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Knee implant designs' kinematic performance in various everyday activities

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Abstract
This randomized controlled trial's objective was to assess and contrast the three total knee arthroplasty (TKA) implant designs' six degrees of freedom (6 DOF) knee joint mobility throughout a variety of daily activities. Seventy-five TKA patients were selected to this trial and randomly allocated a posterior-stabilized (PS), cruciate-retaining (CR), or medial- stabilized (MS) implant. Patients engaged in level walking, step-up, step-down, sit-to-stand, and stand-to-sit exercises six months following surgery. The 6 DOF knee kinematics and the center of rotation of the knee in the transverse plane for each activity were measured using mobile biplane X-ray imaging. Mean 6 DOF knee kinematics for PS and CR were consistently similar, but MS had higher levels of external rotation and abduction and lower levels of lateral shift across all activities. Peak-to-peak anterior drawer for MS was also significantly lower during walking, step-up, and step-down ($p < 0.017$). The center of rotation of the knee in the transverse plane was located on the medial side for MS, whereas PS and CR rotated about the lateral compartment or close to the tibial origin. Based on reduced paradoxical anterior translation at low flexion degrees and a transverse center of rotation that was placed in the medial compartment, MS's kinematic function was more like that of a healthy knee than PS and CR. Throughout all daily activities, 6DOF knee joint motion for PS and CR was generally comparable, however that assessed for MS was noticeably different. The MS design has a highly conforming medial articulation, as seen by the kinematic patterns seen in MS.

Keywords: cruciate retaining, medial stabilized, posterior stabilized, total knee arthroplasty, X-ray fluoroscopy

1. Introduction

The surgical treatment known as total knee arthroplasty (TKA) is quite common and effective for treating individuals with advanced tricompartmental knee osteoarthritis [1]. Each year, over 600,000 TKA procedures are carried out in the US2, which significantly reduces joint discomfort and increases mobility [3]. The kind of prosthesis has been found to have a significant impact on patient outcomes, despite the fact that a variety of variables might affect patient satisfaction after TKA surgery [4-8].

Two types of fixed-bearing prostheses are the posterior- stabilized (PS) and cruciate-retaining (CR) designs, which together comprise most implants used in TKA surgery [9]. Although both designs share similar low-conforming articulating surfaces, the PS implant substitutes posterior-cruciate-ligament (PCL) function with a cam-and-post mechanism to guide anterior–posterior (AP) translation during knee flexion. Although the superiority of PS or CR has been the subject of considerable debate, significant differences in clinical outcome between the two designs have yet to be identified [4, 10, 11]. In comparison with PS and CR, the medial-stabilized (MS) implant is a recent innovation designed to closely mimic the kinematic patterns of the healthy knee [12-14]. MS implant motion is guided by a highly congruent medial compartment featuring a spherical femoral condyle and concave tibial plateau, which behaves similarly to a ball- and-socket joint. A recent study demonstrated superiority of MS over PS across multiple clinical outcomes at 1 and 2 years after surgery [8]. A direct comparison between MS, PS, and CR also found significant 6-month postoperative improvements for MS over PS and CR in Knee Society Score (KSS) 2011 Satisfaction, as well as clinically meaningful 12-month improvements over CR in Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) Pain, Function, and Global subscales [4].

We recently analysed six degrees of freedom (6 DOF) knee kinematics for one cycle of walking in patients implanted with each prosthesis to examine the biomechanical variations between PS, CR, and MS designs [15]. We discovered that the 6DOF kinematics of PS and CR were comparable, however MS showed clear variations [15]. By analysing five activities of everyday living—level walking, step-up, step-down, sitting to standing, and standing to sitting—the current study broadens these findings. Our particular goal was to assess the 6 DOF kinematics of PS, CR, and MS prostheses across these five tasks, compare them to the healthy knee, and make comparisons. Although *in vivo* kinematics for PS, CR and MS have been reported previously [10, 13, 15-25] no study to our knowledge has measured and compared full 6-DOF motion for these three TKA designs across a range of daily activities. Given the kinematic differences observed in walking [15], as well as the geometric disparities of the MS prosthesis, significant differences in 6-DOF knee kinematics were expected across all activities in patients implanted with the MS prosthesis compared with PS and CR. Based on our previous findings for level walking [15], we also predicted that the center of rotation of the knee in the transverse plane would lie on the medial side for MS and on the lateral side for PS and CR across all other activities of daily living.

