**Original Article** Clinics in Orthopedic Surgery 2024;16:455-460 • https://doi.org/10.4055/cios23331

# Change of Segmental Motion Following Total Ankle Arthroplasty Using a 3-Dimensional Multi-segment Foot Model

Gil Young Park, MD, Min Gyu Kyung, MD*,#, Young Sik Yoon, MD†, Dae-Yoo Kim, MD‡, Dong-Oh Lee, MD, Dong Yeon Lee, MD*,§

*Department of Orthopedic Surgery, SNU Seoul Hospital, Seoul,*
**Department of Orthopedic Surgery, Seoul National University Hospital, Seoul,*
*†Department of Orthopedic Surgery, Kangwon National University Hospital, Chuncheon,*
*‡Department of Orthopedic Surgery, Inje University Busan Paik Hospital, Busan,*
*§Department of Orthopedic Surgery, Seoul National University College of Medicine, Seoul, Korea*

**Background:** Total ankle arthroplasty (TAA) enhances patients' subjective outcomes with respect to pain and function. The aim of this study was to analyze the biomechanical changes of the affected limb following TAA using gait analysis with a 3-dimensional multi-segment foot model (3D MFM).

**Methods:** We reviewed medical records, simple radiographs, and gait analyses using a 3D MFM of patients who underwent TAA for severe varus ankle arthritis. Preoperative and postoperative gait data of 24 patients were compared. Postoperative gait analyses were done at least 1 year after surgery.

**Results:** TAA significantly increased stride length ($p$ = 0.024). The total range of motion of all planes in the hindfoot and forefoot showed no significant changes between preoperative and postoperative states. Hindfoot was significantly plantarflexed and pronated after TAA, while forefoot was significantly supinated in all phases. After appropriate calculations, the genuine coronal motion of the hindfoot showed no changes after TAA in all phases.

**Conclusions:** TAA did not result in biomechanical improvements of segmental motions in the forefoot and hindfoot, except for changes to the bony structures. Therefore, it is important to point out to patients that TAA will not result in significant improvement of ankle function and range of motion. Clinicians can consider this information during preoperative counseling.

**Keywords:** *Ankle, Osteoarthritis, Total ankle arthroplasty, Gait, Multi segment foot model*

Ankle osteoarthritis (OA) is a debilitating disease that causes morbidity equivalent to hip OA or congestive heart failure.[1,2] Total ankle arthroplasty (TAA) has become a popular option for the treatment of ankle OA with improvements in the prosthetic design and surgical technique.[3] Recent studies have reported that TAA enhanced

Received October 23, 2023; Revised December 13, 2023; Accepted December 13, 2023
Correspondence to: Dong-Oh Lee, MD
Department of Orthopedic Surgery, SNU Seoul Hospital, 237 Gonghang-daero, Gangseo-gu, Seoul 07803, Korea
Tel: +82-2-333-5151, Fax: +82-2-333-5152, E-mail: ronaki@naver.com
Co-Correspondence to: Dong Yeon Lee, MD
Department of Orthopedic Surgery, Seoul National University Hospital, Seoul National University College of Medicine, 101 Daehak-ro, Jongno-gu, Seoul 03080, Korea
Tel: +82-2-2072-1863, Fax: +82-2-764-2718, E-mail: leedy@snu.ac.kr
#Current affiliation: Department of Orthopedic Surgery, Kyung Hee University Hospital at Gangdong, Seoul, Korea


Clinics in Orthopedic Surgery • pISSN 2005-291X eISSN 2005-4408

patients' subjective outcomes with respect to pain and functional abilities, as well as radiographic outcomes in the static state.[4,5)]

However, biomechanics following TAA are not yet fully understood. Although previous studies employed gait analysis, they were mainly about spatiotemporal parameters, dorsiflexion, and plantarflexion of the ankle in the sagittal plane. Most of these studies analyzed the gait of patients who underwent unilateral TAA.[6,7)] There were only a few studies regarding the change of gait patterns between preoperative and postoperative states of the same affected limb of the patient after TAA.[8-11)]

Gait analysis using a 3-dimensional multi-segment foot model (3D MFM) has recently gained popularity.[12)] Single-segment conventional gait analysis is not ideal for the evaluation of foot and ankle motion because the foot segment is misconceived as s single rigid body.[13)] 3D MFM has the potential to overcome the limitations of the single-segment foot model, which is widely used.[14)] Many diseases, including hallux rigidus and chronic ankle instability, were studied with the use of 3D MFM. However, there are few studies using 3D MFM to analyze the biomechanical changes after TAA.

