appendix 2). The MA-P of the VL was significantly greater than all other quadriceps and the PT ($p < 0.01$, Table 3) and the MA-P of the VM was significantly greater than the central quadriceps (RF and VI) and the PT ($p < 0.01$). Sensitivity analysis demonstrated that for an assumed error of ± 1 pixel in all cardinal directions, the scalar moment arm (MA-P) varied by less than 0.45 mm or less than 4.9% for all tendons (Table 4). The MA-F for all quadriceps and the PT increased with initial knee flexion, but then tended to decrease as the knee flexed past 20° (Figure 2b). There were significant differences when the MA-F of the four quadriceps were compared to the PT ($p < 0.01$, Table 3), although the moment arms of all four quadriceps components were similar.

The RF and VI produced negative values of $\mathbf{RM-P}_{F/E}$, thus the moments generated resulted in patellar extension (Figure 3a, Table 3). The VM and VL had negligible values of $\mathbf{RM-P}_{F/E}$, and the PT produced positive values of $\mathbf{RM-P}_{F/E}$. The VM had a small $\mathbf{RM-P}_{Tilt}$ resulting in medial patellar tilt, whereas the VL had just the opposite (Figure 3b, Table 3). The central quadriceps and the PT had negligible values for $\mathbf{RM-P}_{Tilt}$. $\mathbf{RM-P}_{Spin}$ produced the largest values out of all $\mathbf{RM-P}$ components (Figure 3c, Table 3). The VM and VL tended to produce positive and negative $\mathbf{RM-P}_{Spin}$, respectively, which were significantly different than the other quadriceps and the PT ($p < 0.01$). The RF and VI had small, positive $\mathbf{RM-P}_{Spin}$, while the PT had small, negative $\mathbf{RM-P}_{Spin}$.

Discussion

The muscle moment arm is essential to understanding the mechanics involved in joint motion (Brand and Hollister, 1993; Buford, Jr. et. al., 1997). This is the first study to characterize the moment arms and relative moments of the individual quadriceps components *in vivo* during dynamic volitional activity. The knee joint is made up of two joints that are acted upon in tandem by the quadriceps components.

Therefore, it is important to consider both joints when looking at fundamental concepts like joint geometry. The moment arms were calculated relative to the patellar center of mass, because summing moments about the center of mass or a fixed point greatly reduces the complexity of the moment equations. Summing moments about the tibiofemoral flexion axis or the finite helical axis (effective MA) requires the incorrect assumption that the quadriceps muscles directly impart a moment on the tibia. However, the effective MA was calculated to facilitate comparisons to previous literature.

It is commonly thought that the quadriceps act to tilt the patella laterally due to the normal valgus orientation of the knee. In addition, excessive lateral tilt has been used as a clinical marker for patellar maltracking (Grelsamer and Stein, 2005). In the current study, the tendencies of the VM and VL to produce patellar tilt are evenly balanced. This balance may be disrupted by muscle weakness or a change in moment arm in patients with patellofemoral pain. For example, a weakening of the VM is often considered a cause of patellar maltracking (Makhsous et. al., 2004; Tang et. al., 2001). It remains unknown which component of the moment (force or moment arm) is decreased. The current study provides the first methodology that can accurately distinguish between these two components.

Interestingly, the magnitude of $\mathbf{RM-P}_{Spin}$ for the VM and VL is approximately four times greater than the magnitude of $\mathbf{RM-P}_{Tilt}$ for the same muscles. Therefore, in patellofemoral pain, an imbalance in the force produced by the VM relative to the VL force that leads to excessive lateral tilt would produce excessive negative spin and to a much greater degree. This suggests that patellar spin may play a more important role in patellofemoral kinematics than

previously thought. The importance of patellar spin in knee kinematics is underscored by two recent studies which demonstrated an increase in negative patellar spin in patients with patellofemoral pain (Sheehan et. al., 2008b; Wilson et. al., 2009). Obviously, the interactions between knee geometry and mechanics are complex and factors such as bone shape and rate of torque development will also play a role in the dynamic patellar motion path.

