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In vitro determination of the passive knee flexion axis: Effects of axis alignment on coupled tibiofemoral motions

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ABSTRACT

The natural passive flexion axis of human cadaveric knees was determined using a technique that minimized coupled tibiofemoral motions (translations and rotations), and the kinematic effects of malpositioned flexion axes were determined. The femur was clamped in an apparatus that allowed unconstrained tibial motions as the knee was flexed from 0° to 90°. To establish the natural flexion axis, the femur's position was adjusted such that coupled tibiofemoral motions were minimized. Tests were repeated, first with the femur rotated internally and externally from its original position, and again after positioning the femur to flex the knee about the transepicondylar axis**.** Compared to the transepicondylar axis, flexion about the natural axis significantly reduced mean tibial translation by 66.4% ($p < 0.01$) and varus–valgus rotation by 70.1% ($p < 0.01$). Mean varus–valgus rotation increased by 3.4° (factor of 4) when the femur was rotated 3° internally or externally from the optimum position. Differences in condylar location coordinates between the transepicondylar and natural flexion axes most likely indistinguishable clinically. Knee flexion about an axis that minimizes coupled tibiofemoral motions could be important for placement and orientation of a femoral total knee component and for specimen alignment during biomechanical knee testing.

1. Introduction

The location of the knee's natural flexion axis (FEA) has received considerable clinical interest in relation to total knee replacement (TKR). It is commonly believed that proper alignment of the femoral component is essential to a successful procedure [1,2]. Mal-aligned or mal-positioned TKA components have been linked to knee pain, patella maltracking, and instability [3–5]. Bell et al. [3] measured the rotational alignment of femoral components between pain and no pain cohort groups ($n = 56$ each), and found the femoral component to be internally rotated by 6.2° in the pain cohort compared to the no pain cohort. Berger et al. [4] compared a group of 30 patients with patellofemoral complications to a control group of 20 patients without patellofemoral problems. They found the femoral component to be internally rotated an average of 2.5° in the complications group compared to the control group.

It is reasonable to expect that some patellofemoral complications related to rotational alignment of the femoral component could be related to coupled varus–valgus (VV) motion of the tibia during knee flexion. This VV motion could produce mal-tracking of the patella within the femoral groove of the implant, and produce abnormal pressures at the medial or lateral patellofemoral contact locations resulting in anterior knee pain. We have found no biomechanical studies in the literature that have specifically addressed coupled VV motions produced during knee flexion about an internally or externally rotated knee flexion axis.

Ideally, the flexion axis of the reconstructed knee should approximate that for the intact knee to avoid some of the aforementioned clinical complications. The most frequently cited guide for femoral component alignment is the transepicondylar axis (TEA) located within the posterior femoral condyles [6–10] There are two common definitions of the TEA, both originating from the most prominent point on the lateral epicondyle and directed to a location on the medial epicondyle. The anatomic definition of the TEA uses the most prominent point on the medial epicondyle at the attachment of the superficial fibers of the MCL. However, as noted by Berger et al. [6] often there is not a clearly discernible prominence on the medial epicondyle. Therefore, the surgical definition of the TEA uses the medial sulcus at the attachment of the deep fibers of the MCL [6–10]. On average the surgical TEA is 2° internally rotated from the anatomic definition [11] located approximately 30 mm proximal to the joint line on medial side and 25 mm proximal to the joint line on the lateral side [12].

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Although the TEA is believed to be an approximation of the FEA for knee kinematics, there is doubt as to whether these axes are in fact one and the same. This has led investigators to establish a more accurate description of the FEA. The current consensus is that normal knee kinematics can be described by rotation about two fixed axes, the FEA in the femur and an internal–external rotation axis in the tibia [7,9,13–18] However, there is controversy in locating the exact position and orientation of the FEA due to multiple methods and definitions. Some authors have utilized computed tomography (CT) scans to map fitted cylinders or spheres to the medial and lateral femoral condyles, using the calculated center of each fitted shape to approximate the FEA [9,10,19–22]. Others have employed a mechanical device or virtual axis finder to identify the FEA by minimizing residual coupled tibiofemoral motions [13,15–18,23]. In theory, minimizing coupled tibial motions during flexion–extension should be a more functional method for determining the FEA because an approach that considers femoral condylar contours alone does not include the function of intra and extra-articular ligaments of the knee, that also act to control and guide relative tibiofemoral motions.

