In-Vivo Knee Kinematics in Rotationally Unconstrained Total Knee Arthroplasty

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ABSTRACT: Total knee replacement designs claim characteristic kinematic performance that is rarely assessed in patients. In the present study, in vivo kinematics of a new prosthesis design was measured during activities of daily living. This design is posterior stabilized for which spine–cam interaction coordinates free axial rotation throughout the flexion–extension arc by means of a single radius of curvature for the femoral condyles in the sagittal and frontal planes. Fifteen knees were implanted with this prosthesis, and 3D video-fluoroscopic analysis was performed at 6-month follow-up for three motor tasks. The average range of flexion was 70.1° (range: 60.1–80.2°) during stair-climbing, 74.7° (64.6–84.8°) during chair-rising, and 64.1° (52.9–74.3°) during step-up. The corresponding average rotation on the tibial base-plate of the lines between the medial and lateral contact points was 9.4° (4.0–22.4°), 11.4° (4.6–22.7°), and 11.3° (5.1–18.0°), respectively. The pivot point for these lines was found mostly in the central area of the base-plate. Nearly physiological range of axial rotation can be achieved at the replaced knee during activities of daily living. © 2011 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 29:1484–1490, 2011

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Total knee arthroplasty (TKA) continues to be an efficient surgical treatment, as evidenced by its excellent survivorship and long-term results.[1] Despite these data, patient satisfaction after TKA is still not more than 70–75%.[2,3] Patient functional abilities seem particularly related to restoration of normal motion at the replaced joint.[4–16] This motion can be altered considerably by the geometry of the prosthetic articular surfaces, posterior condylar offset, cruciate ligament retaining/sacrificing, soft tissue balancing, and final lower limb alignment achieved at surgery.

In vivo gait analysis studies, based on kinematics, kinetics, and electromyography of the lower limbs, showed that overall function cannot be fully restored in fixed bearing TKA.[17] Fluoroscopy-based analyses[4,5,18–24] revealed that the non-physiological kinematics patterns at the replaced joint in activities of daily living are accounted for by paradoxical anterior translation and reverse or insufficient rotation of the tibio-femoral contact-line during flexion, i.e., lateral pivoting. This rotation is usually calculated on the tibial base-plate, for the line joining the projection points of the two medial and lateral prosthetic femoral condyles at minimum distances from the base-plate.[25] Bi-directional rotation of this contact-line is usually interpreted as internal/external (or axial) rotation, and the bi-dimensional location of the single point at minimum distance from all these lines over the entire flexion arc as the 2D pivot point. Because of this association, for the analysis of physiological kinematic restoration, the rotation of the contact-line is supposed to be in the range of 15–20°,[26,27] and the pivot point of the contact-lines to be on the medial area of the base-plate.[28] In the normal knee, the femur rolls backwards and rotates externally (internal knee joint rotation) during passive flexion, particularly for high flexion angles.[29]

TKA designers are committed to obtaining more physiological tibio-femoral axial rotation by enhancing both the prosthesis design and the surgical technique. As to the former, due to the necessary sacrifice of one or two cruciate ligaments, tibio-femoral motion has been constrained using modified geometry of the femoral and tibial condyles, spine–cam mechanisms, and polyethylene dishing. More recently, the guided-motion TKA concept has been proposed[14–16]; a relevant in vivo fluoroscopy-based kinematics assessment during activities of daily living revealed that range of motion of the replaced knee can be similar to that of the normal knee.[30,31] A novel rotationally unconstrained and fixed bearing posterior stabilized TKA design (Fig. 1) claims to allow the femur to rotate freely about the tibia in the transverse plane without restricting tibio-femoral contact area, i.e., while maintaining contact stresses below the yield strength of polyethylene.[32] This feature is achieved by a single radius of curvature of the femoral condyles on the frontal plane, by the constrained anteroposterior (A/P) joint translation at the spine–cam interaction throughout the flexion arc, and by a spherical arc in the transverse plane of the insert articulating surface. Lastly, a single radius of curvature of the condyles in the sagittal plane is thought to provide a single fixed axis of flexion and a constant tensioning of the medial and lateral soft tissues for consistent collateral ligament isometry and joint stability throughout the range of motion.

