Effect of single-radius design on in vivo kinematics during stair activities after total knee arthroplasty

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Abstract

Background: The single-radius design is one of the major total knee arthroplasty (TKA) designs and widely used all over the world. The objective of this study was to compare in vivo kinematics between the anteroposterior (AP) single-radius design with mediolateral (ML) single-radius (Non Restricted Geometry; NRG) and ML dual-radius (Triathlon) during stair activities.

Methods: A total of 21 knees in 18 patients (NRG group: 10 knees in 7 patients, Triathlon group: 11 knees in 11 patients) with a clinically successful posterior stabilized TKA were examined. Under fluoroscopic surveillance, each patient performed stair ascending and descending motions. In vivo kinematics were analyzed using 2D/3D registration technique. The knee flexion angle, rotation angle, varus-valgus angle, AP translation of the femorotibial contact point for both the medial and lateral sides of the knee, and post-cam engagement were evaluated.

Results: There were no significant differences between the two groups in rotation angle and AP translation at each flexion angle. Examining the varus-valgus angle, the NRG group showed varus position at an early flexion angle during both stair activities.

Post-cam engagement was observed in both groups during both stair activities. The mean flexion angle of engagement in the NRG group, the post of which was located anterior to the Triathlon, was larger than that in the Triathlon group during both stair activities.

Conclusion: Despite the same AP single-radius TKA, ML single-radius might affect varus motion at an early flexion angle.

Introduction

Total knee arthroplasty (TKA) is one of the most common, elective surgical interventions for the treatment of severe knee osteoarthritis and inflammatory arthritis [1-3]. However some studies have reported that physical limitations persist after surgery [4-7], and patient satisfaction is lower after TKA than after total hip arthroplasty (THA) [8-10]. It is said that satisfaction with activities of daily living such as walking and stair motion is particularly low [11]. Patients who undergo TKA continue to report difficulty in ascending and descending stairs when compared with an age-matched group of healthy individuals [12, 13]. Evaluation of the kinematics during activities of daily living is important to improve satisfaction after TKA in the future.

Previous studies have evaluated the TKA kinematics of stair motions using video fluoroscopy [14-16]. However, these studies focused on stair-stepping that used a single leg, not swinging through with the opposite leg. Previously, an in vivo three-dimensional (3D) kinematics analysis system for TKA based on a two- to three-dimensional (2D/3D) registration technique was developed [17, 18], and this has enabled patients to be allowed motion flexibility and crossleg motion, as in stair ascending and descending.
Investigating the knee kinematics of daily motion in detail can provide useful information about implant design.

The Scorpio Non Restricted Geometry (NRG) (Stryker Orthopaedics, Mahwah, NJ) is a knee joint prosthesis that has high rotatory degree of freedom because of mediolateral (ML) single-radius femoral component design in addition to an anteroposterior (AP) single-radius. Several studies have reported good kinematics and clinical results of AP single-radius implants during squatting and gait activities [19-21]. However, few studies have evaluated the varus-valgus angle to investigate the influence of the ML single-radius design.

Triathlon (Stryker Orthopaedics) is a knee joint prosthesis that has an AP single-radius with ML dual-radius design, and the insert design is different from that of the NRG. Shimizu et al. reported that this implant provides good stability in mid-flexion ranges during squatting [22]. However, the kinematics during stair activities remains uncertain.

The objective of this study was to compare kinematics between the NRG and the Triathlon during stair activities, and to evaluate the influence of the articular design in AP single-radius TKA (Figure 1).

**Methods**

From November 2003 to November 2010, total of 338 NRG posterior stabilized (PS) TKAs were operated and from December 2009 to December 2014, total of 182 Triathlon PS TKAs were operated by the same surgical team. Among these patients 18 patients agreed to participate in the current investigation with institutional review board approval with documents. Finally 21 knees in 18 patients (NRG group: 10 knees in 7 patients, Triathlon group: 11 knees in 11 patients) with a clinically successful PS TKA resulting in a knee society score (KSS) higher than 90 were examined. At the time of fluoroscopic analysis, mean duration of postoperative follow-up was 8.1 months (range, 3 to 14 months) in NRG group and 8.4 months (range, 3 to 12 months) in Triathlon group.

Under fluoroscopy, each patient performed stair ascending and descending motions at a natural pace. A two-step staircase that was 15 cm high and 30 cm deep was used, and the first step was imaged. The sequential motion was recorded as digital X-ray images (1024 × 1024 × 12 bits/pixel, 7.5-Hz serial spot images as a DICOM file) using a 17-inch flat panel detector system (C-vision Safire L; Shimadzu, Kyoto, Japan). The patients practiced the motion several times before recording.

