

New Findings in Six-degrees-of-freedom Kinematics during Stationary Stepping in Patients with Knee Osteoarthritis

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Abstract

Background: Frontal plane knee kinematics are more likely associated with the development or progression of knee osteoarthritis. However, detailed frontal plane knee kinematics remain unclear. Previous studies examined movement during gait, squatting or stair stepping which allowed compensatory motion. However, biomechanical parameters in gait analyses can be modified. Therefore, we analyzed movement during stationary stepping activity while holding a handrail. The purpose was to determine: 1) detailed 6-degrees-of-freedom kinematics during stationary stepping activity in subjects with severe knee osteoarthritis; and 2) the association between unloading and black-loading phases.

Methods: Twenty-four patients (32 knees) with severe medial knee osteoarthritis awaiting total knee arthroplasty were enrolled in this study. Knee kinematics was analyzed using a 3D-to-2D registration technique.

Results: Knee adduction motion and tibial lateral translation increased from the unloading to weight-loading phase ($P=0.027$, $P<0.001$), but tibial internal-rotation motion was not increased ($P=0.204$). Knee adduction motion and tibial lateral translation motion were significantly correlated ($r=0.400$, $P=0.023$). Knee flexion angle during the weight-loading phase was negatively correlated with tibial lateral translation motion ($r=0.597$, $P<0.001$).

Conclusions: A few studies that demonstrated detailed frontal plane knee kinematics have focused on the femoro-tibial motion. Severe knee osteoarthritis induced a greater knee adduction angle during the unloading phase, but the angle showed a smaller increase than that previously reported. Tibial lateral translation also increased during stationary stepping activity. Further work is needed to determine the association between femoro-tibial motion and varus thrust, and the association between knee flexion angle and intra-joint kinematics such as contact points.

Level of Evidence: Cross-sectional study Level III

Keywords: Knee osteoarthritis; Stationary stepping activity; Kinematics; 3D-to-2D registration technique

Introduction

Knee Osteoarthritis (KOA) is a contributor to disability and a risk factor for decreasing quality of life in elderly individuals. In the United States, prevalence of definite radiographic and symptomatic KOA in adults aged 60 years and older was previously reported to be 13.3 and 4.3 million people, respectively [1]. In Japan, the number of patients with symptomatic KOA was estimated to be approximately 7.8 million people aged 40 years and older [2]. The prevalence of radiographic KOA among the Japanese population aged 60 years and older was reported to be 47.0% in men and 70.2% in women [3]. Medial KOA (MKOA) occurs more commonly and the majority of these are primary osteoarthritis. Therefore, MKOA is thought to be a serious issue worldwide and the development of an effective prevention and treatment program for MKOA is crucial.

In order to construct effective therapeutic methods, characteristic movements in MKOA must be understood. It is widely accepted that MKOA is associated with altered frontal plane kinematics and kinetics

during the gait cycle from initial contact to loading response. The MKOA group showed a greater magnitude of external knee adduction moment (KAM) during the stance phase compared to that of control subjects [4,5]. The risk of MKOA progression increased 6.46 times with a 1% increase in KAM [6]. Varus thrust is a potential risk factor for disease progression of MKOA, causing a 4-fold increase in the odds of MKOA progression [7]. In clinical outcomes, varus thrust has been associated with pain during weight-bearing activities [8], and varus thrust combined with static varus malalignment has been strongly associated with knee pain during gait [9]. However, several gait modifications that can reduce KAM have been identified. Hunt et al. [10] concluded that the first peak KAM could be explained by toe-out angle (12%) and trunk lean (13%). Simic et al. [11] performed a systematic review and concluded that KAM reduction was achieved by contralateral cane use, increased step width, medial knee thrust, increased hip internal rotation, weight transfer to the medial foot, and increased trunk lean. Favre et al. [12] concluded that increasing trunk sway, increasing step width, and toeing-in were three modifications that could be combined to reduce KAM variables in patients with MKOA. Therefore, biomechanical parameters in gait analyses can be modified with or without the subject's intention and should be

considered less reliable in determining small kinematic changes over time. Moreover, data obtained using an optical tracking system with skin markers was less accurate in determining internal/external rotation and abduction/adduction due to skin artifacts [13]. Accordingly, considering both skin artifacts and potential changes in kinematic parameters, a more accurate and reproducible measurement system is required, such as a 3D-to-2D registration technique with an in-plane error of 0.54° for rotation and 0.53 mm for translation [14].

