The Vector of Quadriceps Pull is Directed From the Patella to the Femoral Neck

Osamu Tanifuji MD, John David Blaha MD,
Shin Kai PhD

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Abstract

Background The quadriceps is the primary extensor of the knee. Its vector, which is perpendicular to the flexion axis of the knee, is important in understanding knee function and properly aligning total knee components. Three-dimensional (3-D) imaging enables evaluation using a 3-D model of each quadriceps component.

Questions/purposes We calculated the direction and magnitude of the quadriceps vector (QV) and the precision

of the measurement, and asked whether the QV bears a constant relationship to the femur and is aligned with an anatomically based axis on the femur.

Methods Using CT data of 14 subjects, we created a 3-D solid model of each quadriceps muscle component. Vectors (3-D direction and length) for each quadriceps component were determined using principal component analysis for muscle direction and volume for magnitude; vector addition established the directional vector of the combined muscle. The combined vector originating in the center of the patella was compared with the shaft, mechanical, and spherical (center femoral head to center medial side of the knee) axes.

Results The QV passed from the patella center proximally crossing the femoral neck between the femoral head and greater trochanter and was most closely aligned with the spherical axis.

Conclusions The QV axis may be an important reference for alignment of total knee components.

Clinical Relevance The spherical axis can be used in aligning total knee components to the flexion axis of the knee.

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Each author certifies that his or her institution approved or waived approval for the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

This work was performed at the Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI, USA.

O. Tanifuji, J. D. Blaha (✉)

Department of Orthopaedic Surgery, University of Michigan,
1500 E Medical Center Drive, 2912 Taubman Center,
Box 0328, Ann Arbor, MI 48109, USA
e-mail: jdblaha@med.umich.edu

O. Tanifuji

Division of Orthopaedic Surgery, Department of Regenerative
and Transplant Medicine, Niigata University Graduate School
of Medical and Dental Sciences, Niigata, Japan

S. Kai

Center for Fostering Innovative Leadership, Institute
for Research Collaboration and Promotion,
Niigata University, Niigata, Japan

Introduction

Treatment planning for conditions that affect the human knee depends on understanding the anatomy and biomechanics of the structures around the knee. The quadriceps muscle, as the primary extensor of the knee, acts to move the tibia around the flexion axis of the knee. Knowledge of the direction of quadriceps pull will guide TKA component positioning. Literature regarding the direction of quadriceps pull has been inconsistent, with some studies reporting only two-dimensional (2-D) results and others reporting

results using only part of the quadriceps muscle [3, 7, 11, 14, 20, 22, 24–26]. Advances in imaging enable a three-dimensional (3-D) full-muscle model to be constructed for evaluating the quadriceps vector (QV).

Although it commonly is stated that arthroplasty components should be inserted perpendicular to the mechanical axis, an alternative alignment is to place the flexion axis of the replaced joint in the same position as that of the normal knee [4, 9, 10]. A right-angle relationship of the quadriceps to the flexion axis of the knee has been postulated, and thus the QV could be helpful in this type of flexion axis alignment [14]. The trochlear groove of the distal femur is reportedly directed lateral to the femoral head, not toward the femoral head, as would be expected if the QV were aligned with the mechanical axis [5]. In unpublished work we noted that a plane constructed perpendicular to a calculated average flexion axis through the trochlear groove appears to be parallel to a line from the ball-in-socket of the hip at the proximal femur through the ball-in-socket on the medial side of the knee, and postulated that the QV would bear a constant relationship to that line.

The purpose of this study was to develop a method to evaluate the 3-D vector of the quadriceps femoris using a 3-D full-muscle model and determine the precision of the measurement of the QV and the relationship, with particular attention to whether the relationship is constant between the QV and the femur expressed as: (1) the passing point of the axis over the proximal femur; and (2) several anatomic axes: to determine the position of the QV relative to the proximal femur and the relationship of the QV to the anatomic axis (AA; femoral shaft axis), the mechanical axis (MA), and the spherical axis (SA; center of femoral head to center of medial condyle).

