Research Article

IN-VIVO KINEMATICS OF KNEE REPLACEMENT DURING DAILY LIVING ACTIVITIES: CONDYLAR AND POST-CAM CONTACT ASSESSMENT BY THREE-DIMENSIONAL FLUOROSCOPY AND FINITE ELEMENT ANALYSES†

Running title: Contact Assessment in Total Knee Replacement

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ABSTRACT

In total knee replacement, the investigation on the exact contact patterns at the post-cam in implanted patients from real in-vivo data during daily living activities is fundamental for validating implant design concepts and assessing relevant performances. This study is aimed at verifying the restoration of natural tibio-femoral condylar kinematics by investigating the post-cam engagement at different motor tasks. An innovative validated technique, combining three-dimensional fluoroscopic and finite element analyses, was applied to measure joint kinematics during daily living activities in 15 patients implanted with guided motion posterior-stabilized total knee replacement. Motion results showed physiological antero-posterior translations of the tibio-femoral condyles for every motor task. However, high variability was observed in the position of the calculated pivot point among different patients and different motor tasks, as well as in the range of post-cam engagement. Physiological tibio-femoral joint rotations and contacts at the condyles were found restored in the present knee replacement. Articular contact patterns experienced at the post-cam were found compatible with this original prosthesis design. The present study reports replaced knee kinematics also in terms of articular surface contacts, both at the condyles and, for the first time, at the post-cam.

Keywords: total knee replacement, tibio-femoral kinematics, three-dimensional video-fluoroscopy, condylar contacts, post-cam contact, daily living activities, finite element analysis.

INTRODUCTION

Posterior-Stabilized total knee replacement has been introduced in the mid-1970s [1] as an alternative to cruciate retaining designs. The reasons for this innovation are: firstly, to cater for clinical cases of missing or dysfunctional posterior-cruciate ligament (PCL) and, secondly, to achieve a more natural knee kinematics [1,2]. The posterior-stabilized design, particularly for its post-cam mechanism feature, was also meant to avoid posterior subluxation of the tibia, in a way to substitute the degenerated PCL, and to improve the range of knee flexion by allowing femoral roll-back, which potentially can also increase the quadriceps moment arm [3-5]. This design is also expected to limit excessive antero-posterior tibial translation, after resection of the PCL. Posterior-Stabilized total knee replacement has been widely used for more than two decades for patients requiring primary or revision knee replacement, and long-term follow-up studies have reported satisfactory results [2,6-8]. Intra- and post-operative benefits of a posterior stabilized over a cruciate retaining knee replacement, include easier ligament balancing and easier correction of possible severe deformities (by eliminating tight PCL), better restoration of knee kinematics, increased stability and range of motion, reduced quadriceps force in extension and potentially minimized polyethylene wear when more congruent articular surfaces are used [9-11]. However, complications and potential disadvantages include fracture and wear of the tibial post, soft-tissue impingement, and risks of dislocation or instability during flexion [12-17].

In-vivo kinematics of replaced knees during weight and non-weight bearing activities, by using three-dimensional (3D) fluoroscopy, has been largely reported [7,8,18-24]. These studies demonstrated high variability among patients, among surgeons and also among different implant designs. Patterns of the so-called paradoxical kinematics, i.e. anterior translation of the femur during knee flexion, have also been shown. Such paradoxical motion results in reduced knee flexion and effective muscle lever arm of both agonist and antagonist muscle groups [19,25,26]. Antero-posterior translation and axial rotation at the tibio-femoral prosthetic articulation during weight bearing activities is highly dependent on the geometry of the tibial insert. Most of the knee prostheses have been designed to have a distinguished antero-posterior contact between femur and tibial insert. Tibio-femoral contact points should be at about 2/3 of the antero-posterior length of the tibial insert, in order to increase knee flexion and to optimize the extensor mechanism. In this way a good restoration of the PCL function is obtained by the post-cam [24,25,27-29]. The former mechanism, also obtained by the symmetrical and concave geometry of the polyethylene insert at the medial and lateral condyles, is likely to be the main reason for the physiological internal rotation of the tibia during knee flexion, as shown in a number of fluoroscopy data [18-21,30].

