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Differences in gait kinetics and kinematics between patients with rotating hinge knee and cruciate-retaining prostheses: A cross-sectional study

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氏　名：大見　武弘

（指導教員名：　山田　拓実　）

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Original Article

Differences in gait kinetics and kinematics between patients with rotating hinge knee and cruciate-retaining prostheses: a cross-sectional study

Takehiro Ohmi, PT, MS[1)*], Takumi Yamada, PT, PhD[2)], Sadaya Misaki, PT, MS[3)], Tomohiro Tazawa, PT, MS[4)], Ryota Shimamura, PT, MS[5)], Junpei Kato, PT, MS[6)], Kazutaka Sugimoto, MD[4)]

[1)] *Clinical Center for Sports Medicine and Sports Dentistry, Tokyo Medical and Dental University: 1-5-45 Yushima, Bunkyo-ku, Tokyo 113-8519, Japan*
[2)] *Faculty of Health Sciences, Graduate School of Human Health Sciences, Tokyo Metropolitan University, Japan*
[3)] *Department of Rehabilitation Medicine, Sonoda Daiichi Hospital, Japan*
[4)] *Sonodakai Joint Replacement Center Hospital, Japan*
[5)] *Tokyo Metropolitan Rehabilitation Hospital, Japan*
[6)] *NEC Livex, Ltd, Japan*

Abstract. [Purpose] Rotating hinge knee prostheses are often used in primary total knee arthroplasty. However, the biomechanics resulting from this treatment remain unexplored. This cross-sectional study compared patient data on gait kinetics and kinematics to assess the efficacy of primary total knee arthroplasty using a rotating hinge knee or other prostheses. [Participants and Methods] Thirty-three participants were assigned to the following groups: rotating hinge knee (n=7); cruciate-retaining prosthesis (n=7); untreated osteoarthritis (n=10); and young adults as a reference group (n=9). Participant data on biomechanical and spatiotemporal parameters were analyzed. [Results] The postoperative course of the rotating hinge knee group was not significantly longer than that of the cruciate-retaining prosthesis group. The knee varus angle and adduction moment of the rotating hinge knee group were significantly smaller than those of the untreated osteoarthritis group. Gait kinetics and kinematics were not different between the rotating hinge knee and cruciate-retaining prosthesis groups. [Conclusion] Participants who had undergone primary total knee arthroplasty with a rotating hinge knee prosthesis had worse preoperative conditions and demonstrated a similar postoperative gait as those who had undergone total knee arthroplasty with other prostheses. Our findings may be used to tailor rehabilitation programs for participants who have undergone total knee arthroplasty with a rotating hinge knee implant.
Key words: Rotating hinge knee, Gait biomechanics, Total knee arthroplasty

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INTRODUCTION

Total knee arthroplasty (TKA) is a common surgical treatment for severe osteoarthritis of the knee joint (KOA), rheumatoid arthritis, and other similar conditions. In Japan, more than 30,000 TKAs are performed annually[1)]. Osteoarthritis cases identified as grade II or worse according to the Kellgren–Lawrence classification are eligible for TKA. The artificial

*Corresponding author. Takehiro Ohmi (E-mail: ohmi.spt@tmd.ac.jp)

knee joint is composed of a femoral component, joint surface, tibial insert, and/or patellar component. The implants used in TKA differ based on the treatment need. For example, a bicruciate-retaining type implant can preserve both the anterior cruciate ligament and posterior cruciate ligament (PCL)[2, 3], whereas a cruciate-retaining (CR) type implant only retains PCL sufficiency[4] and provides the potential benefit of preserving the PCL[5]. A posterior-stabilized (PS) type implant is substituted for the PCL or acts as a constrained condylar design to address collateral ligament insufficiency[6, 7]. Following a TKA, the knee is affected by the femoral component and tibial insert surface geometries; this allows for targeted decisions on implant types, with retention of the PCL being important for CR TKA and retention of the cam-post mechanism being important for PS TKA[5, 8, 9]. A rotating hinge knee prosthesis (RHK) is used for the treatment of global instability or severe bone loss around the knee[10].

