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Comparison of isometric and anatomical graft placement in synthetic ACL reconstructions: A pilot study

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ABSTRACT

Correct graft placement is critical to the success of anterior cruciate ligament reconstructions (ACLR). Whilst current trend is to insert the graft in an anatomical location, synthetic grafts have shown to better perform when they are located in an isometric position. Placement, however, is largely dependent on the surgeon and no consensus has been reached for synthetic grafts.

Kinematic flexion-extension data of four separate cadaveric knees was obtained using an optical tracking system. Knees were CT-scanned and computer models were developed for each specimen. Three different graft insertion techniques were simulated in each of the computer models. Kinematic data obtained from the optical tracking was applied to the 3D computer models to simulate knee flexion-extension, and virtual change in ACL graft length was measured over the cycle for each insertion technique. Length changes were plotted onto the Radiological-Quadrant.

The isometric region on the femur was found to be a band spreading from the mid to deep end of the Blumensaat's line down to the shallow-inferior end of the femoral condyle. The JP Laboureau isometric point technique was consistently located in the isometric zone, with the following coordinates on the Radiographic-Quadrant: $t=0.375$ (SD 0.0066), $h=0.227$ (SD 0.0266). The Bernard–Hertel and Charlie Brown anatomical placement methods were located (13%, −6%) and (8%, −15%) away, from the JP Laboureau isometric point, respectively, based on t- and h- coordinates of the Radiographic-Quadrant.

This study has determined the isometric region using three-dimensional analysis relative to the Radiographic-Quadrant. The JP Laboureau method best finds the isometric point. This information is useful for synthetic graft placement.

1. Introduction

Today's ACL reconstructions (ACLR) are routine procedures that aim to restore stability and mobility as closely to the intact knee as possible [1,2]. Current options for replacing the damaged and torn ACL are autologous grafts, allografts and synthetic grafts [3,4].

While autologous grafts, such as patellar tendon and hamstring, and allografts have played a major role in ACLR, issues such as donor site morbidity and the potential for disease transmission remain. Another important factor is the strength of the graft post-operatively. While long-term animal studies have shown that autologous and allograft strength increases over time [5–8], the immediate post-operative graft strength is generally mechanically weaker [9,10] with allografts experiencing this lower strength for a longer period of time than autografts [5]. The synthetic grafts do not need to undergo the same period of revascularisation and remodelling [9,11]. They can withstand greater loads at an early stage. Strengths of around 2500 N have been reported for synthetic grafts [11] which are comparable to those reported for a native ACL [12,13]. Synthetic grafts have gained popularity among athletes in recent years, due to the accelerated rehabilitation and hence earlier return to activity [2,14]. Weakening of synthetic grafts over time has been reported [15]. An animal study by Wang et al. [15] found a 24% decrease in strength after tissue ingrowth 6 months post-operatively. However, the role of the graft was to provide synovitis and better designs, which increase the resistance to torsional fatigue and to wear and tear [16,17].

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The Ligament Advanced Reinforcement System (LARS), which is made from polyethylene terephtalate, has a scaffold structure which allows tissue in-growth between the ligament fibres in the intra-articular segment [4,18]. It is expected that the scaffold in conjunction with the surgical technique of preserving the ACL stump provides the optimal condition for healing to occur [19]. With this in mind, it is highly desirable for the graft to experience minimal stresses in the early phases of healing. Therefore to ensure early return to activity before the natural ACL had healed.

Early synthetic grafts initially showed promising results but in the longer term were fraught with mechanical failures and complications [4]. Immunological responses, osteolysis, foreign-body synovitis and graft rupture were some of the issues reported [20–22] The newer generation synthetic grafts possess mechanical properties, which are closer to the intact ACL [4]; exhibit better biocompatibility due to the removal of potential machining residues and oils that could elicit that the graft does not overstretch, lose its elasticity and result in permanent deformation, an isometric placement is favourable for these types of grafts [9] (Fig. 1).

Isometric placement of the ACL graft minimises the change in length of the ligament over the range of normal knee motion. This technique has been routinely used over the last few decades [23]. However, in recent years, a trend towards anatomical placement has emerged, as it better restores the natural kinematics of the knee [24,25], particularly when using double bundle reconstruction. Also, there have been reports which have found increased ACLR failures due to non-anatomical placement [26,27]. The inability of the reconstruction to restore normal kinematics is believed to play a role in contributing to joint degeneration over time [28,29] due to the altered force vectors. In the case of synthetic ligaments, such as the LARS, however, many surgeons still opt to use the isometric placement technique. The results

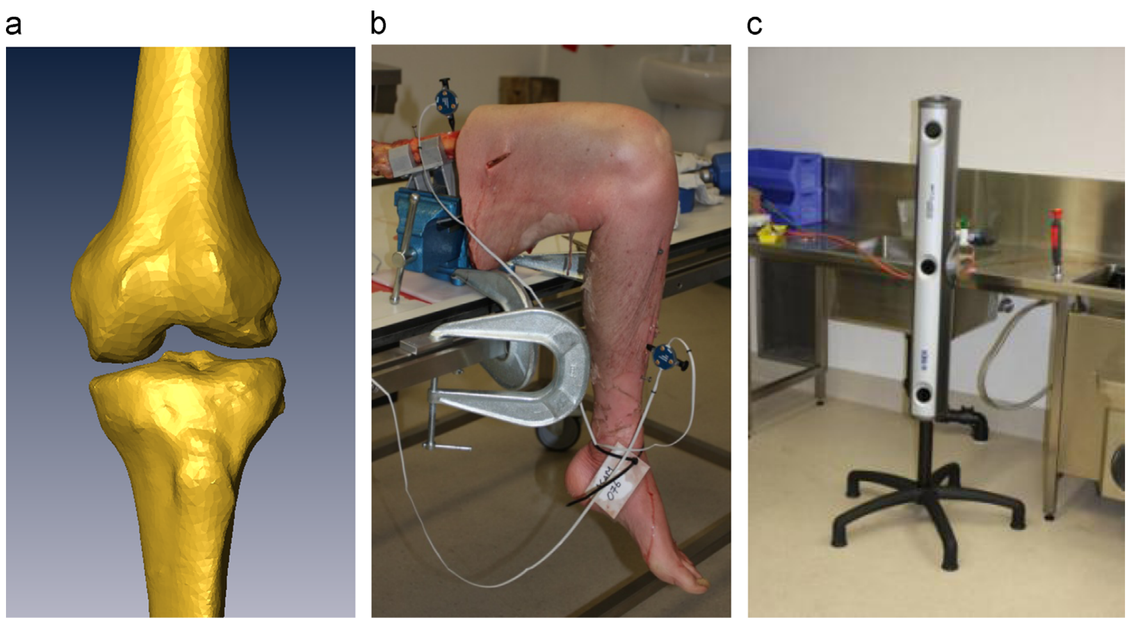

Fig. 1. Scanned and reconstructed femur and tibia (a) the same specimen positioned for testing (b) and the Optotrak camera system (c).

