Patients with end-stage ankle arthritis often complain of long-term pain and disabilities, and in severe cases patients may present with gait disturbance. Tibiotalocalcaneal (TTC) arthrodesis is a popular procedure, which helps to relieve pain and correct severe deformity in cases of end-stage ankle arthritis combined with subtalar joint arthritis.

This procedure also serves as a salvage option for failed ankle arthroplasty or hindfoot operations.

One of the major differences from tibiotalar (TT) arthrodesis is that the fusion construct is extended to the subtalar joint.

**Background:** Tibiotalocalcaneal arthrodesis is an established surgical procedure for treating patients with end-stage ankle joint arthritis and subtalar joint arthritis. Although it greatly relieves pain, a major drawback is loss of range of motion. Although it is known to restrict an additional subtalar joint compared to tibiotalar arthrodesis, there is a lack of gait analysis studies comparing the two methods. This study aimed to evaluate the differences in kinematics of the foot and ankle joints between tibiotalar and tibiotalocalcaneal arthrodesis. We also compared preoperative and postoperative statuses for each surgical method.

**Methods:** The study included 12 and 9 patients who underwent tibiotalar and tibiotalocalcaneal arthrodesis, respectively, and 40 healthy participants were included in the control group. The DuPont foot model was used to analyze intersegmental foot and ankle kinematics during gait.

**Results:** Compared to controls, both tibiotalar and tibiotalocalcaneal arthrodesis resulted in slow gait speed with reduced stride length, increased step width, and decreased range of sagittal plane motion. Both fusion methods showed similar range of motion in all segments and planes following surgery. Coronal positions showed more supination of the forefoot and pronation of the hindfoot segment after each operation, particularly tibiotalocalcaneal arthrodesis. Gait after tibiotalocalcaneal arthrodesis did not significantly differ from that after tibiotalar arthrodesis, but there was a tendency of more pronation in the hindfoot segment.

**Conclusions:** Both fusion methods limited foot and ankle motion in similar ways. Comparing tibiotalar and tibiotalocalcaneal arthrodesis suggests that additionally fusing the subtalar joint does not cause greater movement restriction in patients. Objectively comparing tibiotalar and tibiotalocalcaneal arthrodesis will facilitate further understanding of the effect of tibiotalocalcaneal arthrodesis on movement and the value of subtalar joint motion for improved preoperative counselling.

**Keywords:** Ankle, Arthritis, Arthrodesis, Gait analysis
which possibly influences hindfoot motion.

It is widely believed that functional outcomes of TT arthrodesis are better than those of TTC arthrodesis. In a previous study by Ajis et al., TT and TTC arthrodesis patient-reported outcomes were compared. While both surgical methods showed satisfactory outcomes, patients in the TT arthrodesis group expected higher postoperative activities but were less likely to reach their desired level. Although this study included a large cohort of patients for each arthrodesis method, patient-reported outcomes are subjective and can be biased. Thus, a more objective way to assess and compare TT and TTC arthrodesis is needed.

The subtalar joint plays an essential role in ankle inversion and eversion movements. According to a previous cadaveric study, when subtalar arthrodesis was performed, range of foot and ankle motions was restricted by 83% of inversion and 88% of eversion. In another study, transverse tarsal motion decreased by 40% following isolated subtalar arthrodesis. Hence, we anticipated that there might be a significant difference in foot and ankle motion between TTC and TT arthrodesis as they differ in terms of subtalar joint motion. To the best of our knowledge, few studies have compared TT and TTC arthrodesis using a multi-segment foot model (MFM). Therefore, in this study, we performed gait analysis using a three-dimensional MFM to evaluate the intersegmental foot and ankle kinematics between TT and TTC arthrodesis. We also compared preoperative and postoperative statuses for each surgical method. We hypothesized that the gait pattern between TTC and TT arthrodesis groups would be distinct, especially in the hindfoot segment, and that a significant change in gait pattern would occur postoperatively.

**METHODS**

**Study Participants and Protocol**

This is a level III, retrospective, case-control study. Prior to performing the study, the study protocol was approved by Institutional Review Board of Seoul National University Hospital (No. H-1806-151-953). Considering the retrospective nature of the study, the requirement for informed consent was waived by the Board. The study was conducted in accordance with the Declaration of Helsinki.

This study included 12 patients who underwent TT arthrodesis (TT group) and 9 who underwent TTC arthrodesis (TTC group) between January 2011 and January 2021 at the authors’ institution. The inclusion criteria were as follows: (1) patients with end-stage ankle arthritis, (2) minimum of 1 year of follow-up after fusion, and (3) preoperative and postoperative gait analysis data available. The exclusion criteria were as follows: (1) neuromuscular disease involving the lower extremities, (2) spinal pathology limiting daily activities, and (3) any congenital deformities including vertical talus or tarsal coalition.

In the TT group, 9 patients had posttraumatic arthritis and 3 had primary arthritis. In the TTC group, 4 had posttraumatic arthritis, 2 had primary arthritis, 2 had failed ankle surgery, and 1 had rheumatoid arthritis. For the control group, the gait data of 40 older healthy participants between the ages of 60 and 69 years from previously recruited healthy controls were used. The inclusion criteria were as follows: (1) absence of any history of fracture or surgical procedure involving the lower extremities; (2) no observed radiographic findings of progressive osteoarthritis (Kellgren-Lawrence grade 3 or 4) of the hip, knee, ankle, or foot; (3) no subjective symptoms of pain in the lower extremities; and (4) no history of cardiovascular or respiratory underlying disease that might affect gait.