Measurement of KAM can be obtained during stationary stepping activity. The stepping activity involves a single-leg standing phase similar to the mid-stance of gait, which induces lateral thrust due to the modified knee alignment. This task may be more advantageous than gait for measuring knee biomechanics because of the improved reproducibility including KAM since holding on to hand rails stabilizes the trunk, controls foot angle, knee extension angle, and step width, and eliminates the effects of step length. This task also allows fluoroscopic imaging so that radiographic measurement techniques can be utilized. Furthermore, abnormal contact kinematics [15] and lateral translation [16] of the tibia may be associated with extrusion of the medial meniscus [17].

Detailed kinematics of the knee during stepping activity, including tibial lateral translation or anterior translation, is of interest to determine the nature of thrust action. Previous gait analyses using skin markers reported knee adduction motion of 3.2° [18] in patients with MKOA with thrust action, whereas 5.9° [19] and 7.2° [20] were reported in patients with severe MKOA. These studies did not demonstrate medial-lateral or antero-posterior translations. A limitation of the skin marker system involves inaccuracy caused by skin artifacts, as reported by Benoit et al. [21], who demonstrated that skin-marker derived kinematics during gait had an absolute error of 3.1° (adduction) and 5.5 mm (medial/lateral translation) in mid-stance compared with measurements obtained using bone-pin.

Because the improved accuracy and reproducibility of stationary stepping is more advantageous for following the progression of MKOA, collection of cross sectional kinematic data in MKOA would facilitate future longitudinal or intervention studies. The purpose of this study was to determine detailed 6-degrees-of-freedom (6DOF) kinematics between the unloading and loading black phases in subjects with severe MKOA during stationary stepping activity.

We hypothesized that: 1) patients with severe MKOA present an increase in femoro-tibial adduction and tibial lateral translation from the unloading phase to the loading phase; and 2) the amount of adduction movement is associated with the amount of tibial lateral translation. To test these hypotheses, we utilized the 3D-to-2D registration technique based on anteroposterior X-ray images, which allows non-invasive and accurate measurement of knee kinematics during stationary stepping activity *in vivo*.

Materials and Methods

Study design and setting

This is a cross sectional study that utilized the baseline data of an ongoing randomized controlled trial (UMIN000024196) evaluating the effects of a home-based rehabilitation program on symptoms and function in MKOA. This study was approved by the institutional review boards of Hiroshima Prefectural Rehabilitation Center and Hiroshima International University. Written informed consent was obtained from all subjects prior to enrollment.

Participants

Subjects were recruited from patients with severe MKOA awaiting total knee arthroplasty (TKA) at a single regional hospital. All subjects who met specific selection criteria were enrolled. Inclusion criteria were: (a) Japanese males and females; (b) between 50 and 85 years old; (c) primary MKOA; and (d) radiographic severity of Kellgren-Lawrence System grade III or IV [22]. Exclusion criteria were: (a) lateral compartment KOA; (b) history of knee surgery; (c) history of any rehabilitation program; (d) any disease involving the knee joint; or (e) history of rheumatoid arthritis, cerebropathy, neuropathy or gout. All subjects underwent TKA after this study in approximately three months.

Activity and fluoroscopic imaging

Stationary stepping activity was chosen for kinematic analyses due to higher accuracy and reproducibility than gait. Each subject was asked to perform the stepping activity during fluoroscopic surveillance using a 17-inch digital image intensifier system (15 Hz, SONIALVISION Safire 17, Shimazu Corp., Japan). The subjects were instructed to hold onto the ipsilateral handrail to avoid trunk lean. To avoid the influence of shoes or insole, all images were obtained while the subject was barefoot. To analyze knee kinematics during stepping activity, we selected frames between the unloading (UL) phase and the end of lateral movement of the knee during the weight-loading (WL) phase (Figure 1).



Figure 1: Stationary stepping activity. Each subject was asked to perform the stepping activity with holding onto the ipsilateral handrail to avoid trunk lean.

Geometric bone model preparations

All subjects underwent Computed Tomographic (CT) scanning (Aquilion, Toshiba Medical Systems Corporation, Japan) with a 0.5 mm slice pitch spanning approximately 150 mm above and below the knee joint line. Geometric bone models of the femur, tibia and fibula were created from the CT images. Exterior cortical bone edges were segmented and converted into polygonal surface models using 3D-Doctor (Able Software Corp., Lexington, MA), and smoothed using Geomagic Studio 2013 (Geomagic, Morrisville, NC). Local coordinate systems were embedded onto the femur and tibia using custom

software VHKneeFitter (University of Colorado Health Sciences Center, Aurora, CO).