The objectives of this study were: (1) to locate the FEA relative to the TEA using a new testing methodology that minimized coupled tibiofemoral motions, (2) to compare the coupled motions resulting from knee flexion about the FEA and TEA, and (3) to measure the effects of internally and externally rotating the FEA from its original position upon VV motion of the tibia. In addition, we sought to determine right–left and male–female differences in axis locations and coupled motions for our specimen group.

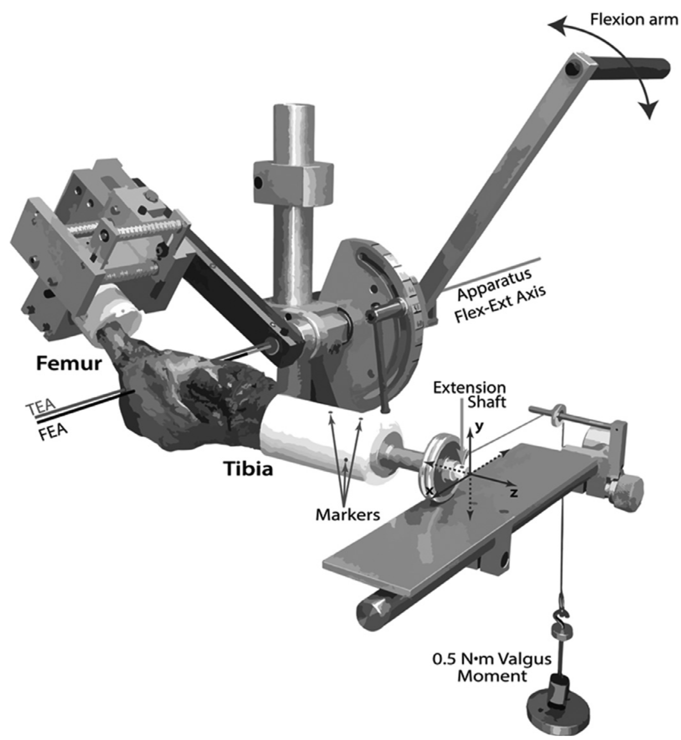

Fig. 1. Custom built apparatus for flexion testing of cadaveric knees. The FEA was determined by minimizing mediolateral (x), anteroposterior (y), and proximal-distal (z) tibial translations (resultant motion $<$ 10 mm).

2. Methods

Thirty-eight fresh-frozen human cadaveric knees were used for this study. This group included 12 right–left pairs (5 male and 7 female pairs). Of the remaining 14 unpaired knees, 9 were male (7 right, 2 left) and 5 were female (3 right, 2 left). The mean age of all specimens was 33 years (18–45 range). The femur and tibia of each were sectioned 30.5 cm from the joint line and potted in cylindrical molds of polymethylmethacrylate (PMMA) acrylic. Knees were manually tested for stability prior to testing.

The femoral acrylic pot was clamped in a custom built test apparatus with the knee inverted (patella facing down; Fig. 1).

Full extension was defined as the angle between the femoral and tibial pots that resulted when a 2 N m extension moment was applied to the knee. The distal end of the tibia was supported by a roller bearing mounted on an extension shaft attached to the distal end of the tibial pot. This configuration allowed unconstrained tibial rotation while permitting anteroposterior and mediolateral displacements at the joint line, and proximal-distal "pistoning" motion of the distal tibia as the knee was manually flexed about the about the axis of the test apparatus. To ensure articular contact at both condyles, a small valgus moment (0.5 N-m) was applied during testing.

Ideally, when the femoral fixture was perfectly positioned, flexion about the FEA would produce no coupled tibial motions (the tibia would remain motionless exclusive of the screw-home tibial rotation). In practice, some amount of coupled tibial motion always occurred. To measure these coupled tibial motions, markers were etched into the tibial pot to track changes in tibial orientation in the sagittal, frontal, and transverse planes. An additional marker was placed on the distal tibial extension shaft to track coupled tibial translations. A three-dimensional coordinate measuring machine, with a positional accuracy of 0.02 mm (Faro Gage, FARO Technologies Inc., Lake Mary, FL), was used to digitize these markers for analysis. The coordinate system for all measurements was set at the distal tibial extension shaft.