The purpose of our study was to assess quantitatively some of these design claims, in particular the

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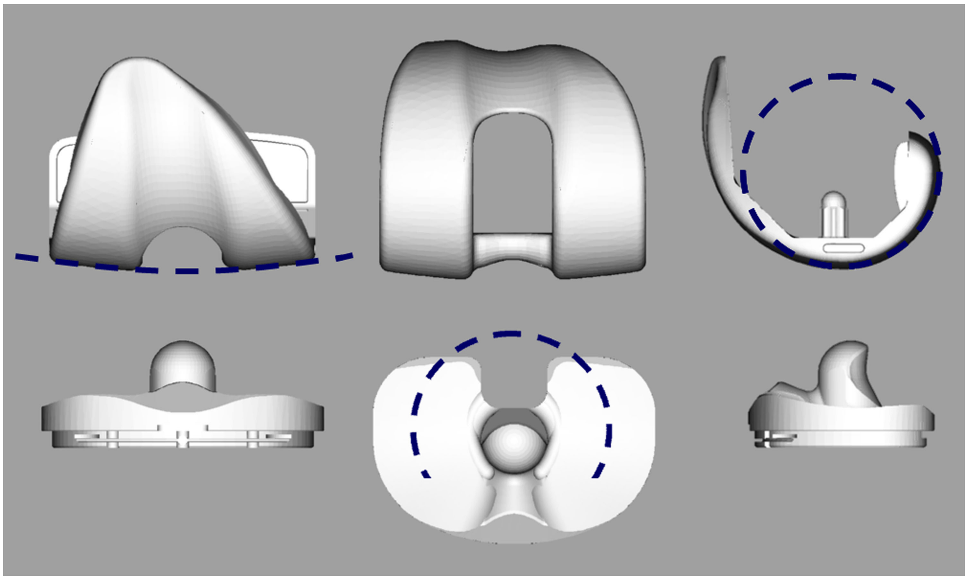

Figure 1. Projection drawings of the articulating components of the prosthesis design; the femur (above) and the polyethylene tibial insert (below) for a right TKA, in their frontal (left), transverse (central), and sagittal (right) views. Respectively, the single distal femoral condyles arc, the so-called spherical arc, and the single radius of curvature of the posterior femoral condyles in the sagittal plane are depicted with dashed circular lines.

wider rotational freedom, in patients implanted with this prosthesis. This assessment was performed by assessing replaced knee kinematics during activities of daily living by means of video-fluoroscopy, particularly analyzing rotations and relevant pivot of the contact-lines during motion. We hypothesized that in a knee replaced with this design, a physiological range of axial rotation can be achieved during activities of daily living.

MATERIALS AND METHODS

Fifteen patients (Table 1) were operated on using a bi-cruciate substituting, fixed-bearing, rotationally unconstrained, and posteriorly stabilized TKA (Scorpio Non-Restrictive Geometry Knee, Stryker®-Orthopedics, Mahwah, NJ). The same patients were analyzed post-operatively at 6 months follow-up by video-fluoroscopic analysis.[22,27] Clinical assessment was performed using the International Knee Society (IKS) score[33] pre-operatively and at follow-up. Primary knee osteoarthritis was diagnosed in all patients, with a mean varus-valgus deformity of 8°.

The patients were all those operated with this prosthesis in the period from January to December 2007, who provided written informed consent as approved by the local Ethics Committee. Neither infection nor severe knee instability were found in any patient. For the best component alignment,[34] every implantation was performed using a surgical knee navigation system (Stryker®-Leibinger, Freiburg im Breisgau, Germany). The anterior longitudinal exposure and medial parapatellar arthrotomy were used. For the alignment of the femoral component, the trans-epicondylar axis was targeted in the transverse plane, the mechanical axis in the frontal plane. The patella was always resurfaced and all components were cemented.