2. Methods

2.1 Design

2.1.1 Participants

Between March 2015 and October 2020, 75 patients who were on the primary TKA waiting list and had been clinically and radiographically diagnosed with knee osteoarthritis were enrolled in the trial (Table 1). The GMK primary posterior stabilised, GMK primary cruciate retained, or GMK spherical TKA implants were randomly allocated to each subject after receiving their informed permission, and they were all procured from the same manufacturer (Medacta International) (Figure 1). All TKA implants were surgically inserted using the recommended method by the manufacturer. Using a measured resection technique, all surgeries aimed to align the femoral and tibial mechanical axes, with the femoral mechanical axis being 6° away from the femoral anatomical axis in the coronal plane. The distal femoral resection was made with a 6° valgus cut angle, guided by an intramedullary rod passed into the femoral intramedullary canal. The proximal tibial resection was made with a 0°–3° tibial slope (3° for CR and 0°–3° for PS and MS), guided by an extramedullary rod aligned with the tibial mechanical axis in the coronal plane. The extension gap between the resected surfaces was checked using a femoral spacer, and referencing jigs were used to assess femoral and tibial compartment size. All operations also involved patella resurfacing. Patients were blinded to the type of implant received and underwent kinematic assessment 6.2±1.1 months after surgery. Inclusion and exclusion criteria, participant recruitment, and randomization have been described previously. Dr. Patnam Mahender Reddy Institute of Medical Sciences, Chevella, RR Dist, Telangana.

Fig 1: The GMK primary posterior stabilised, GMK primary cruciate retained, or GMK spherical TKA implants were randomly allocated to each subject after receiving their informed permission, and they were all procured from the same manufacturer (Medacta International)

Table 1: Data of patients who were on the primary TKA waiting list and had been clinically and radiographically diagnosed with knee osteoarthritis were enrolled in the trial

				Age	Surgery to testing	BMI	Height	Weight	Patients in each activity				
Group	**Patients**	**Males**	**Females**	**years**	**months**	**kg/m^2**	**cm**	**kg**	**Walk**	**StepD**	**StepU**	**SitD**	**StandU**
PS	23	14	9	66.9±7.4	6.2±1.1	31.2±4.4	170.3±8.8	90.0±11.6	23	23	22	23	23
CR	26	16	10	70.9±7.4	5.9±1.2	30.5±5.3	169.5±12.5	87.0±14.4	25	24	22	26	26
MS	26	12	14	67.3±6.5	6.3±0.9	33.4±3.9	165.8±10.0	92.0±16.0	26	24	20	26	26
All	75	42	33	68.4±7.2	6.2±1.1	31.7±4.7	168.5±10.7	89.7±14.2	74	71	64	75	75

2.2 Experimental protocol

Each participant's data was gathered in a single session at the Dr. Patnam Mahender Reddy Institute of Medical Sciences, Chevella, RR Dist, Telangana Laboratory. Throughout the experiment, the individual wore a lead vest, shorts, and sandals. In previously mined areas, 45 retroreflective skin markers were affixed to the participant's upper and lower limbs. Level walking, step-up, step-down, sit-to-stand, and stand-to-sit actions were all captured concurrently in three dimensions (3D), together with ground reaction force and biplane X-ray fluoroscopy data (Figure 2). Prior to collecting data, the individual rehearsed each action.

2.3 Data acquisition and processing

A nine-camera video motion capture system (VICON) sampling at 120 Hz was used to record 3D full-body motion. Four transportable strain gauged force plates (AMTI Accugait) sampling at 1080 Hz were used to detect ground response forces. A Mobile Biplane X-ray (MoBiX) imaging device was used to take biplane X-ray pictures of the knee (1024 1024 pixels, 200 frames/s, and 1/200 s exposure time), and the implant manufacturer's 3D geometric models were used to posture estimate the position of the femoral and tibial TKA components. Information on posture estimation and picture processing has already been released. At 201 evenly spaced time intervals between the beginning and the end of the experiment, the [15, 27] 6 DOF knee kinematics, motion of the femoral condylar center's, and the center of rotation of the knee in the transverse plane were recorded.

6-DOF knee kinematics were described using an anatomical joint coordinate system previously reported by Gray *et al*.15 Motion of the femoral condylar centers and the center of rotation of the knee in the transverse plane were described in the tibial reference frame.15 Walking data were extracted for one complete gait cycle, from heel strike to heel strike of the leg with the TKA implant. Step-up and step-down activities began at heel strike of the leg with the TKA implant and ended at contralateral heel strike. Sit-to-stand and stand-to-sit activities spanned between full knee extension and ~80° of knee flexion.