Efforts are ongoing to develop more technologically advanced TKA implants. The NexGen Rotating Hinge Knee (Zimmer, Warsaw, IN, USA) is a modern TKA implant type with a modular rotating hinge design. It has the following characteristics: modular augments to address bone defects, modular fluted canal filling stems, more reliable alignment, and additional fixation. It allows 25° of internal and 25° of external rotation of the polyethylene inlay and can control tibial translation anteriorly to posteriorly and laterally to medially[10].

Various methods have been explored to assess the kinetics and kinematics of TKA prosthesis. Motion analysis is used for the systematic and objective description of human locomotion characteristics and deficits[11, 12]. Gait, one of the activities of daily living, has been analyzed in numerous previous reports[13–17]. These reports indicate that walking speed, cadence, step length, knee flexion and extension angles, rotation angle, and knee flexion and extension moment during walking do not significantly differ between participants who undergo either CR TKA or PS TKA[13–15, 17]. Gait kinematics of participants who underwent TKA with implant types for other femoral components have also been examined[16]. These reports suggest that despite differences in preoperative knee conditions, there is no significant difference in gait biomechanics after TKA. However, no studies have reported a motion analysis of participants who have undergone TKA with RHK prosthesis.

The purpose of this study was to compare the gait kinetics and kinematics of participants who underwent primary TKA with an RHK prosthesis with those of participants who underwent primary TKA with a CR prosthesis, participants with KOA who did not undergo TKA, and young adults (YA) without TKA as a reference group. Additionally, the study aimed to understand the biomechanical characteristics of participants who underwent primary TKA with an RHK prosthesis. We hypothesized that these participants would have similar knee joint kinetics and kinematics as participants who underwent primary TKA with CR prosthesis.

PARTICIPANTS AND METHODS

This study had a single-center, cross-sectional design. Ethical approval was obtained from the institutional review board of Tokyo Metropolitan University, Arakawa Campus Committee (approval number, 14107). All participants provided signed informed consent before participating in the study.

The participants were divided into four groups: (1) the RHK group (n=7, all females, 13 knees), comprising participants aged over 40 who underwent primary TKA with the NexGen RHK prosthesis (Zimmer Biomet, Warsaw, IN, USA); (2) the CR group (n=7; all females, 13 knees), comprising participants aged over 40 who underwent primary TKA with a CR prosthesis; (3) the KOA group (n=10, all females, 20 knees), comprising participants aged over 40 and diagnosed with severe stage medial KOA; and (4) the YA group (n=9, all females, 18 knees), comprising participants aged 18–30 years. The RHK and CR groups included participants who underwent TKA for KOA in 2016–2018 at least 6 months prior to study participation and could walk independently. The YA group served as a reference since the RHK was developed to replicate the movement of a healthy knee. Participants in the RHK, CR, and KOA groups were recruited using posters placed in the hospital where several authors of this paper were affiliated. Similarly, participants in the YA group were recruited using posters displayed in a university where several authors of this paper were affiliated.

For the RHK and CR groups, participants who had another disease that affected motor function, such as a neurological disease, were excluded from the study, whereas, for the KOA group, those with neurological disorders affecting motor function or those with a significant cognitive decline were excluded. Participants with neurological disorders affecting motor function were excluded for inclusion in the YA group.

The surgeon selected cases for RHK TKA based on the following criteria[18–20]: remarkable bone loss (Anderson Orthopaedic Research Institute grade II or worse), lax medial collateral ligament, and lax knee flexion because of dissociation of the gap balance between extension and flexion implants of more than 30 mm. The CR type of prosthesis was selected by the surgeon for cases with a Kellgren–Lawrence grade of III or worse and intact PCL[21]. The operations were performed by three orthopedic surgeons associated with the same group. The same rehabilitation protocol was used for all participants. Standing and walking practice started from the day after surgery; independent walking using a rolling walker started within 3 days after surgery; acquiring a 90° knee flexion range, independently walking using a T-cane, and ascending stairs (both feet and one step) started within 1 week after surgery; acquiring a 110° knee flexion, ergometer exercise, independent mat activities, and hospital discharge occurred within 2 weeks after surgery. To prevent deep vein thrombosis, participants wore elastic stockings until 2 months after surgery. Icing was continued for up to 3 months after surgery to reduce inflammation. One researcher measured the femoral tibial angle at pre- and post-surgery in the RHK and CR groups.