TT or TTC arthrodesis was performed by an experienced senior foot and ankle surgeon (DYL). A method was chosen according to the corresponding indications: TTC arthrodesis was performed in patients with end-stage arthritis involving both ankle and subtalar joint with symptoms that did not respond well to conservative treatment over 6 months. It was performed using a retrograde intramedullary T2 ankle arthrodesis nail (Stryker, Schönkirchen, Germany). TT arthrodesis was performed in patients with end-stage ankle arthritis, often accompanied by mild subtalar joint arthritis, with symptoms that did not respond well to conservative treatment over 6 months. If there was absence of or minor pain in the subtalar joint, only TT arthrodesis was performed. The surgery was performed with a lateral transfibular approach using cannulated screws. In both groups, all patients maintained a short leg cast and partial weight-bearing with crutches 4 weeks postoperatively and were subsequently allowed to fully bear their weight with an ankle orthosis for another 4 weeks. Union was achieved in all patients at the final follow-up.

**Radiographic Measurements**

For the assessment of preoperative deformity and postoperative alignment, frontal tibiotalar angle (FTTA) was measured. The FTTA was defined as the superomedial angle between the longitudinal axis of the tibia (a line connecting the middle of the proximal and the distal tibial shaft) and the axis of the talus (a line drawn through the shoulders of the talus). For the postoperative FTTA, we utilized the immediate postoperative radiographs as a reference to identify the TT junction when drawing a
line connecting the two shoulders of the talus in the final follow-up radiographs. In addition, the presence of subtalar joint arthritis was checked. According to the modified Kellgren-Lawrence grade, subtalar joint arthritis was classified into five categories: no radiographic findings of osteoarthritis as grade 0; minute osteophytes of doubtful clinical significance as grade 1; and definite osteophytes with mild, moderate, or severe joint space narrowing as grades 2, 3, and 4, respectively. Standing ankle radiographs taken preoperatively and postoperatively at the final follow-up were used for analysis. All radiographic measurements were performed using a picture archiving and communication system software (Infinitt PACS; Infinitt Healthcare Co., Seoul, Korea).

Gait Data Acquisition
Gait data were collected at the Human Motion Analysis Laboratory of our institute. The gait analysis was performed preoperatively and postoperatively at the final follow-up. We used the DuPont foot model for the evaluation of intersegmental foot and ankle motion. We conducted the experimental procedures with the same method as our former studies, including the placement of skin markers, definition of coordinate systems, and method of calculating joint rotation.

In brief, the 15 skin markers were placed as follows: 2 on the knee (medial and lateral), 3 on the tibial shank (upper, front, and rear), 2 on the ankle (medial and lateral), 2 on the hindfoot segment (heel proximal and heel distal), 2 on the midfoot segment (navicular bone and cuboid bone), 3 on the forefoot segment (first metatarsal head, toe, and fifth metatarsal head), and 1 on the hallux. The foot model was defined as consisting of the hindfoot, forefoot, first ray, fifth ray, and hallux. As described previously, a ZXY Euler decomposition of the relative orientation of the anatomical coordinate systems was utilized to calculate the relationships between segments in the sagittal, coronal, and axial planes.

The study participants were advised to warm up for 5 minutes by walking at an easy pace. A single operator (HJY) attached 15 reflective skin markers on each side of the foot and the lower leg. Baseline static data were obtained in a calibration trial with both feet positioned parallel in the coronal axis and flat on the ground. The study participants were instructed to walk barefoot at a comfortable speed on an 8-meter track. Gait data were collected by 12 cameras at a height of 2 meters with an optical motion capture system (Motion Analysis Co., Rohnert Park, CA, USA) at a sample rate of 120 Hz. Eight cameras were located at each octant position (45° intervals), and four additional cameras were located at the front, back, and bilateral sides. The distance between the cameras and the participants was 3 to 7 m. The resolution of the cameras was 1.3 megapixels with 500 frames per second. The translational accuracy was 0.5 mm root mean square, and the angular resolution was 0.3°. Cortex 1.3.0675 (Motion Analysis Co.) was used for real-time tracking of the marker data, motion capture, and post-processing.

Gait Data Post-processing
Spatiotemporal gait parameters including the cadence, speed, stride length, step width, step time, and proportion of stance phase were analyzed. In order to minimize inter-individual variation due to body size, the speed, stride length, and step width were divided by height and designated as n speed, n stride length, and n step width, respectively.

For analyzing kinematic data, three representative strides from five separate trials were selected. Representative strides were selected based on the waveforms of range of motion (ROM) curves, excluding the maximum and minimum curves. To evaluate the intersegmental position of the foot (distal segment relative to proximal segment) during the gait cycle, the whole gait cycle was divided into 100 points with 1% interval and intersegmental angles (ISAs) were collected at each time point as described in a previous study. The calculated parameters were as follows: (1) hindfoot relative to the tibia: dorsiflexion/plantarflexion in sagittal plane, supination/pronation in coronal plane, and internal/external rotation in transverse plane; (2) forefoot relative to the hindfoot: dorsiflexion/plantarflexion in sagittal plane, supination/pronation in coronal plane, and abduction/adduction in transverse plane; and (3) hallux relative to the forefoot: dorsiflexion/plantarflexion in sagittal plane and varus/valgus in transverse plane.