Trials were omitted from analysis if the TKA prosthesis was not captured by the MoBiX imaging system over the entire activity or if the participant could not perform the activity. Mean, maximum, minimum, and peak-to-peak (difference between maximum and minimum) values for each trial were calculated for all participants and all activities. These outcome variables were compared between the three TKA groups using Student's t tests with a significance threshold set at $p < 0.017$, obtained by applying a Bonferroni correction for three pairwise comparisons per dependent variable with an initial significance threshold of $p < 0.05$

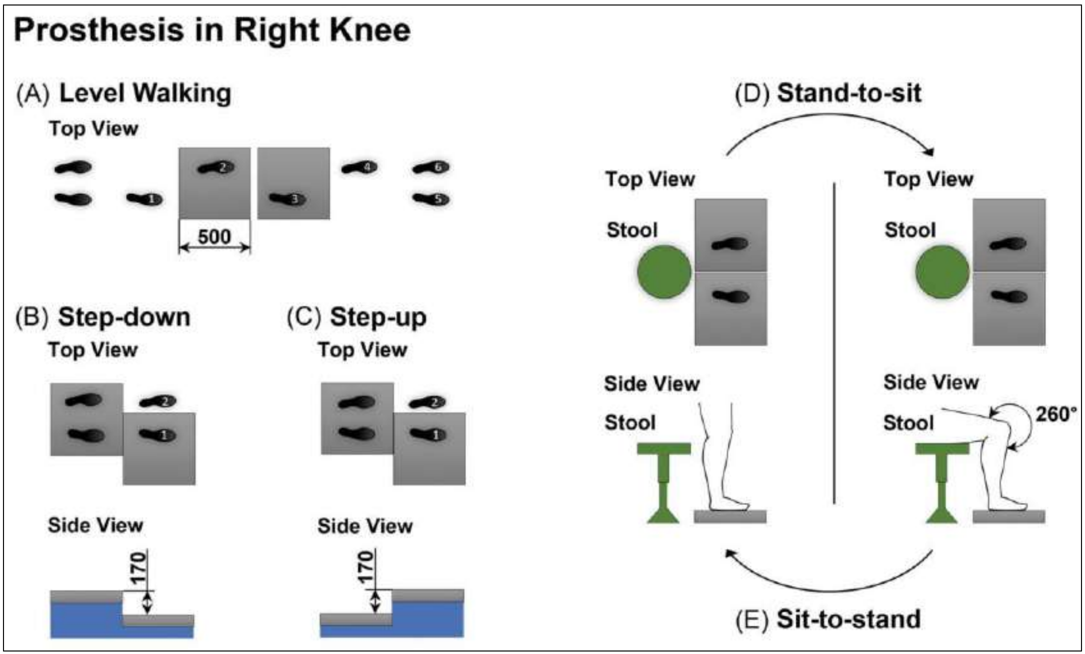


Fig 2: Level walking, step-up, step-down, sit-to-stand, and stand-to-sit actions were all captured concurrently in three dimensions (3D), together with ground reaction force and biplane X-ray fluoroscopy data

3. Results

3.1 6-DOF knee kinematics

Just one significant difference in outcome variables was found across all activities in the knee kinematics of PS and CR (Supporting Information: Table S1, p 0.017). With 36 significant outcome variable variations between PS and MS and 26 significant differences between CR and MS, on the other hand, the knee kinematics for MS were noticeably different from both PS and CR (Supporting Information: Table S1, p 0.017). All TKA prostheses could bend their knees to a maximum of 77°, but there were no discernible differences between the three TKA groups during any of the activities in terms of mean, maximum, minimum, or peak-to-peak knee flexion ($p > 0.017$). MS was 1.3°-3.4° more externally rotated than PS and 1.8°-3.5° more externally rotated than CR when comparing mean external rotation across all activities (Figure 3). In all activities except walking, all three TKA designs rotated internally as the knee flexed and demonstrated external "screw home" rotation with extension (Figure 4). Mean abduction was 0.2°–0.3° greater for MS than PS, with statistical significance observed in all activities except walking ($p < 0.017$, Figure 3). Similarly, mean abduction was 0.2°–0.4° greater for MS than CR, with statistical significance observed in all activities, except step-down ($p < 0.017$). Across all activities, peak-to-peak anterior drawer was 1.2–5.5 mm lower for MS than PS and 0.3–3.3 mm lower for MS than CR (Supporting Information: Table S-1 and Figure 3). At maximum flexion, anterior drawer was greater for MS than PS and CR during all activities, except step-down (Figure 4). As anterior drawer referred to the displacement of the tibial origin with respect to the femoral origin in the anterior direction of the knee, a bigger rise in anterior drawer as the knee flexed indicated more femoral rollback for MS compared to the other two designs. 15 Moreover, during the stance phase of walking, step-down, and stand-to-sit, we saw paradoxical anterior translation (i.e., decreased anterior drawer with knee flexion) for PS and CR up to 30° of knee flexion, but this behaviour was diminished or nonexistent for MS (Figure 4). Statistical significance was found between MS and PS during walking, sit-to-stand, and stand-to-sit (Figure). The mean lateral shift was 0.2-0.5 mm lower for MS than PS and 0.1-0.3 mm lower for MS than CR across all activities.

