Title: The role of the patella tendon angle and patella flexion angle in the interpretation of sagittal plane patello-femoral kinematics of the knee after knee arthroplasty: a modelling analysis.

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Abstract:

Background

Many different measures have been used to describe knee kinematics. This study investigated the changes of two measures, the patella tendon angle and the patella flexion angle, to variations in the geometry of the knee due to surgical technique or implant design.

Methods

A mathematical model was developed to calculate the equilibrium position of the extensor mechanism for a particular tibio-femoral position. Calculating the position of the extensor mechanism allowed for the determination of the patella tendon angle and patella flexion angle relationships to the knee flexion angle. The model was used to investigate the effect of anterior-posterior position of the femur, change in joint line, patella thickness (overstuffing, understuffing), and patella tendon length; these parameters were varied to determine the effect on the patella tendon angle/knee flexion angle and patella flexion angle/knee flexion angle relationships.

Findings

Results showed the patella tendon angle was a good indicator of anterior-posterior femoral position and change in patella thickness, and the patella flexion angle a good indicator of change in joint line, and patella tendon length.

Interpretation

The patella tendon angle/knee flexion angle relationship was found to be an effective means of identifying abnormal kinematics post knee arthroplasty. However, the use of both the patella tendon angle and patella flexion angle together provided a more informative overview of the sagittal plane kinematics of the knee.

Introduction:

Knee arthroplasty is considered an effective procedure however a significant proportion of patients experience pain after the procedure[1–3]. The kinematics of the knee can be altered by both surgical technique and implant design. Undergoing total knee arthroplasty may affect the anterior-posterior position of the femur, the joint line, the patella thickness (overstuffing/understuffing of the patello-femoral joint) and the patella tendon shortening post surgery[4–6]. Knee component designs also play an important part in controlling the kinematics of the knee joint due to their geometry as well as the addition of constraints such as a cam-post mechanism[7–9]. As such kinematic measures of the knee joint are regularly used to assess whether knee arthroplasty designs[9–16] achieve intended design aims or restore native knee kinematics.

Many techniques have been used to investigate the kinematics of the knee using gait analysis, mechanical measurement, magnetic resonance imaging, fluoroscopy, and radiostereomatoghrapic imaging[11,17–21]. A well recognised method used to assess the kinematics of total knee arthroplasty is 2D to 3D reconstruction of fluoroscopic imaging[11,14,15] which has also been used to study kinematics of native knees[22]. More recently the use of MRI has allowed for improved studies of native knee kinematics[19–21]. These methods are complex, time consuming, and resource demanding. Additionally the descriptors most commonly used are tibio-femoral contact points and relative tibio-femoral motion. It may be more accurate to consider both tibio-femoral and patello-femoral joint interaction when assessing the kinematics of the knee. The motion of the patella relative to the tibia is dependant on both the tibio-femoral and patello-femoral joint interactions and has been adopted in the form of the patella tendon angle (PTA) as a simplified measure of sagittal plane kinematics of the knee[23–29] and has an advantage of complex 3D measurements as it can be measured using conventional fluoroscopy [24,30]. The PTA is the angle subtended between the axis of the patella tendon and the tibial axis as illustrated in *figure 1*. The PTA has been shown to be effective in differentiating the kinematics of normal and prosthetic knees[9,16,31] however the interpretation of the PTA is not straightforward[24]. The PTA is often interpreted as an indicator of relative anterior-posterior motion of the femur on the tibia which Stagni *et al.*[24] conclude is not entirely correct. In addition to the PTA other studies looking at sagittal plane kinematics have made the additional use of the patella flexion angle (PFA) to describe patello-femoral kinematics [9,16,25,32]. The PFA is the angle subtended between the femoral axis and the axis through the midline of the patella in the sagittal plane (*figure 1*). It is felt that the use of both PTA and PFA gives a more complete picture of the overall sagittal kinematics of the knee[9,16,25,32].

Both the PTA and PFA are influenced by multiple parameters. In this study a computational sagittal plane model of the knee was used to determine PTA versus knee flexion angle (KFA) and PFA versus KFA relationships to determine their response to alterations in parameters representing changes of interest in a clinical context such as the: 1) anterior-posterior (AP) position of the femur relative to the tibia 2) distal-proximal (DP) position of the femur relative to the tibia leading to an altered joint line 3) change in patella thickness causing overstuffing or understuffing of the patello-femoral joint 4) alteration in patella tendon length leading to patella baja or alta. The study hypothesis is that the synchronous use of both PTA/KFA and PFA/KFA relationships can provide clinically relevant information of sagittal plane knee kinematics over the use of the PTA alone.