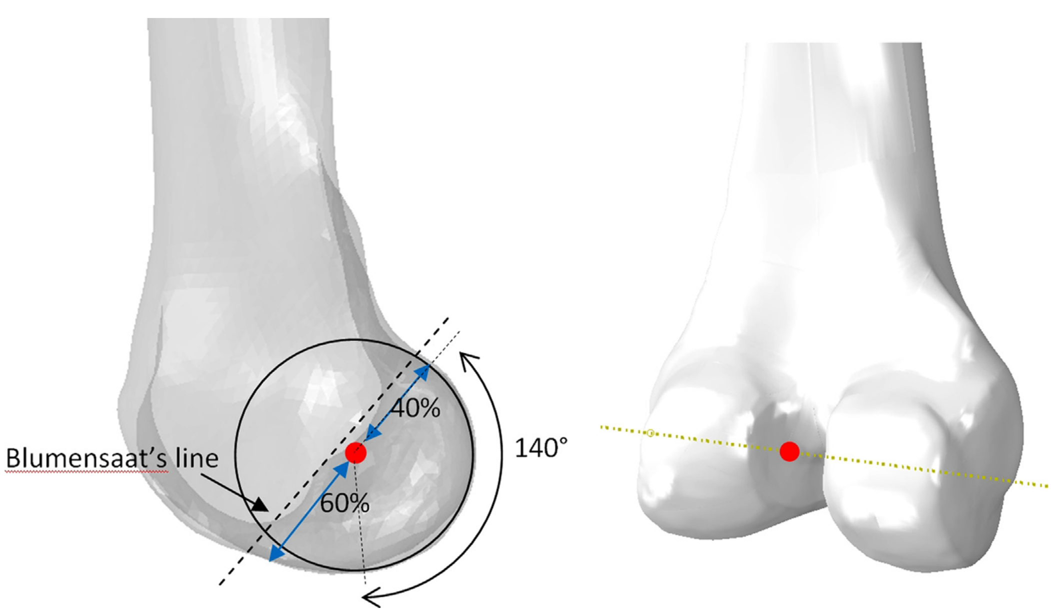

Fig. 2. Femoral insertion point based on the JP Laboureau method.

to date for this type of single-strand implant have been promising with high patient satisfaction rates [11,14,30,31]. For this reason, manufacturers of synthetic ligaments still advocate isometric placement using JP Laboureau's method (Fig. 2 and Fig. 3) as the surgical technique [9,32]. Ultimately however, the preferred method and location of placement is dependent on the surgeon and many opt for anatomical placements such as the Bernard–Hertel (BH) [33] (Figs. 4 and 5) or the Charlie Brown [34] (Fig. 6) ACL insertion points. To aid the surgeon in the selection process, an objective and accurate measurement and assessment of the variability in the ACL length change in three dimensions between the different placement methods (and hence insertion points) is required.

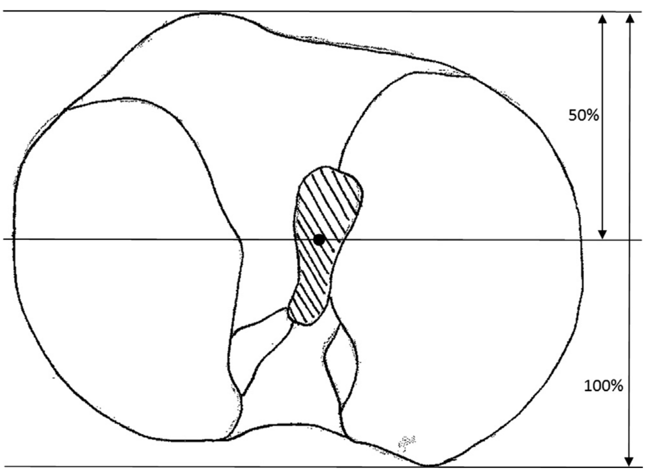

Fig. 3. Tibial insertion point based on the JP Laboureau method (50% of the distance between the most anterior border of the tibial plateau and the posterior border of the medial tibial plateau.(ACL footprint shaded).

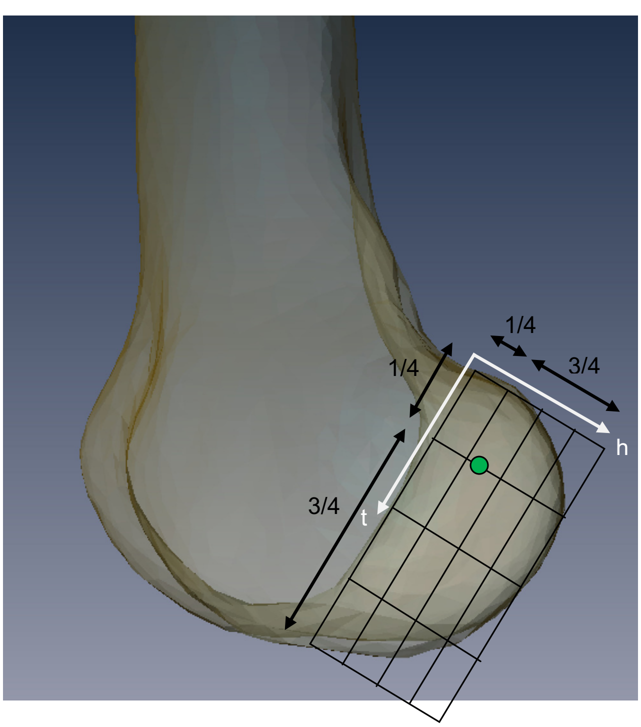

Fig. 4. The Bernard–Hertel grid showing the anatomic insertion point. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The aim of this pilot study was to better understand the relative positions of the different tunnel placements and more specifically, determine (a) how isometric the JP Laboureau method actually is, and (b) how far away from isometric the anatomical ACL graft insertion techniques are. It is hypothesised that the JP Laboureau technique is the best tool for finding the isometric point.

