Journal of Clinical Orthopaedics and Trauma 39 (2023) 102150

Contents lists available at ScienceDirect

Journal of Clinical Orthopaedics and Trauma

journal homepage: www.elsevier.com/locate/jcot

Verification of biomechanical factors of gait related to medial knee loading in patients 6 Months after total knee arthroplasty

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A R T I C L E I N F O

Article history:
Received 24 October 2022
Accepted 31 March 2023
Available online 7 April 2023

Keywords:
Total knee arthroplasty
Gait analysis
Medial knee loading
Knee adduction moment impulse

A B S T R A C T

Background: The knee adduction moment (KAM) is considered an index for estimating the knee mechanical load, and increased KAM peak and KAM impulse are related to increased medial knee load and progression of knee joint degeneration. We aimed to verify the biomechanical factors of gait related to medial knee loading in patients 6 months after TKA.

Methods: Thirty-nine women who underwent TKA were enrolled. A three-dimensional gait analysis was performed 6 months postoperatively to generate data on the lower limb joint angle, moment, and power at the backward component (braking phase) and forward component (propulsion phase) peaks of the ground reaction force. Medial knee loading was evaluated using the time-integrated value of KAM during the stance period (KAM impulse). The higher the value of the KAM impulse, the higher the medial knee joint load. The relationships between the KAM impulse and the data for biomechanical factors were evaluated using partial correlation analysis with gait speed as a control factor.

Results: In the braking phase, the KAM impulse positively correlated with the knee adduction angle ($r = 0.377$) and negatively correlated with the toe-out angle ($r = -0.355$). The KAM impulse positively correlated with the knee adduction angle ($r = 0.402$), the hip flexion moment ($r = 0.335$), and the hip adduction moment ($r = 0.565$) and negatively correlated with the toe-out angle ($r = -0.357$) in the propulsive phase.

Conclusion: The KAM impulse 6 months after TKA was related to the knee adduction angle, hip flexion moment, hip adduction moment, and toe-out angle. These findings may provide fundamental data for controlling variable medial knee joint load after TKA and implementing patient management strategies to ensure implant durability.

1. Introduction

Total knee arthroplasty (TKA) is an intervention tool to improve knee function. While patient satisfaction after the procedure is high[1] and stable long-term results[2] have been reported, durability concerns have been raised, such as polyethylene wear and implant loosening.[3,4] These problems arise from the component malalignment of the implant that occurs after TKA. In particular, biases, such as instability of the knee articular surface, may increase the joint load and lower the implant's durability.[3,5,6]

There are many reports on motion analysis after TKA; in particular, gait analysis is considered a tool to evaluate treatment outcomes.[7–9] The knee adduction moment (KAM) is considered an index for estimating the knee mechanical loading. Increased KAM peak and KAM impulse are associated with increased medial knee load and progression of knee joint degeneration.[10–12] Hence, it is necessary to evaluate the KAM while in gait after TKA to ensure the durability of the implant. Orishimo et al.[13] reported that KAM 6 months or less after TKA was lower than preoperative KAM. However, gait analysis of patients more than 1 year after TKA demonstrated that KAM sometimes returned to preoperative values.[7,9] These findings imply that it may return to presurgical

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https://doi.org/10.1016/j.jcot.2023.102150
0976-5662/

levels of excessive loading over time.

KAM is affected by the magnitude of the ground reaction force and the vertical length of the line of the ground reaction force from the center of knee joint(moment arm).[14] Robbins et al.[15] showed that KAM increases with increasing gait speed, which supports the finding that ground reaction force is related to gait speed.[16] However, factors related to the length of the moment arm should also be considered. A report on knee osteoarthritis has shown relationships between KAM and biomechanical factors of gait, such as knee adduction angle and hip extensor activity during gait.[17,18] Although it has been reported that the patient repeats the preoperative gait pattern after TKA,[19] the biomechanical factors of gait related to KAM need to be clarified for that period, as changes in KAM are expected after 6 months after TKA. Clarifying these relationships could provide fundamental data for controlling medial knee loading after TKA and implementing patient management techniques to ensure implant durability.

