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Title:
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Date:
2017-08-01

Citation:
Guan, S., Gray, H. A., Schache, A. G., Feller, J., de Steiger, R. & Pandy, M. G. (2017). In vivo six-degree-of-freedom knee-joint kinematics in overground and treadmill walking following total knee arthroplasty. Journal of Orthopaedic Research, 35 (8), pp.1634-1643. https://doi.org/10.1002/jor.23466.

Persistent Link:
https://hdl.handle.net/11343/292112

IN VIVO SIX-DEGREE-OF-FREEDOM KNEE-JOINT KINEMATICS IN OVERGROUND AND TREADMILL WALKING FOLLOWING TOTAL KNEE ARTHROPLASTY

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REVISION 1

Submitted as an original article to the *Journal of Orthopaedic Research*

10 August 2016

Word count: 4,195 (Introduction to Discussion)

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Running title. TKA kinematics in overground walking

Author contributions statement. All authors contributed to this work. Experimental study design and subject recruitment were performed by SG, HAG, AGS, MGP, JF and RdeS. Gait experiments and statistical analyses of the data were undertaken by SG, HAG, and AGS. All authors discussed and agreed on results and potential implications. The manuscript was initially prepared by SG, HAG, AGS and MGP, but all authors contributed substantially to its revision and final form and approved the final submitted manuscript.

Conflict of interest statement. All authors declare no conflict of interest.

ABSTRACT

No data are available to describe six-degree-of-freedom (6-DOF) knee-joint kinematics for one complete cycle of overground walking subsequent to total knee arthroplasty (TKA). The aims of this study were firstly, to measure 6-DOF knee-joint kinematics and condylar motion for overground walking following TKA; and secondly, to determine whether such data differed between overground and treadmill gait when participants walked at the same speed during both tasks. A unique mobile biplane X-ray imaging system enabled accurate measurement of 6-DOF TKA knee kinematics during overground walking by simultaneously tracking and imaging the joint. The largest rotations occurred for flexion-extension and internal-external rotation whereas the largest translations were associated with joint distraction and anterior-posterior drawer. Strong associations were found between flexion-extension and adduction-abduction ($R^2 = 0.92$), joint distraction ($R^2 = 1.00$), and anterior-posterior translation ($R^2 = 0.77$), providing evidence of kinematic coupling in the TKA knee. Although the measured kinematic profiles for overground walking were grossly similar to those for treadmill walking, several statistically significant differences were observed between the two conditions with respect to temporo-spatial parameters, 6-DOF knee-joint kinematics, and condylar contact locations and sliding. Thus, caution is advised when making recommendations regarding knee implant performance based on treadmill-measured knee-joint kinematic data.

Keywords: Gait, joint replacement, implant wear, biplane X-ray fluoroscopy, knee model, joint loading

INTRODUCTION

The ability to accurately measure in vivo knee-joint kinematics subsequent to total knee arthroplasty (TKA) is important for determining joint-contact loading at the knee, predicting implant component wear, and evaluating the effects of implant design and surgical technique on TKA performance. Biplane X-ray fluoroscopy is currently the most accurate non-invasive method available for measuring dynamic joint motion with mean errors of 0.29 mm for translations and 0.25° for rotations reported for in vivo measurements of knee-joint kinematics following TKA[1]. There are, however, limitations associated with this method. Because the two sets of X-ray sources and image intensifiers represent a combined mass of up to 150 kg, current systems are designed to remain stationary during operation. Furthermore, the image capture volume is defined by the intersection of two cone-shaped X-ray beams, and is therefore relatively small (i.e., the base diameter and height of each cone beam are typically 300 mm and 1000 mm, respectively). Thus, studies which have used biplane fluoroscopy to record knee-joint kinematics during walking have had to use a treadmill and have been unable to generate data for an entire gait cycle[2-5].

In vivo knee-joint kinematics for treadmill walking may not be identical with those for overground walking. Evidence to support this assertion is available from some skin-marker-based motion capture studies that have observed differences in knee-joint kinematic data for healthy people when comparing treadmill and overground walking[6-8]. Understanding whether or not differences exist between treadmill and overground walking for in vivo knee-joint kinematics in people following TKA is important, as mathematical models used to predict TKA wear patterns are sensitive to imported knee-joint kinematic data[9, 10].

In the present study, a unique Mobile Biplane X-ray (MoBiX) imaging system enabled accurate measurement of TKA knee-joint kinematics during overground walking by simultaneously tracking and imaging the joint. The MoBiX system is capable of measuring six-degree-of-freedom (6-DOF) TKA knee-joint kinematics during overground walking with maximum RMS errors of 0.33 mm for translations and 0.65° for rotations[11]. Our specific aims were firstly, to describe in vivo 6-DOF knee-joint kinematics and condylar motion subsequent to TKA for one complete cycle of overground walking; and secondly, to determine whether such data differed between overground and treadmill gait when participants walked at the same speed during both tasks.

METHODS

Design: One-way repeated measures

Level of Evidence: III

Participants

Ten people (5 females and 5 males; age, 69±6 yrs; height, 166±7 cm; weight, 88±10 kg) with unilateral TKA were recruited to this study. All participants had undergone surgery (Genesis II posterior-stabilized total knee replacement, Smith & Nephew Inc., Memphis, TN, USA) at least 15 months (mean 25 ± 7 months) prior to testing. Approval for the study was obtained from the Human Research Ethics Committee at The University of Melbourne (ID# 1033086) and each participant gave informed consent prior to data collection.

Gait experiments

6-DOF knee-joint kinematics were measured for one complete gait cycle using the MoBiX imaging system (Figure 1)[11], which tracked and imaged the knee at 200 Hz with an image resolution of 1024 × 1024 pixels. The fluoroscopy units on the MoBiX system were set to continuous mode with 110 kV and 13.1 mA. Each participant was exposed to X-ray radiation for no more than 25 seconds for the entire experiment, hence the maximum exposure estimated for each participant was 0.1 mSv. Full-body three-dimensional joint motion data were recorded synchronously with the X-ray images using a 9-camera video-based motion capture system (VICON Motion Systems Ltd., UK) sampling at a rate of 120 Hz. For the overground walking trials, all three components of the ground reaction force (GRF) were recorded using two portable strain-gauged force plates (AMTI Accugait, Watertown, MA) mounted flush with a 4.8 m long wooden walkway and sampling at 1,080 Hz (Figure 1).