The paradoxical joint motion observed in replaced knees pertains not only the anterior translation of the femur during flexion, but also its posterior translation during extension [19,20,31], both likely associated to the post-cam design [3,24,32-35]. Therefore, using computer-based kinematic modeling [36,37], this mechanism has been modified to more constraining contacts, particularly at the anterior aspect of the post-cam [7,21,33,38], designed to mimic the physiological motion of the knee joint. In particular, with this more recent design, the anatomical dishing of the insert, i.e. concave geometry in the medial side and convex geometry in the lateral side, and the asymmetric post-cam mechanism, with different anterior and posterior aspects of the cam were meant to result in the physiological roll-back of the femur during flexion.

The amount of antero-posterior translation at the tibio-femoral joint, and of post-cam engagement during stair, step up, lunge and squatting exercises has been investigated; the related results showed a nearly physiological knee kinematics [7,8,39,40]. However, fluoroscopy-based assessments have mainly focused on tibio-femoral translation and axial rotation, and only a few papers have investigated the full post-cam mechanism during weight and non-weight bearing activities. More specifically, detailed assessments of the exact contact patterns at the post-cam in implanted patients from real in-vivo data during daily living activities are expected to provide fundamental information for validating implant design concepts and assessing relevant performances, but these are not yet available in the literature.

In this study, an innovative validated technique, combining 3D fluoroscopic and finite element analyses [33], was applied to analyze a group of 15 patients who underwent total knee replacement with a constraining post-cam design, during several daily living activities. The aims of our study were 1) to verify whether a constrained post-cam mechanism resulted in physiological knee joint kinematics; 2) to analyze the knee flexion range at which the post-cam mechanism engages; and 3) to investigate the influence of different motor tasks on the post-cam mechanism and on the position and translation of the tibio-femoral contact points.

MATERIALS AND METHODS

Fifteen patients (Table 1) affected by primary knee osteoarthritis were implanted with a post-cam fixed-bearing prosthesis (Journey® Bi-Cruciate Stabilized Knee System; Smith & Nephew, Inc, Memphis, TN-USA). This design claims a better restoration of natural knee kinematics by means of a larger constraining effect, implied by the new post-cam mechanism and by the original shapes of the medial and lateral condyles [7,41,42]. At 6 months after surgery, all patients were evaluated clinically and by 3D video-fluoroscopy in order to derive joint motion at the replaced knee. This is an analytical and retrospective study (Level of Evidence III), conducted after institutional review board approval and in conformity with local ethical regulations; written informed consent was obtained from all patients prior surgery.

In the post-operative clinical evaluation at follow-up, all patients showed good outcome according to the International Knee Society scoring system [43] (corresponding ‘‘knee’’ and “function” mean scores being about 94.9 and 90.7, respectively; the thorough clinical assessment of the present cohort can be found in [7]). As for 3D kinematic evaluation, a fluoroscopic device (digital remote-controlled diagnostic Alpha90SX16; CAT Medical System, Rome, Italy) was used for image acquisitions in a 32-cm-wide field of view during cycles of chair rising-sitting, stair climbing, and step up-down at 10 Hz sampling frequency [7,8,39]. The height of the staircase steps was 21 cm.; the chair height was set for each patient to allow about 80° of initial knee flexion when sitting [7,8,39]. The 3D position and orientation of the femoral and tibial prosthesis components were derived from fluoroscopic images after a preliminary image calibration phase and by an iterative procedure using a shape-matching technique based on the CAD models of the implanted prosthesis (tested translational/rotational accuracy: 0.5 mm / 1.0°) [44]. Corresponding knee joint kinematics was derived using a standard joint convention [45], resulting in relatively normal knee kinematics associated to roll-back and screw-home mechanisms [7].