When moments were summed about a point on the tibiofemoral flexion/extension axis, scalar moment arms for the individual quadriceps components and the PT matched closely with previously published data (Figure 4). Pal, et al. (2007) used finite element modeling to predict muscle moment arms using both the tendon excursion and geometric (tibiofemoral point-of-contact) methods. Their results (tendon excursion method) consistently over-estimate MA-F, compared to the current study, particularly for the VM and VL. Yet, the shape of their predicted curves match closely with the current data. Pal and colleagues (2007) suggested that their estimates were sensitive to the inferior/superior and anterior/posterior origins and insertions of the muscles, which may account for the small differences in magnitude relative to the current data. However, sensitivity analysis from the current work demonstrated limited sensitivity to origin and insertions locations (<5% of MA-P). **RM**s obtained in the current study cannot be directly compared to literature values as no similar data has been published with respect to the patellar center of mass.

The limitations of the current study include the fact not all subjects were represented at all knee flexion angles. Abrupt changes in slope at the extremes of the range of motion may be due to the limited number of subjects included at these points. In addition, a single point was defined as the location of the origin and insertion of each quadriceps component on the quadriceps tendon. As the quadriceps muscles have broad origins and a broad insertion on the patella, the results represent the moment arm of the muscle line of action through the central muscle fibers (Buford, Jr. et. al., 1997). Anatomical studies have shown that the VM can be divided into separate muscle components with differing fiber orientations (Farahmand et. al., 1998); which may be important as other studies have suggested that weakening of the oblique portion of the VM may be related to patellofemoral pain (Makhsous et. al., 2004; Tang et. al., 2001). The current study treated the VM as a single entity because the ability to visualize individual muscle fiber orientations within a single quadriceps component (and therefore locate separate origin points) is limited in the cine-PC image series. Future studies may be able to address the specific problem of patellofemoral pain by determining the moment arms and **RM**s of both the lateral and oblique portions of the VM.

The current study advances the use of cine-PC MRI for full 6 degree-of-freedom tracking of bone, tendon, and muscular structures during a single experiment. The results serve 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 by providing the first *in vivo* 3-dimensional measures of the moment arms and relative moments of the individual quadriceps muscles, measured during dynamic volitional activity. Further exploration is needed to quantify the moment arms of muscles crossing the knee joint in patellofemoral pain and other pathological conditions.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Images from 3D dynamic cine phase contrast series

(a) Anatomic sagittal cine-PC image illustrating the placement of the coronal-oblique imaging plane (red box) parallel to the quadriceps tendon and passing through the myotendinous junction of the vastus intermedius muscle. Not shown: similar coronal-oblique imaging plane passing through the myotendinous junction of the rectus femoris muscle. The sagittal imaging plane bisected the patella and was perpendicular to a line connecting the femoral epicondyles in the axial plane. (A) The distal pole of the patella and (B) the insertion of the patellar tendon into the tibial tubercle are the origin and insertions of the patellar tendon, respectively. (b) Anatomic coronal oblique cine-PC image. The myotendinous junctions of the (C) vastus lateralis, (D) vastus intermedius, and (E) vastus medialis muscles can clearly be identified. White dots represent the points chosen as the myotendinous junctions (C–E), or the insertion of the VI / RF portion of the quadriceps tendon on the patella (F). (c) Mid-patellar axial cine image taken at full extension. VL insertion (G) and VM insertion (H) on the patella are illustrated. NOTE: Point F was chosen from the full extension anatomic image of the sagittal cine-PC sequence. The axial image was taken using an imaging plane that bisected the patella in the sagittal plane.

Figure 2. Mean MA-P and MA-F

(a) Mean MA-P throughout the range of knee flexion calculated with respect to the patellar center of mass. (b) Mean MA-F throughout the range of knee flexion calculated relative to the midpoint of the tibiofemoral flexion/extension axis. Error bars represent one standard deviation.

Figure 3. Mean RM-P calculated with respect to the patellar center of mass
 (A) Mean **RM-P_{F/E}** (positive produces patellar flexion). Grey bars (plotted on right y-axis) represent the number of subjects included in all means for each knee flexion angle. (B) Mean **RM-P_{Tilt}** (positive produces medial patellar tilt) (C) Mean **RM-P_{Spin}** (positive, superior pole rotates laterally). Error bars represent one standard deviation.