Participants were instructed to attend the Biomotion Laboratory at The University of Melbourne on two separate occasions. The first session took approximately one hour and involved familiarizing participants with the experimental protocol and equipment. Participants practiced walking over ground and on a treadmill alongside the MoBiX imaging system until they were comfortable with each task. The second session took approximately 3.5 hours and involved experimental data collection, which took place no more than 1 week after the initial familiarization session.

During data collection each participant wore shorts, a sleeveless lead vest and sandals (Nike Straprunner IV, Beaverton, Oregon). Retro-reflective markers were placed on the participant's

skin following a previously described approach[12]. All participants completed the overground walking trials prior to treadmill walking to ensure walking speeds between the two conditions were matched as closely as possible. The participant was provided with ~10 minutes to practice walking over ground on the wooden walkway, initially without but then with the MoBiX system tracking their implanted knee. Once the participant was comfortable with the testing procedure, they performed two separate overground walking trials at a self-selected speed during which biplane X-ray images of the implanted knee, full-body motion, and GRF data were recorded simultaneously for an entire gait cycle. Overground walking speed was estimated from the average speed of a retro-reflective marker mounted on the posterior aspect of the pelvis over the second sacral spinous process. Next, the wooden walkway and force plates were removed and a treadmill (T9350, Vision Fitness, Morwell VIC) was positioned in the middle of the measurement zone. The participant practiced walking on the treadmill for approximately 3 minutes at a speed matched to their overground walking speed. Participants were permitted to hold onto the handrails of the treadmill if they felt insecure. Once the participant indicated they were comfortable walking on the treadmill whilst being tracked by the MoBiX system, biplane X-ray images and full-body motion data were collected simultaneously for two complete cycles of treadmill walking.

Data Analysis

Heel-strike and toe-off were identified using the trajectories of markers mounted on the posterior aspect of the heel and the dorsal aspect of the first toe, respectively. GRF data recorded for overground walking were used to determine the specific features in these marker trajectories

associated with heel-strike and toe-off. Several temporo-spatial parameters were then determined based upon these events, including stride time, stride length, cadence, stance time, swing time, and stance/swing ratio.

6-DOF joint motion for the implanted knee was determined from the biplane X-ray images using a procedure (described in detail elsewhere[11]) that combined an open-source software program called JointTrack[13] with a custom image processing and pose-estimation program developed in MATLAB (The Mathworks Inc., Natick, MA). A joint coordinate system convention[14] was used to describe 6-DOF knee-joint motion with respect to anatomically meaningful axes (Figure 2). Joint kinematic measurements were filtered using a Butterworth filter with a cut-off frequency of 20 Hz.

The positions of the contact centers in the medial and lateral compartments were calculated for 201 time steps over the gait cycle. To approximate the position of the contact center, the point on the femoral condyle closest to the tibial tray was used for each compartment[9]. The anterior-posterior and medial-lateral positions of the contact center on the tibial bearing as well as the sliding distance and velocity between the femoral component and the tibial bearing were determined for the 201 time steps for each compartment. The total sliding distance (TSD) in each compartment was calculated as the sum of the magnitudes of the sliding distances between the femoral component and tibial bearing over one gait cycle. The absolute sliding velocity (ASV) was calculated as the instantaneous velocity of the contact center on the femoral component relative to the tibial bearing at each time step. The mean ASV for each compartment was

calculated by finding the mean of the absolute values of the sliding velocity at each time step over one gait cycle.

The coefficient of determination (R^2) was used to quantify the degree of association between knee flexion and the remaining five DOFs of knee-joint motion for overground walking. Overground and treadmill walking were compared using various outcome measures, including temporo-spatial parameters, discrete knee-joint kinematic parameters, TSD and mean ASV. Student's paired t-test was used to compare these parameters for the two walking conditions, and differences were considered statistically significant when $p < 0.05$.

RESULTS

Overground walking

The mean self-selected overground walking speed for the participants was 0.93 ± 0.12 m/s. The largest rotational motion was flexion-extension, followed by internal-external rotation and adduction-abduction (Figure 3). The knee was fully extended at heel-strike and then flexed in early stance, reaching a peak flexion angle of 4.2° at contralateral toe-off. It then extended until just prior to contralateral heel-strike, before flexing again in preparation for swing. The knee continued to flex during early swing and then extended fully prior to heel-strike. Peak flexion angle during swing was 53.2° and occurred at 72.5% of the gait cycle. The tibia was externally rotated by 0.9° at heel-strike and continued to rotate externally during loading response before reaching a peak angle of 3.2° near contralateral toe-off. External rotation then decreased and the tibia began to internally rotate. Peak internal rotation of 2.4° occurred at contralateral heel-strike. Internal rotation then decreased and the tibia moved into external rotation just before toe-off.

External rotation increased gradually during swing, peaked, and then decreased in terminal swing. The mean knee abduction angle was 0.1° at heel-strike and remained more-or-less constant until mid-stance (~40% of the gait cycle). The knee then adducted until mid-swing (~75.5% of the gait cycle), where it peaked at 2.5° before decreasing to 0.1° in terminal swing. Flexion-extension and adduction-abduction were strongly associated (R^2 = 0.92), whereas flexion-extension and internal-external rotation were not (R^2 = 0.03).

The largest translational motion during overground walking was joint distraction, followed by anterior drawer and lateral shift (Figure 3). At heel-strike, mean joint distraction was 8.2 mm, which increased slightly during loading response before reaching a peak of 9.6 mm at contralateral toe-off. Joint distraction then began to increase just prior to contralateral heel-strike, reaching a peak value of 25.5 mm during swing (~72.5% of gait cycle). The tibia was located 7.8 mm posterior to the femur at heel-strike, before moving posteriorly by 1.2 mm during loading response and translating anteriorly by 0.9 mm during single leg support. The tibia then translated posteriorly after contralateral heel-strike during the second period of double support. Peak posterior translation during the second period of double support was 16.0 mm and occurred just prior to toe-off, whereas peak posterior translation during swing was slightly greater at 18.0 mm. Total medial-lateral shift was small (1.6 mm). At heel-strike, mean lateral shift was 0.0 mm and varied very little (0.5 mm) during the first half of the gait cycle. The tibia shifted medially at toe-off, then laterally during initial swing, and gradually returned to the neutral position prior to heel-strike. Flexion-extension correlated precisely with joint distraction (R^2 = 1.00) and was also strongly associated with anterior-posterior translation (R^2 = 0.77), but less so with medial-lateral shift (R^2 = 0.39).