Using a previously validated numerical technique [33], in-vivo 3D kinematics obtained from video-fluoroscopy was used as input for a patient specific finite element model of the implant; this was then used to calculate, for each patient and for each motor task, the contact between the femoral and tibial components, therefore both at the condyles and at the post-cam. For the latter, three possible situations were considered: anterior contact, posterior contact, and no contact between cam and post. The femoral component was considered a rigid body and was represented by triangular surfaces (about 11,500 elements); the tibial insert was represented by eight-node 3D hexahedrals (about 15,500 elements). The tibial insert was considered as the fixed reference, and the femoral component was considered to move according to the aforementioned in-vivo joint kinematics. Material models, properties and friction coefficient were chosen according to the literature [33,46,47]. All simulations were performed using Abaqus/Explicit version 6.10-1 (Dassault Systèmes, Vélizy-Villacoublay, France). For each patient and motor task, the 3D coordinates of the medial and lateral femoral condylar contact points on the tibial insert and the tibio-femoral axial rotation, as assessed via finite element analysis, were plotted versus the knee flexion angle. In detail, the contact points were determined by the software as the centroid of the pressure distribution of the medial and lateral femoral condyles on the tibial insert during motion; the contact-line was defined as the line connecting the medial and lateral contact points. The position of the corresponding pivot point was estimated as the least-square approximation of the intersection of all the contact lines calculated throughout the joint motion. This was reported as percentage locations over the antero-posterior length of the tibial insert for normalization, with -50% and 50% being respectively the most posterior and most anterior location. It was also normalized over the medio-lateral width of the tibial insert, -50% and 50% being respectively the most lateral and most medial location. Both length and width of the tibial insert were extracted from relevant computer-aided-drafting models. Furthermore, knee flexion angles at the point of contact of the post-cam, were also determined.

RESULTS

Consistent patterns over patients and motor tasks were observed for the antero-posterior displacement of the medial and lateral condylar contact points versus knee flexion (Figure 1). The range of this antero-posterior displacement at the lateral condyle (about 26, 18 and 30 mm in chair rising, stair climbing and step-up, respectively) is almost double than the one observed at the medial condyle (12, 10 and 15 mm, respectively). This implies an overall internal rotation of the tibia during flexion and also a good restoration of the natural roll-back and screw-home mechanisms at the replaced knee.

Consistent patterns among patients were also observed for the axial rotation of the femoral component with respect to the tibial component (Figure 2). In particular, the knee rotates internally during knee flexion, from about 8° external rotation to about 8° internal rotation. Specifically, the ranges from full extension to maximum flexion were different among the different motor tasks, these being 10.3°, 14.8°, and 20.4° in chair rising, stair climbing and step-up, respectively. When the analysis of this range is limited to the first 30° flexion, the rotation is limited to 6.6°, 5.6° and 10.1°, respectively.

The normalized position of the pivot point was found in a postero-medial location (chair rising, stair climbing and step-up tasks shown in Figure 3, 4 and 5, respectively), although the results show also high variability among patients and motor tasks, particularly in the medio-lateral direction.

This can be appreciated also by looking at these positions when superimposed from all patients and motor tasks (Figure 6), and at the range of rotation of the contact line and the location of the pivot point for each patient and for each motor task for the full range of flexion (Table 2).

As for post-cam contact mechanism, the analysis of the engagement of the tibial post revealed that the contacts of its anterior and posterior parts with the femur cam occur more frequently at small and larger flexion angles, respectively. Particularly, the anterior contact (Figure 7a) started at maximum extension, i.e. mostly in hyper-extension, in all motor tasks and continued till about 10° flexion. At 0° flexion, anterior contact is experienced, according to the motor task, in 40% to 60% of the observed knees. As for the engagement at the posterior aspect of the post (Figure 7b), a much higher variability was found, both among patients and motor tasks. Particularly, contact can occur before 20° flexion in some cases, while at 30° in others; about 60-70% of patients revealed posterior post-cam engagement at 80° flexion.