All participants were assessed at a comfortable walking pace using a three-dimensional motion analysis system (Vicon Nexus; Oxford Metrics, London, UK) with 10 cameras operating at a sampling rate of 100 Hz. The ground reaction force was captured using two force plates (Kisler Japan, Tokyo, Japan). Fifty-six 9-mm infrared reflective markers were attached to anatomical locations according to the point cluster method. Markers were placed at the following landmarks on both sides; greater trochanters, lateral and medial femoral condyles, the lateral and medial edges of the tibial plateau, lateral and medial malleolus, and second metatarsophalangeal head. Ten and six additional markers were attached to the thigh and shank, respectively. The motor tasks were static standing and walking at a comfortable gait speed on a walkway of approximately 8 m after the participant was able to touch the force plate naturally. A successful trial was defined as a trial in which the patient's entire foot was placed on the surface area of a force plate. The gait speed was an arbitrary speed of the participant's choosing, and the side on which the participants used to start striding was not defined.

The three-dimensional data were imported into the Software for Interactive Musculoskeletal Modeling (SIMM; MusculoGraphics, Santa Rosa, CA, USA). We used the model comprising seven segments, including the pelvis and both thighs, shanks, and feet, which were joined by the hip joints, knee joints, ankle joints, and subtalar joints. Each joint was set to have six degrees of freedom. This model was used for the 36 muscles of each lower extremity. The spatiotemporal parameters (gait speed, cadence, step length, and step width), knee joint angles (flexion, extension, varus, and rotation), and knee adduction moment (KAM) in the stance phase were calculated using SIMM and Plug-in Gait (Vicon Motion Systems, Oxford, UK) software. The knee joint angle included the maximum and minimum flexion angles, the maximum varus angle, the maximum internal/external rotation, the rotation angle (sum of the internal and external rotation angles), and KAM in the stance phase. The KAM was normalized to the individual participant's weight and height (Nm/kg/m).

The spatiotemporal parameters, knee joint angles, and KAM were confirmed to have a normal distribution according to the Shapiro–Wilk test and histogram analysis. Participant's demographics, spatiotemporal parameters, and knee joint angles were compared among the four groups using analysis of variance and post-hoc Tukey tests. KAM was compared between groups using analysis of covariance controlling for gait speed. Effect sizes were computed as an indicator of the quantitative strength of the standardized mean differences (η^2); $\eta^2 \geq 0.20$ presents a small effect, ≥0.50 presents a medium effect, and ≥0.80 presents a strong effect. All statistical analyses were performed using SPSS 23.0 J (IBM Corp., Armonk, NY, USA). The significance level was set to p=0.05.

RESULTS

Patient characteristics are presented in Table 1. The age, height, weight, and body mass index were significantly different between the YA group and other groups (p<0.01). There were no significant differences among the RHK, CR, and KOA groups. The postoperative course durations of the RHK and CR groups were 12.0 (24.0) months and 6.0 (1.5) months, respectively (p=0.05, median [interquartile range]). The femoral tibial angles for the RHK and CR groups preoperatively were 180.2 ± 9.0° and 182.5 ± 7.9° (p=0.39) and postoperatively were 175.2 ± 1.5° and 178.9 ± 7.7° (p=0.97), respectively.

All spatiotemporal parameters are summarized in Table 2. Gait speed was significantly faster in the YA group than in the other groups (p<0.01). The RHK group was significantly slower than the CR group and YA group. Step length was significantly longer in the YA group than the other three groups. Step width was significantly narrower in the YA group than the other three groups (p<0.01, respectively).