Methods:

Sagittal Plane Model

A two-dimensional mathematical sagittal plane model of the knee was developed, similar to previously described models[26,33,34], to calculate the equilibrium position of the extensor mechanism for a specified position of the femur relative to the tibia. The model described the geometry of the femur as a curve and the patella as rectangular. To describe the calculation the parameters used must first be defined. The parameters are illustrated in *figure 1* and described below:

- Tibial tubercle position (*O*): The tibial tubercle is the point on the tibia where the patella tendon is attached. The tibial tubercle is taken as the origin (0,0) of the model.

- Femoral geometry: This is the sagittal plane outline of the femur. In the case of this model this is taken as a circle described by the equation:

$$(x-h)^2 + (y-k)^2 = r^2 \qquad \textit{equation 1}$$

where (*h,k*) describes the position of the femur relative to *O,* and *r* is the radius.

- Patella length (*pl*): This is the length of the patella taken to be the distance between the patella tendon attachment at the distal pole (*dp*) of the patella and the quadriceps tendon attachment to the proximal pole (*pp*) of the patella.

- Patella tendon length (*ptl*): This is the length of the patella tendon representing the distance between *O* and *dp*.

- Patella thickness (*pw*): This was the distance between the patella axis (line through *dp* and pp) and the contact surface of the patella on the femur.

- Knee flexion angle (*KFA*): This is the angle between the femoral axis and the tibial axis.

- Patella tendon angle (*PTA*): This is the angle between the patella tendon and the tibial axis.

- Patella flexion angle (*PFA*): This is the angle between the femoral axis and the patella axis.

As in previously described sagittal plane models[26,34] number of assumptions were made:

- The difference in thickness between the trochlea groove and the patella facet contact surfaces on the femoral condyles of the implant was assumed negligible. This allowed the patella to be represented as being rectangular as proposed by Yamaguchi[35].

- The patella tendon was considered inextensible.

- The force acting through the quadriceps tendon was parallel to the femoral axis until quadriceps tendon wrap took place.

- Both the patella and quadriceps tendons were in tension at all times.

- At higher degrees of flexion, the quadriceps tendon wraps around the antero-distal femur which changes its angle of action on the patella. This was accounted for by keeping the quadriceps axis unchanged beyond 87.5 of knee flexion; which is the angle at which quadriceps wrap was taken to occur[26].

The driving input to the model was the relative position (*h,k*) of the femur relative to the tibial tubercle (*O*). Knowing the position of the femur relative to *O* and its description in the for of *equation 1* meant that the curve describing the femur could be described with in the axis (*O*).

Step 1:

Having determined the femoral contact surface within *O the* patella contact point on the femur could be calculated. The patello-femoral contact point (x_{cp},y_{cp}) was assumed to lie on the femur where $h-r \leq x_{cp} \leq h$ and $y \geq 0$. Assuming the contact between patella and femur to be frictionless meant that the patella axis lay parallel to the tangent of the curve at (x_{cp},y_{cp}). The patella axis could then be described using the equation of a line:

$$y = mx + c \qquad \textit{equation 2}$$

Where *m* is the gradient which is equal to the gradient of the tangent of the femur, which in turn is the derivative (*y'*) of *equation 1*. The definition of the femoral geometry in *equation 1* is an implicit function which could be differentiated by applying the chain rule: so for any point (x_{cp},y_{cp}) on a curve defined by *equation 1* the tangent at this point has the gradient:

$$m = y' = \frac{(h - x_{cp})}{(y_{cp} - k)} \qquad \textit{equation 3}$$

The patella axis is parallel to the tangent where the distance between the two lines is the thickness of the patella (*pw*).

Step 2:

Knowing the patella axis and the length of the patella tendon meant that the position of the distal pole of the patella could be determined by finding the point of intersection between the patella axis and a circle of radius *ptl* circumscribed around the tibial tubercle (*O*). Having determined the distal pole of the patella the equation of a line describing the patella tendon between (*O*) and (*dp*) axis could be determined.