The ISAs (position) in the middle of eight specific phases of gait cycle (initial contact 0%–2%, load response 6%–8%, mid-stance 21%–23%, terminal stance 40%–42%, preswing 55%–57%, initial swing 67%–69%, mid-swing 80%–82%, and terminal swing 93%–95%) were measured to compare the position of the foot and ankle segments, and the change in the ISAs (motion) between phases was calculated as previously described.

Statistical Analyses
The Shapiro-Wilk test was used to evaluate normality of data. When comparing nonparametric parameters between the TT and TTC groups, the Mann-Whitney U and Fisher’s exact tests were used for continuous variables and
categorical variables, respectively. The Wilcoxon signed-rank test was used to compare gait parameters preoperatively and postoperatively. When comparing TT, TTC, and controls, the Kruskal-Wallis test was used, followed by Dunn’s post-hoc comparison. IBM SPSS ver. 26.0 (IBM Corp., Armonk, NY, USA) was used for all statistical analyses. A $p < 0.05$ were considered statistically significant.

Statistical parametric mapping (SPM) of the $t$-value from the unpaired $t$-test ($\alpha = 0.05$) was conducted additionally using MATLAB R2021a (The MathWorks Inc., Natick, MA, USA). SPM of the $t$-value was used to demonstrate the difference in postoperative continuous curves between the TT and TTC groups, calculated using the open-source SPM1d code (www.spm1D.org).  

**RESULTS**

There were no significant differences in the demographic data between the patient group and the control group (Table 1). The TT group included 6 men and 6 women, the TTC group included 6 men and 3 women, and the control group included 20 men and 20 women. The average follow-up period was 28.2 months (range, 14–114 months) in the TT group and 28.3 months (range, 13–57 months) in the TTC group. Although preoperative FITTA was smaller in the TT group than the TTC group, there was no significant difference ($p = 0.088$) (Table 2). In the postoperative period, both groups demonstrated neutral alignment of FITTA, with no significant difference ($p = 0.464$). However, preoperative presence of subtalar arthritis was significantly higher in the TTC group ($p = 0.019$). In the TT group, there were 3 patients with grade 2 and 3 patients with grade 3 subtalar joint arthritis. All patients in the TTC group were diagnosed with grade 4 subtalar joint arthritis. There was no newly developed subtalar joint arthritis during the follow-up period in the TT group.

On the temporal gait parameters, while there were no significant changes after TT arthrodesis, gait speed ($p = 0.028$) and stride length ($p = 0.011$) significantly increased after TTC arthrodesis (Table 3). Postoperatively, both TT and TTC groups showed similar patterns in all temporal gait parameters. However, the postoperative values of the TT group were significantly different from those of the control group: slower gait speed ($p < 0.001$), shorter stride length ($p = 0.002$), larger step width ($p = 0.002$), and greater proportion of stance phase ($p = 0.009$). In addition, the postoperative values of the TTC group were significantly different from those of the control group: slower gait speed ($p = 0.001$), shorter stride length ($p = 0.001$), and larger step width ($p < 0.001$). Lastly, on the preoperative compar-

---

**Table 1. Demographic Data of Study Participants**

| Variable         | TT group (n = 12) | TTC group (n = 9) | Control group (n = 40) | $p$-value* |
|------------------|------------------|------------------|------------------------|------------|
| Age (yr)         | 67.8 ± 7.2       | 64.1 ± 9.7       | 65.4 ± 2.6             | 0.390      |
| Height (cm)      | 181.1 ± 9.6      | 184.4 ± 6.9      | 160.3 ± 10.0           | 0.400      |
| Weight (kg)      | 65.6 ± 9.2       | 68.2 ± 8.4       | 63.1 ± 9.9             | 0.230      |
| Body mass index (kg/m$^2$) | 25.1 ± 1.6 | 25.2 ± 2.0 | 24.5 ± 3.1 | 0.753 |
| Foot width (cm)  | 9.8 ± 0.5        | 9.9 ± 0.9        | 9.8 ± 0.8              | 0.380      |

*Values are presented as mean ± standard deviation. TT: tibiotalar, TTC: tibiotalocalcaneal. *Result of the Kruskal-Wallis test.

**Table 2. Radiographic Data of Study Participants**

| Variable                                       | TT group (n = 12) | TTC group (n = 9) | $p$-value |
|------------------------------------------------|------------------|------------------|-----------|
| Preoperative frontal tibiotalar angle (°)       | 77.1 ± 7.9       | 86.3 ± 13.9      | 0.088*    |
| Postoperative frontal tibiotalar angle (°)      | 88.2 ± 1.5       | 88.7 ± 0.9       | 0.464*    |
| Preoperative presence of the subtalar arthritis | 6                | 9                | 0.019†    |