3.2 Trajectories of the femoral condylar centers

Peak-to-peak displacements of the centers of the femoral condyles were typically greater in the AP direction than in the medial-lateral (ML) direction, except for the medial condyle for MS.

For walking, peak-to-peak displacements of the medial and lateral condylar centers ranged from 7.4 mm to 11.0 mm in the AP direction and below 2.4 mm in the ML direction. Similarly, across all other activities peak-to-peak displacements ranged from 2.6 mm to 8.8 mm in the AP direction and were less than 1.6 mm in the ML direction. For MS, peak-to-peak AP displacement of the lateral condylar center was between 1.2 mm and 6.2 mm greater than that of the medial condyle across the five activities (Figures 5 and 6), demonstrating a pivoting motion about the medial compartment. For both PS and CR, peak-to-peak AP displacement of the medial condylar center was similar to or greater than that of the lateral condylar center in all activities. Peak-to-peak AP displacement of the medial condyle was 1.9–7.9 mm lower for MS compared to PS, and 2.2–5.9 mm lower for MS compared to CR, which was statistically significant across all activities (Table S-2, p < 0.017; see also Figure 5).

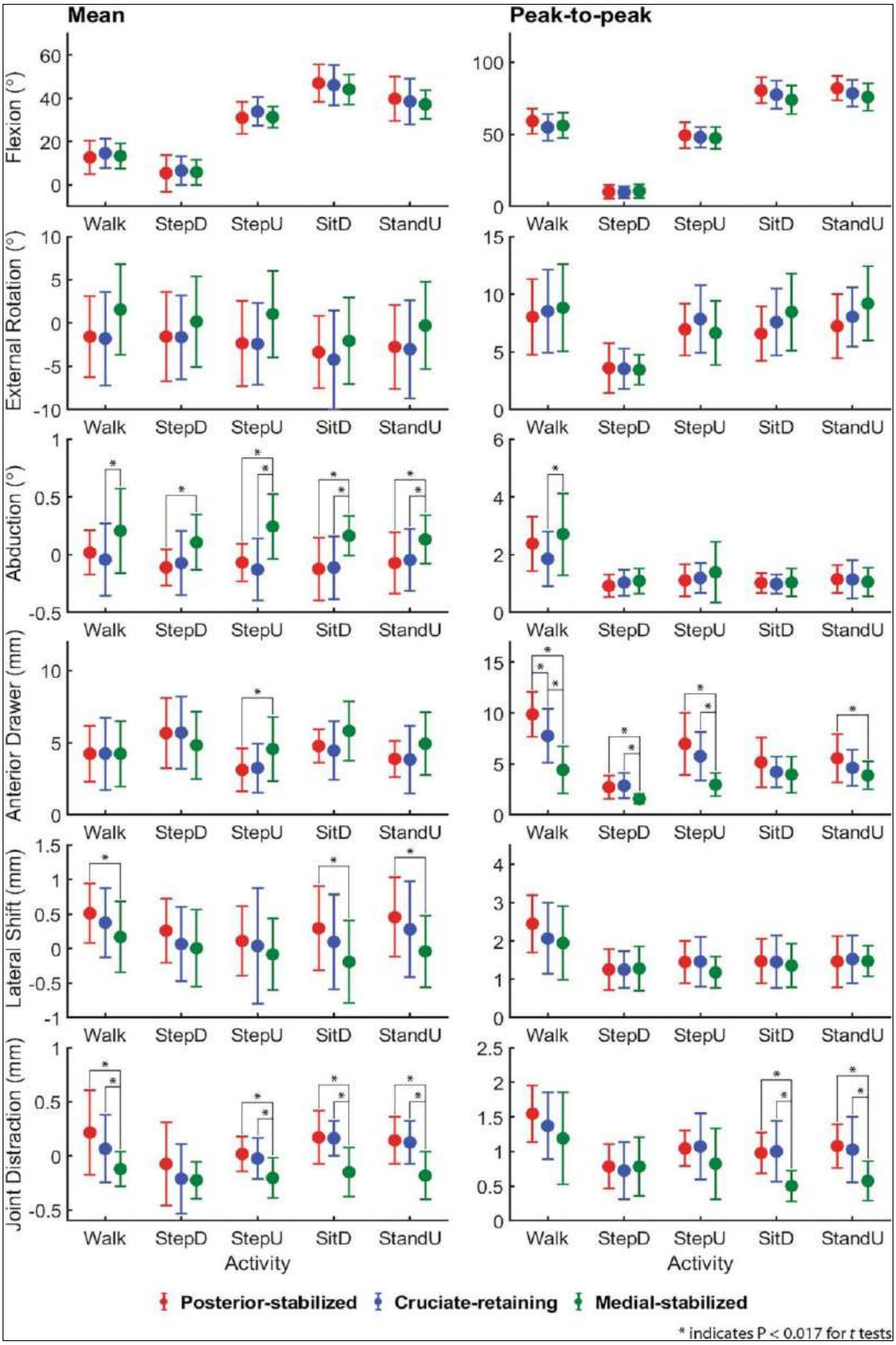


Fig 3: MS was 1.3°-3.4° more externally rotated than PS and 1.8°-3.5° more externally rotated than CR when comparing mean external rotation across all activities

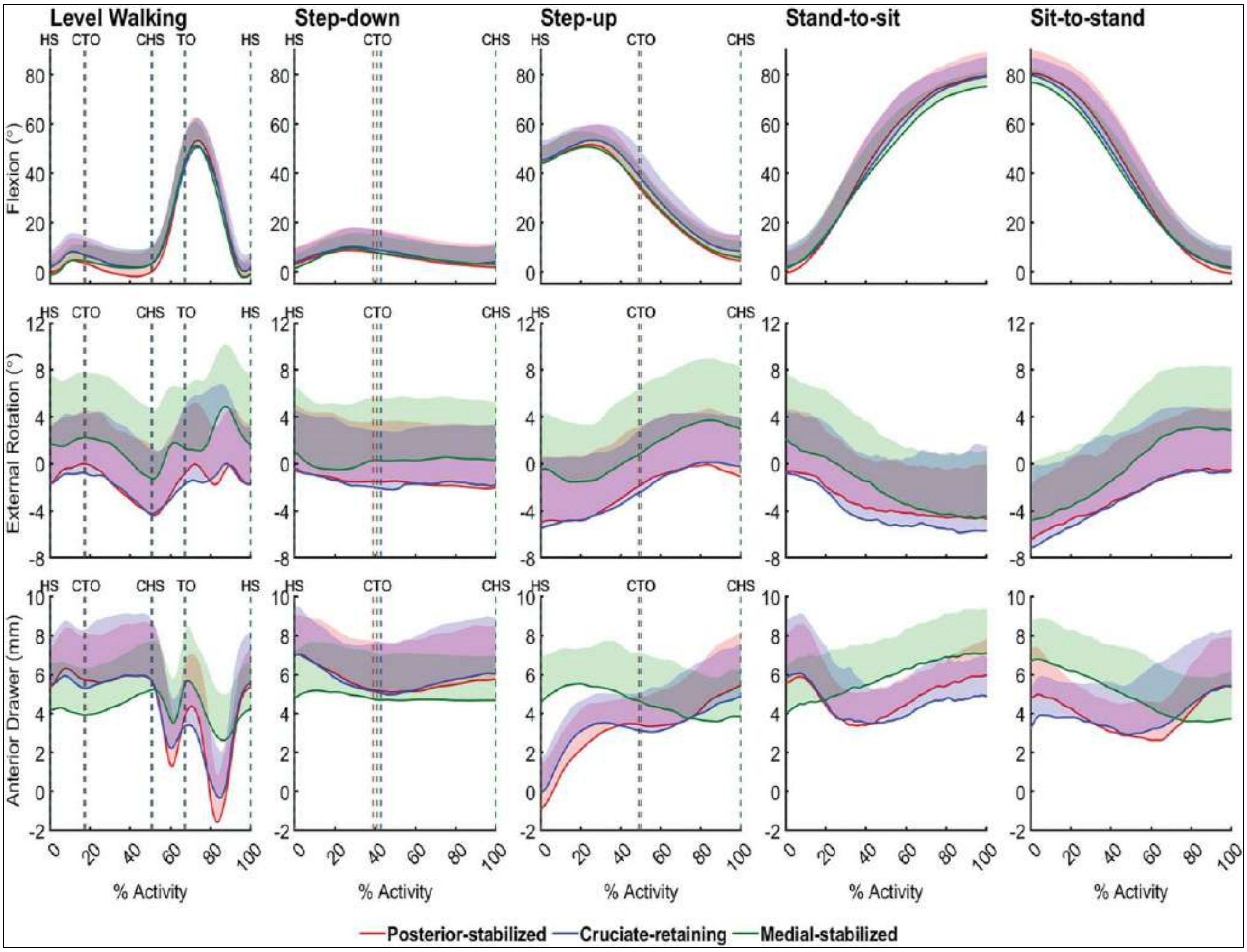


Fig 4: In all activities except walking, all three TKA designs rotated internally as the knee flexed and demonstrated external "screw home" rotation with extension