Therefore, we sought to analyze the biomechanical changes of the affected limb following TAA using gait analysis with a 3D MFM. Our hypothesis, per previous studies using single-segment gait analysis, was that TAA would enhance the spatiotemporal parameters of patients compared to those in the preoperative state and increase the range of motion of the forefoot and hindfoot in all planes.

## METHODS

### Ethical Statements

All study subjects provided informed consent, and the study protocol was approved by the Institutional Review Board at Seoul National University Hospital (IRB No. H-1010-047-335). All research protocols were carried out per the ethical standards of the Institutional Review Board and with the Declaration of Helsinki.

### Participants

We reviewed medical records, simple radiographs, and gait analyses using a 3D MFM of patients who underwent TAA for severe varus ankle arthritis in our hospital. The inclusion criteria were patients (1) who completed preoperative and postoperative (at least 1 year after surgery) gait analysis using a 3D MFM, (2) with no perioperative complications including postoperative infection, aseptic loosening, heterotopic ossification, or periprosthetic osteolysis, (3) with no significant postoperative functional deficits, (4) with normal hip and knee joints observed from preoperative scanogram radiographs, and (5) with minimal pain at postoperative follow-up with visual analog scale scores lower than 3. We excluded patients (1) who underwent other simultaneous procedures such as calcaneal osteotomy or supramalleolar osteotomy combined with TAA and (2) with other joint problems. As a result, a total of 24 patients were included in our study. The demographic characteristics are presented in Table 1.

All patients were operated by a single senior surgeon (DYL), and TAA was performed using the HINTEGRA (Newdeal) mobile bearing system in all patients.

### Radiographic Evaluation

Two orthopedic surgeons with more than 5 years of experience (GYP, DYK) determined the OA stage in all study patients from preoperative simple radiographs of the weight-bearing anteroposterior ankle. We employed both the Takakura and the Knupp ankle OA classification systems for each stage.[15,16)]

### Gait Analysis Using an MFM

All patients underwent routine preoperative assessment using a 3D MFM using 15 markers upon admission to the hospital for surgery. Three-dimensional gait analysis with MFM was done according to the previously known protocol.[13,17)] Kinematic data of segmental motion of the foot were analyzed with Foot 3D Multi-Segment Software (Motion Analysis) while the patients walked along an 8-m track at a comfortable speed. Three representative strides selected from 5 individual trials were used for each patient. Then, spatiotemporal gait parameters including cadence, speed, stride length, step width, step time, and stance du-

**Table 1.** Demographics of Study Population

| Variable | Value |
|---|---|
| Sex (male : female) | 12 : 12 |
| Age (yr) | 62.3 ± 6.4 |
| Body mass index (kg/m$^2$) | 26.2 ± 3.4 |
| Laterality (right : left) | 15 : 9 |
| Stage | |
| Takakura | 3a: 1, 3b: 2, 4: 14 |
| Knupp | 1: 1, 2a: 1, 2b: 1, 2c: 4 |

Values are presented as number or mean ± standard deviation.

ration were obtained. Intersegmental positions during 8 phases of gait (initial contact, loading response, midstance, terminal stance, preswing, initial swing, midswing, and terminal swing) were collected.

We postulated that gait analysis using a 3D MFM would help us better understand the structural changes of each segment in the foot and ankle after TAA. However, such structural changes may confound genuine motions of each segment in different gait phases between preoperative and postoperative states. Therefore, an additional adjustment process for comparing the genuine motion of each segment between preoperative and postoperative states after TAA was done. Each intersegmental position in the curves of the gait graphs obtained at the final follow-up was subtracted by the difference between the parameter of the midstance phase in the preoperative gait and that in the final follow-up gait, according to the previous supporting literature that the position of the midstance phase could reflect the radiographic standing position (Figs. 1 and 2).[13]

### Statistical Analysis

All continuous variables including spatiotemporal gait parameters were analyzed using the Wilcoxon test for the comparison between the preoperative state and the final follow-up state after TAA. All statistical analyses were performed using IBM SPSS software version 22 (IBM Corp.). The level of significance was set at $p$-value < 0.05.