All definitions and procedures for the local coordinate systems were previously described in detail [23]. The femoral coordinate system was embedded using the cylindrical axis (CA) of the posterior femoral condyles [24]. The origin was defined at the mid-section of the CA between the lateral and medial epicondyles [24]. The vertical axis (VA) was defined as parallel to the femoral shaft on the sagittal plane and perpendicular to the CA on the frontal plane. The tibial coordinate system was defined around a virtual rectangle fitted onto the contour of the tibial plateau. To avoid highly variable morphology and the high prevalence of spur formation at the posterior contour of the osteoarthritic tibial plateau, the rectangle was fitted at the level of the top of the fibular head parallel to the tibial plateau plane. Then, the rectangle was translated superiorly so that it fit the bottoms of the medial and lateral tibial plateaus. The center of the rectangle was defined as the tibial origin, through which the medial/lateral and anteroposterior axes were defined as two axes of the tibial coordinate system.

Model registration and data processing

In vivo three-dimensional positions and orientations of the femur and the tibia were determined using a validated 3D-to-2D registration technique [14,25,26]. Using the custom JointTrack program (sourceforge.net/projects/jointtrack), the bone model was projected onto the calibrated fluoroscopic image, and its three-dimensional pose was iteratively adjusted to match its silhouette with the silhouette of the bones on the fluoroscopic images (Figure 2). In the knee joint, this matching method has an estimated accuracy of 0.53 mm for in-plane translation, 1.6 mm for out-plane translation, and 0.54° for rotations [14,26].

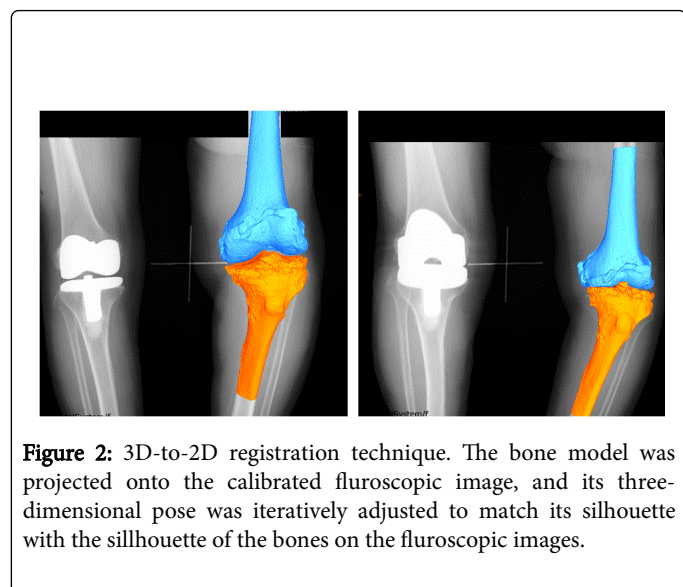


Figure 2: 3D-to-2D registration technique. The bone model was projected onto the calibrated fluoroscopic image, and its three-dimensional pose was iteratively adjusted to match its silhouette with the silhouette of the bones on the fluoroscopic images.

We performed all registration procedures manually because automatic edge detection in osteoarthritic bones with osteophytes has a negative impact on the accuracy of registration results. Once the registration procedures were complete for a sequence of activity, 6-DOF joint kinematics was computed using commercial software 3D-

JointManager (GLAB Inc., Higashihiroshima, Japan). Kinematics was obtained using the local coordinate systems defined around the intra-articular morphology of the tibia and femur (Figure 2).

Statistical analysis

Characteristics and kinematic parameters of study subjects were summarized using means and 95% confidence intervals [95% CI] as continuous variables. The assumption of normality and equality of variance was assessed using Shapiro-Wilk test. If the data met parametric assumptions, paired t-test was employed to examine differences in UL and WL kinematics [adduction angle, tibial lateral translation and tibial internal-rotation angle]. If the data did not meet parametric assumptions, Wilcoxon signed-rank test was employed.

Pearson's correlation coefficients and Spearman's rank correlation coefficient were calculated to examine relationships among knee flexion, adduction and tibial internal-rotation angles and tibial lateral translation as well as the amounts of change in these parameters.