Beginning at full extension, the knee was flexed from 0° to 90° in 10° increments, with measurements of all markers recorded at each flexion angle. Knee flexion beyond 90° was not possible due to compression of muscle tissue between the tibia and femur, which introduced an artifact to the measured coupled tibial motions. In order to find the FEA, a trial and error procedure was used to adjust the position and alignment of the femoral fixture such that coupled motions at the end of the distal tibial extension shaft were minimized. If the FEA was not coincident with the flexion–extension of the apparatus, the distal end of the tibial extension shaft would experience a combination of VV and proximal-distal motions as the knee was flexed. For some knees, it was possible to reduce these combined motions to near zero. For other specimens, when proximal-distal tibial motion was reduced to near-zero, varus–valgus tibial rotation remained (and vice-versa). In these instances, a compromise femoral position was found such that the resultant displacement of the distal tibial extension shaft (VV + proximal-distal) was less than 10 mm throughout the 90° range of knee flexion. Next, the flexion–extension axis of the apparatus was established by digitizing two points at the center of the cylindrical shaft about which the femur flexed. The digitizer was used to locate the intersection of this axis with the surfaces of the medial and lateral femoral condyles, and small screws were inserted at these points to mark the FEA.

The TEA was then established by manual palpation, locating the apex of the lateral epicondylar eminence and the sulcus of the medial epicondyle (where the deep fibers of the MCL attach). Two additional screws were inserted into the condyles at these locations to mark the TEA. The femoral fixture was re-adjusted such that the TEA was in line with the flexion–extension arm of the test apparatus (confirmed with the digitizer to within 0.1 mm). All measurements of coupled tibial motions were then repeated from 0° to 90° flexion about the TEA. Lastly, the location of the FEA relative to the TEA was measured on both the medial and lateral femoral

Table 1
Maximum coupled tibial motions at the end of the tibial extension shaft.

	Translations (mm ± 1 SD)		
	TEA	FEA	% Reduction
Anteroposterior[a]	1.7 ± 0.9[b]	0.6 ± 0.4	52.0[a]
Mediolateral[a]	18.0 ± 13.0	5.5 ± 2.3	69.7[a]
Proximal-distal	4.1 ± 2.8	3.7 ± 1.3	11.4
Resultant[a]	19.0 ± 13.2	6.4 ± 2.1	66.4[a]
	Rotations (° ± 1 SD)		
	TEA	FEA	% Reduction
Varus Valgus[a]	3.3 ± 2.6	1.0 ± 0.4	70.1[a]
Internal–external	21.7 ± 7.4	20.7 ± 6.4[c]	2.0

[a] FEA significantly less than TEA ($p < 0.01$).
[b] Female significantly less than male by 0.6 mm ($p < 0.04$).
[c] Male significantly less than female by 5.3° ($p < 0.01$).

condyles, and the distances between the FEA and TEA intersections with the condylar surfaces were calculated.

To examine the effect of internal–external rotational malalignment of the FEA about the long axis of the femur upon coupled tibial VV motions, an additional series of knee flexion experiments were performed in which the FEA was rotated ±1.5° and ±3° internally and externally. The resulting coupled VV rotations of the tibia were measured as the knee was flexed continuously from 0° to 90°. **VV** rotation was calculated from the tibial length and medial-lateral displacement of the distal tibial extension shaft (measured using dial indicators).

Paired two-sample Student's *t*-tests were used to compare coupled motions during knee flexion about the FEA and TEA. One-sample Student's *t*-tests were used to compare location of the FEA relative to the TEA on the femoral condyles, and the orientation of the FEA relative to the TEA in the transverse and frontal planes. Unpaired two-sample Student's *t*-tests were used for all male–female and right–left comparisons. For rotational malalignment of the FEA, a one-way repeated measures ANOVA was used to compare coupled VV motion between each offset. Pairwise post hoc comparisons were made using Tukey's HSD procedure. The significance level for all analyses was set at $p < 0.05$.

3. Results

Flexion of the knee about our defined FEA significantly reduced coupled tibial motions compared to flexion about the TEA (Table 1).