## RESULTS

Among all spatiotemporal gait parameters, both stride length ($p = 0.024$) and normalized stride length ($p = 0.030$) at the final follow-up after TAA significantly increased compared to the preoperative state (Table 2). When comparing raw curves between preoperative and postoperative states, there were significant differences in the loading response ($p = 0.037$), midstance ($p = 0.037$), initial swing ($p = 0.043$), and midswing phase ($p = 0.016$) in the sagittal plane of the hindfoot (Fig. 1). There were significant differences in the terminal swing ($p = 0.028$) in the coronal plane of the hindfoot. There were no significant differ-

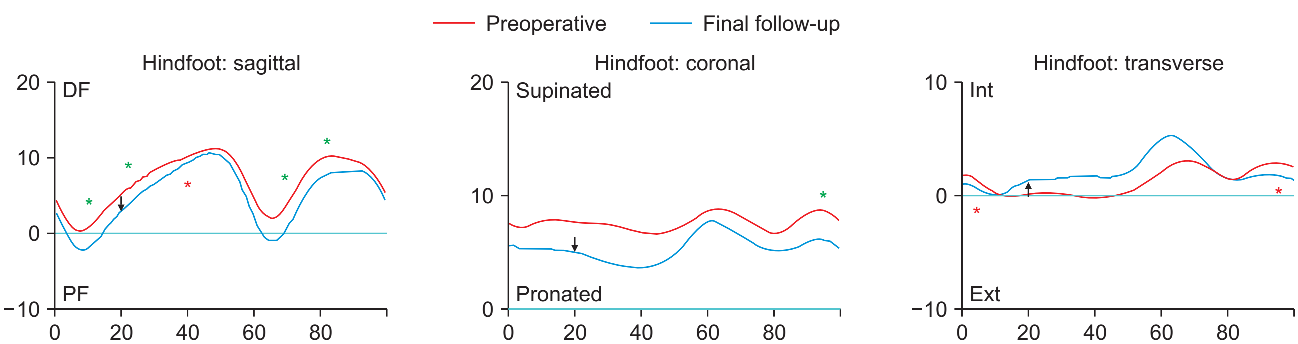


**Fig. 1.** Average motion of the hindfoot in the preoperative and final follow-up after total ankle arthroplasty. The green asterisks indicate significant differences in comparison to the raw curve, while the red asterisks indicate significant differences in genuine motion in each gait phase. DE: dorsiflexion, PF: plantarflexion, Int: internal rotation, Ext: external rotation.

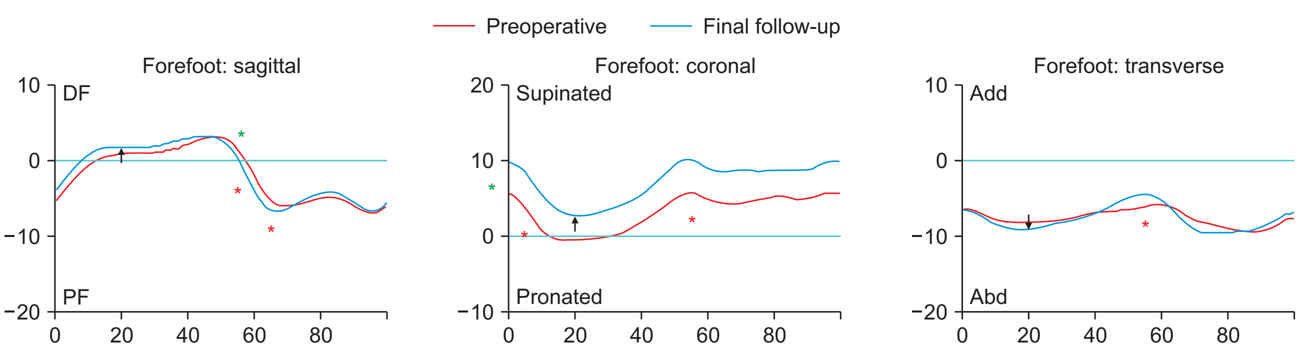


**Fig. 2.** Average motion of the forefoot in the preoperative and final follow-up after total ankle arthroplasty. The green asterisks indicate significant differences in comparison to the raw curve, while the red asterisks indicate significant differences in genuine motion in each gait phase. DE: dorsiflexion, PF: plantarflexion, Add: adduction, Abd: abduction.