In this study, we aimed to verify the biomechanical factors of gait related to medial knee loading in patients 6 months after TKA. The hypothesis was that medial knee loading would demonstrate a relationship to biomechanical factors, such as knee adduction angle, hip adduction moment, and extensor function, during gait. In addition, toe angle is a kinematic variable that has been shown to affect KAM,[20] and we hypothesized that this contact pattern would be related to medial knee loading.

2. Materials and methods

2.1. Participants

The data of 188 women without a history of a central disease who underwent primary TKA between October 2013 and January 2021 were acquired from the clinical data of our hospital. All patients underwent rehabilitation according to protocol, and were discharged in approximately 4 weeks. No outpatient rehabilitation was provided after discharge. Of the 188 patients, 39 patients, whose three-dimensional gait analyses were available 6 months after TKA, were enrolled. One hundred and forty-nine out of the 188 patients could not undergo a three-dimensional gait analysis due to reimbursement system issues, hospital transfers, or other unknown reasons. Consent for the use of clinical data was obtained by opt-out through a form while in the hospital, and appropriate opportunities for refusal were provided. This study was performed with the approval of the ethics committee.

2.2. Gait analysis

Gait analysis was performed using a three-dimensional motion system (Coretex 6; Motion Analysis, Santa Rose, CA, USA) and force plates (AMTI; Watertown, MA, USA). The sampling frequency were set to 60 Hz for kinematic data and 300 Hz for force data. Twenty-nine reflective markers with a diameter of 14 mm were affixed on the body according to Helen Hays marker set. Six months after TKA, participants were asked to walk three trials at a self-selected speed.

Gait data were analyzed using visual3D (C-Motion, Inc., Germantown, MD, USA). The three-dimensional coordinates and force plate data were low-pass filtered at 6 and 18 Hz, respectively. During the stance phase, the lower limb joint angle, moment, and power parameters were calculated. The joint moment and power were normalized for body weight. The angle of the foot segment in the horizontal plane relative to the ground surface was determined to calculate the toe angle. The average of these data were calculated respectively. Using the backward component peak of the ground reaction force (braking phase) and the forward component peak of the ground reaction force (propulsion phase), gait parameters were extracted at each time-point, as described by Andriacchi et al.[21]

2.3. Medial knee loading

KAM impulse was used as an index of medial knee loading. KAM impulse was calculated as the time integration of KAM during the stance period, and the higher the value, the higher the medial knee joint load.[22] In this study, the KAM impulse of the operated limb was calculated, and the mean value was adopted.

2.4. Statistical analysis

Statistical analyses were completed using IBM SPSS Statistics version 27 (IBM Corp.; Armonk, NY, USA). A partial correlation analysis was used to examine the relationships between the KAM impulse and the biomechanical factors using gait speed as a control factor ($p < 0.05$).[15,23]

3. Results

Table 1 shows the participant characteristics. Table 2 presents the results of the gait biomechanics data. Correlation coefficients between KAM impulse and gait parameter values extracted from the gait analysis are shown for the operated side (Table 3).

KAM impulse was positively correlated with the knee joint adduction angle ($r = 0.377$, $p = 0.020$) and negatively correlated with the toe-out angle ($r = -0.355$, $p = 0.029$) in the braking phase. KAM impulse was positively correlated with the knee adduction angle ($r = 0.402$, $p = 0.012$), the hip flexion moment ($r = 0.335$, $p = 0.039$), and the hip adduction moment ($r = 0.565$, $p = 0.0002$) and negatively correlated with the toe-out angle ($r = -0.357$, $p = 0.028$) in the propulsive phase.