A comparison of the kinetics and kinematics of the groups is summarized in Table 3 and Figs. 1–4. The sagittal angle was smaller in the KOA group than the YA group. The knee varus angle was larger in the KOA group than in the other three groups (p<0.01, respectively), and was smaller in the RHK group compared with the YA group (p=0.02). The KOA group had a larger KAM with gait speed as the covariate compared with the other groups (p<0.01, respectively). The other parameters were not significantly different among the groups.

Table 1. Participant demographics of each group

Items	RHK group n=7, 13 knees (Mean ± SD)	CR group n=7, 13 knees (Mean ± SD)	KOA group n=10, 20 knees (Mean ± SD)	YA group n=9, 18 knees (Mean ± SD)	ES η^2 value
Age (years)*	68.7 ± 14.0	73.0 ± 4.9	70.5 ± 4.8	23.3 ± 2.6	0.9
Height (cm)*	150.1 ± 7.6	149.0 ± 0.1	149.2 ± 3.9	158.9 ± 4.0	0.5
Weight (kg)**	69.8 ± 10.8	58.1 ± 10.4	62.7 ± 9.6	53.6 ± 4.8	0.3
BMI (kg/m^2)***	31.1 ± 5.0	26.2 ± 4.5	28.3 ± 4.8	21.2 ± 1.5	0.5

All items were compared among the four groups using analysis of variance and post-hoc Tukey tests.
RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults; ES: effect size; BMI: body mass index.
*The YA group was significantly younger in age and lesser in height than the other groups (p<0.01).
**The YA group was significantly lighter in weight than the RHK group (p<0.01).
***The YA group had a significantly lower BMI than the RHK and KOA groups (p<0.01).

Table 2. Spatiotemporal parameters of each group

Items	RHK group (Mean ± SD)	CR group (Mean ± SD)	KOA group (Mean ± SD)	YA group (Mean ± SD)	ES η^2 value
Gait Speed (m/s)*	0.9 ± 0.2	1.1 ± 0.2	0.9 ± 0.3	1.2 ± 0.1	0.5
Step Length (m)**	0.5 ± 0.7	0.5 ± 0.1	0.5 ± 0.9	0.7 ± 0.2	0.3
Step Width (m)***	0.2 ± 0.4	0.1 ± 0.4	0.2 ± 0.1	0.1 ± 0.0	0.1
Cadence (steps/min)†	111.4 ± 10.2	116.1 ± 8.7	106.8 ± 11.8	119.7 ± 6.8	0.3

All items were compared among the four groups using analysis of variance and post-hoc Tukey tests.
RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults.
*The YA group has faster gait speed than the other three groups. The RHK group was significantly slower than the CR group and YA group ($p<0.01$ respectively).
**The YA group had a significantly longer step length than the other groups ($p<0.01$ respectively).
***The YA group had a narrower step width than the other three groups ($p<0.01$ respectively).
†The KOA group was lower than the YA group ($p<0.03$).

Table 3. The results of average in stance phase of each group

Items	RHK group (Mean ± SD)	CR group (Mean ± SD)	KOA group (Mean ± SD)	YA group (Mean ± SD)	ES η^2 value
Flexion angle (°)	19.5 ± 6.7	14.6 ± 5.0	14.0 ± 10.4	25.7 ± 3.3	0.1
Extension angle (°)	−14.2 ± 4.7	−7.8 ± 3.6	−9.5 ± 11.6	−11.7 ± 2.9	0.1
Sagittal angle (°)*	6.2 ± 3.8	6.8 ± 4.0	4.9 ± 2.0	14.1 ± 4.6	0.2
Varus angle (°)**	−2.7 ± 2.8	0.9 ± 3.0	5.6 ± 2.3	3.8 ± 2.9	0.6
Internal rotation angle (°)	−2.2 ± 4.1	−1.8 ± 9.9	−1.5 ± 10.7	−5.8 ± 6.9	0.1
External rotation angle (°)	−10.4 ± 5.5	−9.5 ± 9.5	−8.6 ± 10.2	−14.4 ± 6.6	0.1
Rotation angle (°)	8.2 ± 8.5	7.6 ± 8.3	7.0 ± 12.1	8.6 ± 3.2	0.01
KAM (Nm/kg/m)[a]***	0.2 ± 0.0	0.3 ± 0.1	0.4 ± 0.2	0.4 ± 0.1	0.4