The tibiofemoral contact centers shifted more in the anterior-posterior direction than in the medial-lateral and proximal-distal directions during overground walking (Figures 4 and 5). Both the medial and lateral compartment contact centers had similar patterns of anterior-posterior movement throughout the gait cycle, except for early stance where the medial compartment contact center was more posterior compared to the lateral compartment contact center. At heel-strike the medial and lateral compartment contact centers were located at mean distances of 4.2 mm and 3.3 mm posterior to the tibial origin, respectively. Both contact centers then shifted a little further posteriorly during loading response to reach 7.3 mm (medial) and 5.4 mm (lateral). After contralateral toe-off both contact centers moved anteriorly and then began moving posteriorly again subsequent to mid-stance. Anterior translation peaked just prior to toe-off and twice during swing. The maximum displacements of the contact centers in the anterior-posterior direction were 6.4 mm and 4.1 mm in the medial and lateral compartments, respectively. The medial and lateral compartment contact centers had identical patterns of movement in the medial-lateral direction throughout the gait cycle. The contact centers remained almost at a fixed medial-lateral position during most of the stance phase. During terminal stance, the contact centers shifted laterally to a peak lateral position at toe-off, then shifted medially reaching a peak medial position during early swing, and finally shifted laterally again prior to heel-strike. The maximum displacement of the contact centers in the medial-lateral direction was ~2 mm. The contact centers on the femoral component remained relatively fixed in the proximal-distal direction with respect to the tibia for the entire gait cycle. The medial contact center moved distally during late stance and proximally at toe off while the lateral contact center moved

proximally during early swing. Nonetheless, peak-to-peak proximal-distal translations remained < 1 mm (Figure 5).

Overground versus treadmill walking

Four participants walked on the treadmill without using the handrails, while the remaining six placed their fingers lightly on the handrails during ambulation. Stride time, stride length, stance/swing ratio and stance time were all significantly reduced for treadmill compared to overground walking whereas cadence was significantly higher for treadmill walking (Table 1).

Overall, the gross patterns of rotational and translational motions of the knee were similar for overground and treadmill walking (Figure 3), although several discrete parameters displayed statistically significant differences (Table 2). Significant differences occurred mainly in the sagittal plane for flexion-extension, anterior-posterior drawer and joint distraction (Figure 3 and Table 2). The magnitudes of the differences between treadmill and overground walking for all other DOF's were less than 0.5 mm and 1° (Figure 3) for translations and rotations, respectively. Peak knee flexion angle during swing was 3.1° larger (p=0.04) and that at heel-strike was 6.5° larger (p=0.03) for treadmill walking compared to overground walking. Similarly, peak joint distraction during swing was 1.3 mm larger (p=0.01) and joint distraction at heel-strike was 1.8 mm larger (p=0.049) for treadmill walking. Differences between treadmill and overground walking were also evident in the profiles for anterior drawer during the first half of the gait cycle, where anterior-posterior translation remained almost constant in overground walking whereas the tibia translated anteriorly by ~4 mm in treadmill walking (Figure 3).

Subtle differences between treadmill and overground walking were observed in the anterior-posterior, medial-lateral, and proximal-distal positions of the contact centers for both the medial and lateral compartments, with differences being more pronounced in the anterior-posterior direction (Figures 4 and 5). During early stance the contact center in the medial compartment was located more anteriorly for treadmill walking compared to overground walking, whereas during late swing the contact centers in both the medial and lateral compartments were located more anteriorly for treadmill walking compared to overground walking (Figure 5). Sliding velocity in both compartments peaked during late stance and late swing for both treadmill and overground walking (Figure 6). Sliding velocities were higher in both compartments during late stance and lower during late swing for treadmill walking compared to overground walking. However, differences between the two conditions for TSD and mean ASV over one gait cycle in both compartments were not statistically significant (Table 3).

DISCUSSION

We used mobile biplane X-ray imaging to noninvasively measure 6-DOF knee-joint kinematics and condylar motion in 10 people following TKA for one cycle of overground walking. The largest angular displacements occurred for flexion-extension and internal-external rotation whereas the largest translations occurred for joint distraction and anterior-posterior drawer (Figure 3). Strong associations were found between flexion-extension and several secondary joint movements, specifically, adduction-abduction ($R^2 = 0.92$), joint distraction ($R^2 = 1.00$) and anterior-posterior translation ($R^2 = 0.77$), providing evidence of kinematic coupling in the TKA knee during overground gait. In the same 10 people, we also measured 6-DOF knee-joint kinematics for one cycle of treadmill walking at a speed matched to their self-selected

overground speed. Whilst the general patterns of 6-DOF knee-joint kinematics and condylar motions were similar between treadmill and overground walking (Figures 2-4), some clear disparities in kinematic behavior were evident between the two conditions (Table 2). For example, the tibia translated anteriorly relative to the femur for the majority of stance during treadmill walking whereas minimal anterior-posterior translation occurred during the same period of overground walking (Figure 3). Overall, our results show that 6-DOF kinematics and condylar motion at the knee during treadmill walking are not identical with that which occurs during overground walking.

How do 6-DOF knee-joint kinematic data for walking in people following TKA compare to equivalent data in people with healthy knees? Lafortune et al.[15] used intra-cortical pins to measure 6-DOF knee-joint kinematics in five healthy young people for one complete cycle of overground walking at a speed of 1.2 m/s. Our data for knee flexion-extension, anterior-posterior translation and joint distraction for overground walking are consistent with their results. However, differences exist for medial-lateral shift and internal-external rotation, suggesting that these two kinematic DOF's are most sensitive to TKA. Our data for knee adduction-abduction are also substantially different from that reported by Lafortune et al.[15]. Whilst we found the knee to adduct during swing, these authors reported a contrary pattern of abduction, which may be explained by differences in the bone coordinate systems used. Using a similar measurement approach to the present study, Kozanek et al.[3] recorded 6-DOF knee-joint kinematics via biplane fluoroscopy in 8 healthy young adults for the stance phase of treadmill walking at a speed of 0.67 m/s. The patterns of knee flexion-extension and internal-external rotation found in the present study are similar to those of Kozanek et al.[3]. However, the pattern of anterior-posterior

