

# Ankle Arthroplasty and Ankle Arthrodesis: Gait Analysis Compared with Normal Controls

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**Background:** This study compared patients with isolated end-stage ankle osteoarthritis, after undergoing either total ankle arthroplasty or arthrodesis, using gait analysis and patient-reported outcome measures to elucidate differences between the two treatment options, as compared with a healthy control group.

**Methods:** Gait analyses were performed on patients with isolated ankle arthritis more than one year after undergoing either total ankle arthroplasty or arthrodesis during a ten-year period. Validated outcome questionnaire data were obtained. Seventeen patients undergoing total ankle arthroplasty, seventeen patients undergoing arthrodesis, and ten matched control subjects were included for comparison.

**Results:** Patients who had undergone arthroplasty, when compared with patients who had undergone arthrodesis, demonstrated greater postoperative total sagittal plane motion ( $18.1^\circ$  versus  $13.7^\circ$ ;  $p < 0.05$ ), dorsiflexion ( $11.9^\circ$  versus  $6.8^\circ$ ;  $p < 0.05$ ), and range of tibial tilt ( $23.1^\circ$  versus  $19.1^\circ$ ;  $p < 0.05$ ). Plantar flexion motion was not equivalent to normal in either group. Ankle moments and power in both treatment groups remained significantly lower compared with the control group ( $p < 0.05$  between each treatment group and the control group for both variables). Gait patterns in both treatment groups were not completely normalized. Improvements in patient-reported Ankle Osteoarthritis Scale and Short Form-36 scores were similar for both treatment groups.

**Conclusions:** The gait patterns of patients following three-component, mobile-bearing total ankle arthroplasty more closely resembled normal gait when compared with the gait patterns of patients following arthrodesis. Dorsal motion in the sagittal plane was primarily responsible for the differences. Improvement in self-reported clinical outcome scores was similar for both groups. Further investigation is needed to determine why patients who have undergone total ankle arthroplasty do not use the plantar flexion motion in the terminal-stance phase and to explain the limited increase in power generation at toe-off after arthroplasty. Results obtained from this study may be used for future modifications of ankle prostheses and may add to clinicians' ability to inform patients of predicted functional outcomes prior to the treatment of end-stage ankle osteoarthritis.

**Level of Evidence:** Therapeutic Level II. See Instructions for Authors for a complete description of levels of evidence.

Surgical management of patients with end-stage ankle arthritis has traditionally involved both ankle arthrodesis and shoe modification. Ankle arthrodesis effectively relieves pain and improves function; however, comparative studies have demonstrated that the patients' functional outcomes remain significantly lower than normal, and there are measurable abnormalities in their gait parameters<sup>1</sup>. Long-term retrospective clinical studies have identified a high prevalence of ipsilateral hindfoot arthritis with associated deterioration in outcomes<sup>1-3</sup>.

Total ankle arthroplasty was introduced in the 1970s. Initial results were poor, largely because of early loosening<sup>4,5</sup>. Newer studies suggest that implant survival rates are 70% to 95% for follow-up from two to twelve years<sup>6-9</sup>. A recent systematic review of intermediate and long-term outcomes comparing arthroplasty with arthrodesis indicated that the risk of early complications and long-term failure associated with either procedure is comparable<sup>10</sup>. With the continued refinement of prosthetic design and surgical technique, the use of

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arthroplasty has resurged during the last decade; the results from newer implants look promising, with improved durability, functional outcomes, and implant longevity<sup>6-9,11,12</sup>. The enthusiasm is tempered with caution, as a comparison of international registry data with clinical study results has found that implant inventors reported significantly lower revision rates compared with those data reported in the registries<sup>13</sup>.

Treatment with arthrodesis or arthroplasty decreases pain and improves function in patients with advanced ankle pathology. Nonetheless, surgeons continue to strive to restore the joint to a near-normal state, not only to improve ankle function, but also to delay the onset of peritalar joint arthritis. Improvement in function and the success of these procedures are commonly evaluated with the use of subjective, patient-reported outcome measures, which are valuable tools for understanding changes in ankle function from the patient's perspective. In contrast, gait analysis is an objective outcome measure that can help elucidate differences in ankle function after arthroplasty or arthrodesis. A study that uses both patient-reported outcome measures and objective outcome measures would provide a more comprehensive evaluation of the differences in ankle function between arthrodesis and arthroplasty.