**Table 2.** Spatiotemporal Gait Parameters of Study Population in the Preoperative State and Final Follow-up State after Total Ankle Arthroplasty

| Variable | Preoperative (n = 24) | Final follow-up (n = 24) | *p*-value |
|---|---|---|---|
| Cadence (step/min) | 107.3 ± 7.2 | 107.6 ± 9.3 | 0.549 |
| Speed (cm/sec) | 92.1 ± 14.2 | 97.7 ± 14.2 | 0.063 |
| Normalized speed (%) | 57.6 ± 8.5 | 61.1 ± 7.7 | 0.059 |
| Stride length (cm) | 103.6 ± 14.8 | 109.2 ± 13.0 | 0.024 |
| Normalized stride length (%) | 64.7 ± 7.8 | 68.3 ± 5.9 | 0.030 |
| Step width (cm) | 12.5 ± 2.9 | 13.4 ± 3.5 | 0.097 |
| Normalized step width (%) | 7.8 ± 1.7 | 8.4 ± 2.0 | 0.110 |
| Step time (sec) | 0.56 ± 0.04 | 0.56 ± 0.06 | 0.511 |
| Stance duration (%) | 62.6 ± 2.1 | 62.6 ± 1.9 | 0.864 |

Values are presented as mean ± standard deviation.

ences in all phases in the transverse plane of the hindfoot.

Meanwhile, there were significant differences in the preswing ($p = 0.043$) in the sagittal plane of the forefoot (Fig. 2). There were significant differences in all phases in the coronal plane of the forefoot. In other words, the forefoot supination was observed after TAA. There was no significant difference in all phases in the transverse plane of the forefoot. The total range of motion of all planes in the hindfoot and forefoot showed no significant changes between the preoperative and final follow-up states.

To compare the genuine range of motion of each segment, we adjusted all curves of the final follow-up as described above. For this shift, the midstance point in the curves of the final follow-up was translocated to the midstance point in the curves of the preoperative state (Figs. 1 and 2). As a result, the sagittal genuine motion of the hindfoot in the terminal stance of TAA at the final follow-up was significantly more dorsiflexed than that of the preoperative state ($p = 0.016$) (Fig. 1). The coronal genuine motion of the hindfoot in all phases showed no difference between the 2 groups. In the transverse plane of the hindfoot, there were significant differences in the initial contact ($p = 0.012$), loading response ($p = 0.009$), and terminal stance ($p = 0.009$).

A genuine change of the forefoot sagittal motion in the preswing ($p = 0.006$) and initial swing ($p = 0.046$) of the TAA follow-up curve showed more plantarflexion than that of the preoperative curve (Fig. 2). Coronal motion of the forefoot in the loading response ($p = 0.026$) and preswing ($p = 0.049$) of the TAA follow-up curve showed more supination than that of the preoperative curve. Transverse motion of the forefoot in the preswing ($p = 0.004$) of the TAA follow-up curve showed more internal rotation than that of the preoperative curve.

## DISCUSSION

This study confirmed that TAA significantly increased stride length; however, it did not increase the range of motion of all planes in the hindfoot and forefoot in all gait phases. After TAA, hindfoot was plantarflexed and pronated in most of the gait phases, and the forefoot was more dorsiflexed in the preswing phase and was supinated through all phases. Genuine motion of the hindfoot after TAA was more dorsiflexed in the terminal stance. Genuine coronal motion of the hindfoot showed no change after TAA. After TAA, the forefoot was more plantarflexed in the preswing and initial swing phases. Forefoot was more supinated in the loading response and preswing phase, while more internally rotated in the preswing phase.

There were few literatures comparing preoperative and postoperative states of gait patterns using MFM from the affected limb before and after TAA. We think that the lack of previous knowledge regarding this issue may be due to the difficulty in interpreting the gait pattern changes after TAA. Not only can TAA correct the whole structural changes such as hindfoot alignment or the talar tilt, but also can change the range of motion in all foot and ankle joints. Lee et al.[13] observed that in MFM, intersegmental angles of each segment measured in the midstance phase best correlate with conventional radiographic indices of foot and ankle. Thus, we analyzed gait patterns with 2 methodologies, including the direct comparison of raw gait curves between 2 groups and the comparison of modified curves after adjusting static changes of the foot and ankle after TAA.