304 translation reported by these authors differs somewhat from that obtained for treadmill walking
305 in the current study. Our results indicate that the tibia translates anteriorly relative to the femur
306 between heel-strike and contralateral heel-strike, whereas Kozanek et al.[3] found the tibia to
307 translate posteriorly and then anteriorly during early stance and to remain nearly constant
308 thereafter until contralateral heel-strike. These differences are likely due to the absence of the
309 cruciate ligaments in the knees of our participants who had all undergone posterior-stabilized
310 TKA surgery. Kozanek et al.[3] also reported a joint distraction of ~2 mm for the intact knee
311 during stance compared to ~13 mm in the present study. This difference may be explained by the
312 different coordinate systems selected for the femur. Kozanek et al.[3] located the origin of the
313 femur on the transepicondylar axis, which is close to the geometric axis of the condyles, whereas
314 the origin of the femur in the present study was chosen in accordance with methods established
315 by Grood and Suntay[14] and was located more distally on the femur (Figure 2).
316
317 Joint distraction calculated in the present study represents the distance between the femoral and
318 tibial origins measured along the Z-axis of the tibia (Figure 2) and should not be interpreted as a
319 measure of the tibia separating from the femur. We note, however, that the tibiofemoral contact
320 points on the medial and lateral condyles of the femur moved less than 1 mm along the Z-axis of
321 the tibia for the duration of the gait cycle (Figure 5).
322
323 Our results regarding differences between treadmill and overground walking are consistent with
324 previous studies that compared knee kinematics calculated from motion capture data in healthy
325 age-matched individuals. Watt et al.[8] found cadence increased by 6.78 steps/min and stride
326 length decreased by 0.09 m for treadmill compared to overground walking. Our results indicate

similar differences for the two conditions with an increase in cadence by 8.78 steps/min and a decrease in stride length by 0.10 m for treadmill compared to overground walking. Our participants also displayed reduced stance time but kept swing time almost unchanged for treadmill compared to overground walking. This resulted in a reduced stance-to-swing ratio of 0.12 for treadmill walking, which is consistent with Parvataneni et al.[6] who reported a reduction of 0.13. Wass et al.[16] reported that the knee flexion angle at heel-strike increased by 4.1° for treadmill compared to overground walking, which is similar to the increase of 6.6° found here.

Several factors may have contributed to the differences in knee-joint kinematics between overground and treadmill walking observed in the present study. The TKA patients may have increased their cadence during treadmill walking in an attempt to gain better balance control on the moving belt. Alternatively, the limited length of the treadmill may have had a psychological effect on the participants who tried to avoid reaching the end of the treadmill belt by using a shorter stride length, and hence a faster cadence. Increased knee flexion at heel-strike has been reported as a strategy adopted for coping with the uncertainty involved in running on an irregular surface[17]. A slightly bent knee at heel-strike reduces the effective mass and allows for better shock attenuation, which may also reduce the potential for injury[17, 18]. Perhaps our participants flexed their knees more at heel-strike during treadmill walking to cope with the uncertainty associated with an unfamiliar activity. One of the most noticeable differences in knee kinematics between treadmill and overground walking was related to anterior drawer at heel-strike, with the tibia positioned more posteriorly relative to the femur during treadmill walking compared to overground walking (Figure 3). We speculate that for treadmill walking, the hamstring muscle generates a larger force during terminal swing to maintain a more flexed knee at heel-strike. The

increased hamstring force pulls back on the proximal tibia causing the tibia to translate posteriorly. This result is consistent with the increased activation of the biceps femoris during terminal swing reported for treadmill walking[19].

Flexion-extension, anterior-posterior translation and internal-external rotation have been reported as the main contributors to implant wear[20]. Whilst profiles for internal-external rotation were similar for overground and treadmill walking, increases in knee flexion and anterior-posterior translation and a reduction in stride time for treadmill walking collectively contributed to an increase in sliding velocity, especially during late stance (Figure 6). This increased sliding velocity together with relatively high joint contact loads during late stance may be particularly relevant to calculations of implant wear as mathematical models used to predict tibial bearing wear have relied on knee-joint kinematics measured during treadmill walking[10]. Further research is needed to establish whether wear patterns are indeed different between treadmill and overground walking.

The present study is not without limitations. First, the MoBiX imaging system moving alongside the participants may have intimidated and hence adversely affected the participants' natural gait. We gave each participant the opportunity to practice overground and treadmill walking with the mobile gantry mechanism in operation, both during the familiarization session and again during the test session immediately prior to data collection. Data were collected only after each participant gave verbal confirmation that they were comfortable with the equipment and experimental protocol. Because the MoBiX system tracked and imaged the participants' knees

during both overground and treadmill walking, it is unlikely that this factor contributed to the observed differences in knee kinematics between the two walking conditions.

Second, six of the participants in the present study could not reproduce arm swing during treadmill walking as they elected to use the handrail for additional support. A study on familiarization to treadmill walking in unimpaired older people (aged 67 to 80) revealed that more participants were able to walk without the use of handrails as familiarization increased[16]. However, even after 14 minutes of familiarization only five participants out of 16 were able to walk without the use of handrails and two of the participants could not complete the task due to fatigue and requested that the treadmill be stopped at 7 minutes and 10 minutes[16]. Thus, in the current study more subjects may have been able to walk without the use of the handrails had more time been allocated for familiarization to treadmill walking. Nevertheless, we did provide participants with familiarization periods comparable to those reported in the literature. Varying lengths of treadmill familiarization times have been reported, including 30 seconds[4], at least 2 minutes[8], 3 minutes[21], 2 to 4 minutes[6] and 14 minutes[16]. Our participants undertook one familiarization session and had a total practice time of at least 7 minutes on the treadmill prior to data collection. We therefore suggest that this duration was appropriate because we were able to collect data before participants became fatigued and also because it is longer than the durations employed by many previous studies.

Third, the results of the present study are based on one particular design of posterior-stabilized TKAs. Nevertheless, our findings are consistent with other studies measuring differences in temporo-spatial parameters and knee-joint angles between overground and treadmill walking for

healthy elderly subjects[6, 8]. This may be an indication that the locations of tibiofemoral contact and other kinematic parameters at the knee are different for overground and treadmill walking in healthy older subjects and perhaps in patients with other TKA designs as well. Further research is needed to better understand these issues.

In summary, the results of this study yield accurate measurements of 6-DOF knee-joint kinematics and condylar motion for one complete cycle of overground TKA gait. Although the measured kinematic profiles for overground walking were grossly similar to those for treadmill walking, several statistically significant differences were observed between the two conditions with respect to temporo-spatial parameters, 6-DOF knee-joint kinematics, and tibiofemoral joint contact center motion. Thus, caution is advised when making recommendations regarding TKA performance based on treadmill-measured knee-joint kinematic data.

ACKNOWLEDGMENTS

This study was funded in part by an Australian Research Council Linkage Projects Grant (LP0990369) and an Innovation Fellowship from the Victorian Endowment for Science, Knowledge and Innovation provided to MGP. We thank Smith & Nephew Inc. for providing the geometric models of the knee implants used for pose-estimation.