3.3 Knee center of rotation in the transverse plane

The center of rotation of the knee in the transverse plane was located 19.0–23.5 mm medial to the tibial origin for MS in all activities (Figure 7). In contrast, the transverse center of rotation was located lateral to the tibial origin for PS and CR in all activities except sit-to-stand and stand-to-sit for PS (Figure 7). No significant difference was observed in the location of the transverse center of rotation between PS and CR across all activities, whereas MS was significantly more medial compared to the other two designs ($p < 0.017$).

4. Discussions

Differences in knee joint motion between the MS implant and the two more conventional TKA designs reflect differences in component geometry, specifically, a spherical medial femoral condyle and a highly congruent tibial bearing characterizing the MS prosthesis. Increased external rotation and abduction of the tibia relative to the femur were consistent features of MS in all activities, as the medial condyle swiveled within a conforming tibial plateau. Smaller peak-to- peak anterior drawer was also consistently observed in MS across all activities due to the restricted translation of the medial femoral condyle. The kinematic function of the MS implant shared more similarities with that reported for the healthy knee28 than PS and CR with greater femoral rollback and medial pivoting observed more consistently across all activities. A recent study of healthy knee motion by Thomeer *et al*. [28] observed increasing anterior drawer with knee flexion across multiple activities of daily living, including level walking, downhill walking, and stair ascent and descent. This result describes posterior translation of the femur relative to the tibia with knee flexion, or femoral rollback, which provides superior range of motion by mitigating posterior impingement at high flexion angles. Femoral rollback has also been reported to aid knee implant durability by reducing sliding shear stresses on the polyethylene tibial bearing [29]. Walking and stand-to- sit comprised intervals of increasing knee flexion and showed greater femoral rollback at maximum flexion for MS compared to PS and CR (Figure 4). During the same activities, substantial paradoxical anterior translation (i.e., decreasing anterior drawer with knee flexion) was present for PS and CR at low flexion angles, and anterior drawer was greatest near full extension rather than at maximum flexion (Figure 4).

The presence of paradoxical anterior translation for PS and CR is reflected in the trajectory of the medial femoral condyle, which translated significantly more in the anterior direction during all activities compared to MS (Figures 5 and 6). Numerous fluoroscopic studies of PS motion during deep knee bend have observed minimal femoral rollback between 10° and 60° of flexion and significant rollback only after 90° [16, 21, 22, 25]. To our knowledge only one study has reported significant femoral rollback between 30° and 90° of knee flexion during a deep knee bend for CR [21] whereas others describe similar kinematic behavior to PS [19, 20, 22-24].

These findings suggest prominent femoral rollback is typically not observed in the PS and CR designs during daily activities, as knee flexion rarely exceeds 90° in these activities.

This behavior could be attributed to an unengaged cam-and-post mechanism or a lax PCL at the flexion angles tested, which may explain the lack of clear differences in AP translation between PS and CR during the activities performed. Screw home motion is another kinematic pattern of the healthy knee in which the tibia rotates externally relative to the femur as the knee reaches terminal extension. Although PS, CR, and MS have all shown desirable internal rotation of the tibia relative to the femur during a deep knee bend, [16, 22, 23, 30] inconsistent or loss of screw home motion has been reported during knee extension following TKA surgery [19, 31–34].

In the present study, screw home motion was observed during step-up and sit-to-stand in all three prosthetic designs (Figure 4). Interestingly, a loss of screw home motion was observed during walking for all three TKA prostheses, which differs from results obtained for the healthy knee where normal screw home motion was present across multiple activities of daily living, including walking.28 For all three TKA designs, the tibia did not rotate internally relative to the femur during initial swing and was subsequently unable to rotate externally with extension during mid-swing. The lack of internal rotation may be partially explained by resection of the ACL, a feature of all three implant designs that has been shown to reduce internal rotation with flexion [35].