The values in Table 1 represent means for the total range of motion for that particular measurement during 0° to 90° of knee flexion. Resultant tibial translation was significantly less when flexed about the FEA compared to the TEA (66.4% reduction; $p < 0.01$), although proximal-distal displacements (one component of the resultant) were not (Table 1). There were no significant right–left or male–female differences in coupled translations, with the exception of anterior–posterior tibial translation where female knees translated 0.6 mm less than male knees when flexed about the TEA ($p < 0.04$).

Coupled VV tibial rotation with the FEA was significantly less ($p < 0.01$) compared to the TEA (Table 1), with a mean reduction of 70.1%. Coupled IE rotations were not significantly different between the two axes (Table 1). Mean IE rotations in male knees were 5.3° less than female knees when flexed about the FEA ($p < 0.01$).

On the medial condyle, the FEA was located 5.2 ± 3.2 mm posterior and 9.0 ± 4.3 mm distal to the TEA ($p < 0.01$; Fig. 2A). On the lateral condyle, the FEA was located 7.3 ± 3.6 mm posterior and 9.7 ± 4.1 mm distal to the TEA ($p < 0.01$; Fig. 2B).

The FEA was 1.4 ± 3.2° externally rotated ($p < 0.02$) and 0.5 ± 3.5° varus (not significantly different) from the TEA (Fig. 3A and B).

The FEA in the male knees was significantly more external to the TEA than in female knees (2.4 ± 2.4° vs. 0.4 ± 3.5°; $p < 0.01$). Otherwise, there were no significant left-right or male–female differences. Compared to the optimal alignment position (neutral rotation), rotating the FEA internally or externally by ± 1.5° and ± 3.0° significantly increased VV motion by factors of 2.18 and 4.0, respectively (Table 2).

4. Discussion

This study utilized a custom testing apparatus to locate the FEA, and to measure coupled tibiofemoral motions resulting from knee flexion about the TEA and FEA. We found the FEA to be located significantly more posterior and distal to the TEA, and oriented 1.4° external to the TEA in the transverse plane. The FEA was essentially parallel to the TEA in the frontal plane. These differences in position and orientation between the two axes resulted in significantly less coupled tibial motions during passive knee flexion about the FEA compared to the TEA. Internally or externally rotating the FEA from its optimal position significantly increased the coupled varus–valgus rotation of the tibia.

A variety of experimental methodologies have been used previously to determine the FEA and define its location relative to the TEA. Churchill et al. [15] utilized an Oxford knee rig to produce

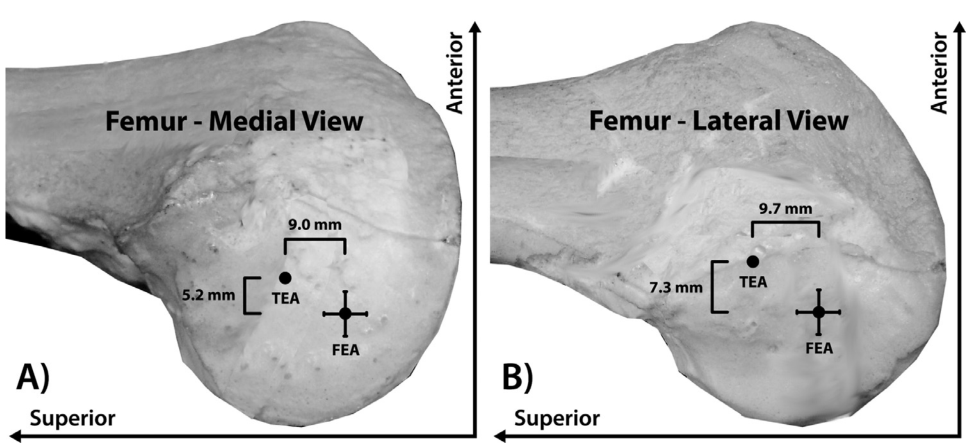

Fig. 2. The mean location of the FEA with respect to the TEA on (A) the medial femoral condyle and (B) the lateral femoral condyle. The FEA was posterior and inferior to the TEA on both condyles ($p < 0.01$).