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467

TABLES

468 Table 1: Temporo-spatial gait parameters measured for treadmill and overground walking.
469 CHS, contralateral heel-strike.

	Overground [a]	Treadmill [a]	Difference [a]	P-value	Effect size
Walking speed (m/s)	0.93	0.93	-0.00	0.82	0.06
Stride time (s)	1.28	1.17	-0.11	0.00*	0.97
Cadence (steps/min)	95.11	103.90	8.78	0.00*	0.98
Stride length (m)	1.17	1.07	-0.10	0.00*	0.98
Stance/swing ratio	1.92	1.80	-0.12	0.01*	0.84
Stance time (s)	0.84	0.75	-0.09	0.00*	1.00
Swing time (s)	0.44	0.42	-0.02	0.08	0.42
CHS (% of gait cycle)	49.63	50.58	0.95	0.24	0.20

470 * Significant difference ($p<0.05$)

471 [a] Mean values across subjects.

472
473

Table 2: Mean values of representative knee-joint kinematic parameters measured for treadmill and overground walking. 'Increment during single support' describes the increment in knee abduction angle at contralateral heel-strike compared to the value at contralateral toe-off.

		Overground [a]	Treadmill [a]	Difference [a]	P-value	Effect size
Anterior Drawer (mm)	Value at heel-strike	-7.84	-11.35	-3.52	0.00*	0.98
Joint Distraction (mm)	Value at heel-strike	8.15	9.97	1.81	0.05*	0.53
	Peak value during gait cycle	25.67	26.99	1.33	0.01*	0.88
Flexion (degree)	Value at heel-strike	-1.50	5.01	6.51	0.03*	0.63
	Peak value during gait cycle	53.84	56.95	3.11	0.04*	0.59
Abduction (degree)	Increment during single support	-0.26	0.20	0.46	0.01*	0.78

* Significant difference ($p<0.05$)

[a] Mean values across subjects.

482 Table 3: Total sliding distance (TSD) and mean absolute sliding velocity (ASV) measured for
483 treadmill and overground walking. All data are for one complete gait cycle.

Wear Parameter	Condyle	Overground [a]	Treadmill [a]	Increase [a]	P-value	Effect Size
TSD (mm)	Medial	68.77	67.98	-0.79 (-1%)	0.73	0.06
	Lateral	67.97	66.35	-1.62 (-2%)	0.38	0.13
Mean ASV (mm/s)	Medial	54.15	58.93	4.78 (9%)	0.07	0.45
	Lateral	53.77	57.27	3.49 (6%)	0.10	0.37

484 [a] Mean values across subjects

485

FIGURE LEGENDS

Figure 1: Schematic diagram illustrating the experimental setup for the overground walking trials. The mobile biplane X-ray (MoBiX) imaging system comprised of two fluoroscopy units and a customized robotic gantry mechanism. The two X-ray tubes and two image intensifiers were mounted on the robotic gantry and were moved along the horizontal and vertical guides by horizontal and vertical servomotors, respectively. A wooden walkway (dimensions 4.8 m x 0.6 m) was placed on the floor between the two horizontal guides, and two force plates were mounted on the walkway as shown. As the participant walked along the walkway, a high-speed digital camera imaged a retroreflective marker located near the implanted knee, and these images were then relayed to a real-time computer (not shown) that generated velocity commands which controlled the motion of the X-ray units via the servomotors. Biplane X-ray images were captured at 200 Hz for all trials. Nine high-speed VICON cameras (one camera which was mounted on the ceiling is not shown) surrounding the MoBiX system were operated at 120 Hz to record the trajectories of retro-reflective skin markers, while the force plates sampled at 1,080 Hz and recorded all three components of the ground reaction force. A synchronization light (Sync Light) was used to synchronize the biplane X-ray image data with the video motion capture data. For the treadmill walking trials, the wooden walkway was removed and a treadmill was placed on the floor between the two horizontal guides of the gantry mechanism.

Figure 2: Coordinate systems defined for the femoral and tibial components of a left posterior-stabilized total knee replacement. The origin of the femoral reference frame was located at the posterior-most point on the mid-plane of the intercondylar notch. The Z-axis (Z_F) was assumed to be perpendicular to the transverse flat surface of the femoral component. The X-axis (X_F) was taken parallel to the posterior chamfer and perpendicular to the Z-axis. The Y-axis (Y_F) was mutually perpendicular to the Z-axis and X-axis. The Y-axis (Y_T) of the tibial component was assumed to be parallel to the medial and lateral surfaces of the cam post and parallel to the tibial tray. The X-axis (X_T) was taken parallel to the tibial tray and perpendicular to the Y-axis. The Z-axis (Z_T) was mutually perpendicular to the X-axis and Y-axis. The origin of the tibial reference frame was positioned at the center of the minimum bounding rectangle of the tibial tray and offset proximally from the tibial tray by a distance equal to the nominal thickness of the tibial bearing. X_F and Z_T were assumed to be body-fixed axes. The floating axis (W) was defined as mutually perpendicular to the body-fixed axes (X_F and Z_T), consistent with the definition given by Grood and Suntay[14]. Flexion (R_1), abduction (R_2), and external rotation (R_3) were measured for the tibia about X_F, W, and Z_T. Lateral shift (T_1), anterior drawer (T_2), and joint distraction (T_3) were measured as translations of the tibial origin relative to the femoral origin along X_F, W, and Z_T, respectively.

Figure 3: 6-DOF knee-joint kinematics measured for overground and treadmill walking. Positive angular displacements of the tibia relative to the femur are described by flexion,

abduction, and external rotation (first row), while positive translations of the tibia relative to the femur are described by lateral shift, anterior drawer, and joint distraction (third row). TM-OG represents the difference in knee-joint rotations (second row) and in knee-joint translations (fourth row) between treadmill (TM) and overground (OG) walking. All curves represent mean data while the shaded areas represent ± 1 standard deviation from the mean. Two trials of each task were analyzed for seven of the ten participants. For the remaining three participants, one had only 1 overground trial and 1 treadmill trial; one participant had 1 overground trial and 2 treadmill trials; and one participant had 2 overground trials and 4 treadmill trials. The vertical dotted lines mark the following gait events: CTO – contralateral toe-off; CHS – contralateral heel-strike; TO – toe-off; HS – heel-strike. Rotations and translations are described in an established joint coordinate system[14]. Translations of the femur in the tibial reference frame[3] are given in the Supplementary Material (Figure S-1).