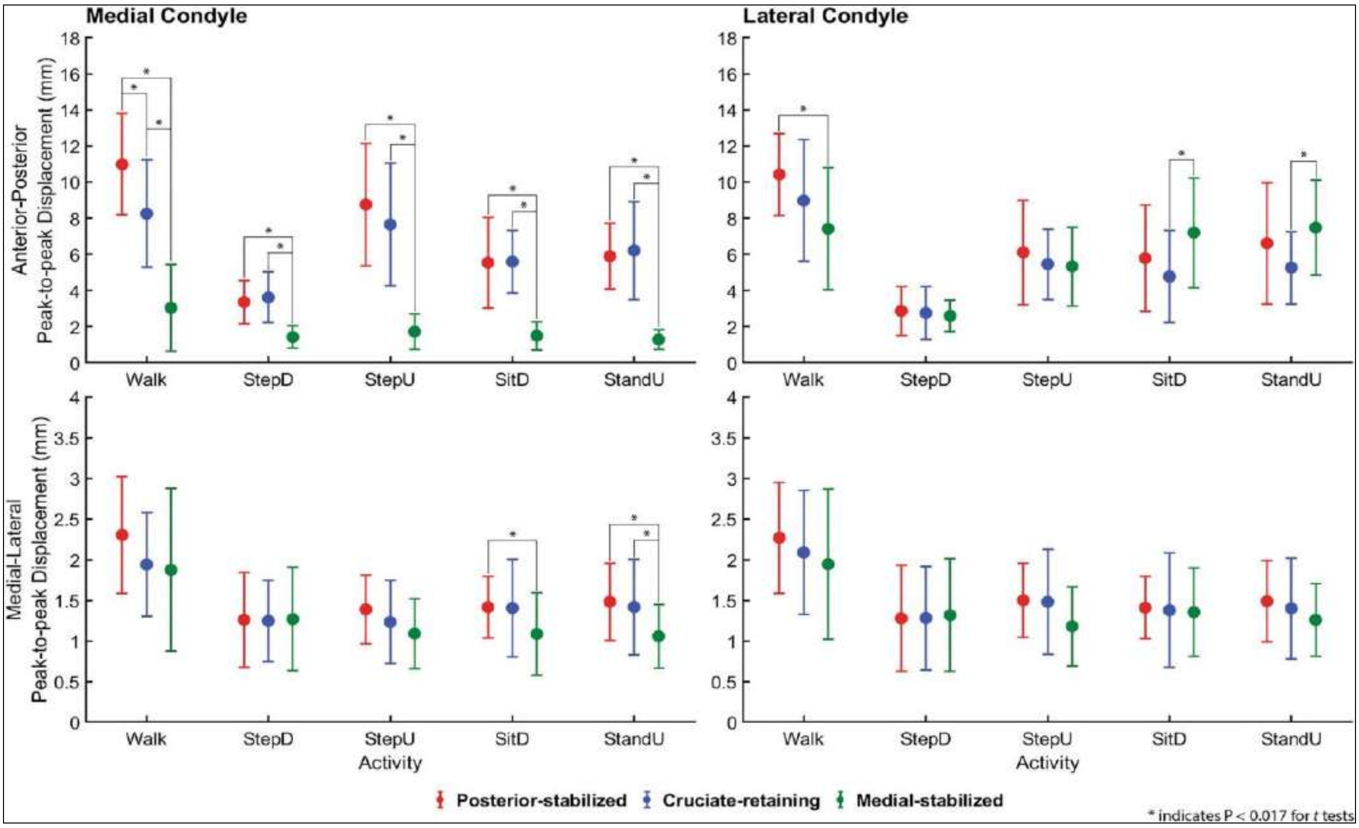
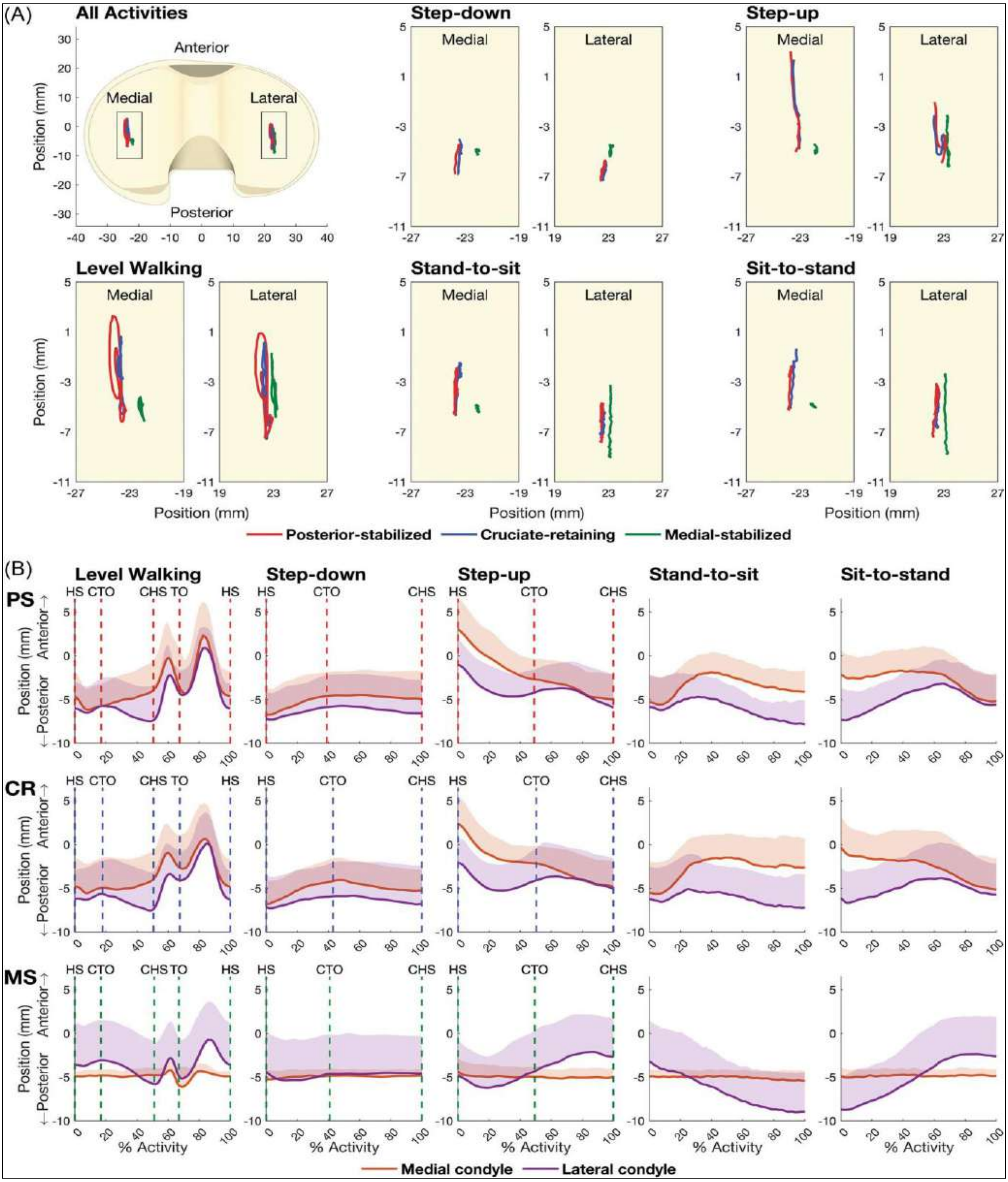