In spite of the increasing prevalence of total ankle replacements, research on the effect of this surgical intervention on gait mechanics is limited. Ankle dorsiflexion during early-stance phase is important for knee stability<sup>14</sup>. Ankle joint plantar flexion kinetics during late-stance phase account for 80% of trunk support and forward progression during gait, underscoring the importance of ankle function to normal gait<sup>14</sup>. Early gait studies following arthroplasty revealed poor outcomes<sup>15-17</sup>. More recent studies have shown a general trend toward normalization of gait patterns<sup>18-24</sup>. A key to improving outcomes for patients with ankle arthroplasty may be the ability for arthroplasty to normalize ankle gait mechanics, most importantly ankle dorsiflexion during early-stance phase and ankle plantar flexion power during late-stance phase.

The purpose of this study was to compare groups of patients with isolated end-stage osteoarthritis of the ankle undergoing either arthroplasty or arthrodesis with healthy controls, using three-dimensional gait analysis and patient-reported outcome measures to comprehensively evaluate differences among groups both objectively and from the patient's perspective. The patient groups were also compared with regard to health, age, weight, and sex-matched controls.

## Materials and Methods

The present study was performed with approval of the research ethics boards of our institutions; all participants signed an informed consent form prior to inclusion. The trial was registered at ClinicalTrials.gov (NCT00921076). Patients who underwent either ankle arthrodesis or ankle arthroplasty from 2000 to 2010 at a teaching hospital in a large, urban center were screened for inclusion on the basis of the presence of isolated ankle arthritis. All surgical procedures were performed by the senior author (T.D.). Strict exclusion criteria were applied to ensure that gait pattern differences could be attributed to treatment alone. Exclusion criteria included the presence of major lower-limb trauma or pathology, bilateral ankle arthritis, subtalar arthritis, major medical

comorbidities (severe coronary artery disease, chronic obstructive pulmonary disease, kidney or liver failure), inflammatory seropositive arthritis, previous hip or knee arthroplasties, ipsilateral midfoot or triple fusions, neurologic disease causing abnormality of gait, disease affecting cognitive function, post-traumatic arthritis in patients with a history of a Grade-II or III open fracture to the limb, and patient age of over eighty years. Patients who consented to participate in the study completed a gait analysis study one year postoperatively, as well as preoperative and one-year postoperative general health (Short Form-36 [SF-36]) and region-specific (Ankle Osteoarthritis Scale [AOS]) outcome measures. All patients were followed with lateral standing, flexion, and extension radiographs of the ankle. In addition, a group of healthy individuals with painless joints were recruited from the same large urban center as controls and were matched on the basis of sex, age, and weight.

For the purpose of the current study, we performed a conservative sample-size calculation based on the study by Wu et al.<sup>25</sup>. With use of a two-tailed, two-sample *t* test, we set the population standard deviation to 7° of sagittal plane motion during gait and considered a clinically significant difference between the two groups (the ankle arthrodesis group and the arthroplasty group) to be 10°. Therefore, the current study required fourteen patients in each group to have sufficient power (>80%) to detect a difference of 10° of total sagittal range of motion during gait. The Type-I error probability assumed was 0.05.

All surgical procedures were performed by the senior author (T.D.) with use of surgical techniques for ankle arthroplasty and ankle arthrodesis as described previously<sup>1</sup>. Patients who underwent ankle arthroplasty received either the Hintegra (Integra LifeSciences, Plainsboro, New Jersey)<sup>26</sup> or the STAR (Scandinavian Total Ankle Replacement; Waldemar Link, Hamburg, Germany; now distributed by SBI, Morrisville, Pennsylvania)<sup>27</sup> mobile-bearing total ankle replacement.

## Gait Analysis

Bilateral barefoot gait data were collected. Participants wore T-shirts and tight-fitting shorts during the examination to allow for accurate marker placement. A single evaluator (S.K.) with seven years of experience applied the markers on all participants. Gait data were collected at 60 Hz with use of a 7-camera Vicon MX motion capture system (Vicon, Oxford, United Kingdom). Ground reaction forces were recorded with two Bertec force plates (Bertec, Columbus, Ohio), sampling at 1200 Hz, located in the center of the walkway.