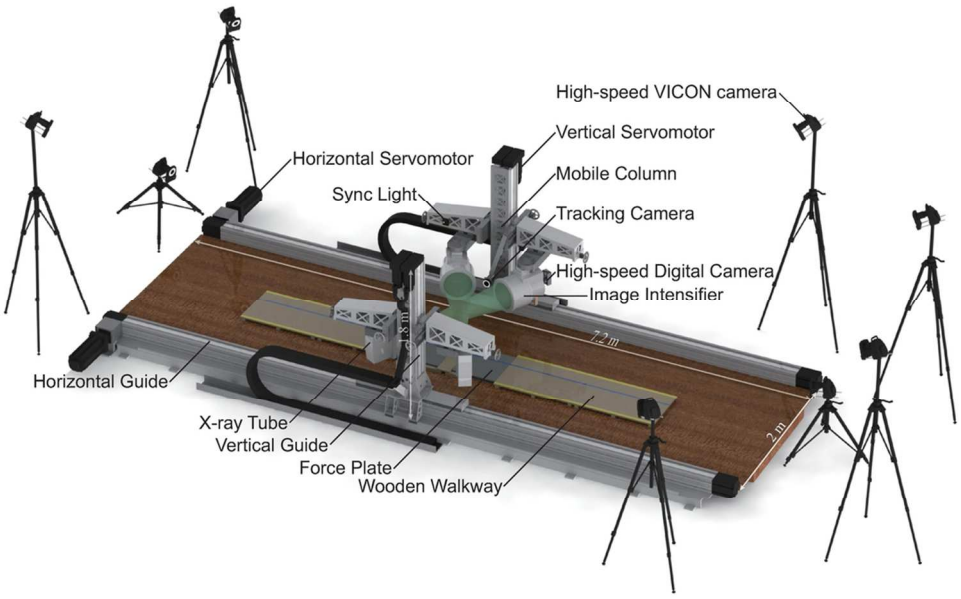
Figure 4: Mean trajectories of the tibiofemoral contact centers plotted on the top surface of the tibial bearing for one cycle of both overground walking (OG) and treadmill walking (TM). The tibial coordinate system is defined in Fig 2; scales used for the anterior-posterior and medial-lateral axes are in millimeters. The insets show scaled-up views of the contact center trajectories in the medial and lateral compartments. The red and blue dots represent the mean positions of the contact centers calculated over one gait cycle for treadmill and overground walking, respectively. The asterisks indicate statistically significant (p<0.05) differences in the positions of the mean contact centers between overground and treadmill walking.

554

555 Figure 5: Mean anterior-posterior, medial-lateral, and proximal-distal positions of the contact
556 centers in the medial and lateral compartments of the tibiofemoral joint for one gait
557 cycle. Data shown are described in the tibial reference frame. Anterior, medial, and
558 proximal displacements are positive. All curves represent mean data while the shaded
559 areas represent ± 1 standard deviation from the mean.

560

561 Figure 6: Absolute sliding velocity between the femoral component and the tibial bearing
562 plotted for one gait cycle. All curves represent mean data while the shaded areas
563 represent ± 1 standard deviation from the mean.



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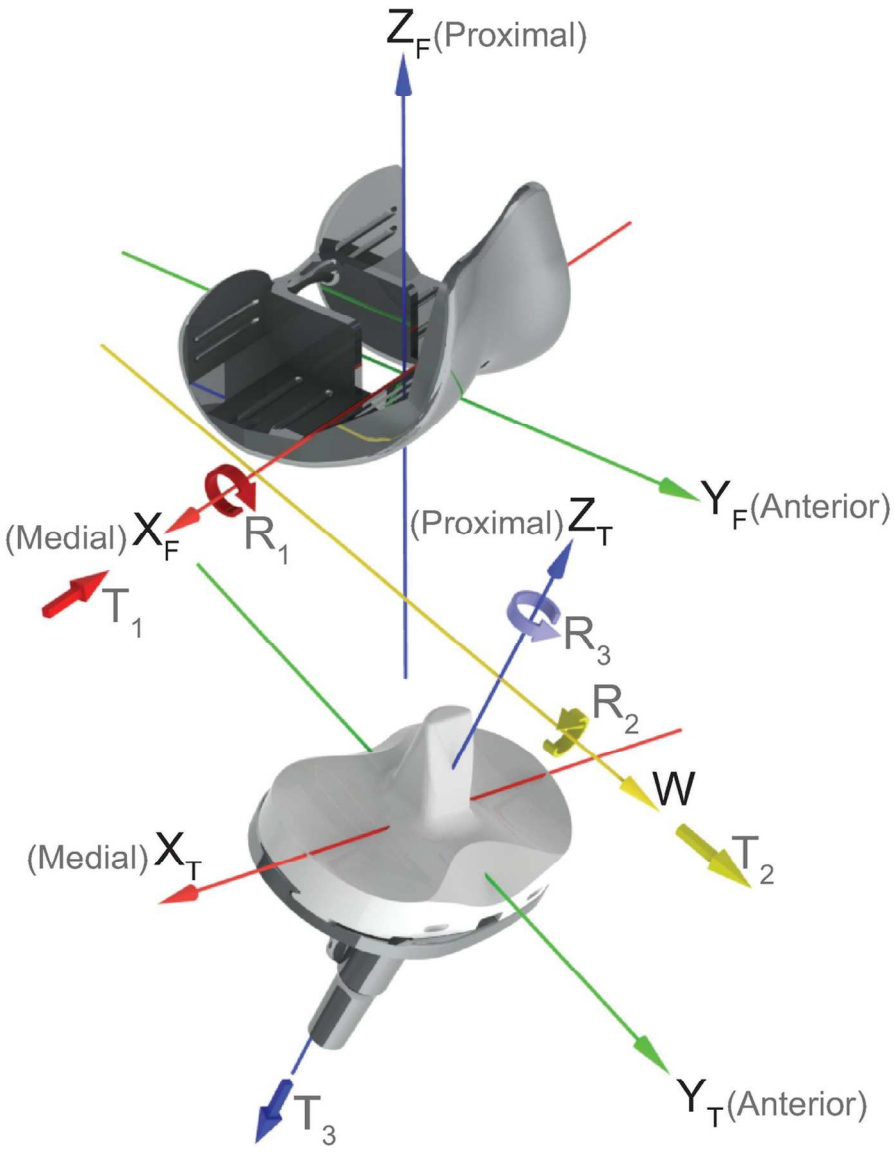