4. Discussion

There was a positive correlation between the KAM impulse and the adduction angle during the braking and propulsion phases. Charles et al.[24] investigated the relationship between the static and dynamic alignments of the knee joint on the frontal plane during gait 3 months after TKA and found no significant correlation between the two. Orishimo et al.[13] compared the static knee joint alignment and the knee adduction angle while in gait at 6 months and 1 year after TKA, respectively, to preoperative levels. Static knee adduction alignment decreased 1 year after TKA, but the knee adduction angle while in gait decreased 6 months after TKA and then reverted to preoperative values 1 year after TKA. In other words, even if the static knee joint alignment was within the normal range, the knee adduction angle increased while in gait and

Table 1
Patient information (results at 6 months after TKA).

	Thirty-nine women
Age (years)	69.6 ± 6.9
Height (cm)	153.0 ± 7.0
Weight (kg)	57.9 ± 8.2
BMI (kg/m2)	24.8 ± 3.5
Range of motion of knee flexion (°)	121.3 ± 9.3
Range of motion of knee extension (°)	−1.0 ± 2.0
FTA operated limb side (°)	176.6 ± 2.0
FTA unaffected limb side (°)	179.8 ± 6.8
Gait speed (m/s)	1.0 ± 0.2

Mean ± standard deviation.
BMI: body mass index.
Implant: all patients cement.
FTA: femorotibial angle.

Table 2
Gait biomechanics data (results 6 months after total knee arthroplasty).

Item	Breaking phase	Propulsion phase
KAM impulse (Nm*s/BW)	0.5 ± 0.2	
Hip extension angle(°)	2.7 ± 2.0	30.4 ± 4.1
Hip adduction angle(°)	2.4 ± 1.5	0.5 ± 3.3
Knee flexion angle(°)	7.8 ± 2.8	17.2 ± 6.3
Knee adduction angle(°)	0.1 ± 1.3	1.7 ± 2.7
Ankle dorsiflexion angle(°)	−1.2 ± 7.2	13.3 ± 9.4
Toe-out angle(°)	4.4 ± 5.1	3.5 ± 5.9
External hip flexion moment(Nm/BW)	0.8 ± 0.2	−0.1 ± 0.3
External hip adduction moment(Nm/BW)	0.4 ± 0.2	0.3 ± 0.1
External knee flexion moment(Nm/BW)	0.2 ± 0.1	0.2 ± 0.2
External knee adduction moment(Nm/BW)	0.2 ± 0.1	0.2 ± 0.1
External ankle dorsiflexion moment(Nm/BW)	0.01 ± 0.10	0.8 ± 0.1
Hip extension joint power(W/BW)	0.6 ± 0.3	−0.03 ± 0.26
Knee extension joint power (W/BW)	−0.2 ± 0.3	−0.5 ± 0.4
Ankle plantarflexion joint power(W/BW)	−0.03 ± 0.11	1.8 ± 0.8

n = 39, mean ± standard deviation.
braking phase: point of peak value of backward component of floor reaction force while in gait propulsion phase: point of peak value of forward component of floor reaction force while in gait.
Toe-out angle: Abduction angle of the foot with respect to the floor.
BW: body weight knee adduction moment impulse (KAM impulse): time integral of KAM during the stance phase.

Table 3
Partial correlation coefficients between the knee adduction moment impulse and gait biomechanics data(r).

Item	KAM impulse (Nm*s/BW)	
	Beaking phase	Propulsion phase
Hip extension angle(°)	0.109	0.116
Hip adduction angle(°)	−0.254	0.161
Knee flexion angle(°)	0.118	0.081
Knee adduction angle(°)	0.377*	0.402*
Ankle dorsiflexion angle(°)	0.028	0.021
Toe-out angle(°)	−0.355*	−0.357*
External hip flexion moment(Nm/BW)	−0.090	0.335*
External hip adduction moment(Nm/BW)	0.227	0.565**
External knee flexion moment(Nm/BW)	−0.078	−0.074
External knee adduction moment(Nm/BW)	0.481**	0.862**
External ankle dorsiflexion moment(Nm/BW)	−0.150	0.274
Hip extension joint power(W/BW)	0.125	−0.087
Knee extension joint power (W/BW)	0.082	0.140
Ankle plantarflexion joint power(W/BW)	−0.144	0.163

n = 39, *: $p < 0.05$, **:$p < 0.01$.
Partial correlation coefficients: using gait speed as control factors knee adduction moment impulse (KAM impulse): time integral of KAM during the stance phase.