Femorotibial motion was analyzed using a 2D/3D registration technique, which uses computer-assisted design (CAD) models to reproduce the spatial position of the femoral and tibial components from single-view fluoroscopic images [17, 18, 23]. The accuracy of estimating relative motion between metal components was 0.5° or less in rotation and 0.4 mm or less in translation [17].

The images of the ground touch of the TKA leg on the first step were identified, and the following four phases were selected: 1) at foot strike (FS) (non-weight-bearing); 2) during the stance phase before
crossleg motion (full weight-bearing); 3) during the stance phase after crossleg motion (still weight-bearing); and 4) at foot off (FO) (non-weight-bearing) [24]. The knee flexion angle, rotation angle, varus-valgus angle, AP translation of the femorotibial contact point for both the medial and lateral sides of the knee, and post-cam engagement were evaluated. A local coordinate system at the component was constructed according to the previous study [24]. The knee flexion angle, rotation angle, and varus-valgus angle were described using the joint rotational convention of Grood and Suntay [25]. Flexion, external rotation, and valgus of the femoral component relative to the tibial component were denoted as positive. Positive or negative values of AP translation were defined anterior or posterior to the axes of the tibial component. The femorotibial contact was visualized as the region on the insert surface where the proximity was less than the 0.5-mm threshold [17]. Post-cam engagement was determined by the intersection of the CAD model surfaces of the femoral cam and the tibial post. Measurement results were analyzed statistically using the Mann-Whitney U-test. Values of $p < 0.05$ were considered significant.

Results

Patient background characteristics (Table 1)

The mean age at the time of surgery was 75.7 years (range, 71 to 82 years) in the NRG group and 71.2 years (range, 53 to 80 years) in the Triathlon group. The mean body height at the time of analysis was 159.8 cm (range, 148.0 to 168.0 cm) in the NRG group and 154.5 cm (range, 152.8 to 156.0 cm) in the Triathlon group. The mean spina malleolar distance (SMD) at the time of analysis was 85.5 cm (range, 79.7 to 95.0 cm) in the NRG group and 85.1 cm (range, 81.5 to 90.3 cm) in the Triathlon group. The mean body weight at the time of analysis was 60.5 kg (range, 58.0 to 71.0 kg) in the NRG group and 63.7 kg (range, 51.9 to 81.7 kg) in the Triathlon group. Three knees were of male patients and 7 knees were of female patients in the NRG group, while all knees were of female patients in the Triathlon group. All knees had medial osteoarthritis (Kellgren and Lawrence grade ) in the NRG group, while 9 knees had medial osteoarthritis (Kellgren and Lawrence grade ) and 2 knees had inflammatory arthritis (Larsen grade ) in the Triathlon group. There were no significant differences in the patient background characteristics.

X-ray evaluation

The radiographic component position was evaluated following the Knee Society TKA Roentgenographic Evaluation. In the anteroposterior view, the alignment of the femoral component was 95.2 (standard deviation (SD) 1.8) ° flexion in the NRG group and 95.3 (SD 1.3) ° flexion in the Triathlon group (α angle), and the tibial angle was 89.7 (SD 1.1) ° in the NRG group and 89.7 (SD 1.3) ° in the Triathlon group (β angle). In the lateral view, the alignment of the femoral component was 5.3 (SD 4.8) ° flexion in the NRG group and 3.0 (SD 1.0) ° flexion in the Triathlon group (γ angle), and the tibial posterior slope was 3.7 (SD 1.5) ° in the NRG group and 3.2 (SD 1.9) ° in the Triathlon group. There were no significant differences in the radiographic component positions.

Knee flexion, rotation, and varus-valgus angle (Figure 2)
During stair descending, the mean flexion angle at FS was 4.1 (SD 3.1) ° in the NRG group and 8.0 (SD 3.7) ° in the Triathlon group. Knees were gradually flexed from FS to FO. The mean flexion angle at FO was 43.9 (SD 19.8) ° in the NRG group and 35.5 (SD 11.8) ° in the Triathlon group. The mean flexion angle at FS was significantly smaller in the NRG group than in the Triathlon group. During stair ascending, the mean flexion angle at FS was 57.8 (SD 10.0) ° in the NRG group and 69.2 (SD 7.7) ° in the Triathlon group. Knees were gradually extended from FS to FO. The mean flexion angle at FO was 7.2 (SD 6.1) ° in the NRG group and 9.4 (SD 3.7) ° in the Triathlon group. The mean flexion angle at FS was significantly smaller and the mean flexion angle during the stance phase before crossleg motion was significantly larger in the NRG group (Figure 2A).