Knee joint angles were compared among the four groups using analysis of variance and post-hoc Tukey tests. KAM was compared between the groups using analysis of covariance (ANCOVA) controlling for step length.
KAM: knee adduction moment; RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults.
*The KOA group had a significantly smaller sagittal angle than the YA group ($p=0.02$).
**The KOA group had a significantly larger varus angle than the other three groups ($p<0.01$, respectively), and the RHK group had a smaller varus angle than the YA group ($p=0.02$).
***The RHK, CR, and YA groups were significantly smaller than the KOA group ($p<0.01$, respectively).

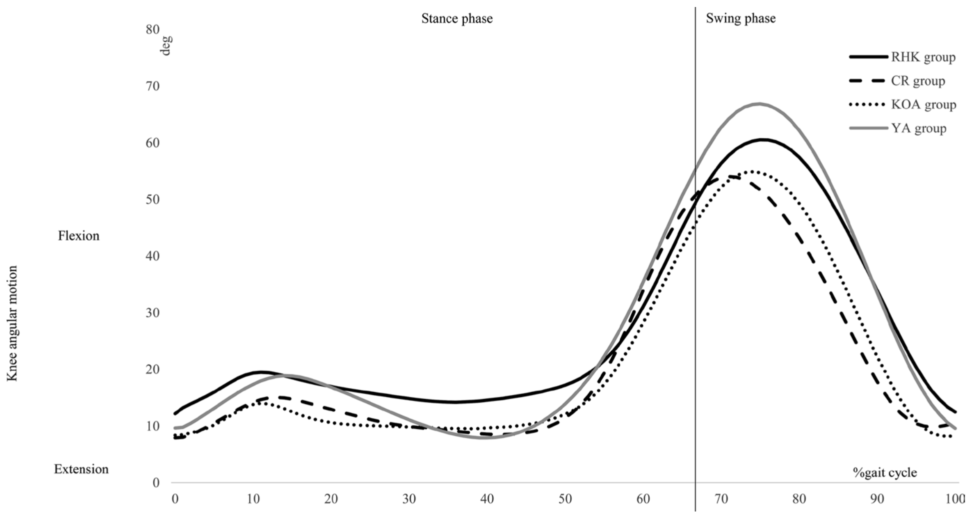

Fig. 1. Knee angular motion (sagittal plane).
The continuous line, dash line, dot line, and light-colored line show the RHK, CR, KOA, and YA groups, respectively.
RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults.