Materials and Methods

CT images (LightSpeed[®] VCT or Discovery[®] CT750 HD; GE Healthcare, Waukesha, WI, USA) of the thigh from the hip to below the knee were obtained for each study patient. Subjects were selected from those with archived CT scans performed for a pulmonary embolism protocol and were included if, based on history and present illness, no evidence existed of major lower extremity trauma or musculoskeletal surgery. The patients were positioned supine for these examinations in standard positions for clinical examination, but no other specific position was used. We excluded subjects whose CT images showed obvious deformity. The CT images of 14 subjects, seven right and seven left lower extremities, met inclusion criteria and were evaluated fully by a radiologist (BS) to confirm absence of deformity. The mean age of the subjects was 39 years (range, 30–40 years) and included nine

men and five women with a mean body height of 175 cm (range, 154.9–190.5 cm). This study was performed according to the protocol exempted from review by the Investigational Review Board of the University of Michigan, Ann Arbor, MI, USA.

A 3-D digital model of the femur, patella, and each quadriceps component (rectus femoris, vastus medialis, vastus lateralis, vastus intermedius) was constructed manually from CT data using 3-D visualization and modeling software (ZedView[®]; LEXI, Tokyo, Japan) (Fig. 1). The window of the image was changed to maximize the interface between muscles and the outline of the muscle was determined for each slice of the scan by the same researcher (OT) for each slice and each subject. Several referencing bony landmarks were chosen to establish the anatomic femur-based coordinate system (Model Viewer[®]; LEXI). By using a femur-based coordinate system the position of the subjects in the CT scanner is irrelevant. The geometric center axis (GCA), ie, a line connecting the

Fig. 1A–B Constructed 3-D digital models of (A) the femur and patella and (B) the bone and quadriceps components are shown.

centers of spheres representing the medial and lateral posterior femoral condyles, was defined as the femoral X-axis (positive laterally). The origin of the coordinate system was defined as the midpoint between the centers of these posterior femoral condylar spheres. The femoral Z-axis was defined as being perpendicular to the X-axis and in a plane formed by the X-axis and a line connecting the femoral origin and the center of the femoral head (positive superiorly). The femoral Y-axis was defined as the cross product of the Z-axis and X-axis (positive anteriorly) (Fig. 2) [21]. Each muscle's vector direction was calculated

Fig. 2 The coordinate system was constructed based on the GCA, which is a line connecting the centers of spheres representing the medial and lateral posterior femoral condyles.

from the principal component analysis using the long axis as the vector direction. The magnitude was calculated by the ratio of each quadriceps component muscle volume. The overall QV was calculated from the sum of each muscle's vector (Fig. 3). The origin of the overall vector was set to the center of the patella.

The position of the overall QV was analyzed as (1) the QV's passing point at the level of the center of the femoral head (XY plane) (Fig. 4) and (2) the angle between the QV and several axes based on anatomic points on the femur. In analyzing the position of the vector, the 3-D models were normalized to a femoral head radius of 25 mm and the position reported relative to this normalized model. The anatomic axes included (1) the femoral shaft axis (AA), (2) the MA, and (3) a new concept, the SA, a line connecting the center of the femoral head and the center of the medial posterior femoral condyle. The QV was calculated in the 3-D space, and the angle projected on the coronal plane was defined in two ways (Fig. 5). The first included the GCA and the center of the femoral head (GCA plane). The second included the clinical (bony prominence of medial and lateral epicondyle) transepicondylar axis (TEA plane) and the center of the femoral head [16].