DISCUSSION

In general, the present study was aimed at assessing, with a robust technique, joint motion in the replaced knee, but, particularly and originally, it was aimed at substantiating the post-cam engagement both in its anterior and posterior aspects. To this purpose, a recently published validated technique [33], which combines in-vivo 3D fluoroscopic kinematics and finite element analysis, was applied on joint motion data from a cohort of patients during three standard activities of daily living. The results of the present analyses provided enough evidence for the three aforementioned aims. In particular, aim 1), physiological patterns and ranges of motion were consistently observed at the replaced knees among patients; these were also found to be consistent with the preliminary results of the present cohort and technique [33], as well as with previous fluoroscopic studies [20,21,48]. The post-cam mechanism, aim 2), specifically at the anterior and posterior aspect of the post, occurred respectively during knee extension, particularly toward hyperextension, and from 80° flexion onward, though a high variability among patients was observed between 20° and 80° flexion. Interestingly, about 15% of patients did not show any post-cam engagement. This post-cam engagement varied considerably over the analyzed motor tasks, aim 3), apart from the effect on the antero-posterior translation of the tibio-femoral contact points, which was similar among the three different motor tasks.

A number of in-vivo studies have reported high variability in kinematic patterns at the replaced knee, as associated to different prostheses, even within the posterior-stabilized design. Paradoxical tibio-femoral motion has also been shown in the presence of post-cam [3,19,20,31,32,34,35]. However, there was a lack of knowledge on the influence of the post-cam mechanism on the amount of antero-posterior translation of the two contact points, on the medial and lateral tibial condyles. In the present study, the consistent posterior translation of the femur contact on the lateral tibial condyle is remarkably larger than the one on the medial tibial condyle, very similarly to what occurs in the natural knee [49]. The restoration of the physiological screw home mechanism is revealed here in the analyzed knees, independently from the motor task, by the posterior contact translations and large axial rotation combined to flexion. This likely results from the present design of the prosthesis that features a double shaped post-cam and a dishing geometry at the tibial condyles in the rest of the polyethylene insert, which should also provide intrinsic joint stability. A large internal rotation was observed throughout the knee range from hyperextension to the maximum flexion, apart from the range between 10° and 35°. This is very important, particularly considering that the restoration of the normal axial rotation is essential also to gain physiological flexion in weight bearing [50]. As for the post-cam mechanism and its engagements, the observed high variability over patients and over motor tasks may be accounted for to the subject-specific action of the agonist and antagonist muscles, necessary for knee balancing during highly demanding weight bearing activities. For example, an early post-cam engagement, together with a more posterior position of the lateral condyle contacts, occurred at the beginning of stair climbing, i.e. at the extension phase, at about 80° flexion associated with the initial monopodal lifting of the body (Fig.7b). The effect of the post-cam mechanism, combined with the magnitude and pattern of axial rotation in these replaced knees, was also a general medial location for the pivot contacts point. This effect was observed in all three motor tasks, though the pivot point position was slightly more lateral in the step-up than in the other two tasks (Fig. 3). This concurs with the literature, where the pivot point position was shown to depend upon the prosthesis design and the locomotors tasks [8,18,39,48]. However, an overall variability, in terms of knees motion patterns and pivot and contact point positions, has been observed also in normal, i.e. physiological, knees [49].

The present study is limited by the number of patients analyzed, but the overall consistency of the results support the value of the study. It is confirmed that the finite element analysis performed on the results of the 3D video-fluoroscopy analysis contributes to a smoother and coherent final joint motion, particularly important for sensitive kinematics analyses such as the calculation of pivot point locations.

In conclusion, the present study reports kinematics of the femoral and tibial components in replaced knees, not only in terms of standard joint motion along the three anatomical planes, but also in terms of articular surface contacts, both at the condyles and, for the first time, at the post-cam. Specifically, physiological tibio-femoral joint rotations and contacts at the condyles were found restored in the present knee replacement. Articular contact patterns experienced at the post-cam were found compatible with this original prosthesis design.