Out of plane translation (anterior-posterior) was excluded from analyses in this study due to the limited reliability of these data. All data were analyzed using SPSS Statistics v21 (SPSS Inc., Chicago, IL) with the significance level set at alpha=0.05. Post-hoc power analyses were performed using G*Power 3.1.2 (Franz Faul, Universitat Kiel, Germany)

Results

Characteristics of all subjects are demonstrated in Table 1. Thirty-two knees of twenty-four patients (six males and eighteen females) with a mean age of 71.9 [69.1, 74.7] years were examined in this study (Table 1).

Number of knees (patients)	32(24)
Sex (Male/Female)	6/18
Age (years) Mean [95% CI]	71.9 [69.1, 74.7]
Body height (cm) Mean [95% CI]	153.6 [150.5, 156.7]
Body weight (kg) Mean [95% CI]	65.8 [61.6, 70.6]
BMI (kg/m ²) Mean [95% CI]	27.7 [26.5, 28.9]
CI: confidence interval, BMI: body mass index	

Table 1: Subject characteristics.

6DOF kinematics

Knee flexion angle at UL was 25.5 [21.8, 29.1] and knee flexion angle at WL was -0.2 [-3.3, 2.9]. Knee adduction angles significantly increased from UL 5.0° [4.2, 6.0] to WL 5.8° [4.8, 6.8] (P=0.027). Tibial lateral translation significantly increased from UL 6.2 [5.4, 7.1] mm to WL 8.7 [7.6, 9.8] mm (P<0.001). Tibial internal-rotation angles at UL and WL were 0.9° [-1.3, 3.1] and 1.5° [-0.6, 3.7], respectively, and the difference was not significant (P=0.303) (Table 2) (Figure 3).

	UL	WL	Amount of change	p value
Knee flexion angle (degree) Mean [95% CI]	25.5 [21.8, 29.1]	-0.2 [-3.3, 2.9]	25.7 [21.6, 29.7]	
Knee adduction angle (degree) Mean [95% CI]	5.0 [4.2, 6.0]	5.8 [4.8, 6.8]	0.7 [0.1, 1.3]	0.027
Tibial lateral-translation (mm) Mean [95% CI]	6.2 [5.4, 7.1]	8.7 [7.6, 9.8]	2.4 [1.7, 3.2]	<0.001
Tibial internal-rotation (degree) Mean [95% CI]	0.9 [-1.3, 3.1]	1.5 [-0.6, 3.7]	0.6 [-0.6, 1.9]	0.303

Table 2: Six degrees-of-freedom kinematics during stationary stepping activity.

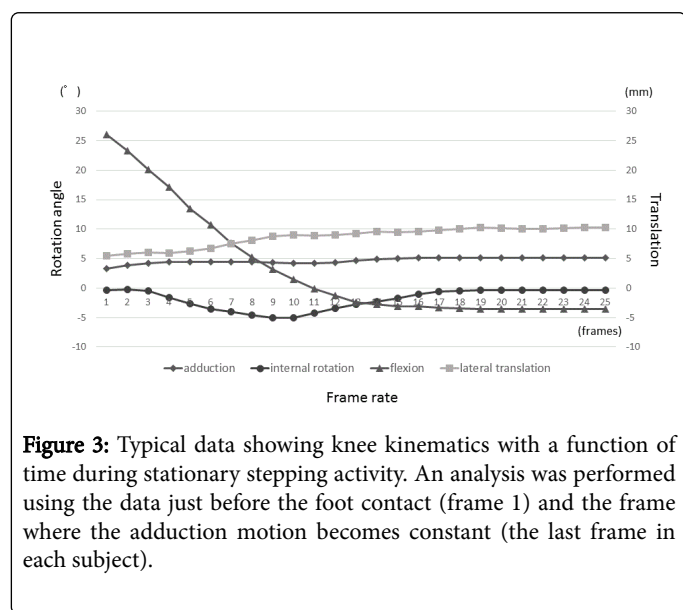


Figure 3: Typical data showing knee kinematics with a function of time during stationary stepping activity. An analysis was performed using the data just before the foot contact (frame 1) and the frame where the adduction motion becomes constant (the last frame in each subject).

Correlation between UL and WL kinematics

Associations of knee adduction angle, tibial lateral translation, and tibial internal-rotation angle between the UL and WL phases demonstrated positive correlations ($r=0.803$, $P<0.001$; $r=0.739$, $P<0.0001$; and $r=0.836$, $P<0.001$, respectively). The amount of change in adduction positively correlated with both knee adduction angle at WL ($r=0.464$, $P=0.007$) and the amount of tibial lateral translation ($r=0.400$, $P=0.023$). The amount of change in tibial lateral translation also correlated with knee adduction angle at WL ($r=0.523$, $P=0.002$). The amount of change in tibial internal-rotation was not significantly correlated with the amount of change in knee adduction angle or tibial lateral translation ($r=0.317$, $P=0.077$; $r=0.227$, $P=0.212$, respectively).