The mean rotation angle at FS during stair descending was 6.3 (SD 8.7) ° in the NRG group and 1.9 (SD 2.9) ° in the Triathlon group. External rotation was observed from FS to FO. The mean rotation angle at FO was 8.2 (SD 12.0) ° in the NRG group and 4.0 (SD 4.2) ° in the Triathlon group. During stair ascending, the mean rotation angles at the four phases were 7.0 (SD 12.0) °, 6.5 (SD 10.6) °, 5.8 (SD 10.2) °, and 6.9 (SD 9.2) ° in the NRG group and 2.8 (SD 3.9) °, 4.2 (SD 3.3) °, 4.4 (SD 3.1) °, and 4.0 (SD 2.9) ° in the Triathlon group. There were no significant differences between the two groups (Figure 2B). However, the mean flexion angle was different between the two groups, so further investigation was done at each flexion angle, but there were no significant differences.

In the NRG group, varus position was observed at FS during stair descending and from the stance phase after crossleg motion to FO during stair ascending. The mean varus-valgus angle at FS during stair descending was -1.0 (SD 1.5) ° in the NRG group and 0.29 (SD 0.87) ° in the Triathlon group. The mean varus-valgus angle from the stance phase after crossleg motion to FO during stair ascending was -0.79 (SD 0.44) ° to -0.74 (SD 0.53) ° in the NRG group and -0.037 (SD 0.48) ° to -0.011 (SD 0.40) ° in the Triathlon group (Figure 2C). In the investigation at each flexion angle, there were significant differences at the early flexion angle (Figure 2D). The differences between the maximum varus-valgus angle and the minimum varus-valgus angle during stair descending were 2.1 (SD 2.4) ° in the NRG group and 1.5 (SD 1.8) ° in the Triathlon group. There was no significant difference between the two groups. The differences between the maximum varus-valgus angle and the minimum varus-valgus angle during stair ascending were 3.4 (SD 3.5) ° in the NRG group and 1.2 (SD 0.52) ° in the Triathlon group; both were significant differences.

**AP translation**

During stair descending, the medial femorotibial contact points at the four phases were -2.9 (SD 2.9) mm, -3.2 (SD 2.4) mm, -2.4 (SD 3.1) mm, and -3.1 (SD 4.1) mm in the NRG group and -4.7 (SD 2.5) mm, -5.0 (SD 1.9) mm, -4.3 (SD 1.5) mm, and -3.5 (SD 1.8) mm in the Triathlon group. The lateral femorotibial contact points at the four phases were -7.4 (SD 3.9) mm, -7.2 (SD 4.9) mm, -6.8 (SD 4.0) mm, and -6.7 (SD 4.2) mm in the NRG group and -6.2 (SD 2.1) mm, -6.4 (SD 1.7) mm, -7.1 (SD 1.6) mm, and -6.8 (SD 2.4) mm in the Triathlon group. During stair ascending, the medial femorotibial contact points at the four phases were -1.0 (SD 4.9) mm, -0.79 (SD 4.2) mm, -3.2 (SD 3.6) mm, and -2.7 (SD 3.5) mm in the NRG
group and -4.7 (SD 1.9) mm, -2.8 (SD 1.4) mm, -2.9 (SD 1.3) mm, and -3.7 (SD 1.7) mm in the Triathlon group. The lateral femorotibial contact points at the four phases were -4.9 (SD 4.4) mm, -4.8 (SD 4.7) mm, -7.2 (SD 5.0) mm, and -7.5 (SD 4.3) mm in the NRG group and -6.9 (SD 1.5) mm, -6.3 (SD 2.1) mm, -6.2 (SD 2.2) mm, and -6.8 (SD 1.4) mm in the Triathlon group.

There was no significant difference between the two groups during stair descending. On the other hand, the medial contact point in the Triathlon group was significantly posterior compared to the NRG group at FS during stair ascending. However, in the investigation at each flexion angle, there were no significant differences between the two groups (Figure 3).

**Post-cam engagement (Figure 4)**

During stair descending, post-cam engagement was observed in 2 knees (20.0%) from the stance phase after crossleg motion in the NRG group. On the other hand, 7 knees (63.6%) in the Triathlon group were engaged. The mean flexion angle of the engagement was 62.1 (SD 2.4) ° in the NRG group and 37.9 (SD 10.0) ° in the Triathlon group. During stair ascending, post-cam engagement was observed in all knees from FS. The mean flexion angle of the engagement was 58.7 (SD 10.3) ° in the NRG group and 34.2 (SD 16.9) ° in the Triathlon group. The mean flexion angle of the engagement in the NRG group was larger than that in the Triathlon group significantly during both stair activities.

**Discussion**

In vivo 3D kinematics during stair activities were investigated among AP single-radius designs. NRG has an ML single-radius design, while Triathlon has an ML dual-radius design. Since stair activities are necessary in daily living, it is important to evaluate how an ML single-radius design that has a high rotatory degree of freedom influences the kinematics during stair activities.