All patients were analyzed by video-fluoroscopy during stair-climbing, chair-rising, and step-up. For the former, a staircase of three 21-cm high steps was used. For the latter, only the first of these steps was climbed. The chair height was set for each patient for him/her to start with the knee at about 80° flexion. The data collection and analysis procedures were discussed previously[4,22,35] and performed by means of a standard fluoroscope (digital remote-controlled diagnostic Alpha90SX16, CAT Medical System, Rome, IT). 3D positions and orientations of the metal prosthesis components were obtained from each fluoroscopic image by an iterative procedure using a CAD-model-based shape matching technique.[35] Previous validation work showed that these measurements have an accuracy of <0.5 mm and $<1°$ in the sagittal plane.[35]

Joint flexion at the replaced knee was calculated using a standard convention.[36] Condylar contacts were assumed on the medial and lateral compartments as the two pairs of points at minimum distance between the femoral prosthetic condyles and the tibial base-plate.[4] The positions of these contact points (CPs) were then expressed in the tibial base-plate reference frame, in terms of percentage locations over its A/P length, thus irrespective of the different sizes: 0% and 100% corresponded to the most posterior and most anterior location, respectively. Patterns of A/P motion of the CPs were therefore obtained independently for the medial and lateral condyles. Also, the difference between A/P locations of the CPs at maximum extension and flexion was considered the posterior femoral roll-back (PFR). The contact-line rotation was defined as the rotation of the line connecting the medial and lateral CPs with respect to the medio-lateral axis on the tibial base-plate (defined as the axial rotation of the joint). For each kinematic variable over the samples analyzed, data were resampled at 1° intervals, and reported over predefined knee flexion angles, either at 1° or at 10° increments, starting from 0°.

RESULTS

Clinical findings at the time of fluoroscopy assessment (Table 1) revealed passive knee range of flexion of

Table 1. Demographic Data and General Clinical Information of the Patients

Parameter	Mean ± SD	Max	Min
Number of patients	15	—	—
Age (years)	68.5 ± 10.0	79	58
Gender: male/female	5/12	—	—
Weight (Kg)	83 ± 12.5	108	60
Height (cm)	163.4 ± 7.3	175	152
BMI	31.1 ± 5	38	25
Pre-operative X-ray mechanical axis (varus)	8.1° ± 12.5°	16°	9°
Pre-operative IKS score, knee	58.6.0 ± 8.5	69	50
Pre-operative IKS score, function	55 ± 7.4	70	50
Pre-operative range of motion (degree)	104.2° ± 8.9°	120	90
Post-operative IKS score, knee	89.9 ± 5.6	100	67
Post-operative IKS score, function	81.3 ± 9.5	100	50
Post-operative range of motion (degree)	110.5° ± 11.3°	140	90

The IKS score is reported for both the knee and function sections, pre-operatively and post-operatively.

110.5° ± 11.3° (range: 90–140°), IKS knee score of 89.9 ± 5.6 (67–100), and IKS function score of 81.3 ± 9.5 (50–100), demonstrating satisfactory outcomes.

The video-fluoroscopic analysis (Table 2) revealed large knee joint flexion for most patients, the largest in chair-rising as expected. The corresponding axial rotation ranges were also large, about 10° on average, with peaks as high as 22°. This rotation, when seen versus flexion (Fig. 2), revealed that about 5° internal rotation is progressively achieved along the first 70° of flexion for all three tasks; for the following 10° flexion, an additional 5° rotation is experienced only in