2. Methods

2.1. Subject specific anatomy and kinematics

Following ethical approval, four fresh-frozen, intact cadaveric lower limbs (males and females, ages 60–80) with no apparent osteoarthritis or anatomic deformity were sourced (from Science Care) in preparation for kinematic testing. Three well-spaced fiducial markers (metal pins) were inserted into the femur and in the tibia of each lower-limb. The lower limbs, with their attached markers, were CT-scanned at a resolution of $1 \times 1 \times 1.25\ mm^3$. The femurs and tibias were then segmented using a semi-automated algorithm in Amira 4.0 (ZIB, Berlin, Germany) to create three-dimensional geometry models (Fig. 1). Local femur and tibia coordinate systems were defined using bony landmarks according to Grood and Suntay's [35] joint coordinate system.

The same cadaveric specimens were then prepared for passive kinematic testing. In each case, the femur was positioned and held firmly in a vice. First, using a hand-held digitising probe the coordinates of all 3 fiducial markers on the femur and the tibia were recorded. This registration step was necessary to determine the relationship between each leg and its attached markers and sensors and to facilitate the application of the motion data from the cadavers to the computer models.

A rigid body sensor was then placed in the femur and one in the tibia. These sensors were connected to the data acquisition unit of the Optotrak Certus motion capture system (NDI, Waterloo, Canada) (Fig. 1). The knee was taken through passive knee flexion and extension of a range of approximately 0–90°. The sensors were programmed to record three-dimensional coordinates with respect to the femur. Sampling frequency was 100 Hz.

An in-house program was written in Python, which first extracted the captured three-dimensional translational and rotational raw motion data. This data was then used to calculate the kinematics of the knee using the joint coordinate system convention and the results were graphed.

2.2. Graft tunnel insertion points

Three different ACL insertion techniques for ACL graft reconstructions were evaluated. The methods included the JP Laboureau [9], Bernard–Hertel [33] and the Charlie Brown [34] method. Whilst these are all surgical techniques, this study replicated and applied each of these three isometric point location techniques to computer models of each specimen. In practice, image-intensifiers are used to view and position the joint; this study manipulated the 3D geometry model of the bones to obtain the same corresponding view and then applied the same steps as would surgically. Below is a detailed description of each of the isometric point location techniques.

The *JP Laboureau* method first requires the posterior femoral condyles to be superimposed, whilst viewing the sagittal view in real-time using an image-intensifier or similar [9]. In this study, this technique was replicated by adjusting the position of our femur geometry model in a computer aided design (CAD) software program until the posterior femoral condyles were overlayed. A circle was then superimposed over the condyles such that it covered a 140° arc of the posterior condyles. The JP Laboureau method also requires that this point is located approximately at 60% of the AP length of the condyle, when measured on a line going through the centre of the circle and parallel to the Blumensaat's line. An axis was drawn through the centre of the circle and the point where this axis intersected the bony surface in the intercondylar notch on the lateral side, was taken as the femoral insertion point according to the JP Laboureau method (Fig. 2).

The tibial point was selected by viewing the tibial plateau in the superior-inferior view, such that the mechanical axis of the tibia was orthogonal to this viewing plane. The most anterior border of the tibial plateau and the posterior border of the medial tibial plateau (MTP) were used as references. The tibial point was defined as approximately 50% of the distance between these two borders [9](Fig. 3).

The *Bernard–Hertel*, or Radiographic Quadrant, method uses a grid overlayed on the lateral femoral condyle [33]. The grid parameters are h and t, where t is defined as the total sagittal diameter of the lateral femoral condyle measured along Blumensaat's line and h is defined as the height of the intercondylar space measured as the distance between the Blumensaat's line and a tangent to the distal subchondral bone contour of the condyle parallel to Blumensaat's line. The distances h and t create a rectangle which is divided up into four on each side (Fig. 4).

According to Bernard et al. [33], this method was based on an anatomic study, which measured the locations of the ACL footprints in a series of cadavers and reported them in relation to the grid. Their study found the insertion point to be located at: $t=24.8\%$ and $h=28.5\%$ (as shown by the green dot in Fig. 4). This is otherwise described as the point located in the distal corner of the most supero-posterior quadrant.

The tibial point used for the Bernard–Hertel method was based on the anatomical position of the ACL footprint as defined by many authors [36–38]. Colombet et al. [37] found the antero-medial (AM) bundle to be 36% and the postero-lateral (PL) bundle to be at 52%; Kasten et al. [38] found AM to be 35% and PL to be at 48%. According to Amis and Jakob [39] and Staubli and Rauschning [40], the ACL graft should be centred 43% posteriorly on the tibia. This dimension was used in this study.

The *Charlie Brown*, or anatomic, method uses the Bernard–Hertel grid as a reference, except that it suggests different values for the parametric coordinates, h and t. The suggested values are based on anatomic measurements of the AM and PL bundle locations ($t=25\%$, $h=25\%$ and $t=33\%$, $h=50\%$, respectively), where the midpoint of the two bundle locations is the isometric point ($t=29.2\%$, $h=37.5\%$ (blue dot)), as shown in Fig. 5; and is therefore sometimes referred to as the ‘anatomic’ method.