*Values are presented as mean ± standard deviation. TT: tibiotalar, TTC: tibiotalocalcaneal. *Result of the Mann-Whitney $U$-test. †Result of the Fisher’s exact test.
Table 3. Temporal Gait Parameters

| Parameter             | Pre-TT (n = 12) | Post-TT (n = 12) | Pre-TTC (n = 9) | Post-TTC (n = 9) | Control (n = 40) | p-value*  | p-value†  | p-value‡  | p-value§  | p-value|||  p-value**  |
|-----------------------|-----------------|-----------------|----------------|-----------------|-----------------|-----------|-----------|-----------|-----------|-----------|
| Cadence (step/min)    | 105.3 ± 8.5     | 106.3 ± 8.2     | 110.3 ± 5.4    | 109.1 ± 5.9     | 112.8 ± 8.7     | 0.638     | 0.374     | 0.048     | 0.056     | 0.678    | 1.000     | 0.065     |
| Speed (m/sec)         | 0.89 ± 0.12     | 0.92 ± 0.16     | 0.84 ± 0.18    | 0.89 ± 0.19     | 1.12 ± 0.09     | 0.347     | 0.028     | < 0.001   | < 0.001   | 0.001    | 1.000     | 0.776     |
| Speed††               | 0.55 ± 0.09     | 0.58 ± 0.10     | 0.51 ± 0.10    | 0.54 ± 0.11     | 0.70 ± 0.06     | 0.347     | 0.021     | < 0.001   | < 0.001   | < 0.001  | 1.000     | 0.522     |
| Stride length (cm)    | 100.8 ± 9.4     | 104.1 ± 14.5    | 91.5 ± 17.9    | 97.5 ± 16.9     | 120.1 ± 9.5     | 0.272     | 0.011     | < 0.001   | < 0.001   | < 0.001  | 1.000     | 0.434     |
| Stride length††       | 62.8 ± 7.3      | 65.1 ± 9.4      | 55.5 ± 9.8     | 59.7 ± 9.4      | 75.0 ± 4.9      | 0.209     | 0.111     | < 0.001   | < 0.001   | < 0.001  | 0.699     | 0.039     |
| Step width (cm)       | 142 ± 3.0       | 137 ± 4.3       | 155 ± 4.0      | 160 ± 2.6       | 99 ± 2.2        | 0.530     | 0.767     | < 0.001   | < 0.001   | < 0.001  | 0.568     | 0.227     |
| Step width††          | 8.8 ± 1.4       | 8.5 ± 2.2       | 9.5 ± 2.5      | 9.8 ± 1.7       | 6.1 ± 1.3       | 0.530     | 0.594     | < 0.001   | < 0.001   | < 0.001  | 0.742     | 0.286     |
| Step time (sec)       | 0.57 ± 0.04     | 0.57 ± 0.04     | 0.55 ± 0.03    | 0.55 ± 0.03     | 0.54 ± 0.04     | 0.638     | 0.441     | 0.050     | 0.062     | 0.619    | 1.000     | 0.065     |
| Proportion of stance phase (%) | 63.6 ± 1.4 | 63.3 ± 2.6 | 63.5 ± 1.4 | 62.9 ± 3.2 | 61.1 ± 1.3 | 0.583 | 0.260 | 0.003 | 0.009 | 0.078 | 1.000 | 0.508 |

Values are presented as mean ± standard deviation.
Pre: preoperative, Post: postoperative, TT: tibiotalar, TTC: tibiotalocalcaneal.
*Wilcoxon signed-rank test between Pre-TT and Post-TT states.
†Wilcoxon signed-rank test between Pre-TTC and Post-TTC states.
‡Kruskal-Wallis test of post-TT, post-TTC, and control groups.
§Results of Dunn’s post-hoc comparison between post-TT and control groups following the Kruskal-Wallis test.
||Results of Dunn’s post-hoc comparison between post-TT and post-TTC following the Kruskal-Wallis test.
**Results of Mann-Whitney U-test between Pre-TT and Pre-TTC groups.
††Normalized with the subject’s height (speed, stride length, and width divided by subject’s height and multiplied by 100).
Table 4. ROM of the Foot and Ankle Segment