The precision of the measurement was determined by measuring four randomly selected subjects at three different times by the same researcher but on different days and evaluating the differences between the calculated QVs. Mean angular differences for each repetition of the measurement were calculated as:

Fig. 3A–D (A) A bone and quadriceps 3-D model is shown. (B) The muscle is removed and the vector for each quadriceps component is shown. Direction is calculated from the principal component analysis. Magnitude is calculated by the ratio of each quadriceps component muscle volume. (C) The overall QV is calculated from vector addition of each component muscle's vector. RF = rectus femoris; VI = vastus intermedius; VM = vastus medialis; VL = vastus lateralis. (D) The overall quadriceps vector is shown.

Fig. 4 The quadriceps pull vector's passing point at the level of the center of the femoral head (XY plane) was determined.

1. $(\text{langle between } QV1_x \text{ and } QV2_x| + \text{langle between } QV1_x \text{ and } QV3_x| + \text{langle between } QV2_x \text{ and } QV3_x|) \div 3$

where QVn_x = the QV calculated in repetition x of the three repetitions. The maximum angular differences and 95% CI of the angular differences also are calculated (Table 1).

The data sets were tested for normal distribution and equal variances and the test used to establish significance was based on the results of distribution and variance. We determined differences between the QV and the anatomic axes AA, MA, and SA in 3-D space and in 2-D space projected onto the GCA plane and the TEA plane. In 3-D space the three angles (QV-AA, QV-MA, and QV-SA) had normal distribution but not equal variances and therefore one-way ANOVA and Games-Howell post hoc test were used. When evaluating the projection onto the GCA plane, the QV-SA data did not have a normal distribution and therefore the Kruskal Wallis test was used with the Mann-Whitney test used as a post hoc test. When projected on only the TEA plane, the three angles had normal distribution and equal variances and thus one-way ANOVA and Tukey post hoc tests were applied. Statistical analyses were performed using SPSS[®] statistical software (Version 12; SPSS Inc, Chicago, IL, USA).

Results

For evaluation of precision, the mean difference between the three QV calculations in 3-D space was 0.21° and the

maximum difference was 0.41° . When projected on the GCA plane, the mean and maximum differences between the three QV calculations were 0.13° and 0.38° , respectively. The 95% CIs of the differences for the QV in 3-D space and in the coronal plane were $0.21^\circ \pm 0.095^\circ$ and $0.13^\circ \pm 0.082^\circ$, respectively.

In all 14 subjects, the QV at the level of the center of the femoral head was anterolateral to the center of the femoral head. The mean $\pm$ SD vector position was 33.6 ± 6.0 mm lateral (range, 22.6 mm lateral to 41.1 mm lateral) and 41.6 ± 9.0 mm anterior (range, 27.6 mm anterior to 57.7 mm anterior) from the center of the femoral head, placing the vector anterior to the femoral neck (Fig. 6).

In 3-D space, the mean angles between the QV and the AA, MA, and SA were $3.1^\circ \pm 1.4^\circ$ (range, 0.8° – 5.6°), $3.4^\circ \pm 0.8^\circ$ (range, 2.0° – 4.8°), and $2.3^\circ \pm 0.9^\circ$ (range, 0.7° – 3.6°), respectively. The angle for the SA was smaller than that for the MA ($p = 0.005$) and for the AA ($p = 0.208$). The difference between the QV to AA and QV to MA was minimal ($p = 0.723$).

When projected to the GCA plane, the mean angles between the QV and the AA, MA, and SA were $2.8^\circ \pm 1.2^\circ$ (range, 0.7° – 5.0°), $3.3^\circ \pm 0.8^\circ$ (range, 2.0° – 4.8°), and $0.8^\circ \pm 0.7^\circ$ (range, 0.0° – 2.1°), respectively. The QV was less than 1° different from the SA and the difference was smaller than for the other two axes ($p < 0.001$ for both). The differences seen between the QV to AA and QV to MA angles were minimally smaller ($p = 0.251$).