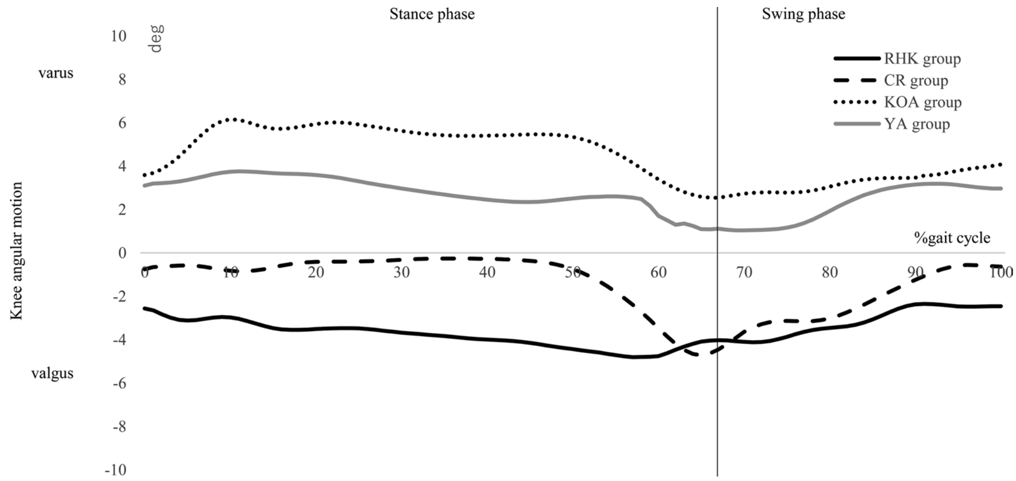

Fig. 2. Knee angular motion (frontal plane).
The continuous line, dash line, dot line, and light-colored line show the RHK, CR, KOA, and YA groups, respectively. RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults.

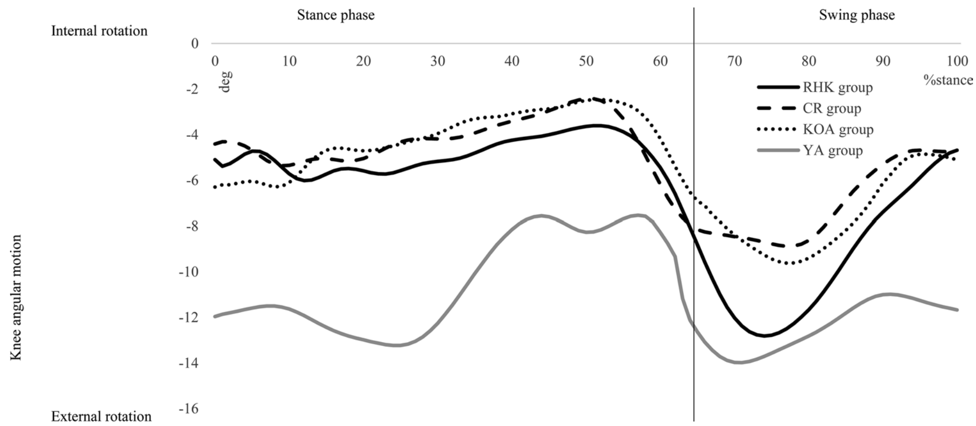

Fig. 3. Knee angular motion (horizontal plane).
The continuous line, dash line, dot line, and light-colored line show the RHK, CR, KOA, and YA groups, respectively. RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults.

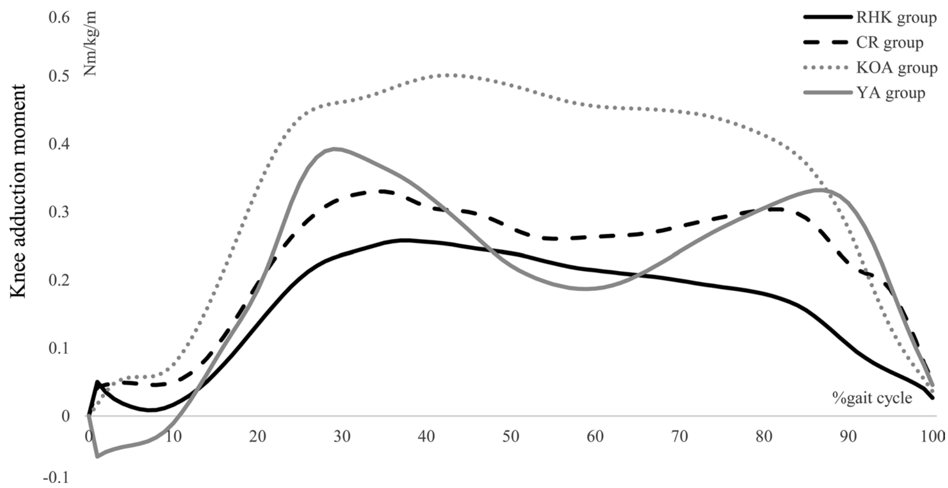

Fig. 4. Knee adduction moment.
The continuous line, dash line, dot line, and light-colored line show the RHK, CR, KOA, and YA groups, respectively. RHK: rotating hinge knee; CR: cruciate retaining; KOA: knee osteoarthritis; YA: young adults.