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FIGURE CAPTIONS

Figure 1: Average antero-posterior displacement of the lateral (left) and medial (right) contact points on corresponding tibial condyles plotted versus knee flexion. Standard deviation is also reported at each 10° flexion. The three motor tasks are shown separately, chair rising (A), stair climbing (B), and step-up (C).

Figure 2: Average tibio-femoral axial rotation plotted versus knee flexion for the three motor tasks. Negative and positive values correspond to external and internal rotation, respectively. Standard deviation is also reported at each 10° flexion.

Figure 3: Position of the pivot points in chair rising for each patient (blue dots) and on average over patients (red dot). These are plotted in % locations over the antero-posterior length of the tibial insert, -50% and 50% being the most posterior and most anterior location, respectively, and over the medio-lateral width of the tibial insert, -50% and 50% being the most lateral and most medial location, respectively.

Figure 4: Position of the pivot points in star climbing (same graphical representation as in Figure 3).

Figure 5: Position of the pivot points in step-up (same graphical representation as in Figure 3).

Figure 6: Position of the pivot points (same graphical representation as in Figure 3) in all the three motor tasks analyzed for each patient (blue dots) and on average among all tasks and patients (red dot).

Figure 7: Percentage of patients where the post-cam contact occurred at a certain knee flexion angle reported for the three motor tasks. Anterior (A) and posterior (B) parts of the post-cam are shown separately.

Table 1: Patients' demographic data.

Patient	Age (Years)	Body Mass Index	Gender (M=male; F= female)	Side (L=left; R=right)
1	*58*	*36*	*F*	*R*
2	*69*	*25*	*M*	*R*
3	*69*	*33*	*F*	*R*
4	*68*	*26*	*M*	*L*
5	*77*	*23*	*F*	*R*
6	*65*	*29*	*F*	*R*
7	*69*	*31*	*F*	*R*
8	*75*	*24*	*F*	*L*
9	*69*	*34*	*F*	*R*
10	*71*	*28*	*M*	*R*
11	*75*	*25*	*M*	*R*
12	*75*	*21*	*F*	*L*
13	*75*	*24*	*F*	*R*
14	*72*	*30*	*M*	*L*
15	*80*	*31*	*F*	*R*
Average	***71.1±5.4***	***28.0±4.4***	**---**	**---**

Table2: Amplitude of contact line rotation and location of the pivot point reported for each patient and for each motor task throughout knee flexion range. The latter is reported in % locations over the antero-posterior (AP) length of the tibial insert, -50% and 50% being the most posterior and most anterior location respectively, and over the medio-lateral (ML) width of the tibial insert, -50% and 50% being the most lateral and most medial location respectively.

Patient	Amplitude of Contact Line Rotation (°)			Pivot Point ML Location (%)			Pivot Point AP Location (%)		
	Chair Rising-Sitting	*Stair Climbing*	*Step Up-Down*	*Chair Rising-Sitting*	*Stair Climbing*	*Step Up-Down*	*Chair Rising-Sitting*	*Stair Climbing*	*Step Up-Down*
1	*13.4*	*11.6*	*9.1*	*79*	*89*	*6*	*-1*	*-11*	*-8*
2	*20.1*	*5.6*	*10.3*	*28*	*30*	*40*	*-6*	*-11*	*-11*
3	*16.7*	*19.1*	*22.7*	*38*	*40*	*56*	*-2*	*-2*	*-4*
4	*15.2*	*8.7*	*15.8*	*51*	*24*	*35*	*-15*	*-14*	*-16*
5	*18.0*	*2.4*	*10.9*	*51*	*164*	*36*	*-19*	*-1*	*-12*
6	*14.4*	*12.2*	*13.8*	*4*	*131*	*21*	*-5*	*-1*	*-6*
7	*17.1*	*2.6*	*11.5*	*14*	*25*	*34*	*-13*	*-4*	*-6*
8	*7.8*	*16.4*	*10.3*	*109*	*57*	*42*	*-4*	*-13*	*-24*
9	*6.9*	*19.5*	*11.4*	*5*	*10*	*16*	*-9*	*-13*	*-10*
10	*8.7*	*6.6*	*35.7*	*53*	*18*	*33*	*-28*	*-9*	*-27*
11	*18.6*	*14.0*	*12.8*	*14*	*8*	*7*	*-11*	*-13*	*-9*
12	*19.3*	*4.2*	*9.8*	*53*	*6*	*63*	*-18*	*-17*	*-21*
13	*13.4*	*14.6*	*4.6*	*84*	*19*	*44*	*-5*	*-7*	*-11*
14	*9.8*	*9.4*	*10.2*	*18*	*8*	*51*	*-14*	*-7*	*0*
15	*7.7*	*2.2*	*3.9*	*6*	*57*	*19*	*-14*	*-1*	*-12*
Average	***13.8±4.6***	***9.9±6.0***	***12.9±7.7***	***40.5±32.1***	***45.7±47.6***	***33.5±17.0***	***-10.9±7.4***	***-8.3±5.4***	***-11.8±7.4***