Knee flexion angle at WL was negatively correlated with knee adduction angles during the UL and WL phases ($r=-0.412$, $P=0.019$; $r=-0.377$, $P=0.034$, respectively), tibial lateral translation during the WL phase ($r=-0.461$, $P=0.008$) and amount of change in tibial lateral translation ($r=-0.597$, $P<0.001$). The amount of change in knee flexion correlated with tibial lateral translation at WL ($r=0.357$, $P=0.045$) and the amount change in tibial lateral translation ($r=0.543$, $P=0.001$).

Discussion

This study investigated detailed 6DOF kinematics between the unloading and loading phases in patients with severe MKOA during stationary stepping activity, which was chosen to avoid potential

compensations as well as intra-subject variability. The results of this study demonstrated that the knee adduction angle and tibial lateral translation were significantly increased from UL to WL, which confirmed our first hypothesis. Further, the amount of change in adduction angle was associated with the amount of change in tibial lateral translation. The knee flexion angle at WL was negatively correlated with the knee adduction angle during the UL and WL phases, tibial lateral translation during the WL phase, and the amount of change in tibial lateral translation. These findings supported the second hypothesis. To our knowledge, this is the first study using the 3D-to-2D registration technique to present detailed frontal plane kinematics during stationary stepping activity in severe MKOA. Understanding the increase in tibial lateral translation during stationary stepping activity may contribute to the future development of effective rehabilitation programs or devices.

There are several limitations in this study. First, stationary stepping might have caused knee kinematics to differ from those in gait. Because gait analyses involve several compensations, we consider stationary stepping a more reproducible testing task to determine the kinematic changes in the knees with MKOA over time. Second, the frame rate of fluoroscopic imaging was only 15 Hz. However, since we used only two images during a stepping cycle (UL and WL) and the activity was slow enough, the low sampling rate of 15 Hz would not have affected the results of this study. Third, the 3D-to-2D registration method using single-plane fluoroscopic images provides limited measurement accuracy for out-of-plane kinematics [14]. Therefore, we did not include anterior-posterior translation in this study. Although the study had a small sample size, post-hoc power analyses of tibial lateral translation and knee adduction angle indicated that 8 subjects and 49 subjects, respectively, would be required to achieve statistical power >0.8 . Thus, the kinematics of the knee adduction angle was underpowered.

The knee adduction angle was significantly increased in the current study. However, the amount of change in the knee adduction angle from UL to WL phases was only 0.7° [0.1, 1.3] during the stationary stepping activity. Farrokhi et al. [16] reported that the knee adduction angle increased by 2.2° during the loading response phase in patients with MKOA using DSX (Dynamic Stereo X-ray). The adduction motion during the stepping in the current study was considerably smaller than that in a recent registration study analyzing gait [16]. However, their patients had knees with low K/L grades (grade II or higher), demonstrating a knee adduction angle of only 2.8° at initial contact. Our patients had more severely affected knees with an average knee adduction angle of 5.1° during the UL phase. Considering the smaller knee adduction motion in the current study compared to that in the previous study, the knees of our patients demonstrated greater deformity and stiffness.

The angles demonstrated in this study differed from those in studies using a 3D-motion capture system with skin markers, which is less accurate for abduction/adduction [13] and translation [21]. The knee adduction motion during gait detected using skin markers in previous studies [19,27] was greater than that shown in this study. Nagano et al. [19] showed that severe MKOA had a significantly greater adduction angle of 0.4° at foot contact and a larger adduction motion of 5.9° compared to those in normal subjects. Fukaya et al. [27] showed that the knee adduction angle was 12.3° at initial contact and 15.5° at loading response. Knee adduction motion in this study was smaller than the values shown in previous studies. Since the grade of knee degeneration in our study population was similar to that in the previous studies, analysis using the skin marker system might involve a measurement bias toward greater knee adduction angle during loading during the response phase. Furthermore, we chose stationary stepping activity holding a handrail to avoid compensations such as trunk lean and variable step width. Therefore, our results may be more accurate and reproducible than those of previous studies using skin markers.