Step 3:

Having determined the position of the patella axis in *step 1*, the *dp* in *step 2*, and knowing the patella length (*pl*) meant the position of the proximal pole of the patella (*pp*) could be calculated.

Step 4:

The quadriceps axis was then described as the line parallel to the femoral axis passing through *pp*.

Step 5:

Based on the assumption that the extensor mechanism was in equilibrium at any given moment during extension and flexion it follows that the forces acting on the patella were in equilibrium. This meant that the patella axis, quadriceps axis, and the normal to the tangent of the femur through the patello-femoral contact point would be concurrent[26,34].

The fixed parameters used in the calculations were: $O = (0,0)$, $r = 25$ mm, $ptl = 50$ mm, $pl = 30$ mm, $pth = 7.5$ mm. For each input (femoral position *h,k*) for a corresponding KFA) the equilibrium position of the extensor mechanism was found by optimizing for x_{cp}. For each value of x_{cp} the the *steps 1-5* were performed to minimize the point of convergence between the axes acting through the patella to give PTA and PFA outputs. The calculation described was performed using Microsoft Excel (v12, Microsoft, Washington, USA) and Microsoft Visual Basic (Microsoft, Washington, USA) macros.

Calculation of baseline femoral positions (h,k)

The femur is known to move posteriorly relative to the tibia with flexion [19-21]. To calculate the effect of a change in parameters throughout a range of flexion baseline positions of the femur relative to the tibia for each point in flexion were required. To determine the starting femoral input positions (*h,k*) for every 10^o of knee flexion between 10^o and 90^o KFA the calculation was performed in reverse to determine the femoral positions. Using the mathematical model described with the PTA and KFA as an input allowed for the calculation of the position (h,K) as an output. For every 10^o of knee flexion between 10^o and 90^o KFA the normal values for the PTA were input into the model to obtain baseline values for *h,k* at 10^o intervals between 10^o and 90^o KFA. The input PTA/KFA values were taken to be those measured for a group of 20 healthy knees using fluoroscopic measurement in a previous study [31].

Variation of Parameters

The effect on PTA and PFA of variation in relative AP femoral position, joint line, patella thickness (overstuffing/understuffing of the patello-femoral joint), and patella tendon length were investigated. To investigate the effect of changing specific parameters influenced during surgery or implant design the model was run whilst varying the relevant parameters individually:

1. AP position of the femur (*h*) was varied between -2.5mm and 2.5mm at 0.5mm intervals either side of the baseline position.
2. The joint line (*k*) was varied between -2.5mm and 2.5mm at 0.5mm intervals either side of the baseline position.
3. The patella thickness (*pw*) was varied between -2.5mm and 2.5mm at 0.5mm intervals either side of the baseline position.

4. The patella tendon length (*ptl*) was varied between -2.5mm and 2.5mm at 0.5mm intervals either side of the baseline position.

Parameter Response

The model outputs were the PTA/KFA and PFA/KFA relationships. In addition to these a measure of responsiveness for both the PTA and KFA was calculated for each of the four variables under investigation. To quantify the response the amount of change was plotted against the average change in parameter to determine the associated gradient. The gradients were calculated in RStudio (Version 0.99.484, 2009-2015 RStudio, Inc.) using linear least squares regression. In addition to individual gradients representing the changes seen by the PTA and PFA profile relative to changes in respective parameters a *response ratio* representing the responses of the two output parameters (PTA & PFA) ; a large ratio representing the PTA being more sensitive to a change in a particular parameter and a smaller ratio indicating that the PFA was more sensitive.

Results:

The PTA and PFA relationships with knee flexion illustrating the effect of change with variation of the AP position of the femur (*h*), DP position of the femur (*k*), patella thickness (*pw*), and patella tendon length (*ptl*) are shown in *figures 2&3.*

AP position of the femur (h):

With variation of the AP position of the femur (*h*) the PTA increased with a more anterior position of the femur and similarly the PTA decreased with a more posterior position of the femur as illustrated by the range in *figure 2a.* Similarly the PFA increased with anterior movement of the femur and decreased with posterior motion of the femur *(figure 3a)* however the range of change in PFA was less than that seen for the PTA. This difference in range of the two measures is illustrated in *figure 4-top left* which shows the average change in angle associated with a change in *h*. The gradient of the PTA is greater than that of the PFA meaning it is more sensitive/responsive to AP change than the PFA.