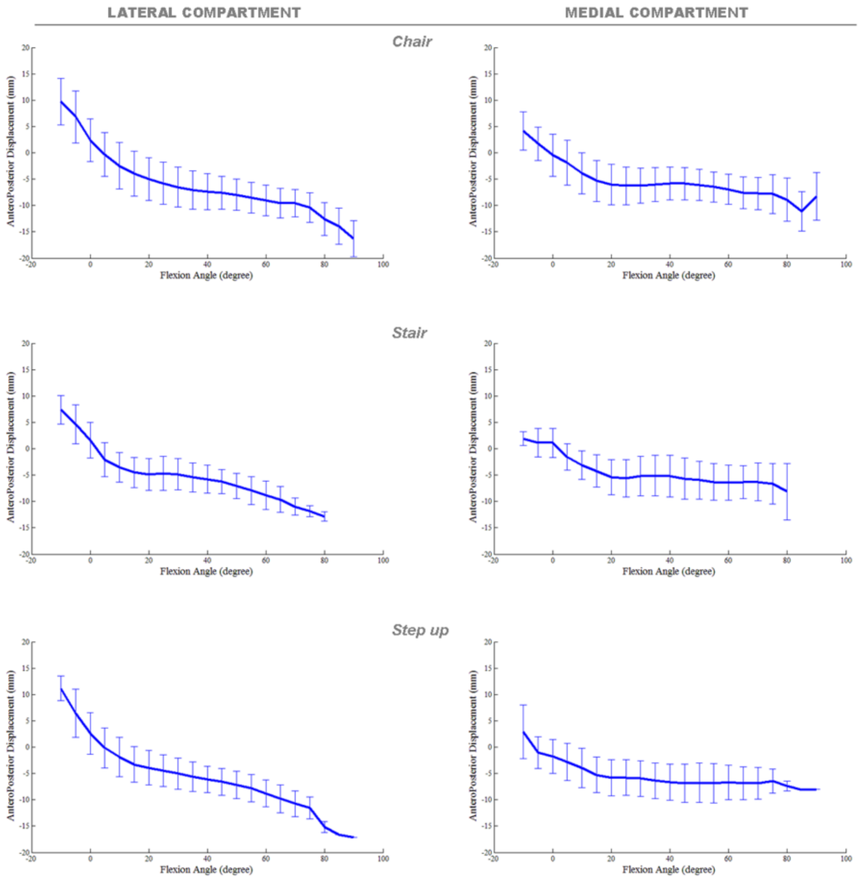
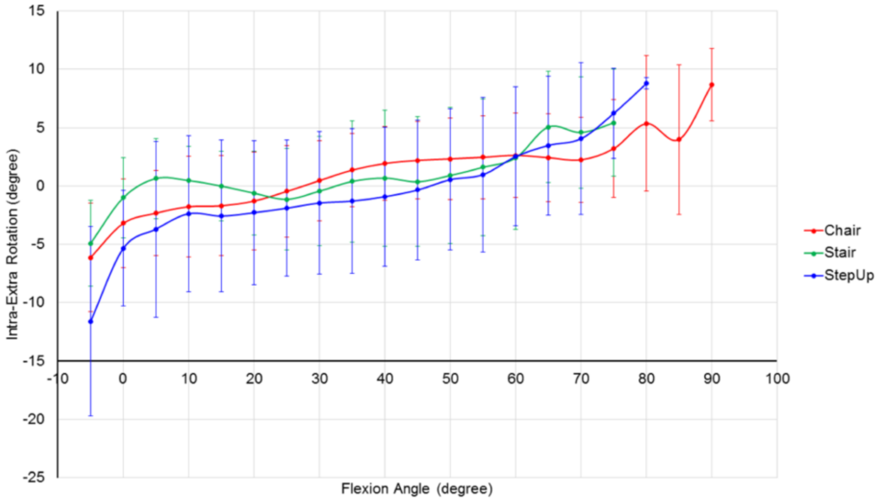