Fig. 6 summarises all three methods. The femur insertion points are represented by a red (JP Laboureau), green (Bernard–Hertel) and blue dot (Charlie Brown). The tibial insertion point for all three methods is situated in the centre of the ACL footprint,

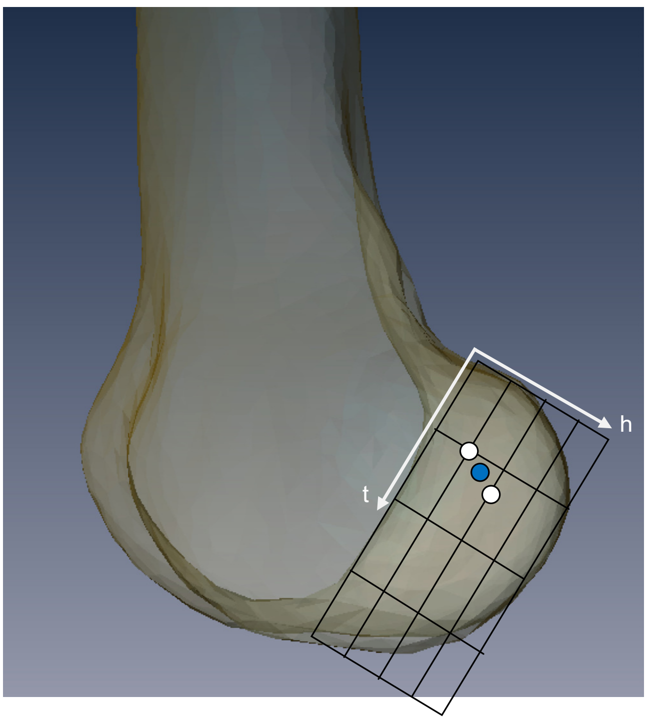

Fig. 5. Illustration showing the centres of the AM and PL bundle locations (white dots) and the midpoint (blue dot) in relation to the Bernard–Hertel grid. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

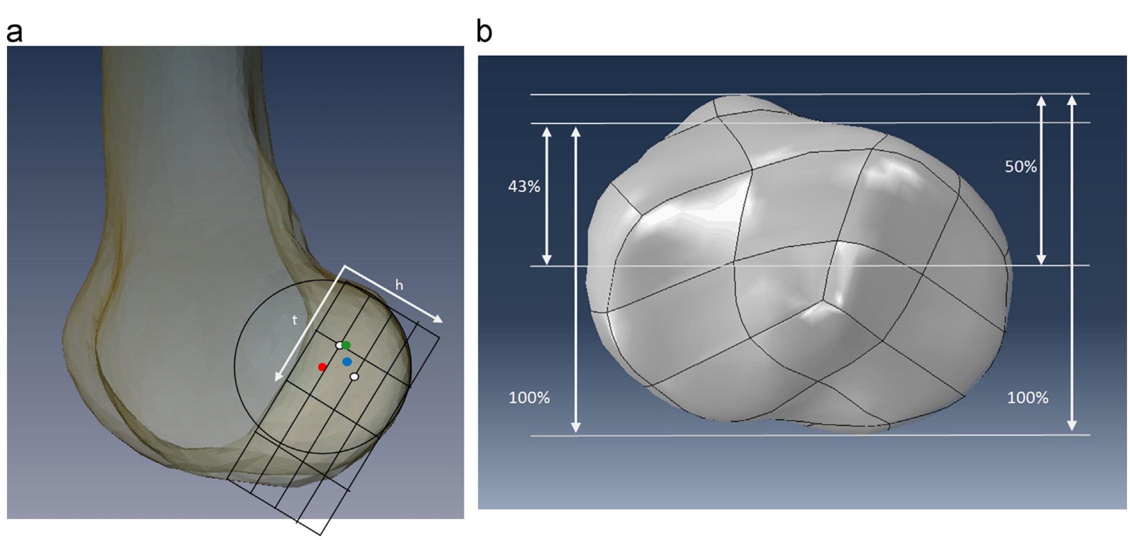

Fig. 6. (A) An example of a femur with the JP Laboureau circle, the Bernard–Hertel grid and three femoral insertion points (the JP Laboureau, red dot; the Bernard–Hertel, green dot and the Charlie Brown, blue dot, points. White dots are the AM and PL bundle locations). (B) Tibial insertion points based on 43% and 50% of the tibial plateau. 43% is based on the Amis-Jakob as well as the Staeubli-Rauschning lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with the JP Laboureau method defining this point as 50% of the distance between the most anterior border and most posterior border of the tibial plateau (Fig. 3 and Fig. 6) and the Bernard–Hertel and Charlie Brown methods using 43% of the posterior distance Fig. 6. Table 1 summarises these parametric values.

2.3. Isometric length calculations

Having determined the ACL insertion points on the femur and tibia for each method, the motion capture data from the cadaveric study was then applied to the computer models for each of the cadaveric specimens, in order to calculate the change in length of the ACL.

For each of the three methods, the distance between the femoral and tibial insertion points was calculated (as a straight line) for each time point in the passive flexion-extension cycle. The change in the distance was calculated relative to the full extension position and graphed for the 0–90° flexion range. These calculations were made based on the raw 3D motion capture data.

Additionally, this study tried to optimise the location of the insertion point on the femur by finding the point on the femur that displayed the lowest change in distance from a given point on the tibia over the entire range of knee motion. To achieve this, several tens of points were created on the femur and the change in distance between each of these points and the tibial point calculated. To create the femoral points, points at regular intervals were extracted from the BH grid and projected onto the surface of the femur. This was completed for both tibial points (43% and 50%). To best identify the optimum point, a series of contour plots were created (one for each specimen) showing the maximum change in distance at each of these femoral points. The definition of isometry in this study was a femoral point whose distance from the tibial point did not change by more than $+/-3$ mm. A "nearly isometric" behaviour of the ACL graft is said to be desirable, with a maximum 3 mm lengthening of the graft [41–45].

3. Results

3.1. Passive knee kinematics

The passive knee kinematics were calculated based on the ISB recommended Grood and Suntay joint coordinate system [35]. Fig. 7 shows the typical motions with reference to time and Fig. 8 displays the rotations and translations with reference to flexion angle. All data showed normal kinematics including typical characteristics such as the screw-home mechanism.

Table 1
Parametric values.