| Variable                          | Pre-TT (n = 12) | Post-TT (n = 12) | Pre-TTC (n = 9) | Post-TTC (n = 9) | Control (n = 40) | p-value* | p-value† | p-value‡ | p-value§ | p-value¶ | p-value** |
|-----------------------------------|-----------------|------------------|-----------------|-----------------|-----------------|----------|----------|----------|----------|----------|----------|
| Hallux relative to forefoot       |                 |                  |                 |                 |                 |          |          |          |          |          |          |
| Sagittal ROM                      | 26.20 ± 4.36    | 24.68 ± 3.90     | 21.06 ± 6.11    | 20.96 ± 3.90    | 34.58 ± 3.74    | 0.272    | 0.594    | < 0.001 | < 0.001 | < 0.001 | 1.000    | 0.039    |
| Transverse ROM                    | 8.61 ± 3.24     | 9.59 ± 2.74      | 7.66 ± 3.97     | 6.86 ± 2.53     | 8.17 ± 2.42     | 0.158    | 0.678    | 0.058    |          |          | 0.619    |
| Forefoot relative to hindfoot     |                 |                  |                 |                 |                 |          |          |          |          |          |          |
| Sagittal ROM                      | 9.41 ± 2.24     | 8.80 ± 2.02      | 9.03 ± 3.31     | 8.50 ± 2.80     | 12.59 ± 2.68    | 0.308    | 0.515    | < 0.001 | < 0.001 | 0.002   | 1.000    | 0.477    |
| Coronal ROM                       | 9.08 ± 1.95     | 10.33 ± 1.33     | 10.22 ± 3.29    | 9.47 ± 3.46     | 9.75 ± 2.87     | 0.060    | 0.767    | 0.536    |          |          | 0.394    |
| Transverse ROM                    | 7.13 ± 2.45     | 7.86 ± 2.05      | 6.16 ± 1.43     | 5.06 ± 2.33     | 11.76 ± 3.41    | 0.182    | 0.441    | < 0.001 | 0.002   | < 0.001 | 0.446    | 0.286    |
| Hindfoot relative to tibia        |                 |                  |                 |                 |                 |          |          |          |          |          |          |
| Sagittal ROM                      | 11.27 ± 2.68    | 12.43 ± 1.28     | 10.18 ± 3.31    | 8.67 ± 2.16     | 20.96 ± 3.34    | 0.060    | 0.214    | < 0.001 | < 0.001 | < 0.001 | 0.687    | 0.670    |
| Coronal ROM                       | 5.73 ± 1.61     | 6.59 ± 2.37      | 5.53 ± 1.71     | 5.23 ± 1.65     | 10.94 ± 3.08    | 0.060    | 0.859    | < 0.001 | < 0.001 | < 0.001 | 1.000    | 0.943    |
| Transverse ROM                    | 7.54 ± 3.73     | 8.49 ± 2.14      | 6.73 ± 1.67     | 6.02 ± 2.66     | 11.52 ± 4.41    | 0.308    | 0.441    | < 0.001 | 0.177   | 0.001   | 0.256    | 0.943    |

Values are presented as mean ± standard deviation. Pre: preoperative, Post: postoperative, TT: tibiotalar, TTC: tibiotalocalcaneal, ROM: range of motion. *Wilcoxon signed-rank test between the Pre-TT and Post-TT states. †Wilcoxon signed-rank test between the Pre-TTC and Post-TTC states. ‡Kruskal-Wallis test of post-TT, post-TTC, and control groups. §Results of Dunn’s post-hoc comparison between post-TT and control groups following the Kruskal-Wallis test. ¶Results of Dunn’s post-hoc comparison between post-TTC and control groups following the Kruskal-Wallis test. **Results of Mann-Whitney U-test between Pre-TT and Pre-TTC groups.
ison of TT and TTC groups, only normalized stride length was significantly higher ($p < 0.039$) in the TT group.

The ROM of each segment is described in Table 4. Both TT and TTC groups showed no significant changes in ROM in any segment after each operation. Both arthrodesis methods showed similar ROM in all segments and planes when compared with the postoperative data. However, the postoperative sagittal ROM of the hallux segment was significantly smaller in both the TT ($p < 0.001$) and TTC ($p < 0.001$) groups when compared to the control group. The preoperative ROM in the sagittal plane of the hallux segment was significantly smaller in the TTC group than in the TT group ($p = 0.039$). The postoperative sagittal and transverse ROMs of the forefoot segment were significantly smaller in both the TT ($p < 0.001$, $p = 0.002$) and TTC ($p = 0.002$, $p < 0.001$) groups when compared to the control group. In addition, the postoperative sagittal and coronal ROMs of the hindfoot segment were significantly smaller in both the TT ($p < 0.001$ and $p < 0.001$) and TTC ($p < 0.001$ and $p < 0.001$) groups when compared to the control group. Lastly, the postoperative transverse ROM of the hindfoot segment was significantly smaller in the TTC group than in the control group ($p = 0.001$).

The ISAs of the foot and ankle segments relative to the proximal segment during the entire gait cycle are demonstrated in Figs. 1-4. When we compared the preoperative foot and ankle kinematics of the TT and TTC groups, there were no significant differences throughout the gait cycle across all segments and planes (Fig. 1).

Comparison of the preoperative and postoperative foot and ankle kinematics of the TT group is shown in Fig. 2. In the hallux segment, the TT group showed significantly decreased dorsiflexion in the mid-stance ($p = 0.041$), terminal stance ($p = 0.006$), initial swing ($p = 0.039$), and coronal planes ($p = 0.006$) when compared to the control group.

![Fig. 1. Comparison of the average preoperative (Pre) kinematics of the distal segment relative to the proximal segment between the tibiotalar and tibiotalocalcaneal arthrodesis groups. The horizontal axis shows the whole gait cycle and the vertical axis shows the range of motion. TT: tibiotalar, TTC: tibiotalocalcaneal, DF: dorsiflexion, PF: plantarflexion, Add: adduction, Abd: abduction, Int: internal rotation, Ext: external rotation.](image-url)
In the hallux segment, the TT group showed significant varus position in the mid-stance ($p = 0.028$) and preswing ($p = 0.008$) phases after surgery. In the forefoot segment, the TT group showed significant supination in the initial contact ($p = 0.034$), terminal stance ($p = 0.041$), mid-swing ($p = 0.005$), and terminal swing ($p = 0.012$) phases after surgery. In the hindfoot segment, there was no significant preoperative-to-postoperative change in the sagittal plane in the TT group. There was a tendency for less supination in the TT group after surgery, but it was significant only in the mid-swing ($p = 0.038$) and terminal swing ($p = 0.038$) phases.