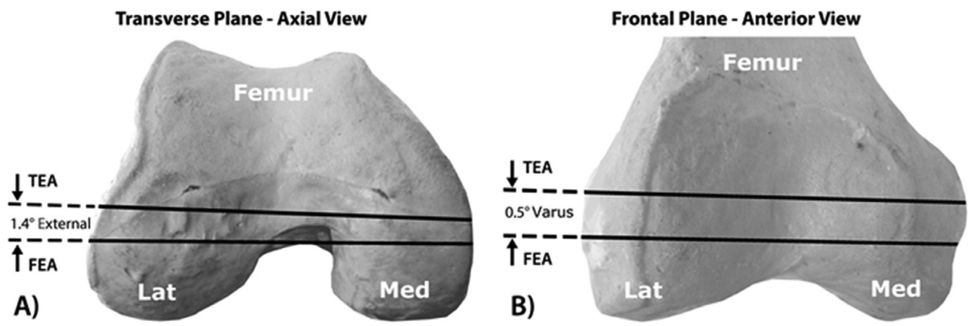

Fig. 3. The FEA is (A) 1.4° external ($p < 0.011$) to the TEA in the transverse plane (axial view of the distal femur) and (B) 0.5° varus (not significantly different) to the TEA in the frontal plane (anterior view of the distal femur).

Table 2
Maximum coupled varus–valgus (VV) rotation of the tibia during knee flexion about the FEA when offsetting femoral internal–external alignment.

	FEA ± Internal–external femoral alignment				
	3° Int.	1.5° Int.	Neutral	1.5° Ext.	3° Ext.
VV°	4.4 ± 1.1	2.4 ± 1.0	**1.1 ± 0.7**	2.4 ± 0.7[a]	4.5 ± 1.0[b]

Note: All values significantly different from each other except where noted ($p < 0.01$).
[a] Not significantly different from 1.5° Int.
[b] Not significantly different from 3° Int.

knee flexion under equilibrium conditions with quadriceps loading, and calculated the location of the FEA using a compound hinge model for kinematic analyses. The FEA was defined through the centers of spheres matching the medial and lateral condylar surfaces using CT scans, and electromagnetic position sensors were used to track motion of the tibial plateau relative to the FEA. They found the FEA to be 0.2 ± 2.4 mm anterior and 0.1 ± 2.7 mm proximal to the TEA on the medial condyle, and 0.2 ± 2.7 mm anterior and 0.6 ± 2.9 mm proximal to TEA on the lateral condyle. There are several factors that must be considered when comparing their results to ours. Electromagnetic position sensors are known to have interference issues at low sampling rates in the presence of metal [24]. Additionally, establishing the FEA was not based on minimized tibiofemoral motions. As reported by Victor et al. [19] knee flexion in an Oxford knee rig can produce significant coupled tibial motions, with up to 20 mm of relative anteroposterior tibiofemoral motion.

Using computational and mapping methodologies, Asano et al. [9] performed an in vivo study on 9 subjects in static weight-bearing knee flexion positions. CT scans were used for analysis of knee flexion angles from 0° to 90° in 15° increments. They determined the FEA location by tracking the center of the ankle joint during flexion and calculating the center point of its arc on the femur. The FEA was projected onto CT images of both the medial and lateral femoral condyles, and its intersection was found to be 1.0 ± 1.7 mm from the medial epicondylar sulcus and 0.6 ± 2.7 mm from the lateral epicondylar eminence.

Yin et al. [10] analyzed in vivo kinematic data from a single leg lunge maneuver using bi-planar x-ray imaging and 3D-2D registration techniques. They calculated the locations of the FEA and TEA by analyzing the vertical distances from the axis center of rotation to the surface of the tibial plateau. They found that the mean angular deviation between the FEA and TEA in the transverse plane was 2.72°, which approximately double the comparable difference found in our study. These authors did not report coordinate locations for the intersections of these axes on the surfaces of the medial and lateral condyles.

Eckhoff et al. [21] performed CT scans on 10 cadaveric knees, and mapped best fit cylinders to the medial and lateral condyles, using the center point of each cylinder to define the FEA. This was a femoral imaging study only, with no simulation of flexion–extension movements. On the lateral condyle, the FEA ranged from 1 mm to 6 mm posterior and 1 mm to 10 mm distal to the TEA, whereas we found an FEA range of −3 mm to 14 mm posterior and 2 mm to 19 mm distal. On the medial side, the FEA ranged from 0 mm to 18 mm posterior and 4 mm to 13 mm distal to the TEA, whereas we found an FEA range of −3 mm to 13 mm posterior and 1 mm to 20 mm distal. The orientation of their FEA was 2.3° internal and 1.8° valgus from the anatomic TEA. Our FEA was 1.4° external and 0.5° varus from the surgical TEA. While both their study and ours concluded that the FEA is posterior and distal to the TEA, the differences in axis orientation could be due to methodology and sample size. They used the anatomic definition for the TEA and we used the surgical definition (as previously discussed). Furthermore, mapping a best fit cylinder to the posterior portion of the condylar profile alone does not take into account the changing radii of the condyles and its effect of coupled tibiofemoral motion.