DP change (k):

The PTA change with DP change (*k*) decreased with proximal movement of the femur and vice versa however, the range of change in angle was narrow (*figure 2-top right***)**. Conversely the change in PFA with variation in *k* showed a wide range in change of angle increasing with proximal movement and decreasing with distal movement of the femur (*figure* 3-top right*).*

Patella tendon length (ptl):

The effect of variation of the patella tendon length (*ptl*) on the PTA and PFA is shown in *figure 2-bottom right*. Both PTA and PFA decreased with an increase in patella tendon length (*figure 3-bottom right*). The difference in range of the two measures is illustrated in *figure 4-bottom right* which showed the average change in angle in PFA associated with a change in *ptl* was significantly greater than the PTA.

Patella thickness (*pw*):

The effect of variation of the patella thickness (*pw*) on the PTA and PFA is shown in *figures 2-bottom left & 3-bottom left*. Both PTA and PFA show a positive gradient representing an increase of PTA and PFA corresponding with an increase in patella thickness.The range of change in angle with variation was greater for the PTA as compared to the PFA which is illustrated by the increased gradients of the PTA an PFA versus change in *pw* plots in *figure 4-bottom left*.

Response ratios:

The sensitivity of the PTA and PFA to changes in respective parameters are summarized in *Table 1* with the corresponding response ratios.

Discussion:

A mathematical model of the knee extensor mechanism in two-dimensions was used to determine the kinematics of the patello-femoral joint in the sagittal plane. Specifically, the model calculated the PTA/KFA and PFA/KFA relationships for which the extensor mechanism was in equilibrium for a particular tibio-femoral position and KFA was developed. With the use of the model it was noted that PTA/KFA and PFA/KFA relationships were influenced to different extents by a change in parameters illustrating that the use of both measurements in tandem would be more meaningful than using each as a single measure. Calculation of the PTA and PFA using mathematical formulae allowed the changes in specific parameters to be directly linked to observed changes in PTA and PFA. Where in the past these parameter changes were inferred, mathematical description of the extensor mechanism allows for the detailed analysis of the influence changing particular parameters related to design and surgical technique had on the extensor mechanism. The modelling technique used is similar to those described in previous studies[26,34] . A previous paper by van Duren et al.[34] showed that the use of a patello-femoral model to predict the PTA/KFA relationship correlated closely with values measured in vivo.

The value of the PTA decreases with flexion from extension corresponding to rollback of the femur on the tibia[18,27,28,31,32]. To investigate what effect the AP position of the femur had on the sagittal plane kinematics the AP position of the femur (*h*) was varied between -2.5mm and 2.5mm at 0.5mm intervals either side of the starting value. Both the PTA and PFA increased with anterior movement of the femur (*figure 4*). This increase in PTA with anterior motion of the femur corresponds with observations reported in the literature[24,26,34] and the decrease with flexion due to femoral rollback relative to the tibia. The steeper gradient of the PTA curve in *figure 4* indicates that the PTA is more sensitive to anterior posterior movement than the PFA. The AP position of the femur relative to the tibia is an important consideration in many total knee replacement designs. In the normal knee the position of the femur is, in part, maintained by the cruciate ligaments and meniscal constraints which are removed during knee replacement. Knee replacement designs incorporate constraints such as conforming bearing surfaces and cam/post mechanisms to influence the AP position of the femur to recreate femoral rollback. The results show that both the PTA and PFA respond to the change in AP position however the PTA was more sensitive and so would be a more effective measure of AP change.

Variation in the patella width (*pw*) showed a similar response as was shown to variation in AP position; with both the PTA and PFA increasing with an increase in patella thickness, and the was PTA more sensitive to change. Often the patella is resurfaced during total knee arthroplasty; it is important to retain the correct patella thickness which has been shown to alter both kinematics of the patello-femoral joint as well as the tibio-femoral joint[36–38]. In contrast the distal proximal movement of the femur relative to the tibia (*k*) resulted in a larger change in the PFA but with little change in the PTA (*figure 5*). DP change corresponds to a change in the joint line which has a tendency to become elevated during surgery which has been shown to result in both patello-femoral and tibio-femoral kinematics[39–41]. Fornalski et al.[39] performed a cadaveric study looking at the effect of joint line elevation and similar to our results showed a significant increase in patella femoral angle with an increase height of the joint line. The corresponding change in PTA with variation in the DP position of the femur was very small which showed that it is a less effective indicator of DP change.