Next, we compared the preoperative and postoperative foot and ankle kinematics of the TTC group (Fig. 3). In the hallux segment, the TTC group showed significant plantar flexion in the initial swing ($p = 0.028$), mid-swing ($p = 0.021$), and terminal swing ($p = 0.015$) phases after surgery. The TTC group showed significant varus position throughout the gait cycle after surgery (load response, $p = 0.028$; mid-stance, $p = 0.028$; terminal stance, $p = 0.021$; mid-swing, $p = 0.015$; and terminal swing phase, $p = 0.038$). In the forefoot segment, the TTC group demonstrated significant supination in the mid-stance ($p = 0.038$), terminal stance ($p = 0.038$), preswing ($p = 0.038$), initial swing ($p = 0.028$), and mid-swing ($p = 0.028$) phases after surgery. In the hindfoot segment, there was no significant preoperative-to-postoperative change in the sagittal plane. There was a tendency of less supination postoperatively throughout the gait cycle, but it was significant only in the mid-swing ($p = 0.038$) and terminal swing ($p = 0.038$) phases. Moreover, the TTC group showed significant internal rotation in the load response ($p = 0.038$) and terminal stance.
Lastly, comparison of the postoperative foot and ankle kinematics between the TT group and TTC group in each segment is shown in Figs. 4 and 5. In the hallux segment, there were no significant differences between the two groups. In the forefoot segment, there were no significant differences between the two groups aside from in the preswing phase ($p = 0.046$) in the transverse plane. The SPM results correlated with these findings (Fig. 5). However, when compared to the control group, the TT group showed distinct gait patterns in the coronal plane during the whole gait cycle (initial contact, $p = 0.002$; load response, $p < 0.001$; mid-stance, $p < 0.001$; terminal stance, $p = 0.002$; mid-swing, $p = 0.029$; and terminal swing phase, $p = 0.009$) after surgery.

**DISCUSSION**

Ankle arthrodesis has been considered a promising method for pain relief in patients with advanced ankle joint arthritis. While ankle arthrodesis may reduce pain and realign deformities, sacrificing ROM is one of the major limitations. Moreover, the subtalar joint, which plays an
important role in ankle inversion and eversion, is also sacrificed in TTC arthrodesis. Patients face significant concerns about the postoperative ambulatory status, changes in gait patterns, and ability to return to work, sports, and recreational activities.\(^4\)

Although previous studies have reported changes in gait patterns after TT or TTC arthrodesis,\(^{24,25}\) there are few objective studies that compare the two methods simultaneously and analyze how they differ or compare the two methods postoperatively against a normal control. Chopra and Crevoisier\(^8\) performed a study focusing on patients who underwent TT and TTC arthrodesis and showed that both operations led to significant alterations in gait and bilateral gait asymmetry. The extended adjacent joint restriction in TTC arthrodesis did not seem to deteriorate gait outcomes.\(^8\) Malerba et al.\(^7\) also compared the two methods in a small population (6 TT, 6 TTC, and 10 controls) and demonstrated that despite sacrificing the subtalar joint in TTC arthrodesis, no significant differences were found in temporal gait parameters compared to TT arthrodesis, though major differences between TT and TTC arthrodesis were found in the transverse plane. However, preoperative gait analysis data were excluded in both studies.\(^7,8\)

In this study, we performed gait analysis using the DuPont foot model (MFM) in end-stage ankle arthritis patients who underwent either TT or TTC arthrodesis. We found that gait patterns in specific segments were altered postoperatively and the patients had similar gait patterns. In addition, a sufficient number of age- and sex-matched control group data were included for comparison.

Compared to controls, patients in both arthrodesis
groups walked slowly postoperatively with reduced stride length and increased step width, but no significant differences were exhibited between the two groups. These findings are consistent with those of previous studies on ankle arthrodesis.\textsuperscript{7,25} The possibility of no difference between the two groups may be attributed to the fact that the presence of subtalar joint arthritis in the TT group was 50%, although it was significantly lower than that in the TTC group. Based on these results, sacrificing additional subtalar joints may not be detrimental in terms of temporal gait parameters. In addition, the TTC group showed improved walking speed and stride length postoperatively compared to the preoperative status.

Our ROM data for all segments showed that there were no significant differences after the operation in each patient group. This is probably due to poor ROM in end-stage ankle arthritis, even preoperatively. Tenenbaum et al.\textsuperscript{24} noted that the loss of sagittal motion after ankle arthrodesis is small because patients with severe arthritis and loss of motion are generally candidates for arthrodesis procedures. However, both groups showed markedly decreased ROM after surgery across all segments, especially in the sagittal plane, when compared to the control group. This corresponds with the study of Thomas et al.,\textsuperscript{25} in which postoperatively TT arthrodesis patients showed significantly decreased ROM in the sagittal, coronal, and transverse planes of the hindfoot and midfoot during gait, compared to normal controls. Moreover, a previous study found that the majority of alterations in gait patterns following both TT and TTC arthrodesis are in the toe region, suggesting weaker push-off after arthrodesis.\textsuperscript{8} Based on these results, it is reasonable to assume that there is limited compensation for ROM below the ankle joint after TT and TTC arthrodesis. A recent study by Eerdekens et al.\textsuperscript{26} supports our idea that the biomechanical behavior of the distal foot joints is unchanged following TT fusion.