LATERAL COMPARTMENT
MEDIAL COMPARTMENT
Chair
Stair
Step up
AnteroPosterior Displacement (mm)
Flexion Angle (degree)

Figure 1



Intra-Extra Rotation (degree)
Flexion Angle (degree)
Chair
Stair
StepUp

Figure 2

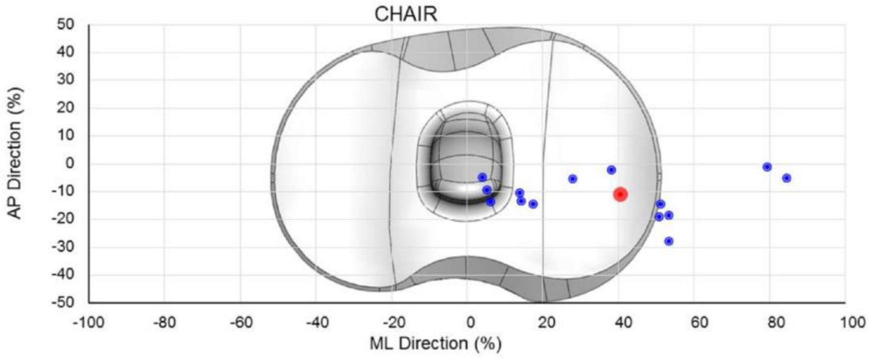

CHAIR
AP Direction (%)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-100
-80
-60
-40
-20
0
20
40
60
80
100
ML Direction (%)

Figure 3

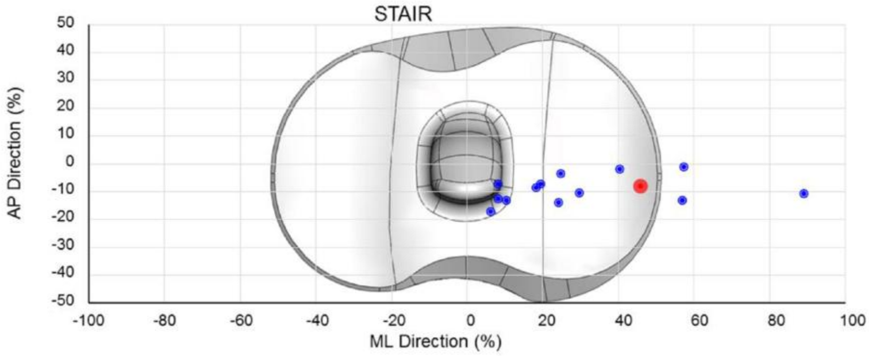

STAIR
AP Direction (%)
ML Direction (%)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-100
-80
-60
-40
-20
0
20
40
60
80
100