The patella tendon length is often changed after surgery with studies reporting that the patella tendon shortened after TKR[4,5,42,43] and others noting lengthening after lateral UKA[44]. The effect on sagittal kinematics[41] and clinical outcome[45] of patella infra or alta after TKA has been addressed previously in the literature but remains unclear. In this study the effect of change in patella tendon length on sagittal plane kinematics was modelled by varying the patella tendon length (*ptl*). Varying the *ptl* resulted in the PFA decreasing with an increase in the patella tendon length. The PTA also decreased with an increasing *ptl* but the response of the PTA was very small in comparison to that of the PFA (*figures 2c & 3c*) as was the case in variation of the patella thickness. This indicated that the PTA is a bad measure of change in the patella tendon length. In contrast the PFA was shown to be an effective measure of changes to the patella tendon length.

The patella tendon angle was shown to be a good indicator of changes in AP position of the femur but a bad indicator of changes in DP femoral position and patella tendon length. This was shown by the response indicated by the gradients in *figure 4* . The PFA in contrast responded well to DP femoral position and patella tendon length. These observations are summarized as response ratios in *Table 1*. However, it should be noted that apart from the parameters investigated in this study there are other influences on the PTA/KFA and PFA/KFA relationships. For example, the shape of the femoral component such curvature and depth of the trochlea groove will effect a change in the PTA and PFA. This means it is important to be aware of the changes made to the knee joint when interpreting sagittal plane kinematic outcomes. Stagni *et. al.* [24] conclude that the PTA/KFA relationship cannot demonstrate anterior posterior translation of the femur on the tibia and therefore cannot disclose much about femoral rollback. We agree that the PTA/KFA relationship is not a direct measure of femoral roll back but it is sensitive to AP motion of the femur relative to the tibia and as such it remains eligible as a clinical indicator of AP change after knee arthroplasty. Additionally if it is used in conjunction with the PFA/KFA relationship the interpretation of the sagittal plane kinematics is more reliable as an overall representation of the extensor mechanism.

It is interesting to note from graphs of PTA/KFA and PFA/KFA (figure 2 & 3) that changes in parameters appear to have a larger effect on PTA as compared to PFA. This is because the relative change over the range of flexion (approximately 15º for the PTA and 50º for the PFA) rather than absolute change. It is possible that this will make it more difficult to get clinical measures of PFA that are accurate enough to detect the changes due to parameter alterations. This will make the clinical measurement of PFA more prone to error.

Study limitations do exist. There are the inherent limitations as with any modelling study. In this study the model was limited to the sagittal plane. Although the majority of motion in the knee occurs in the sagittal plane the tibio-femoral and patello-femoral joints are three-dimensional joints. We have limited this study to investigating the effect of parameters predominantly relevant in the sagittal plane but the model was unable to quantify the effect of parameters outside of the sagittal plane. It is Important to note that the medial-lateral movement and rotation of the patella which remain important factors in patello-femoral kinematics cannot be modelled in the sagittal plane. Additionally a number of geometric assumptions were made as described in the methods. The foremost of this is the representation of the femur as a circle which is simplified compared to the complex geometry of the distal femur[46]. This potentially introduces errors, however these are unlikely to affect the conclusions made in this study. This would be an area for improvement in future models. We have also made the assumption that the patella tendon was inextensible; the inclusion of a more accurate modelling of an extensible tendon would possibly change our absolute findings (tendon lengthening would have a greater effect of PFA than PTA) but only minimally. Although simplified the sagittal model as described has previously been shown to correspond with in vivo measurements[34]. The parameter variations explored in our model were chosen for the purposes of exploring the effect on the extensor mechanism measures but did not necessarily correspond to clinically significant values; joint line elevation in practice can easily exceed the 2.5mm change we analysed[39] and the patella tendon length is only deemed significant with a change of greater than 10%[4]. Taking this into account suggests that a future study corresponding actual changes seen *in vivo* to their effect in PFA and PTA would prove informative.