Table 2. Results From the Fluoroscopy-Based Analysis

	Stair climbing	Chair rising	Step-up
Flexion	70.1° [60.1° ÷ 80.2°]	74.7° [64.6° ÷ 84.8°]	64.1° [52.9° ÷ 74.3°]
Contacts, translation			
A/P medial CP (mm)	3.1 [4.2 ÷ 7.3] ± 1.7	5.5 [4.9 ÷ 10.4] ± 1.8	3.6 [4.7 ÷ 8.3] ± 1.8
A/P lateral CP (mm)	4.8 [4.3 ÷ 9.1] ± 1.8	7.5 [5.7 ÷ 13.2] ± 1.5	5.2 [5.1 ÷ 10.3] ± 1.8
A/P medial CP (% Tib size, posterior = 0%)	37.3 [32.0 ÷ 40.5] ± 4.0	35.6 [25.5 ÷ 39.0] ± 4.1	35.5 [30.8 ÷ 38.8] ± 4.0
A/P lateral CP (% Tib size, posterior = 0%)	36.5 [27.7 ÷ 40.5] ± 4.1	33.1 [18.7 ÷ 36.9] ± 3.4	35.4 [26.1 ÷ 37.9] ± 4.1
A/P medial CP (% Tib size, posterior = 0%)			
At max extension (°)	34.0 ± 2.1	35.5 ± 6.7	34.4 ± 2.2
At max flexion (°)	34.0 ± 1.9	26.3 ± 1.2	33.8 ± 4.5
A/P lateral CP (% Tib size, posterior = 0%)			
At max extension (°)	36.1 ± 4.6	35.7 ± 3.6	34.6 ± 3.0
At max flexion (°)	32.0 ± 1.8	19.8 ± 1.2	33.6 ± 5.5
Medial PFR (mm)	0.5± 1.0	3.5 ± 1.7	−2.1 ± 1.5
Lateral PFR (mm)	1.4 ± 1.8	6.7 ± 1.3	0.6 ± 1.2
Contacts, rotation			
Contact-line rotation (°; + internal)	9.4 [4.0 ÷ 22.4] ± 4.6	11.4 [4.6 ÷ 22.7] ± 4.5	11.3 [5.1 ÷ 18.0] ± 4.0
Contact-line internal rotation (°, + internal)			
At max extension (°)	1.5 ± 3.9	1.5 ± 3.2	−1.3 ± 1.0
At max flexion (°)	1.0 ± 4.2	6.5 ± 1.4	1.0 ± 3.2

A/P translation of the medial and lateral tibio-femoral CP on tibial base-plate, both in millimeters and in percentage of the A/P size of the tibial plate (% Tib size; 0% and 100% being respectively the most posterior and the most anterior part), and contact-line rotations are reported for the three motor tasks. The over all patients mean values ±standard deviation, together with the entire range, in square brackets, i.e., the minimum and maximum values, are reported. The PFR on the medial and lateral tibial compartments is also reported. For the translations in percentage and the contact-line rotations, the values at 0° and at reached max flexion in all motor tasks are reported.

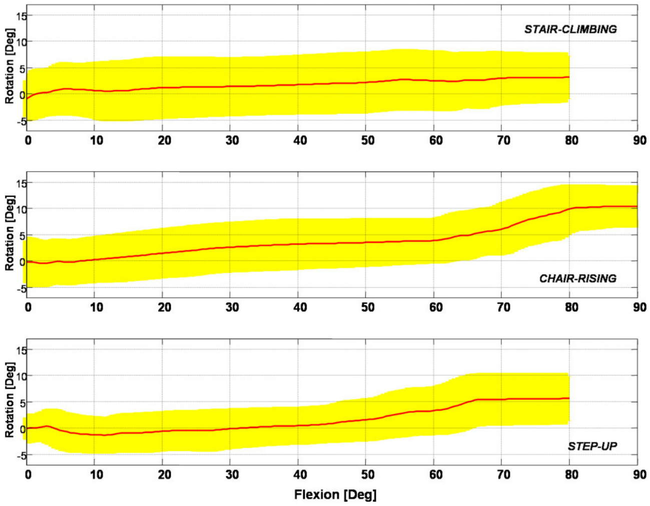

Figure 2. Means and standard deviations of the knee axial rotation versus flexion for the three motor tasks; positive values are for internal rotations.

chair-rising. No evidence of condylar lift-off was observed in any of the motor tasks in any of the patients.