could affect the KAM as a result. The positive relationship observed in this study between KAM impulse and knee adduction supports these conclusions.

We found that the KAM impulse was positively related to the hip adduction moment in the propulsive phase. Chang et al.[25] suggested that a decrease in the hip adduction moment during the stance phase is related to a decrease in medial knee loading and prevents the progression of medial knee osteoarthritis. As the magnitude of the external center-of-gravity shift increases while in gait, the hip adduction moment becomes higher. In this case, the increase in the outward center-of-gravity shift may result in an increase in the medial knee joint load, increasing the KAM impulse. The hip abductor muscles may influence the outward center-of-gravity shift. It has been reported that hip abductor muscle strength after TKA recovers to preoperative levels only 3 months after TKA.[26] Therefore, although not measured in this study, the degree of recovery of hip abductor muscle strength could have resulted in a relationship between KAM impulse and hip adduction moment.

The positive correlation between KAM impulse and hip flexion moment in the propulsive phase is consistent with our hypothesis. Saari et al.[27] found that an increase in hip flexion moment occurs in patients who underwent TKA compared with the healthy age-matched controls. The hip extension moment while in gait occurs during the propulsive phase and is considered to reflect the function of the hip extensor muscle group.[28] An increase in KAM impulse is related to an increase in the outward center-of-gravity movement,[29] which is considered to interfere with forward propulsion. Research on knee osteoarthritis has identified decreased hip flexor muscle activity as a factor related to increased KAM,[18] and the present study showed a similar relationship. This suggests that hip flexion moment in the propulsive phase is a parameter to focus on as a factor related to KAM 6 months after TKA.

In gait patterns with more laterally directed toe angles, the ground reaction force vector is close to the knee joint center, decreasing KAM.[30,31] The present study's finding that there was an inverse correlation between KAM impulse and toe-out angle supports this interpretation. However, previous studies have also found that a decrease in KAM occurred in the gait pattern of patients with knee osteoarthritis, in which the toe-out angle was intentionally decreased.[32] Hence, the interpretation of the relationship between KAM impulse and toe angle is limited.

This study had some limitations. First, only women were included in this study. Gender differences occur in biomechanical factors of gait after TKA, with a higher KAM reported in men than in women.[33] This makes it difficult to make the same interpretations for men as for women. Second, the cut-off value of the KAM impulse used in this study was not defined. It has been reported that an increase in KAM impulse leads to a limitation in gait function and worsening of pain[29]; however, the definition for the normal range of KAM impulse is unclear. Future studies are required to verify the upper and lower values of KAM impulse that can be tolerated. Third, our findings were measured 6 months after TKA. Lower extremity muscle strength and gait parameters are reported to vary over a period of up to 1 year after surgery.[13,34] Therefore, there is a need for successive verification of the interpretation of these findings.

There was a relationship between KAM impulse 6 months after TKA and biomechanical factors of gait pertaining to knee adduction angle, hip adduction moment, hip flexion moment, and toe-out angle supporting our hypothesis. These findings may provide fundamental data for controlling variable medial knee joint load after TKA and implementing patient management strategies to ensure implant durability.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors, and no material support of any kind was received.

Ethics statement

The study protocol was approved by the ethics committee of Josai International University (approval number 10M200002). Consent for the use of daily medical records was obtained by opt-out through a form while in the hospital, and appropriate opportunities for refusal were provided for use of daily medical records.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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