Figure 4. Reported moment arms relative to the midpoint of the tibiofemoral flexion/extension axis (A) For the patellar tendon. (B) For the central quadriceps components (RF and VI). RF (black), VI (grey). (C) For the VL (black) and VM (grey). Pal, et al. (2007) is shown twice because data was reported for two methods of calculation: the tendon excursion (TE) method and the geometric (Geo) or TF contact method.

Table 1
Summary of Published Knee Moment Arm Studies

Author	Date	Knee Muscles	Sample Type	Sample Size	Static or Dynamic	Measurement Method	Point*
Good, et al.	1984	quadriceps	cadaver	5	dynamic	Direct load	Joint Line / Point of Contact
Draganich, et al.	1987	quadriceps	cadaver	6	static	Direct load	TF Center of Pressure
Visser, et al.	1990	RF, VL, VM, VL, BF, G	cadaver	6	static	Tendon excursion	Center of Rotation
Spoort, et al.	1992	RF, Sm, St, Gr, Sar, BFL, GM, GL	cadaver	1	static	Tendon excursion	Center of Rotation
Buford, et al.	1997	RF, VL, VM, VL, PT, Sm, St, Gr, Sar, BFL, BFS, Pop, GM, GL	cadaver	15	dynamic	Tendon excursion	F/E axis
Yamaguchi, et al.	1989	quadriceps	2-D model	1	static	Direct load	Center of Rotation
Pal, et al.	2007	RF, VL, VM, VL, PT, Sm, St, BFL, BFS	3-D model	1	dynamic	Tendon excursion	ISA
Current Study	2009	RF, VL, VM, VL, PT	in-vivo	22	dynamic	3-D geometric	Patellar Center of Mass

Knee Muscles: RF = Rectus Femoris; VL = Vastus Lateralis; VM = Vastus Medialis; VL = Vastus Lateralis; PT = Patellar Tendon; Sm = Semimembranosus; St = Semitendinosus; Gr = Gracilis; Sar = Sartorius; BF(L or S) = Biceps Femoris (Long or Short); G(M or L) = Gastrocnemius (Medial or Lateral)

* Point: Point about which moments were summed.

TF = Tibiofemoral; F/E axis = Flexion/Extension axis; ISA = Instantaneous screw Axis; PF = Patellofemoral

Table 2**Subject demographics**

	Demographics
Gender	11 Male, 11 Female
Age (years)	24.9 ± 5.0
Height (cm)	170.8 ± 7.7
Weight (kg)	67.9 ± 12.7
Epicondylar Width (mm)	77.3 ± 6.8

Table 3

Significant Differences in Moment Arms

The left (unshaded) portion of the table identifies which muscle moment arm pairs were significantly different when calculated with respect to the patellar center of mass. A significant difference in the MA or RM between two muscles is indicated by * ($p<0.05$) or ** ($p<0.01$) in their intersection box. A dash indicates no significant difference.

	VM	VL	VI	RF
MA-P	VL	**		
	VI	**	**	
	RF	**	**	-
	PT	**	**	-
RM-P _{E/E}	VL	-		
	VI	**	**	
	RF	**	**	-
	PT	**	**	**
RM-P _{Tnt}	VL	**		
	VI	**	**	
	RF	**	**	-
	PT	**	**	-
RM-P _{Spin}	VL	**		
	VI	**	**	
	RF	**	**	-
	PT	**	**	**
MA-F	VL	-		
	VI	-	-	
	RF	-	-	-
	PT	*	*	**

Table 4
Mean (range) sensitivity of MA-P to an assumed error of ± 1 pixel in all cardinal directions

Tendon	Mean Absolute Difference (mm)	% Change in MA-P (%)
VI	0.44 (0.39 – 0.45)	4.1 (3.1 – 4.9)
RF	0.43 (0.37 – 0.45)	4.8 (3.2 – 6.2)
VL	0.41 (0.38 – 0.42)	1.9 (1.8 – 2.1)
VM	0.25 (0.23 – 0.27)	1.5 (1.4 – 1.7)
PT	0.26 (0.25 – 0.28)	2.5 (2.2 – 2.8)