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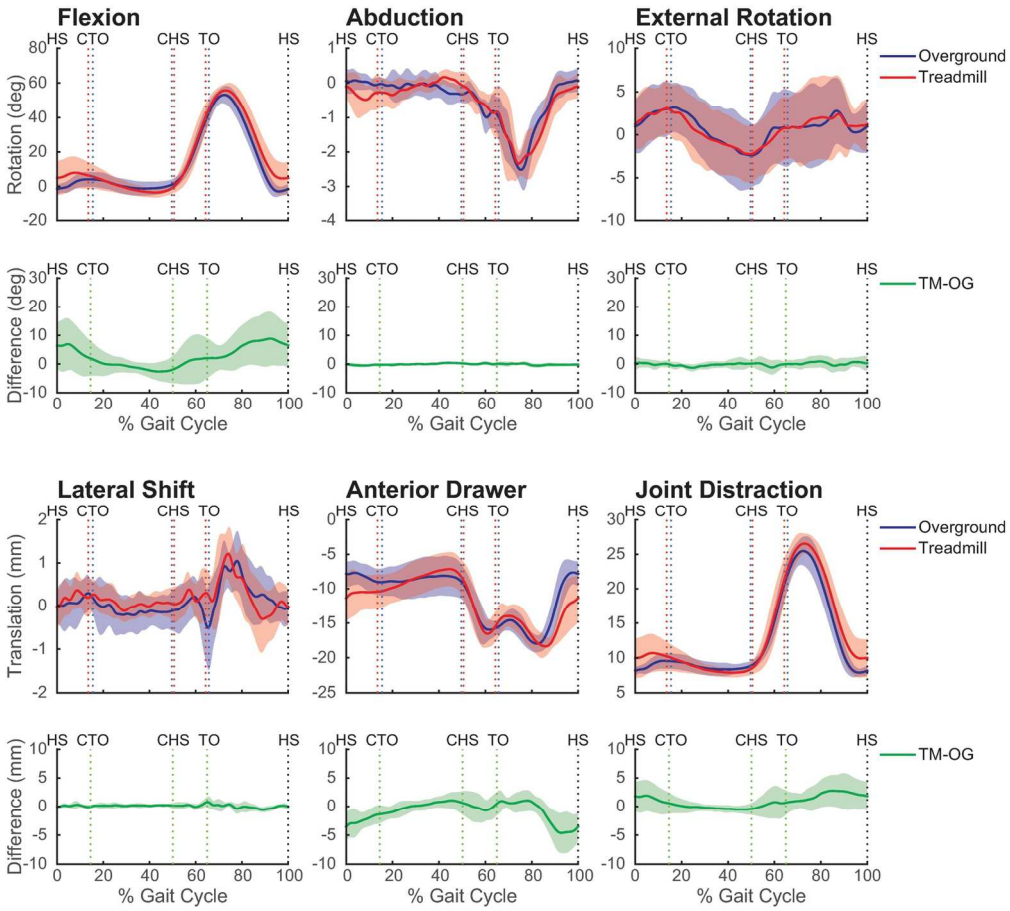

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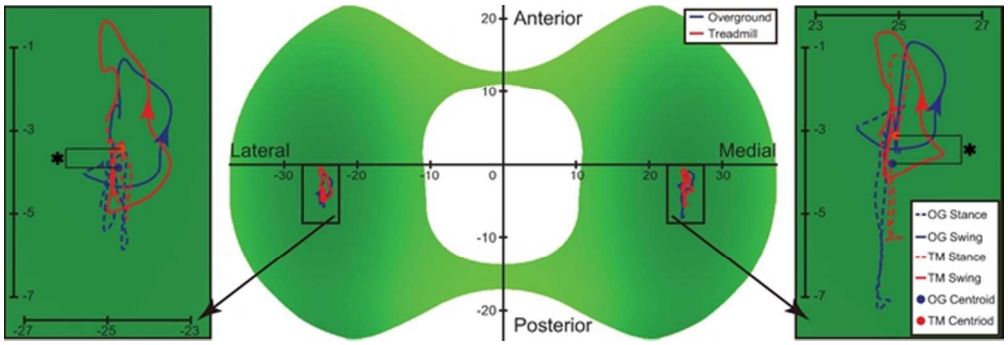

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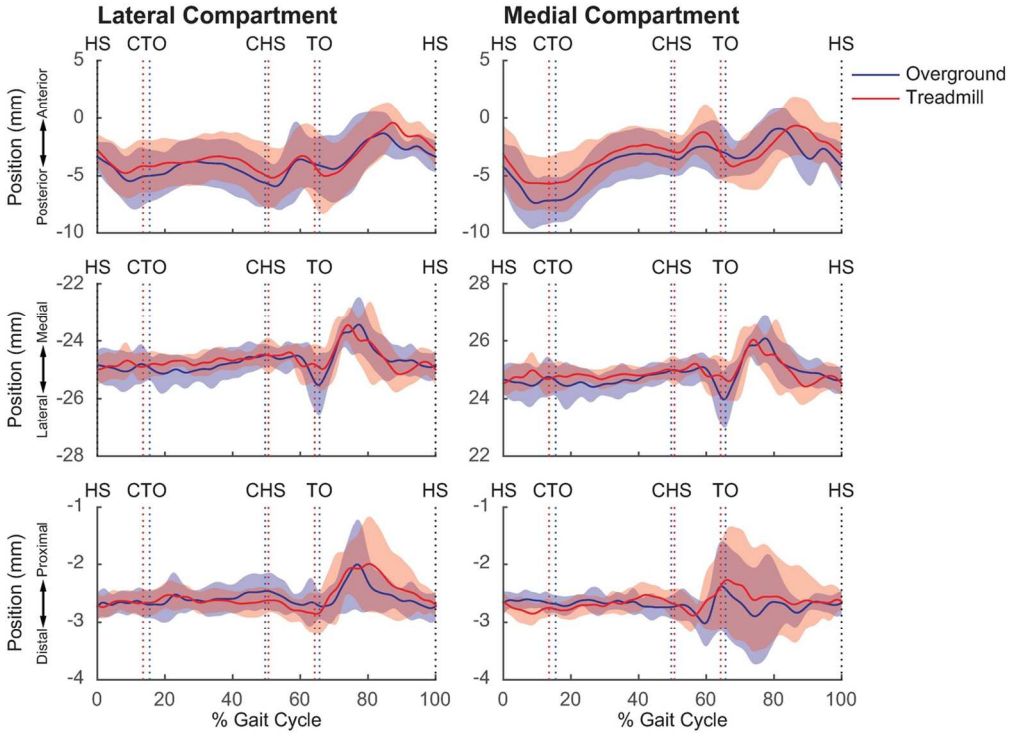