These large rotations were combined with A/P translations of the CPs (Table 2), with peaks in chair-rising of 10 mm on the medial and 13 mm on the lateral compartments. The CPs moved consistently about one third of the A/P length, over motor tasks, and patients. However, CP displacements from maximum extension to maximum flexion, i.e., PFRs, were small for the three tasks (Table 2), implying that the natural roll-back and screw-home mechanisms were limited in these knees over the first 80–90° flexion. In all motor tasks, medial and lateral CP displacements were generally located posteriorly throughout the flexion arc (between about 30% and 40% of the A/P tibial length; Fig. 3), posterior translation of both occurred at flexion angles >60°, and a small anterior translation of the medial CP occurred in the initial 40° flexion.

Consistent with these findings, the pivot point of the contact-lines (Fig. 4) was found mostly in the central area of the base-plate; in percentage of the medio-lateral width, the location was 1.3 ± 22.8 lateral, 0.7 ± 33.8 lateral, and 5.0 ± 17.4 medial in stair-climbing, chair-rising, and step-up, respectively. This measure exhibited large inter-patient variability: a medial, central, and lateral location was found respectively in 33%, 40%, and 27% of the knees in stair-climbing, 40%, 13%, and 47% in chair-rising, and 27%, 73%, and 0% in step-up.

DISCUSSION

In the human knee joint, kinematics is no longer physiological after rupture or removal of one or both cruciate ligaments. In TKA design, because of the difficulty of preserving both these ligaments, the functional approach has been exploited, designing the articulating surfaces to cope with removal of the anterior and, in many cases, also the posterior cruciate ligament.[37] Many such designs have been proposed and implanted in the last two decades, but little has been reported about their kinematics performance in vivo. Our study was aimed at contributing to this knowledge. To this end, three activities of daily living were analyzed; though these are limited by experiencing knee flexions >90°, these represent frequent and demanding exercises for TKA patients. For these activities, the physiological pattern of axial rotation is not established in the literature; therefore, conclusions can be taken only about its range.

The introduction of the spine–cam mechanism was meant to restore the rolling-back and screw-home mechanisms throughout a comfortable flexion arc, together with the necessity of limiting excessive A/P relative translations between the tibial and femoral components.[38] The position and shape of the spine and cam have been investigated thoroughly, together with the associated dishing of the insert, to mimic as much as possible natural tibio-femoral mobility and laxity.[26,39] The design features for this mechanism include the flexion angle at which the relevant engagement starts to occur, in combination with the posterior slope of the tibial base-plate and/or of the polyethylene insert.[22] Despite these thoughtful design concepts, non-physiological kinematics patterns have been reported for these TKA designs even in vitro,[40] particularly limited femur rollback and limited range of axial rotation, which are known to affect critically the maximum flexion angle. In fact, joint flexion must be coupled to A/P sliding of the components and axial rotation over flexion,[28,29] i.e., a preferred combined motion pattern exists as guided by the ligaments and the articular surfaces.[26] It is difficult to fully restore the combination of flexion, A/P motion, and axial rotation in TKA.

The design analyzed in our study claims an improved function of the spine–cam to increase axial rotation. Optimization of the extensor mechanism was sought by the single radius of curvature of the femoral condyles in the sagittal plane and by the A/P position of the spine, which was meant to correspond to the position of the natural flexion axis. A correct tensioning of the collateral ligaments was thought to be accomplished by this single radius of curvature in the sagittal plane of the femoral component. Finally, a physiological axial rotation was sought by the single radius of curvature of the femoral condyles in the frontal plane and by a corresponding dishing of the polyethylene insert. Our results suggest that a large range of axial rotation, here represented as the rotation of the contact-line (Table 2), in fact can be attained during activities of daily living at knees replaced with the design analyzed in the present study. This large range likely accounted for the effective and unconstrained articulation between the femur condyles and the polyethylene insert and for the A/P constraint of the spine–cam mechanism. In