Conversely, when we took a closer look at the ISA (position) of the coronal plane of the forefoot relative to

**Fig. 5.** Differences between continuous curves for postoperative tibiotalar and tibiotalocalcaneal arthrodesis statuses using statistical parametric mapping (SPM) of the t-values from the unpaired t-test ($\alpha = 0.05$). $t$ denotes alpha-based critical threshold.
the hindfoot segment (Fig. 2), compared to the control group, the TT group exhibited gait patterns close to supination postoperatively. In addition, although only significance was noted in the terminal stance phase, the TT group overall showed less supination in the coronal plane of the hindfoot relative to the tibial segment. In other words, for the TT group, the preoperative varus position of the hindfoot was corrected towards a slightly valgus (pronation) position, and midfoot segment compensation was relieved to make a plantigrade gait. This was also supported by our radiographic results, in which preoperative hindfoot varus was corrected to neutral postoperatively.

In comparison, a more significant gap in gait patterns after TTC arthrodesis was present in the coronal plane of the forefoot and hindfoot segments (Fig. 3). This can be explained by the fact that following TTC arthrodesis, the tibio-talo-calcaneal complex corrects overall coronal plane alignment, and there is no need for midfoot segment compensation. While there were alterations in gait patterns in specific segments after each operation, our data, which compare TT and TTC arthrodesis, failed to show a statistically significant difference (Figs. 4 and 5). Originally, we hypothesized that the gait patterns of the TTC and TT arthrodesis groups would be distinct, especially in the hindfoot segment, owing to the restriction of subtalar joint motion. Although our data did not show significant differences, our clinical experience and additional analysis using SPM show a difference in a large portion of the gait cycle in the coronal plane of the hindfoot segment. The less meaningful difference between the two groups may be explained by the fact that the MFM used in this study may not be accurate in evaluating subtalar and Chopart joint motion. Although previous studies have demonstrated high repeatability, this may be an innate limitation of the current marker system. Furthermore, perhaps due to the limitations of skin markers, there was a tendency for motion artifacts. Additionally, the small number of patients in each group may have contributed to the difficulty in demonstrating statistical significance. Future studies are needed to further elucidate the differences between the two groups using more refined marker sets and adequate numbers of patients.

Even if objective methods with these possible limitations are acknowledged, there being no significant difference in hindfoot motion between the two groups does not necessarily mean that patients with both ankle and subtalar joint arthritis should undergo TT arthrodesis instead of TTC arthrodesis. Similarly, we do not believe that TTC arthrodesis should be performed in patients slated for TT arthrodesis with mild subtalar arthritis just because there is no difference in hindfoot motion. Rather, the results of our study should be understood clinically in context of counseling the patients preoperatively. In our clinical experience, patients are often reluctant to undergo TTC arthrodesis for fear of sacrificing both the TT and subtalar joints, with concerns about quality of life postoperatively. Based on our study, patients undergoing TTC arthrodesis should be counseled as follows: (1) it is expected that walking speed and stride length will increase significantly in the postoperative period when compared to the patients’ preoperative status; (2) the preoperative condition is so severe that even if surgery such as TTC arthrodesis is performed, there is not much difference in hindfoot motion compared to TT arthrodesis, which will rather help reduce pain; and (3) ROM across all segments and planes will still be diminished when compared to individuals with intact ankle and subtalar joints.

This study has several limitations. First, as this study was retrospectively designed, the diagnosis and follow-up period of the patients were heterogeneous, although both the TT and TTC arthrodesis groups showed similar average follow-up periods of 28 months. A prospective cohort study with a homogeneous follow-up period and unified diagnosis should be conducted for further analysis. Second, although this study focused on objective comparison between TT and TTC arthrodesis using MFM, it would be better to assess the final functional outcome of the two techniques with a combination of gait data and patient-reported subjective outcomes.

In conclusion, patients in both the TT and TTC arthrodesis groups walked slowly with reduced stride length and increased step width compared to the control group. In contrast to patients’ concerns and our hypothesis, patients’ ROM in all segments was already diminished in the preoperative period, and no significant change was seen postoperatively. The coronal positions of the forefoot segment showed more supination and the hindfoot segment more pronation postoperatively, and the difference was larger after TTC arthrodesis. Although we anticipated significant alterations in hindfoot motion when an additional subtalar joint was sacrificed by TTC arthrodesis, statistically significant difference was not observed in gait data. This objective gait study may facilitate further understanding of TTC and TT arthrodesis motion and provide an opportunity to reconsider the value of subtalar joint motion. Moreover, the results of the current study could be used to reduce unnecessary concerns for patients with end-stage ankle arthritis combined with subtalar arthritis who are candidates for TTC arthrodesis.
CONFLICT OF INTEREST

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

ACKNOWLEDGEMENTS

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry, and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project No. 1711138420, KMDF_PR_20200901_0193).

We sincerely appreciate Seong Hyun Kim, Hye Sun Park, and Hyo Jeong Yoo (Human Motion Analysis Laboratory of Seoul National University Hospital) for their technical support in collection and analysis of the kinematic data from the study subjects.