Based on previous studies, spatiotemporal gait parameters, often referred to as the vital signs of gait, are known to improve after TAA.[9,18] Queen et al.[19] observed marked improvements of spatiotemporal gait parameters from the patients who underwent 2-component TAA, although they did not take account the values for healthy controls. Meanwhile, the other 2 studies, Valderrabano et al.[10] and Brodsky et al.,[11] using TAA with a 3-component implant reported that stride length improved by 5 cm and 17 cm, cadence by 5.6 cm/sec and 12.9 steps/min, and walking speed by 12 cm/sec and 25.6 cm/sec, respectively. In our study, only stride length showed a significant improvement by approximately 6 cm, which was similar to the report of Valderrabano et al.[10] Walking speed increased by some degree, but lacked statistical significance. These discrepancies may be due to several factors: racial differences, different levels of sports activities, or the small number of the study population.

Previous studies using a 2- or 3-component TAA system reported improvements in sagittal motion of 4°, inversion movement of 1.1°, and transverse motion of 1.6°.[10,11,20] Brodsky et al.[8] noted less overall motion in all planes after TAA compared to the unaffected limb in their gait study using MFM. We also observed that the overall range of both hindfoot and forefoot motion in all planes showed no significant improvements after TAA. We assumed that the unchanged spatiotemporal parameters except for stride length may be related to no changes in the range of motion. The preservation of the range of motion of the hindfoot and forefoot may be our expected outcome after TAA, rather than an additional gain of range of motion.

Our comparison of raw gait curves between the 2 groups revealed that the outcome of gait analysis using an MFM would reflect the correction of static structural deformity caused by TAA. Our study population was patients with varus ankle OA, with varus hindfoot and pronated forefoot. Thus, the hindfoot in the final follow-up curve after TAA was significantly pronated in several phases, while the forefoot was supinated in all phases. The possible reason the hindfoot is not significantly pronated in several phases unlike the forefoot would be the genuine motions of the hindfoot may be much improved by TAA than those of the forefoot, masking the structural change in several phases.

After TAA, we expected that neutral alignment of the hindfoot would enable further supination of the hindfoot in the preswing phase followed by powerful push-off compared to the preoperative state with varus hindfoot. However, coronal movements showed no differences between the 2 groups. We think that a limited subtalar range of motion in advanced ankle OA cannot be restored after TAA. In this context, in patients with simultaneous subtalar and tibiotalar OA, subtalar fusion combined with TAA would not result in further functional impairment compared to TAA alone, in terms of hindfoot range of motion. Although our study patients had no symptoms or radiographic evidence of subtalar arthritis, soft-tissue adhesions or small osteophytes in the ankle joint may limit the range of motion of the subtalar joint. There were significant improvements in several genuine motions, including dorsiflexion in the terminal stance after TAA, which may be a preceding step to enhanced spatiotemporal parameters.

This study has several limitations. First, the effect of OA stage or clinical subjective score on gait pattern following TAA was not considered in this study. Symptoms or severity of ankle OA could have affected the outcome of this study. However, all study population had end-stage OA and required surgery as conservative treatment failed. All patients showed no antalgic gait during the preoperative gait study because the gait did not cause pain as the track was short (8 meters). Second, hindfoot alignment was not measured in gait analysis because this parameter was not routinely assessed in the past. Debate over the accurate measurement of hindfoot alignment is ongoing. Moreover, we performed additional comparisons after the correction of the baseline difference of structural changes to overcome this limitation. Third, varied postoperative follow-up periods at which gait analyses were performed might affect gait patterns. However, all follow-up gait analyses were done at least 1 year postoperatively. There were also no specific events that could have affected gait outcomes between TAA surgery and the follow-up gait analysis in all cases.

In conclusion, contrary to the belief that TAA may result in a mildly increased range of motion, TAA could not cause a biomechanical improvement of segmental motions in the forefoot and hindfoot, except for the structural changes of the bone. Clinicians can consider this information during preoperative counseling for TAA.

## CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

## ACKNOWLEDGEMENTS

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2016R1D1A1B02009379).