Method	Femoral insertion point		Tibial insertion point
	Parametric *t* coordinate	Parametric *h* coordinate	
JP Laboureau	NA	NA	50% of the distance from most anterior border to most posterior border
Bernard–Hertel	0.248	0.285	43% of Amis-Jakob line (anterior border of tibial plateau to most posterior border)
Charlie Brown	0.292	0.375	43% of Amis-Jakob line (anterior border of tibial plateau to most posterior border)

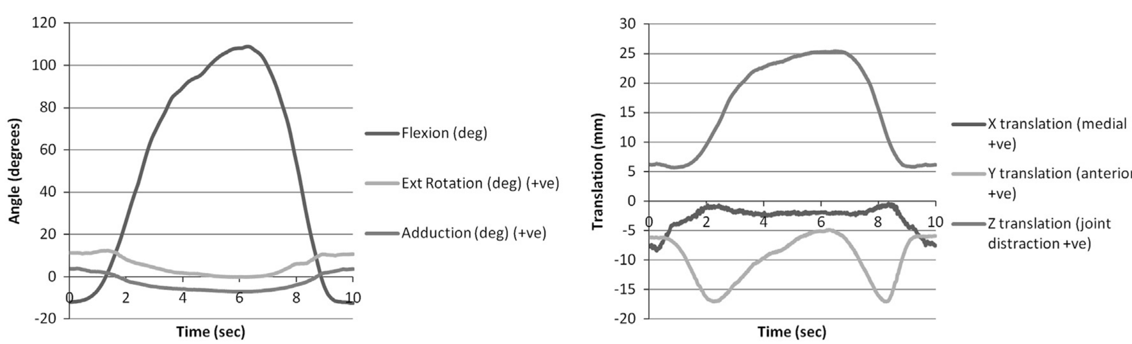

Fig. 7. Knee motions with reference to time (rotations on left and translations on right).

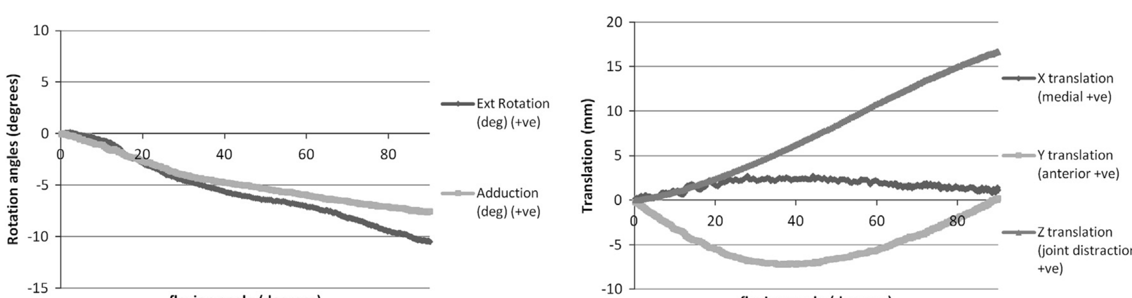

Fig. 8. Typical rotations and translations with reference to flexion angle.

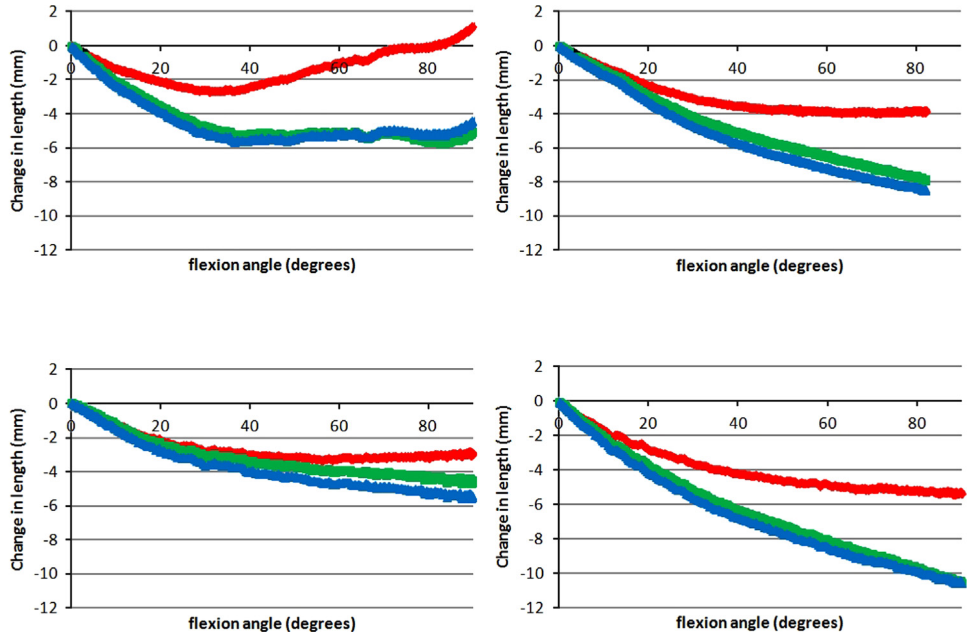

Fig. 9. Change in graft length of four specimens over a 90° flexion cycle (Specimen 3, 1, 2 and 4 clockwise from top left), red is JP Laboureau, green is BH and blue is CB. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Isometric length calculation

The change in distance between the femoral and tibial insertion points for four specimens over a 90° flexion cycle are shown in Fig. 9. In two of the four cases (Specimen 3 and 4), the JP Laboureau point was isometric (within the +/−3 mm threshold); the other two specimens were outside this range but still more isometric than the Bernard–Hertel and Charlie Brown methods. Also, even though two specimens were outside this range, both experienced more than 3 mm of laxity, and therefore the graft would still not be under risk of deformation.

The Bernard–Hertel and Charlie Brown points were similar in behaviour to each other. Length changes were generally a decrease from the original length (at full extension), which indicates that the graft was becoming lax with flexion. One specimen displayed a positive change in length, which indicates some tension in the graft. However, this was within the +/−3 mm isometric range.

Fig. 10 shows an example of a contour plot for a femoral condyle. The plots were created based on the calculated distances between the tibial insertion point and all the feasible femoral insertion points on the higher resolution Bernard–Hertel grid. The plot covers the feasible areas of insertion on the femur and shows the maximum change in the distances in insertion points over a full flexion cycle, for the entire region. These plots provide a clear visualisation of the change in distances over the region. Moving towards the red region indicates tension in the ligament and moving towards blue indicates laxity of the ligament. Ideally, the graft would be positioned in the green region, which is surrounded by the dashed isolines. This would be the most isometric region.