In summary the PTA is a good indicator of changes in relative tibio-femoral position and changes in patella thickness or patello-femoral over/under stuffing, and the PFA a good indicator of change in joint line and changes in patella tendon length. Although the PTA/KFA relationship is an established means of identifying abnormal kinematics post knee arthroplasty we propose, based on our findings, that in agreement with the hypothesis the use of both the PTA/KFA and PFA/KFA together would give a more complete overview of the sagittal plane kinematics of the knee. Consequently this would be a more accurate and informative measurement of sagittal plane kinematic changes after knee arthroplasty this would provided surgeons with a simple clinical technique to analyse the influence of parameters related to design and surgical technique on the extensor mechanism. Additionally the model has been used to assist in the interpretation of the PTA/KFA and PFA/KFA relationships with regard to 1) AP position of the femur relative to the tibia 2) DP position of the femur relative to the tibia leading to an altered joint line 3) change in patella thickness causing overstuffing or understuffing of the patello-femoral joint 4) alteration in patella tendon length leading to patella baja or alta.

Figures:

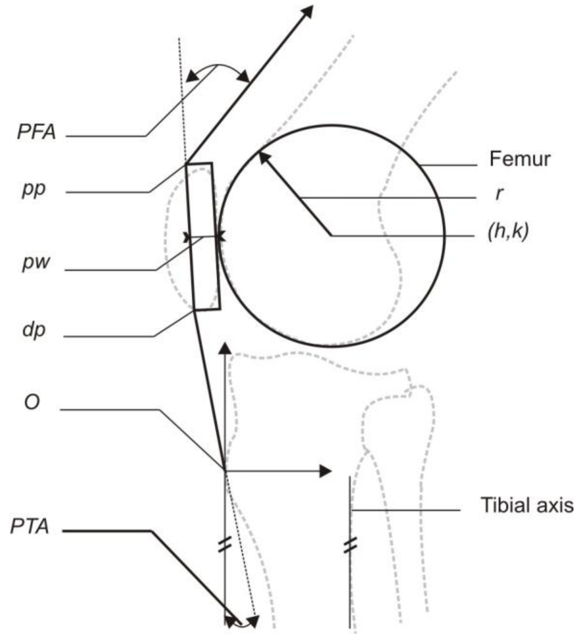

figure 1: Illustration of the model setup overlaying the sagittal representation of the knee showing the parameter descriptions: tibial tubercle (*O*), distal pole of the patella (*dp*), patella thickness/width (*pw*), proximal pole patella (*pp*), femur origin (*h,k*), radius of femur (*r*), patella tendon angle (PTA), and patella flexion/femoral angle (PFA).

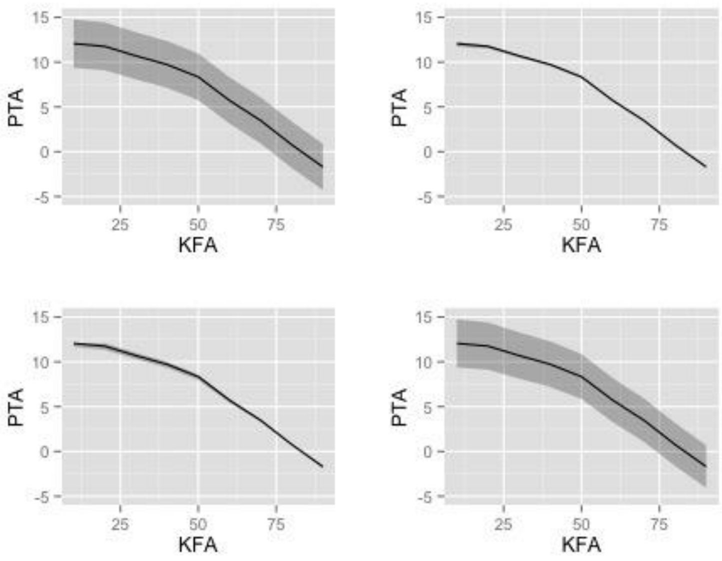

figure 2: Chart showing the patella tendon angle / knee flexion angle (PTA/KFA) relationship. The bold line represents the original relationship and the shaded area represents the range of change in the PTA corresponding to the -2.5mm to +2.5mm change in (top left) AP position (*h*), (top right) DP position (*k*), (bottom right) patella thickness (*pw*), (bottom left) patella tendon length (*ptl*) .