DISCUSSION

The main findings of this study were as follows: 1) the knee varus angle and KAM of the RHK and CR groups were smaller than those of the KOA group, 2) the knee varus angle and KAM of the RHK and CR groups were not significantly different to those of the YA group, and 3) there was no difference in biomechanics during gait between the RHK and CR groups. These findings supported our initial hypothesis.

The knee varus angle and KAM of the RHK and CR groups were significantly smaller than those of the KOA group. This was due to the correction of the knee alignment following TKA surgery. There was no difference among the groups in terms of knee flexion and extension angles during gait in the stance phase. The flexion angle in the stance phase of gait is reported to be decreased in participants who have undergone primary TKA[22], but is not significantly different from that of controls[23, 24]. In our study, the knee flexion angle of the RHK group in the stance phase supported the latter finding. The knee flexion angle during gait in participants who underwent primary TKA with RHK was comparable with those reported in previous studies. Both RHK and CR groups presumably had improved biomechanics during gait due to TKA surgery in the frontal plane.

There was no significant difference in knee joint angles, except the varus angle, and the KAM in the RHK and CR groups was comparable with that of the YA group. The results of our study were in line with those of previous reports, in which the KAM was not significantly different between the control groups and participants at 1 year post-TKA[25–27]. The KAM of the RHK group in this study was equivalent to or slightly smaller than that reported in a previous study[28] and was comparable with that of participants who underwent TKA with other components. The knee varus angle of the RHK and CR groups was significantly smaller than that of the YA group, suggesting that the medial knee support mechanism of the RHK and CR groups may have been looser. These results indicated that the biomechanics of the knee during gait in the RHK and CR groups were closer to the knee motion of the YA group.

There were no biomechanical differences in KAM or other knee biomechanical differences during gait between the RHK and the CR group. The KAM is related to frontal lower limb alignment, and an increase in the KAM is directly related to an increase in the medial compartment load in the knee[29–31]. Prodromos et al.[32] reported that static knee alignment can predict dynamic knee loading. There was no difference in the femoral tibial angle at post-surgery between the RHK and CR groups. It is highly probable that there was no difference in the knee varus angle or KAM during walking. The RHK group had a poor knee condition before TKA, and the RHK is a highly restrictive implant. It is considered that the KAM of the RHK group was equivalent to that of the CR and YA groups because of the influence of the implant design.

We showed kinetics and kinematics data for rotation, which underlies RHK development concepts during gait. Showing such motion analysis data to participants who are planning to undergo primary TKA with an RHK prosthesis may help guide postoperative motion and rehabilitation. It is necessary to verify whether the development concept of RHK is reflected in other daily activities, such as climbing up and down stairs, sitting down, and standing up.

This study had some limitations. First, it was unclear whether participants who underwent RHK TKA would exhibit a similar recovery process as that of participants who underwent CR TKA since this was a cross-sectional study. Fortin et al.[33] reported that the Western Ontario and McMaster Universities Osteoarthritis Index function plateaus after six months from primary TKA. It is unknown whether participants who undergo primary TKA show changes in kinetics and kinematics of gait during recovery. This research question can be addressed in a prospective study. Second, the participants in each group were all females, and it is unclear whether our results could be equally applicable to males. Further studies are needed to analyze gait kinetics and kinematics in males.

This study analyzed the kinetics and kinematics of a comfortable gait in participants who have undergone primary TKA with an RHK prosthesis and found that these characteristics did not differ from those of participants who underwent TKA with a CR prosthesis. Despite a worse preoperative condition in participants who underwent RHK-type TKA, their gait characteristics resembled those of participants who underwent TKA with other prosthetic components. Our results provide information that can be used to tailor rehabilitation for participants who have undergone TKA with RHK. Future research should analyze the kinetics and kinematics of the knee joint in other daily movements.

Funding and Conflict of interest

TY received research support from Zimmer Biomet, LLC. However, the sponsor had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. There are no patents, products in development, or marketed products to declare. Authors other than TY have no conflicts of interest.

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