Fig. 11 shows the contour plots for all four specimens (four rows) for the two cases: with the tibial insertion point at 50% and at 43% (two columns) of the AP plateau distance. The left column shows the results for a tibial insertion point at 50% and the right column shows the tibial insertion at 43% of the tibial plateau.

In all cases, the JP Laboureau point was shown to be most functionally isometric. In two of the four specimens the JP point

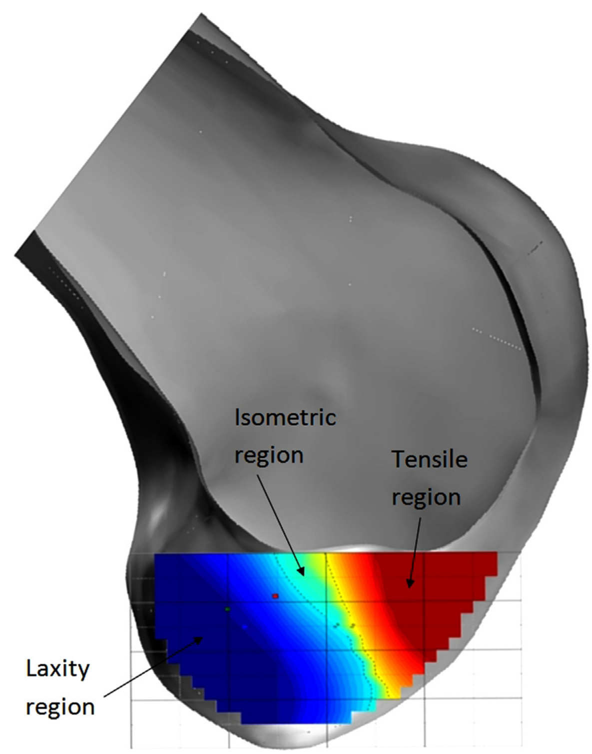

Fig. 10. A colour contour plot showing regions on the Bernard–Hertel grid where graft would undergo potential tension (red regions) and laxities (blue regions). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fell within the isolines, which reflects an even higher level of isometricity. The other two points on the femur were consistently more lax and similar in laxity to each other. According to these contour plots the most isometric region, in clinical terms, would be more shallow and possibly more superior, than what is currently the normal practice.

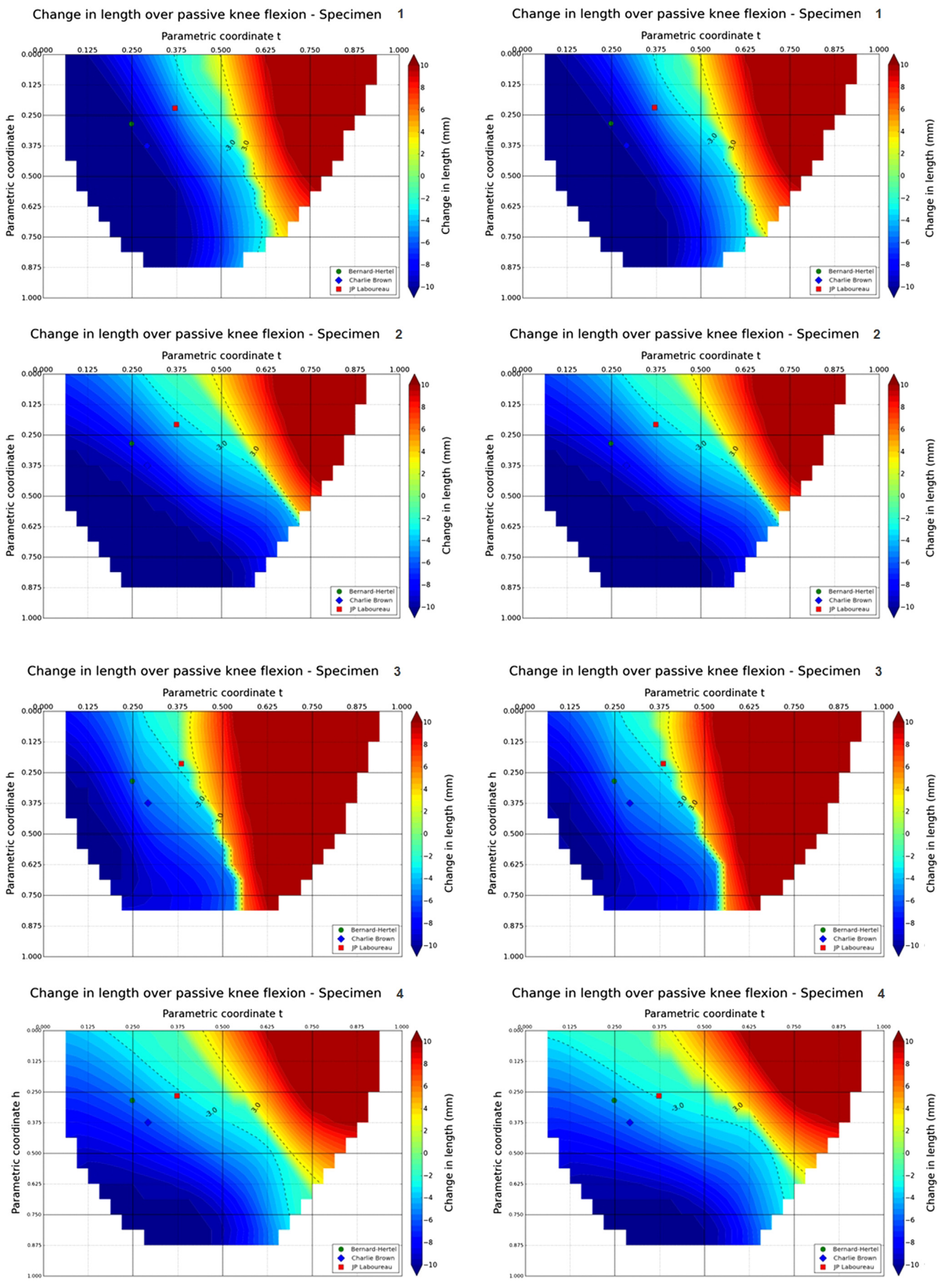

Fig. 11. Colour plots showing isometric behaviour(columns are 50% vs. 43% of tibial plateau). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
JP Laboureau points referenced to the Radiographic Quadrant (Bernard–Hertel grid).