There were wide inter-subject variations in tibial external rotation and there were no changes from UL to WL in the current study. In normal knees, the tibia demonstrates external rotation during knee extension. However, several authors reported that osteoarthritis (OA) knees show an abnormal pattern of rotational kinematics. Saari et al. [28] showed that knees with medial arthritis demonstrated decreased tibial internal rotation in knee flexion during squatting. Hamai et al. [29] also reported reduced tibial external rotation in OA knees near extension. Farrokhi et al. [16] showed that MKOA had less external rotation during gait. Takemae et al. [30] reported that only five of 20 OA knees demonstrated normal tibial external rotation during active knee extension during squatting, five demonstrated reverse screw-home movement, and ten demonstrated no rotation pre-operatively. Accordingly, it is understandable that there were no clear rotational kinematic patterns in MKOA observed in this study.

Only a few studies have reported on tibial lateral translation [16,28]. Farrokhi et al. [16] showed that knees with MKOA tended toward tibial lateral translation during gait. Saari et al. [28] also showed that the lateral femoral condyle shifted 20° medially during extension (not significant). The current study demonstrated that knee adduction motion was associated with tibial lateral translation motion. Tibial lateral translation has the potential to move the medial meniscus medially, causing extrusion. Meniscal damage without surgery is a risk factor for the development of radiographic MKOA [31]. Meniscal extrusion was associated with an increased risk of rapid cartilage loss [32] as well as subchondral bone lesions and tibial plateau bone expansion in patients with MKOA [33]. A previous study showed that medial meniscus extrusion was associated with a higher peak knee adduction moment [17]. Moreover, osteophytes in the tibial eminence and intercondylar notch of the femur as an early sign of MKOA [34] may be caused by tibial lateral translation. We suggest that abnormal knee kinematics involving not only knee adduction angle but also tibial lateral translation should receive greater attention. Future studies should be designed to determine whether the tibial-plateau-plane kinematics can be modified by an exercise program or device, and whether such kinematic changes can induce any change in tibial lateral translation and adduction angle.

The knee flexion angle at WL correlated negatively with the amount of change in tibial lateral translation. Less knee extension around heel-strike was associated with greater loss of medial tibial cartilage [35] and increased knee flexion at initial contact resulted in a significant

peak KAM increase [36]. Therefore, knee flexion contracture or extension lag may be the cause of increased knee flexion in subjects with MKOA. Furthermore, knee flexion moment had greater influence on tibial cartilage change, which leads to MKOA progression [37]. However, gait analyses of patients with MKOA demonstrated that the knee flexion angle at initial contact tended to be increased compared to that in normal knees [16,38]. Results of the current and previous studies suggest that greater knee flexion during the WL phase may contribute to a reduction in joint stress caused by abnormal contact kinematics.

The strength of the internal validity of this study should be pointed out. First, we used a 3D-to-2D registration technique combined with fluoroscopy, which is an accurate and well-established technique to measure *in vivo* knee kinematics. The 3D-to-2D registration technique developed by Banks et al. [25] offers superior precision when measuring dynamic knee kinematics *in vivo*. This method using single plane fluoroscopic images was less accurate for out-of-plane kinematics because the actual front and back 3D-pose of bone-models on the screen involves a greater error. Therefore, kinematic analyses of squatting or stair ascent/descent motion in the literature avoided reporting medial/lateral tibial translation relative to the femur. Stationary stepping activity in the frontal plane chosen in this study allowed antero-posterior fluoroscopic imaging to improve the accuracy of medial-lateral translation measurements. Farrokhi et al. [16,39] showed detailed KOA kinematics using dual plane fluoroscopic images. This method was more accurate than analyses using single plane fluoroscopic images, but had a smaller radiographic area, which limited the ability to record greater movement of the joints. The single plane fluoroscopic method has a 17 ×17-inch field of view to allow analysis of squatting and stepping. Second, all analyses were performed by a single investigator to avoid potential inter-investigator errors. Thus, systematic error, for example while embedding the local coordinate system into bone models, would not have influenced these results. As for external validity, the results of this study can be generalized to patients aged 50 years and older with severe MKOA, but is currently limited to Japanese populations.

Conclusions

In conclusion, both knee adduction angle and tibial lateral translation increase from the UL to WL phases in subjects with severe MKOA. Knee flexion angle during the WL phase showed a negative correlation with tibial lateral translation motion. These findings can be generalized to Japanese populations with severe MKOA. Biomechanical association between tibial lateral translation and knee adduction, as well as their associations with varus thrust action will be further investigated in our future studies.

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