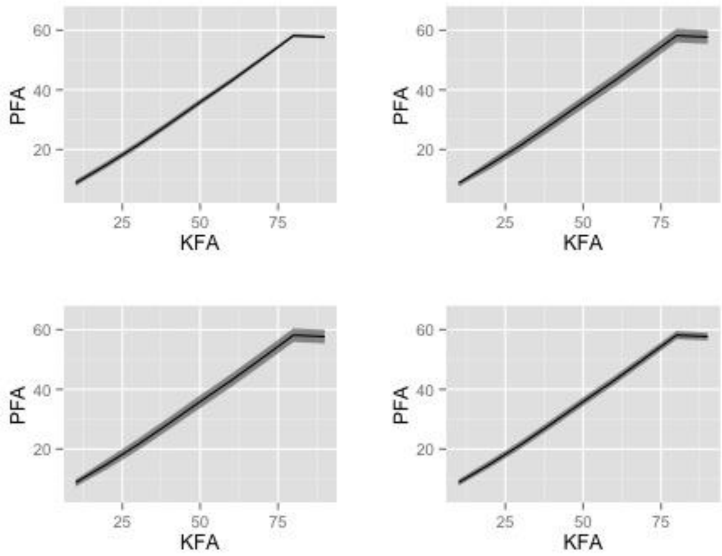

figure 3: Chart showing the patella flexion angle / knee flexion angle (PFA/KFA) relationship. The bold line represents the original relationship and the shaded area represents the range of change in the PFA corresponding to the -2.5mm to +2.5mm change in (top left) AP position (*h*), (top right) DP position (*k*), (bottom right) patella thickness (*pw*), (bottom left) patella tendon length (*ptl*) .

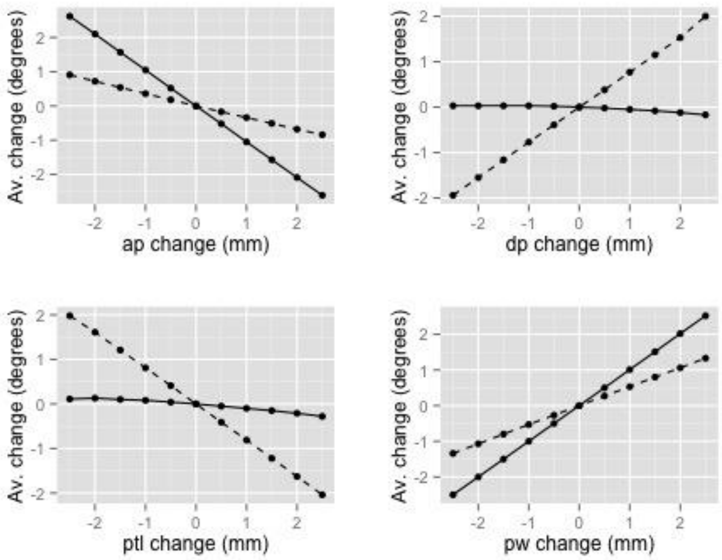

figure 4: Chart showing the the change in patella tendon angle (PTA) v. parameter change (bold line) and patella flexion angle (PFA) v. parameter change (broken line) relationships for variations corresponding to the -2.5mm to +2.5mm change in (top left) AP position (*h*) {*please note AP change refers to the position h (see figure 1) as such negative values correspond to anterior displacement and positive values with posterior displacement of the femur relative to the tibia*} ,(top right) DP position (*k*), (bottom right) patella thickness (*pw*), (bottom left) patella tendon length (*ptl*) .

Tables:

	PTA	PFA	PTA/PFA
h	-1.05	-0.35	3.00
k	-0.04	0.78	-0.05
pw	1	0.53	1.89
ptl	-0.08	-0.81	0.10

Table 1: table showing an overview of the gradients (degrees/mm) for the PTA/parameter variation & PFA/ parameter variation relationships as seen on the plots in figure 4 as well as the ratios (no unit) comparing the PTA to PFA gradients. The ratios represent the response of the two output parameters; a large ratio representing the PTA being more responsive to a change in parameter; a smaller ratio indicating that the PFA was more responsive.

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