	Parametric *t* coordinate	Parametric *h* coordinate
Specimen 1	0.370	0.220
Specimen 2	0.374	0.208
Specimen 3	0.385	0.213
Specimen 4	0.373	0.266

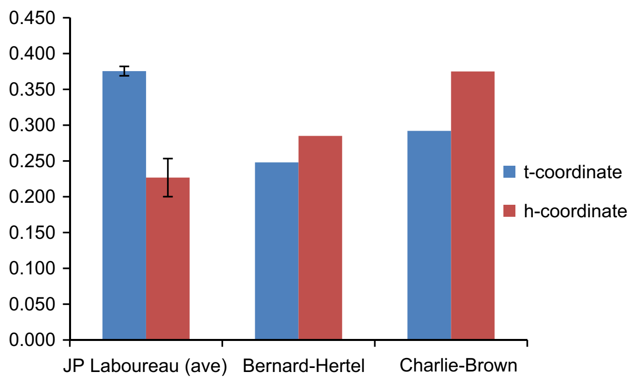

Fig. 12. Location of JP Laboureau isometric points on the Radiographic Quadrant (Bernard–Hertel grid) compared with anatomical points.

The *Bernard–Hertel* and *Charlie Brown* methods uses parametric coordinates to identify the insertion point. The *JP Laboureau* method, however, uses a circle. This study found the JP Laboureau points to be relatively consistent in location and therefore likely to be located relative to the Radiographic Quadrant (Bernard–Hertel grid). The t and h coordinates of the JP Labourau point relative to the Bernard–Hertel grid are shown in Table 2. The location, relative to the Bernard–Hertel grid was $t=0.375$ (SD 0.0066), $h=0.227$ (SD 0.0266) on average.

The difference in position of the JP Laboureau to the Bernard–Hertel and Charlie Brown points were found to be (13%, −6%) and (8%, −15%), respectively, as can be seen in Fig. 12.

4. Discussion

Several techniques are currently employed in order to locate the femoral insertion point of an ACL graft. Current thinking has shifted towards anatomical reconstructions [1] where graft insertion points are positioned in the original native ACL footprint locations. Also, double-bundle anatomic reconstructions can replicate the AM and PL bundle activations at different flexion angles and can increase functionality and stability. However, these are technically more difficult to undergo and results to date are still inconclusive. Single-bundle reconstructions are still the more common reconstruction method [46]. These techniques are well suited to autografts and allografts. However, synthetic ligaments by nature have different requirements. Isometric placement is preferred and has been long identified as a critical factor in ACLR of synthetic grafts, as this ensures excessive graft forces and hence permanent deformation are avoided. This is particularly important in the case of synthetic ligaments, which have a more limited elastic region than soft-tissue. The JP Laboureau method is one method of identifying the isometric graft insertion point.

This study identified the isometric regions, verified the location of JP Laboureau points and compared these points to those obtained using anatomical location techniques, in an attempt to better understand the actual differences between these different techniques.

This study evaluated the change in distance between the femoral and tibial insertion points of four different specimens (based on straight line distances) over a full flexion cycle under three different graft insertion techniques. This study found the JP Laboureau method to be the most isometric, whilst the Bernard–Hertel and Charlie Brown methods were very similar to each other in behaviour. Of the four specimens used in this study, two of which were located using the JP Laboureau method fell within the +/−3 mm isometric zone threshold. The other two specimens fell outside this zone. However, they did not undergo any tensions which could compromise the integrity of the graft. Rather, they were undergoing laxities of greater than 3 mm. This could potentially cause instability issues. However, the main purpose of synthetic ligaments, such as the LARS, is to act as a scaffold for regrowth of the native ACL and therefore potential instabilities would be combated with the presence of a new native ACL. Also, the level of laxity was much less in the JP Laboureau method compared with the other two methods. The other two insertion location methods (Bernard–Hertel and Charlie Brown) did not fall within the isometric zone, for the entire flexion range, in any of the four specimens.

Similar to the current results, previous studies have shown that posterior placement of the graft causes the insertion points to approach each other and create graft slackening (blue regions in colour maps); and that anterior placement will cause the insertion points to move apart with knee flexion and cause stretching (red regions in colour maps). Therefore isometric placement is ideally situated between these two extremes. This study found the most isometric regions to be a band which spreads from approximately the mid to deep end of the Blumensaat's line down to the shallow-inferior end of the femoral condyle. These results are in general agreement with some other published studies [47–49]. This study found the JP Laboureau insertion point on the femur to be generally more distal and anterior, or in surgical terms, more shallow and superior compared with the other two points, making it more isometric than the other two methods.

Hefzy et al. [49] published a similar study which also measured the changes in distance between possible insertion points. They found a 3–5 mm band on the femoral condyle which produced

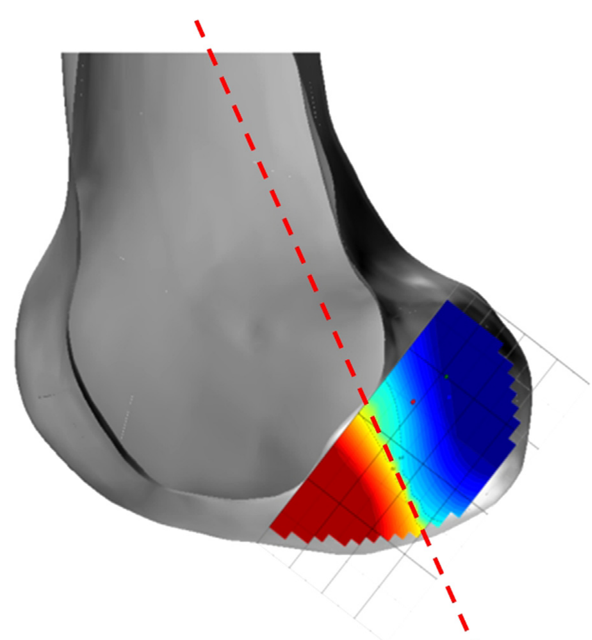

Fig. 13. Femoral isometricity zone. Very similar to that defined by O'Brien [48] and Hefzy et al. [49]. The direction of the zone is consistent among the different studies.

isometric motions. O'Brien et al. [48] also mapped out isometric zones based on flexion-extension. Their zones were again similar in location and direction to that found in this study (Fig. 13).