REFERENCES

1. Chopra S, Crevoisier X. Preoperative gait asymmetry in end-stage unilateral ankle osteoarthrosis patients. Foot Ankle Surg. 2019;25(3):298-302.
2. Russotti GM, Johnson KA, Cass JR. Tibiotalocalcaneal arthrodesis for arthritis and deformity of the hind part of the foot. J Bone Joint Surg Am. 1988;70(9):1304-7.
3. Chou LB, Mann RA, Yaszay B, et al. Tibiotalocalcaneal arthrodesis. Foot Ankle Int. 2000;21(10):804-8.
4. Ajis A, Tan KJ, Myerson MS. Ankle arthrodesis vs TTC arthrodesis: patient outcomes, satisfaction, and return to activity. Foot Ankle Int. 2013;34(5):657-65.
5. Zhang K, Chen Y, Qiang M, Hao Y. Effects of five hindfoot arthrodeses on foot and ankle motion: measurements in cadaver specimens. Sci Rep. 2016;6:35493.
6. Mann RA, Beaman DN, Horton GA. Isolated subtalar arthrodesis. Foot Ankle Int. 1998;19(8):511-9.
7. Malerba F, Benedetti MG, Usuelli FG, et al. Functional and clinical assessment of two ankle arthrodeses techniques. J Foot Ankle Surg. 2015;54(3):399-405.
8. Chopra S, Crevoisier X. Bilateral gait asymmetry associated with tibiotalocalcaneal arthrodesis versus ankle arthrodesis. Foot Ankle Surg. 2021;27(3):332-8.
9. Lee DY, Seo SG, Kim EJ, et al. Inter-segmental motions of the foot: differences between younger and older healthy adult females. J Foot Ankle Res. 2017;10:29.
10. Lee DY, Kyung MG, Cho YJ, Hwang S, Kang HW, Lee DO. A modified transfibular technique of ankle arthrodesis using partial fibular resection and onlay bone graft. PLoS One. 2020;15(10):e0241141.
11. Willegger M, Holinka J, Nemecek E, et al. Reliability of the radiographic sagittal and frontal tibiotalar alignment after ankle arthrodesis. PLoS One. 2016;11(4):e0154224.
12. Kraus VB, Kilfoil TM, Hash TW 2nd, et al. Atlas of radiographic features of osteoarthritis of the ankle and hindfoot. Osteoarthritis Cartilage. 2015;23(12):2059-85.
13. Kim EJ, Shin HS, Takatori N, et al. Inter-segmental foot kinematics during gait in elderly females according to the severity of hallux valgus. J Orthop Res. 2020;38(11):2409-18.
14. Kyung MG, Cho YJ, Hwang S, Lee DO, Lee MC, Lee DY. Change in intersegmental foot and ankle motion after a high tibial osteotomy in genu varum patients. J Orthop Res. 2021;39(1):86-93.
15. Nicholson K, Church C, Takata C, et al. Comparison of three-dimensional multi-segmental foot models used in clinical gait laboratories. Gait Posture. 2018;63:236-41.
16. Kim EJ, Shin HS, Lee JH, et al. Repeatability of a multi-segment foot model with a 15-marker set in normal children. Clin Orthop Surg. 2018;10(4):484-90.
17. Seo SG, Lee DY, Moon HJ, et al. Repeatability of a multi-segment foot model with a 15-marker set in healthy adults. J Foot Ankle Res. 2014;7:24.
18. 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.
19. Pierrynowski MR, Galea V. Enhancing the ability of gait analyses to differentiate between groups: scaling gait data to body size. Gait Posture. 2001;13(3):193-201.
20. Lee DY, Seo SG, Kim EJ, Kim SJ, Lee KM, Choi IH. Inter-

ORCID

Linying Cao https://orcid.org/0000-0002-0063-1043
Min Gyu Kyung https://orcid.org/0000-0003-4747-2411
Gil Young Park https://orcid.org/0000-0002-8582-7669
Il-Ung Hwang https://orcid.org/0000-0003-4033-5916
Ho Won Kang https://orcid.org/0000-0002-0792-9045
Dong Yeon Lee https://orcid.org/0000-0001-8233-6285
segmental motions of the foot in healthy adults: gender difference. J Orthop Sci. 2016;21(6):804-9.

21. Yoo HJ, Park HS, Lee DO, et al. Comparison of the kinematics, repeatability, and reproducibility of five different multi-segment foot models. J Foot Ankle Res. 2022;15(1):1.

22. 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.

23. Thomas RH, Daniels TR. Ankle arthritis. J Bone Joint Surg Am. 2003;85(5):923-36.

24. Tenenbaum S, Coleman SC, Brodsky JW. Improvement in gait following combined ankle and subtalar arthrodesis. J Bone Joint Surg Am. 2014;96(22):1863-9.

25. Thomas R, Daniels TR, Parker K. Gait analysis and functional outcomes following ankle arthrodesis for isolated ankle arthritis. J Bone Joint Surg Am. 2006;88(3):526-35.

26. Eerdekens M, Deschamps K, Wuite S, Matricali G. The biomechanical behavior of distal foot joints in patients with isolated, end-stage tibiotalar osteoarthritis is not altered following tibiotalar fusion. J Clin Med. 2020;9(8):2594.

27. Schallig W, Streekstra GJ, Hulshof CM, et al. The influence of soft tissue artifacts on multi-segment foot kinematics. J Biomech. 2021;120:110359.