Fig 5: The presence of paradoxical anterior translation for PS and CR is reflected in the trajectory of the medial femoral condyle, which translated significantly more in the anterior direction during all activities compared to MS

Thomeer *et al*. [28] found the center of rotation in the transverse plane for the healthy knee to lie medial to the tibial origin across multiple activities of daily living, including level walking, downhill walking, and stair ascent and descent. In the present study, the transverse center of rotation was consistently located on the medial side in all activities for MS only, whereas for PS and CR the transverse center of rotation was found to be lateral to the tibial origin in all activities except sit-to-stand and stand-to-sit for PS (Figure 6). The location of the center of rotation for MS across all activities (19.0–23.5 mm medial to the tibial origin) was also close to the center of the sphere defining the contour of the medial socket in the transverse plane (20–23 mm medial to the tibial origin). This finding clearly demonstrates the geometric constraint imposed by the MS prosthesis' highly congruent medial compartment. Interparticipant variation in the center of rotation of the TKA in the transverse plane was also substantially reduced for MS compared with PS and CR, highlighting improved consistency in knee kinematic function produced by the MS design. One potential limitation of our study is the relatively short time between surgery and testing (6.2±1.1 months), during which participant knee function may not have yet fully stabilized. Yoshida *et al*.36 reported significant improvements in quadriceps strength and self-reported function between 3 months and 1 year after TKA surgery; however, Minzer *et al*.37 found the same metrics along with the range of knee joint motion to have plateaued by the third month. Another factor to consider is that our analysis of TKA motion focuses on average trends for each TKA prosthesis and hence individual participants may not demonstrate all the kinematic patterns highlighted in this study. Finally, although this study compares knee joint motion for the three TKA designs relative to the healthy knee, greater resemblance to the native knee may not necessarily result in improved clinical outcomes.

Further analysis would greatly benefit from the addition of relevant clinical data, such as the WOMAC or KSS, to draw direct relationships between knee joint motion and patient outcomes. The geometric design of the MS implant is a notable evolution over the more traditional PS and CR designs. Across five daily activities, the present study found 6-DOF motion of PS and CR to be highly similar, whereas MS was appreciably different and more geometrically constrained. Screw home motion remained inconsistent between activities for all three designs; however, MS demonstrated less paradoxical anterior translation and a transverse center of rotation on the medial side, which are features of healthy knee joint motion.



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