When projected on the TEA plane, the mean angles between the QV and the AA, MA, and SA were $2.8^\circ \pm 1.1^\circ$ (range, 0.8° – 4.9°), $3.2^\circ \pm 0.8^\circ$ (range, 2.0° – 4.8°),

Fig. 5A–B The angle between the QV and the anatomic axes (anatomic axis [AA], mechanical axis [MA], spherical axis [SA]) were determined (A) in the 3-D space and (B) projected on the coronal plane.

and $0.8^\circ \pm 0.6^\circ$ (range, 0.0° – 1.9°), respectively. The QV again was less than 1° different from the SA and the difference was smaller than differences of the other two axes ($p < 0.001$ for both). The differences between the QV to AA and the QV to MA angles again were minimal ($p = 0.307$) (Table 2).

Discussion

The quadriceps muscle, as the primary extensor of the knee, is thought to bear a consistent relationship to the flexion axis of the knee. One strategy for total knee component positioning, as opposed to “perpendicular to the

mechanical axis”, is to place components relative to the flexion axis. We developed a method of calculating the theoretical QV, evaluated that method for precision, and used the method to experimentally measure the relationship of the QV to the femur as the passing point of the vector at the proximal femur and as an angular relationship (3-D and 2-D) to commonly used axes describing the femur (AA, MA, SA). The QV was most closely aligned with the SA.

We recognize limitations to this study which are anatomic and that this method cannot be specifically validated. First, our models reflect a simplification of muscle action in that principal component analysis is used to determine vector direction and relative muscle volume to determine vector length. Previous studies have used a similar simplification [7, 8, 12, 13, 17, 19, 20, 22], and it has been a standard in physiology that the line of action of a muscle is along the axis of the muscle and the force is proportional to the area or volume of the muscle. However, not all muscle fibers are aligned with the long axis of the muscle and more complicated models have attempted to take into account the various pennate or penniform alignments of individual muscle fibers. A simplified approach was chosen for this first-order model, but a more complex muscle fiber structure could be incorporated in future models. The CT scans used in this study were taken from images generated for a pulmonary embolism protocol in which the subjects were supine in the scanner. The shape of the muscles could be different in this pose from those in the standing position, which could change the 3-D constellation of points and alter the first principal component calculation and thus the direction of muscle action. Scans with muscles fully contracted could help to overcome this potential problem. No attempt was made to model the differential contraction of the quadriceps elements that might occur in activity [15, 18–20, 26].

The precision of this measurement, when multiple measurements are made by one observer (ie, intraobserver variability) was 0.21° (maximum 0.41° , $CI \pm 0.095^\circ$) for 3-D space and 0.13° (maximum 0.38° , $\pm 0.082^\circ$) for 2-D space (ie, when the vector and axes were projected onto a coronal plane). This gives confidence that the method can be reproduced by one observer with high precision but does not address interobserver variability. (Interobserver variability will be addressed in a subsequent paper.) Because the true vector is not known it is not possible to address accuracy, and thus the method cannot be validated. There is no comparable method described in the literature with which to compare this precision.

Our findings suggest that in all subjects, the QV acted from the center of the patella thorough a point just lateral to the femoral head anterior to the femoral neck.

The QV was most closely aligned with a line from the center of the femoral head through the center of the medial side of the knee, an axis we have termed the “spherical

axis”—SA—since it connects the spherical center of the femoral head to the spherical center of the medial femoral condyle [1, 2]. Because it is likely that the flexion axis of the knee is perpendicular to the pull of the quadriceps [14, 15, 21, 23], the SA can be a reference axis for making bone

cuts such that the flexion axis of the replaced knee can mimic that of the normal knee.