Figure 4

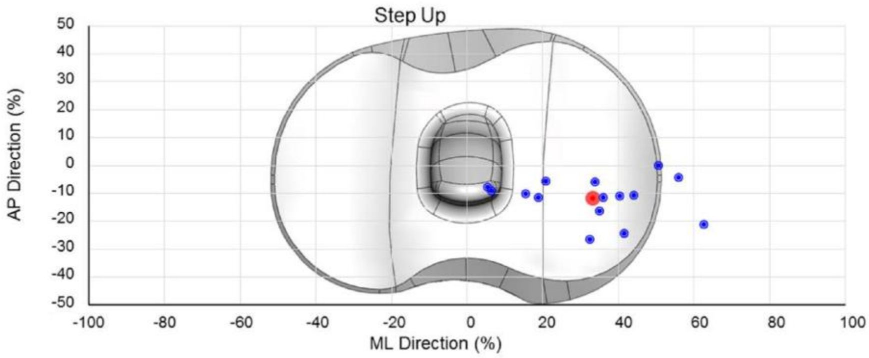

Step Up
50
40
30
20
10
0
-10
-20
-30
-40
-50
AP Direction (%)
-100
-80
-60
-40
-20
0
20
40
60
80
100
ML Direction (%)

Figure 5

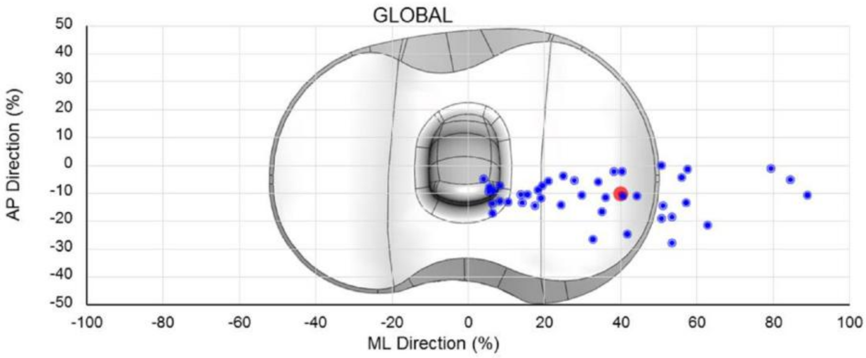

GLOBAL
AP Direction (%)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-100
-80
-60
-40
-20
0
20
40
60
80
100
ML Direction (%)

Figure 6

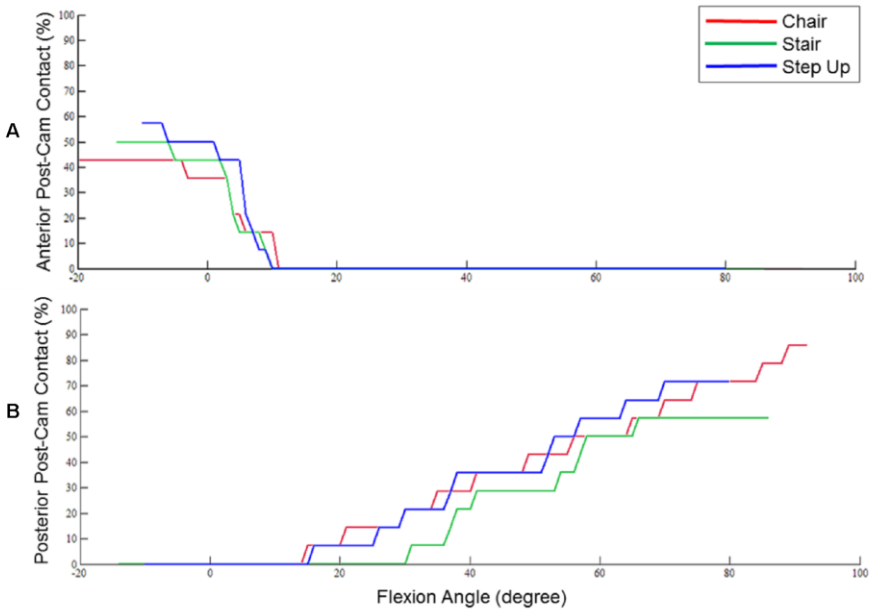

Chair
Stair
Step Up
A
Anterior Post-Cam Contact (%)
B
Posterior Post-Cam Contact (%)
Flexion Angle (degree)

Figure 7