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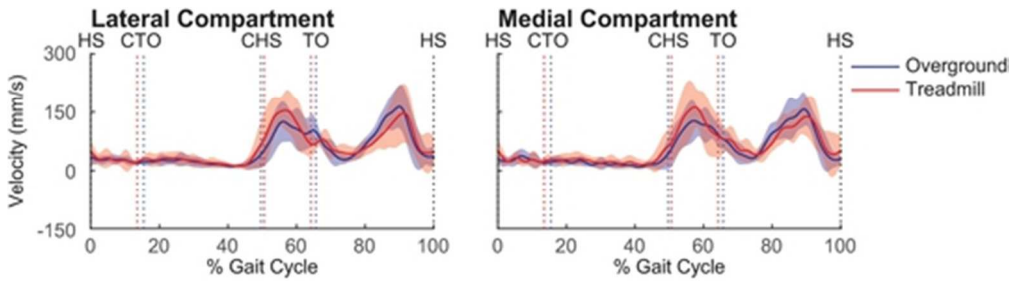

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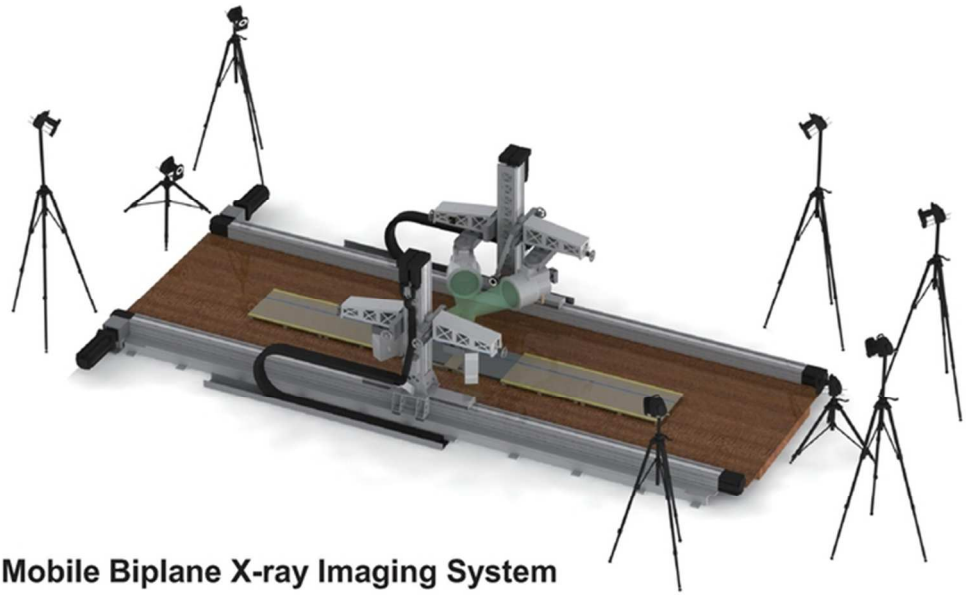

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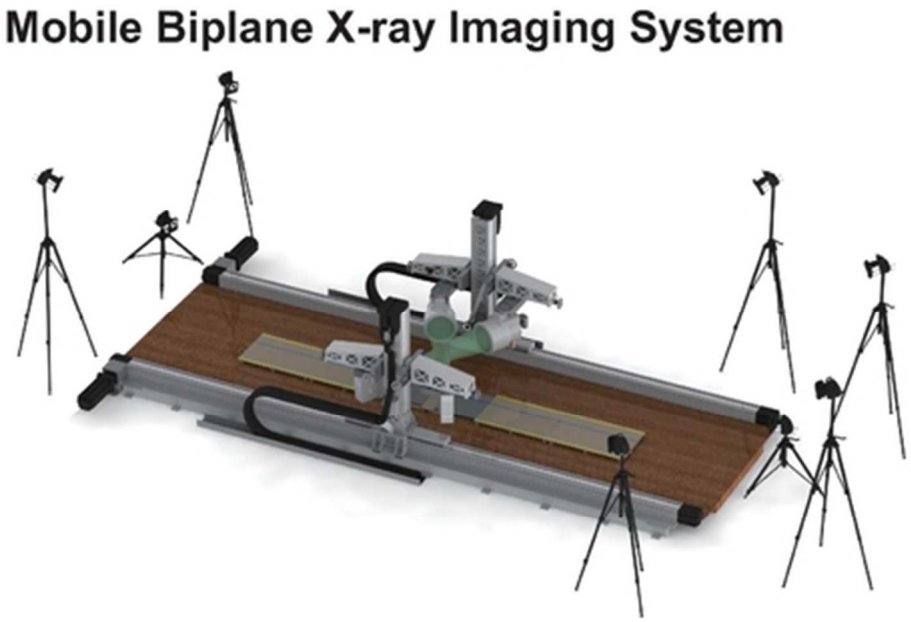

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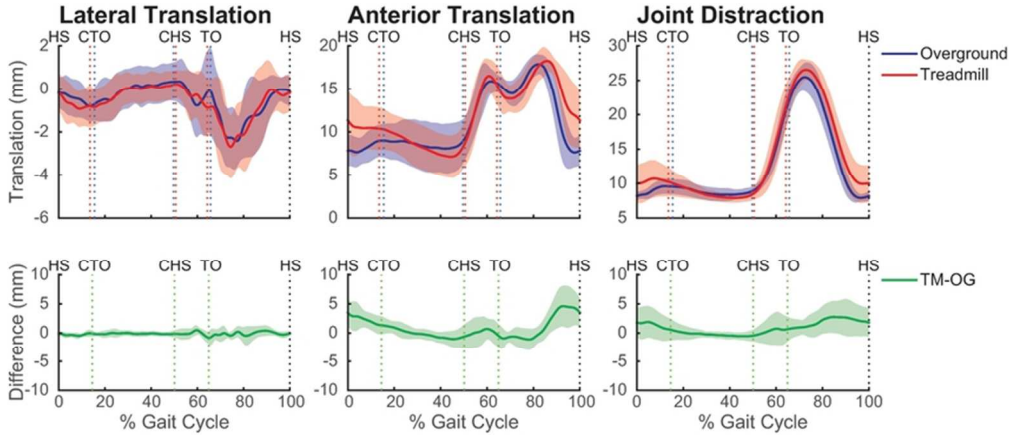

The caption is in the document "TKA Kinematics_supplementary material_21October2016.doc"
Figure S-1
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