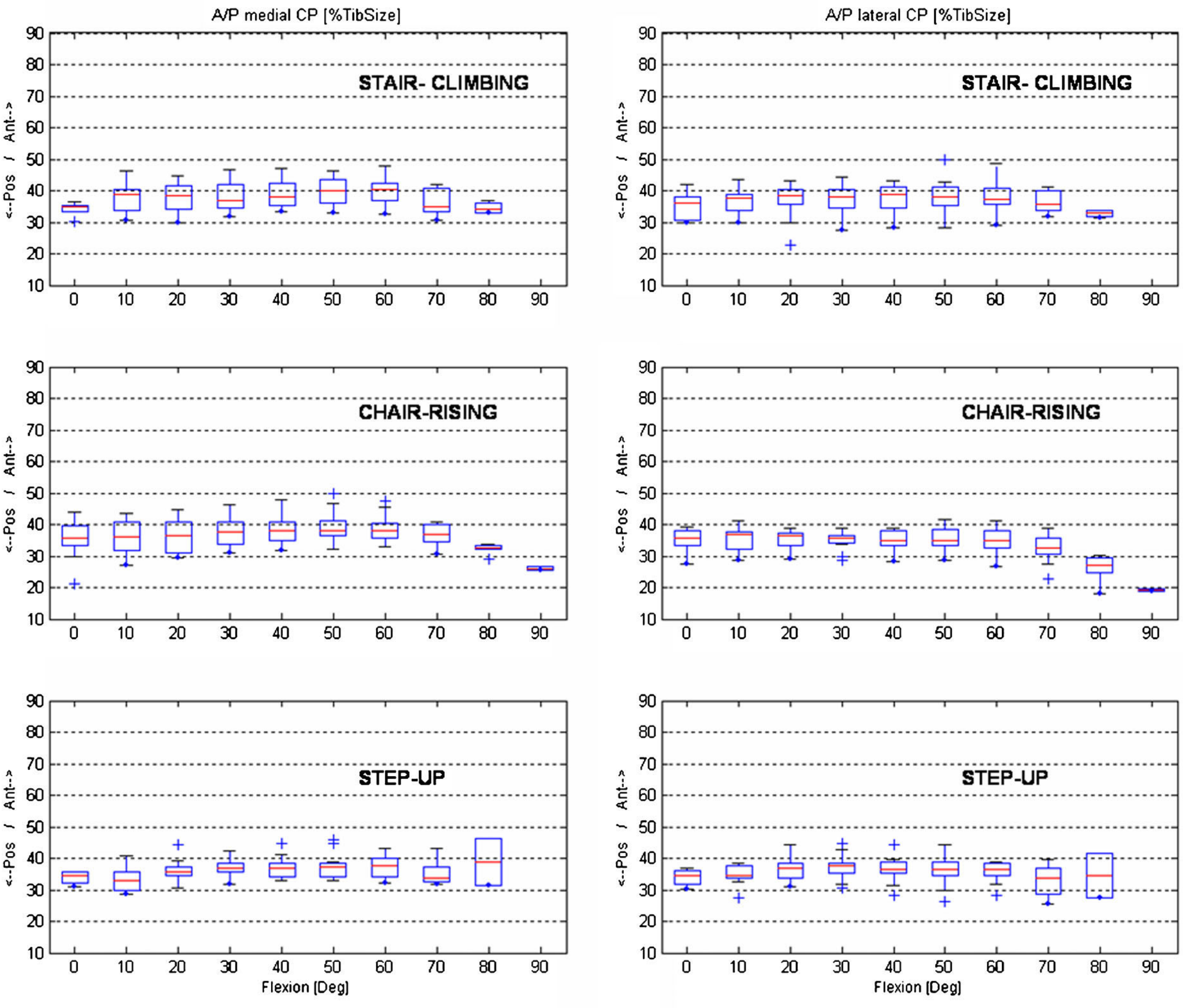

Figure 3. A/P translation of the medial (left) and lateral (right) CP for the three motor tasks, reported as percentage of the A/P length of the tibial base-plate for each 10° knee flexion step. In each plot, the boxes have lines at the lower, median, and upper quartile values over the patients analyzed; the whisker lines extending from each end of the box show the extent of the rest of the data; outliers are reported beyond the ends of the whiskers.