During stair descending, the knees were gradually flexed from FS to FO in both groups. On the other hand, during stair ascending, the knees were gradually extended from FS to FO in both groups (Figure 2A). The previous study that investigated another implant during stair activities reported similar bending motions [24]. The mean flexion angle at FS was significantly smaller in the NRG group than in the Triathlon group during both stair motions. The patients’ mean height and SMD were not significantly different between the two groups, so this suggested that the Triathlon group might accommodate a higher staircase.

There was no significant difference between the two groups in the rotation angle. However, the standard deviation was large in the NRG group. This suggested that the ML single-radius design had a high rotatory degree of freedom (Figure 2B).

In the NRG group, varus position was observed at phases without post-cam engagement, which were influenced mainly by the articular surface (Figure 2D). This suggests that ML single-radius TKA influenced the kinematics during stair activities. However, the differences between the two groups were
less than 1 degree, so that this might not be clinically useful. Jo et al. reported that a single-radius implant was more stable than a multi-radius implant in the varus-valgus angle during mid-flexion under anesthesia, but the differences were less than 1 degree, so it might not be clinically useful, as in the present study [26]. The previous study that analyzed in vitro kinematics using cadavers reported that instability in mid-flexion was caused not by the implant design, but by the ligament laxity [27]. However, the present study analyzed in vivo kinematics, so it might reflect daily activities more accurately.

Regarding AP translation at each flexion angle, there was no significant difference between the two groups. This suggested that the AP single-radius influenced both stair activities. Some previous studies reported that AP single-radius TKA displayed few AP translations during stair activities [20, 28], and this might also be caused by the AP single-radius. However, in the previous study of Tamaki et al, AP single-radius TKA showed a pivot pattern in mid-flexion during squatting [19]. Therefore, despite the same mid-flexion, the kinematics might be different with different kinds of daily activities.

The mean flexion angle of post-cam engagement was larger in the NRG group than in the Triathlon group. The predicted post-cam engagement angles as the implant designs are 65 degrees in the NRG and 45 degrees in the Triathlon. The results of this study were close to the predicted post-cam engagement angles. However, regarding AP translation, there was no significant difference between the two groups around each post-cam engagement angle. We have reported that femoral posterior sliding has been observed during stair ascending and descending in AP multi-radius designs [24]. These facts suggested that the post-cam engagement didn't affect AP translation among the AP single-radius designs during stair activities.

During stair ascending, the differences between the maximum varus-valgus angle and the minimum varus-valgus angle were significantly smaller in the Triathlon group than in the NRG group. In addition, the mean flexion angle of post-cam engagement was smaller in the Triathlon group than in the NRG group. This suggested that the Triathlon is a more kinematically stable design than the NRG during stair ascending.

There are a few limitations to this study. First, only limited cases were analyzed, and therefore, the motions of implants might not be completely reproduced. Second, PS designs were investigated, so the difference between the positions of the posts might affect the condylar radius.

**Conclusion**

Despite the same AP single-radius TKA, an ML single-radius design might influence varus motion at an early flexion angle.

**Abbreviations**

TKA: Total Knee Arthroplasty; THA: Total Hip Arthroplasty; 3D: three-dimensional; SD: Standard deviations; 2D/3D: two- to three-dimensional; NRG: Non Restricted Geometry; ML: mediolateral; AP:
anteroposterior; PS: posterior stabilized; CAD: Computer-aided design; FS: foot strike; FO: foot off; SMD: spina malleolar distance; SD: standard deviation.

Declarations

Ethics approval and consent to participate

This study was approved by Osaka University ethics committee (Number 13106). All of the volunteers in this study provided written, informed consent prior to participation.

Consent for publication

Not Applicable

Availability of data and materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

KK and TT designed the study and the initial draft of the manuscript. KK, TI, and TT contributed to analysis of the kinematic data. TY, MT, ST and TT contributed to analysis a data and manuscript preparation. All other authors have contributed to data collection and interpretation, and critically reviewed the manuscript. The final version of the manuscript was approved by all authors.

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Not applicable

References


**Figures**
Figure 1

Component design. The Scorpio NRG has an AP single-radius design with an ML single-radius. On the other hand, the Triathlon has an AP single-radius with an ML dual-radius.
Figure 2

Flexion, rotation, and varus-valgus angles

(A) Flexion angle. The asterisk indicates p < 0.05.

(B) Rotation angle. There is no significant difference between the two groups during stair motion.

(C) Varus-valgus angle. In the NRG group, varus position is observed at FS during stair descending and from the stance phase after crossleg motion to FO during stair ascending (p < 0.05).

(D) Varus-valgus angle at each flexion angle. There are significant differences at a shallow flexion angle (p < 0.05).
Figure 3

AP translation at each flexion angle. There are no significant differences between the two groups.

Figure 4
Post-cam engagement. The upper row shows the NRG group, and the lower row shows the Triathlon group.