There is a precedent for minimizing coupled tibiofemoral motions to locate the FEA. An early study by Hollister et al. [13] used an axis finder to define the FEA using cadaver knees. They tracked tibiofemoral motions with a camera and LED system during passive flexion–extension and then used a numerical analysis technique to predict an FEA location that would result in minimal tibial motion during flexion. Others have used minimization of coupled tibial motions to establish precise alignment of the FEA within a biomechanical testing apparatus [23,24] where accurate positioning of the knee is necessary to obtain accurate data. More recent investigators have also developed computational models based on these minimization principles, either using a virtual axis finder combined with 3D motion analysis [16], marker-based roentgen stereophotogrammetric analysis [17], or a virtual instrumented spatial linkage method [18]. However, none of these prior studies using minimized coupled tibial motions have described location of the FEA relative to the TEA in terms of condylar coordinates.

Our study has several limitations. We defined the TEA via manual palpation, a technique commonly used in clinical practice. However, this method has been shown to be highly variable [11,25,26]. Our study was performed with passive flexion of cadaveric knees and as such coupled motions of the tibia relative to the femur were guided by condylar geometry and ligamentous restraints alone, without the influence of active knee musculature or the effects of tibiofemoral contact force. It is possible that the abnormal VV rotations produced by rotational malalignment of the FEA axis could be attenuated by in vivo muscular control during in vivo weight-bearing activities. As mentioned above, the in vivo weight bearing study of Asano et al. [9] found condylar intersections with the TEA and FEA to be within 1 mm of one another at static knee flexion angles. The role of simulated knee muscle forces on coupled tibial motions could be a topic for future study.

The most important finding of this study is the dramatic effect of internal–external rotation of the FEA upon coupled VV rotation of the tibia. Varying the internal–external alignment of the FEA by ±3° produced a fourfold increase in coupled VV rotation. As previously noted, rotational malalignment of femoral TKA components has been linked to patellofemoral complications, [4] which in turn could be related to coupled VV rotation of the tibia during knee flexion. Our tests were performed on intact knees without TKR components. However we believe our results could also have relevance to rotational alignment of a femoral TKA component, as many designs seek to replicate normal condylar geometry. We found that the internal–external rotational alignment of the FEA was within 1.4° of the TEA, a difference that is probably not meaningful clinically in terms of surgical practice.

Currently, placement of a femoral knee replacement component is determined by fixtures to guide the bone cuts. The locations of these cuts on the femur have been determined by designers of the implant system, and are unique to each femoral component design. Our test results related to the location of the FEA in the intact knee could impact the design of future TKA implants and instrumentation systems, since replication of a natural flexion–extension axis may be important for successful biomechanical function of a TKA. Furthermore, accurate location of the FEA could also have implications for biomechanical studies related to knee kinematics, where knee flexion about a suboptimal FEA could affect kinematic results due to excessive coupled tibial motions. For example, a cadaveric wear study with mal-rotated femoral components could generate abnormally large VV rotations, that in turn could adversely affect wear patterns on the polyethylene tibial component.

In summary, we found the FEA to be located significantly more posterior and distal to the TEA, and oriented 1.4° external to the TEA in the transverse plane. The FEA was essentially parallel to the TEA in the frontal plane. These differences in position and orientation between the two axes resulted in significantly less coupled tibial motions during passive knee flexion about the FEA. Internally or externally rotating the FEA from its optimal position significantly increased the coupled varus–valgus rotation of the tibia. There were only minor (if any) right–left and male–female differences in coupled tibial motions.

Competing interests

Tissues for this study were provided by the MTF. D.R.M. has previously served as a consultant to MTF and is a member of the MTF Medical Board of Trustees.

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Ethical approval

No live human or animal subjects were used in this study and ethical approval was not required.

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