fact, though limited to about 90° flexion, our results show that the locations of the tibio-femoral CPs in full extension and full flexion are close, in both compartments, at about one-third of the tibial A/P length (Table 2). This posterior position together with the small translations implies a fixed axis of joint rotation and might result in constant tension of the collaterals ligaments over the flexion arc. Therefore the observed large range of axial rotation was not coupled to equivalently large roll-back, most likely because of the small flexion arc experienced during these activities of daily living. The pivot point was central, but the relatively high variability among patients suggests that this position is determined, within the free axial rotation, by the patient-specific balance between internal and external forces. Physiological roll-back and medial pivoting can occur when the exercise under analysis requires knee angles >90°.[32]

The axial rotation was generally found to be internal, about 9, 11, and 11° in stair-climbing, chair-rising, and step-up, respectively. These data are similar to those reported recently with the same TKA design as used in our study, but during deep knee bending with a flexion range of about 0–90°.[32] For the same flexion range, a much smaller range of axial rotation was reported,[40] 5.7° on average, likely accounted for by the bi-condylar design analyzed.

In addition to axial rotation, we also report the pivot point location on the base-plate about which this rotation occurs; in the present design, axial rotation is obtained with a central pivoting in all three motor tasks. In another posteriorly stabilized bi-cruciate substituting TKA, analyzed with the same video-fluoroscopy technique,[30] an even larger range of axial rotation and more physiological roll-back were found, though less consistently over the patients. This design, however, requires careful implantation so that retained soft tissues are compatible with the highly constraining articulating surfaces. In knees where this compatibility is not fully achieved over tensioning for

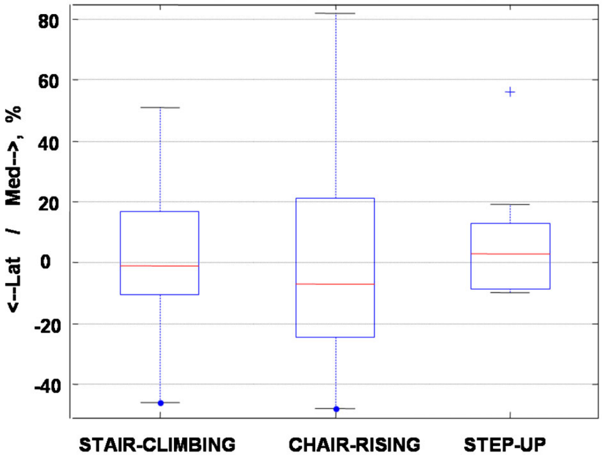

Figure 4. Values of the medio-lateral position of the pivot point of the contact-lines, in percentage of the medio-lateral width of the tibial component for the three motor tasks analyzed. In each plot, the boxes have lines at the lower, median, and upper quartile values over the patients analyzed; the whisker lines extending from each end of the box show the extent of the rest of the data; outliers are reported beyond the ends of the whiskers.

the tissues, overstress of the polyethylene and pain can be experienced.

The present video-fluoroscopic analysis enabled measurements of the 3D kinematics of the replaced knee joint in vivo. We showed that in the present bi-cruciate substituting fixed-bearing TKA design considerable range of axial rotation is exhibited during activities of daily living. However, this rotation was not coupled to other physiological kinematics patterns, such as screw-home and roll-back mechanisms, important for natural patellar tracking and maximal knee flexion in TKA.

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