Previous studies have reported that the AP position of the femoral attachment is the primary determinant of isometry [49,50]. This is reflected in the orientation of the contour lines of both this study and others [47–49]. An anterior or posterior shift of the insertion point is more likely to affect the isometry than a superior or distal shift. When comparing the three different techniques (JP Laboureau, Bernard–Hertel and Charlie Brown), it can be seen that the JP point is distinctly more anterior than the other two, and therefore more isometric (Fig. 10).

Conventional use of the clock face as a means of identifying region of graft insertion is very subjective and subject to inter-observer interpretation and knee flexion angle. Lower positions (i.e. 2 o'clock rather than 1 o'clock) generally offer more rotational stability than a vertically inclined graft. However, a vertically inclined graft is close to the Blumensaat's line and this is seen in the isometric regions. Therefore, there needs to be a compromise between obtaining isometry and maintaining rotational stability.

Although this study found some consistent differences between the femoral insertion points of the JP technique compared with the other two, it should be noted that considering the size of a tunnel is approximately 7 mm, the graft is not a line-to-line structure and that the distance between these three points is within this 7 mm boundary, it is very important that the correct point is selected as the centre of insertion point. A small deviation from the ideal point is shown to alter the isometric behaviour. A simple, accurate and reproducible technique needs to be employed during reconstruction to ensure the margin of error is minimised. The JP Laboureau technique is simple to use, based on this pilot study produces good repeatability; and most importantly can find the three-dimensional isometric point in the knee.

The graft distances calculated in this study were three-dimensional. The graft length was based on the entry coordinates of the insertion points. In this way the graft length was a point-to-point line. The starting point was full extension and it was assumed that at this position the graft was not under tension or laxity. The change in graft length curves (Fig. 9) show the changes in the graft length from the full extension starting point and suggest whether it is likely that the graft will remain intact or undergo permanent deformation under the basic flexion motion. These measurements have previously been based on lateral projections of the graft as taken by imaging equipment in theatre, and therefore the full length changes have not been calculated accurately. The advantage of this study was that 3D measurements were used, providing a realistic assessment of the actual length changes.

The literature shows that the femoral insertion point has a greater effect on graft length changes, as the knee flexes and extends, than does the tibial insertion site [39,45,49]. This is because the tibial point acts as a central pivot which is closer to the femoral attachment [48]. This is confirmed in this study where little difference was observed in the length changes between the 43% and 50% tibial insertion points. The JP tibial insertion point was slightly posterior to the Charlie Brown tibial insertion point; yet this had minimal impact on the results, suggesting that the tibial side is generally more forgiving and less sensitive to isometry.

Some limitations of the study to consider included the small sample size ($n=4$). Ideally, an increase in sample numbers would reinforce the results obtained. There is, however, enough discrepancy between the different techniques and similarity within each group to provide confidence in the findings. With very low standard deviations across the different specimens it is an indication that there are clear differences between the different techniques. Also, the distance calculations were based on the kinematics of the intact knee. There is the possibility that the kinematics are altered after ACLR. However, the other ligaments and the surrounding knee capsule and soft-tissue play a major role in the stability-laxity of the joint and the bone morphology of the knee joint itself has a large influence on the passive kinematic characteristics of the joint.

Ideally, isometric measurements would be made based on strain values rather than actual distance changes. In that way, it would then be possible to compare the 9% maximum strain (based on mechanical testing results) to the actual change in distances. For this calculation to be made, accurate information regarding the exact location of the fixation of the synthetic ligament is required. In the current study, the distance calculations were made from the surface of one bone insertion to another—the tunnels themselves or the fixation points within the tunnels were not considered. Comparing strains based on this value would clearly be misleading, as the graft length would be underestimated and any strains would be overestimated and well above the critical 9% allowable strain. Therefore, accurate locations of the points of fixation of the graft are required to assess strain. Of course, other factors, such as bending of the graft at the tunnel entrance may also affect the integrity of the graft.

Synthetic ligaments have the advantage of minimal morbidity from the operation allowing an early return to unrestricted sports activity; but also carry the risk of possible long term structural failure and reactive synovitis as a result of wear particles. While the short term results have generally been positive [11,14,30], problems such as synovitis have also been reported [51]. Therefore, longer term results are required to better inform the orthopaedic community. In the meantime careful selection of patients is paramount [52].

With regards to graft placement technique, two things are important: finding the correct position and repeatability. The 'correct' position is still somewhat debatable and needs to be assessed clinically on a patient-by-patient basis. However, there are variables which can be evaluated on a technical basis, such as *isometric behaviour*. This study has shown that there are distinct differences in isometric behaviour when comparing different femoral insertion points; and that the JP Laboureau technique is the most functionally isometric. The other test to determine whether a technique is successful is its repeatability. This study found the JP method to be consistently reproducible, similar to the other two grid-based techniques. The intra-observer variability was low, with the JP point observing its own h and t coordinates. However, the inter-observer repeatability may still need to be assessed.

Routine fluoroscopy or a navigation system is recommended when reconstructing ACLs, as this will provide real-time feedback during surgery and enable the surgeon to determine the isometric region for tunnel placement using a simple and reproducible technique.

5. Conclusion

Isometric placement is important for good function and integrity of the ACL synthetic graft. This study used three-dimensional coordinates to calculate the isometric regions in the femur and found this to be a band which spreads from mid to deep end of the Blumensaat's line down to the shallow-inferior end of the femoral condyle. The JP Laboureau method of finding the isometric point was found to be satisfactory, with the graft experiencing the least amount of stretch and laxity. The Bernard–Hertel and Charlie Brown points were located (13%, −6%) and (8%, −15%) away, from the JP Laboureau isometric point, respectively, based on the *t*- and *h*-coordinates of the Radiographic Quadrant. The JP Laboureau technique is the better method of obtaining the isometric point for synthetic ACL reconstructions.

Conflict of interest statement

The authors declare that there is no conflict of interest with this study. And that this study was supported by research funding from Corin.

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