## ORCID

Gil Young Park https://orcid.org/0000-0002-8582-7669
Min Gyu Kyung https://orcid.org/0000-0003-4747-2411
Young Sik Yoon https://orcid.org/0000-0003-2652-5860
Dae-Yoo Kim https://orcid.org/0000-0002-6273-7337
Dong-Oh Lee https://orcid.org/0000-0001-7646-9778
Dong Yeon Lee https://orcid.org/0000-0001-8233-6285

## REFERENCES

1. Glazebrook M, Daniels T, Younger A, et al. Comparison of health-related quality of life between patients with end-stage ankle and hip arthrosis. J Bone Joint Surg Am. 2008;90(3): 499-505.
2. Saltzman CL, Zimmerman MB, O'Rourke M, Brown TD, Buckwalter JA, Johnston R. Impact of comorbidities on the measurement of health in patients with ankle osteoarthritis. J Bone Joint Surg Am. 2006;88(11):2366-72.
3. Haddad SL, Coetzee JC, Estok R, Fahrbach K, Banel D, Nalysnyk L. Intermediate and long-term outcomes of total ankle arthroplasty and ankle arthrodesis: a systematic review of the literature. J Bone Joint Surg Am. 2007;89(9):1899-905.
4. Daniels TR, Mayich DJ, Penner MJ. Intermediate to Long-Term Outcomes of Total Ankle Replacement with the Scandinavian Total Ankle Replacement (STAR). J Bone Joint Surg Am. 2015;97(11):895-903.
5. Haytmanek CT Jr, Gross C, Easley ME, Nunley JA. Radiographic outcomes of a mobile-bearing total ankle replacement. Foot Ankle Int. 2015;36(9):1038-44.
6. Flavin R, Coleman SC, Tenenbaum S, Brodsky JW. Comparison of gait after total ankle arthroplasty and ankle arthrodesis. Foot Ankle Int. 2013;34(10):1340-8.
7. Singer S, Klejman S, Pinsker E, Houck J, Daniels T. Ankle arthroplasty and ankle arthrodesis: gait analysis compared with normal controls. J Bone Joint Surg Am. 2013;95(24): e191(1-10).
8. Brodsky JW, Coleman SC, Smith S, Polo FE, Tenenbaum S. Hindfoot motion following STAR total ankle arthroplasty: a multisegment foot model gait study. Foot Ankle Int. 2013; 34(11):1479-85.
9. Kane JM, Coleman S, Brodsky JW. Kinematics and function of total ankle replacements versus normal ankles. Foot Ankle Clin. 2017;22(2):241-9.
10. Valderrabano V, Nigg BM, von Tscharner V, Stefanyshyn DJ, Goepfert B, Hintermann B. Gait analysis in ankle osteoarthritis and total ankle replacement. Clin Biomech (Bristol, Avon). 2007;22(8):894-904.
11. Brodsky JW, Polo FE, Coleman SC, Bruck N. Changes in gait following the Scandinavian Total Ankle Replacement. J Bone Joint Surg Am. 2011;93(20):1890-6.
12. Leardini A, Caravaggi P, Theologis T, Stebbins J. Multi-segment foot models and their use in clinical populations. Gait Posture. 2019;69:50-9.
13. Lee DY, Seo SG, Kim EJ, et al. Correlation between static radiographic measurements and intersegmental angular measurements during gait using a multisegment foot model. Foot Ankle Int. 2015;36(1):1-10.
14. Deschamps K, Staes F, Roosen P, et al. Body of evidence supporting the clinical use of 3D multisegment foot models: a systematic review. Gait Posture. 2011;33(3):338-49.
15. Takakura Y, Tanaka Y, Kumai T, Tamai S. Low tibial osteotomy for osteoarthritis of the ankle: results of a new operation in 18 patients. J Bone Joint Surg Br. 1995;77(1):50-4.
16. Knupp M, Stufkens SA, Bolliger L, Barg A, Hintermann B. Classification and treatment of supramalleolar deformities. Foot Ankle Int. 2011;32(11):1023-31.
17. Seo SG, Kim EJ, Lee DJ, Bae KJ, Lee KM, Lee DY. Comparison of multisegmental foot and ankle motion between total ankle replacement and ankle arthrodesis in adults. Foot Ankle Int. 2017;38(9):1035-44.
18. Kirtley C. Clinical gait analysis: theory and practice. Elsevier; 2006.
19. Queen RM, De Biassio JC, Butler RJ, DeOrio JK, Easley ME, Nunley JA. J. Leonard Goldner Award 2011: changes in pain, function, and gait mechanics two years following total ankle arthroplasty performed with two modern fixed-bearing prostheses. Foot Ankle Int. 2012;33(7):535-42.
20. Choi JH, Coleman SC, Tenenbaum S, Polo FE, Brodsky JW. Prospective study of the effect on gait of a two-component total ankle replacement. Foot Ankle Int. 2013;34(11):1472-8.