Schulthies et al. [22] evaluated a 2-D (coronal plane) QV in the cadaver by a combination of muscle-directed and fiber-directed modeling. They found the QV is more laterally directed than the anterior superior iliac spine (ASIS), a finding that is not inconsistent with our results in view of the difference in their model. Kan et al. [13] calculated a 3-D QV using information from the vastus medialis and lateralis only, and found in healthy patients that the QV was inclined 2.0° lateral and 2.0° anterior relative to the femoral shaft. This result is different from the QV we calculated, but again not inconsistent, because only distal parts of two of the quadriceps components were used in the analysis. In our study, the QV also passed anterolateral to the center of the femoral head; however, at the level of the femoral neck, the vector passed anterior to the femoral neck located between the femoral head and the greater trochanter. Thus, when observing the results projected on the coronal plane, the QV was located not lateral to the AA but between the MA and the AA. The reason is likely that the studies by Schulthies et al. [22] and Kan et al. [13] did not use a full-muscle model. Eckhoff et al. [5, 6] showed the angle between the sulcus axis calculated at the depth of the trochlear groove and the AA was $1.7^\circ \pm 0.9^\circ$ and the angle between the sulcus axis and the MA was $3.6^\circ \pm 0.5^\circ$. This placed the axis of the sulcus

Table 1. Angular differences of four cases measured three times

Case	Three-dimensional	Two-dimensional
9	0.28	0.28
9	0.38	0.30
9	0.23	0.02
2	0.09	0.05
2	0.11	0.02
2	0.08	0.08
10R	0.06	0.02
10R	0.03	0.03
10R	0.07	0.05
10L	0.34	0.25
10L	0.41	0.13
10L	0.41	0.38
Average	0.21	0.13
95% CI	± 0.095	± 0.082

(Same observer, different days).

Fig. 6A–C (A) The appearance of the QV of a typical subject is shown with the muscles intact. (B) The muscles have been removed showing the QV, femur, SA, and MA. (C) The femur has been removed showing the QV, spherical representation of the femoral head and condyles, SA, MA, and AA.

Table 2. Comparison of the quadriceps vector in three axes

View	Anatomic axis	Mechanical axis	Spherical axis
In 3-D space	$3.1^\circ \pm 1.4^\circ$ (0.8°–5.6°)	$3.4^\circ \pm 0.8^\circ$ (2.0°–4.8°)	$2.3^\circ \pm 0.9^\circ$ (0.7°–3.6°)
Coronal plane (based on GCA)	$2.8^\circ \pm 1.2^\circ$ (0.7°–5.0°)	$3.3^\circ \pm 0.8^\circ$ (2.0°–4.8°)	$0.8^\circ \pm 0.7^\circ$ (0.0°–2.1°)
Coronal plane (based on TEA)	$2.8^\circ \pm 1.1^\circ$ (0.8°–4.9°)	$3.2^\circ \pm 0.8^\circ$ (2.0°–4.8°)	$0.8^\circ \pm 0.6^\circ$ (0.0°–1.9°)

Values are expressed as mean $\pm$ SD, with range in parentheses; 3D = three-dimensional; GCA = geometric center axis; TEA = transepicondylar axis.

Table 3. Values from the literature

Parameter measured	Schulthies et al. [22]	Kan et al. [13]	Eckhoff et al. [5, 6]
QV position	Lateral to ASIS	2° lateral, 2° anterior to AA	Not reported
Sulcus angle	Not reported	Not reported	1.7° ± 0.09 medial to AA 3.6° ± 0.5 lateral to MA

ASIS = anterior superior iliac spine; AA = anatomic axis; MA = mechanical axis.

between the MA and the AA in a position not unlike that of the QV we found. Because the trochlear groove is the pathway of the patella, it is understandable that the quadriceps pulls along the groove (Table 3).

The QV calculated from 3-D solid models of the quadriceps components passes from the top of the patella anterior to the femoral neck just lateral to the femoral head. The QV is most closely aligned with a line from the center of the femoral head to the center of the medial condyle of the knee. The 95% CI based on one observer (ie, interobserver variability) is $0.21^\circ \pm 0.095^\circ$ for 3-D angle and $0.13^\circ \pm 0.082^\circ$ for projection of the angle onto a coronal plane. The QV and its relationship to the femur is a measurement and may be an appropriate guide for rehabilitation and alignment of TKA components.

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