Three-dimensional kinematics of the foot were obtained with use of a one-segment foot model that calculates the ankle angles as the shank relative to the entire foot, derived from an adapted Helen Hayes marker set<sup>28</sup>. Thirty-five spherical reflective markers were used to define the rigid body model<sup>1</sup>; marker positions are shown in the Appendix. Reflective markers were manually identified with use of the Vicon Workstation version 3.7 (Vicon). Local dynamic and bone-embedded coordinate systems were defined for the forefoot (metatarsals, cuneiforms, and cuboid), hindfoot (calcaneus, talus, and navicular), shank, thigh, and pelvis. The motion of the distal segment relative to the proximal segment was obtained with use of Euler angles. A rotation sequence from the sagittal plane to the coronal plane to the transverse plane was used to define the relative forefoot and hindfoot angles to allow for comparisons with previously published data<sup>25</sup>. The remaining segment rotations were defined with use of the Euler sequence of a coronal rotation, a transverse rotation, and a sagittal plane rotation<sup>1</sup>. All trajectories were filtered with use of a generalized, cross-validated spline technique<sup>29</sup>.

Gait trials were performed along a 10-m walkway. Participants were instructed to walk at their regular, self-selected walking speed. At least three complete trials were captured per subject. For a trial to be considered complete, it was required that bilateral markers were not obstructed, allowing for their accurate three-dimensional reconstruction, and that complete force plate data from the affected side were collected. In all cases, an average of three trials was used to obtain a single representative stride. Measures of velocity and percentage of time in stance and swing phases were calculated on the basis of the posterior heel-marker trajectories. Heel-off was determined from the sagittal trajectory of the heel marker, adapted from the method described by Beyaert et al.<sup>30</sup>. At heel-off, the following variables were measured: anterior tilt of the tibia, defined as sagittal plane rotation of the tibia with respect to the global coordinate system; knee flexion, defined as sagittal plane rotation of the tibia with respect to the femur;

TABLE I Temporal Gait Parameters

Parameter	Arthrodesis Group	Arthroplasty Group	Control Group	Power of Study*
Velocity (m/s)				0.139
Mean (and standard deviation)	1.1 ± 0.2	1.1 ± 0.2	1.2 ± 0.2	
95% CI†	1.0 to 1.2	1.0 to 1.2	1.1 to 1.3	
Cadence (steps per second)				0.347
Mean (and standard deviation)	107.8 ± 10.5	111.0 ± 10.5	114.2 ± 6.1	
95% CI†	102.5 to 113.2	105.6 to 116.4	109.8 to 118.5	
Stride length (m)				0.282
Mean (and standard deviation)	1.2 ± 0.2	1.2 ± 0.2	1.3 ± 0.1	
95% CI†	1.1 to 1.3	1.1 to 1.3	1.2 to 1.4	
Stance phase (% of gait cycle)				0.397
Mean (and standard deviation)	60.7 ± 2.1	61.6 ± 2.1	62.2 ± 0.9	
95% CI†	59.6 to 61.8	60.5 to 62.7	61.5 to 62.8	
Heel rise (% of gait cycle)				0.142
Mean (and standard deviation)	46.7 ± 3.1	47.9 ± 2.7	45.4 ± 1.8	
95% CI†	45.1 to 48.2	46.5 to 49.3	44.2 to 46.7	

\*The value shown is (1 - β) when the arthrodesis group was compared with the arthroplasty group. †95% CI = 95% confidence interval.

and the angle between the tibia and the foot, defined as coronal plane rotation of the foot with respect to the tibia. Data were processed to determine temporal kinematic and kinetic parameters with use of BodyBuilder software (Vicon).

### Patient-Reported Outcome Measures

Patients completed preoperative and annual postoperative functional outcome scores including the AOS<sup>31</sup> and the SF-36<sup>32</sup> Health Survey Version 2.0. The AOS evaluates pain and disability related to ankle arthritis, with lower scores indicating lower levels of pain and disability. The AOS was chosen for its validity and reliability in ankle osteoarthritis populations and demonstrated responsiveness in a population of patients who had undergone ankle arthrodesis or arthroplasty<sup>31</sup>. The SF-36 is a general health survey that measures eight scales of physical and mental well-being, which are summarized into Physical Component Summary (PCS) and Mental Component Summary (MCS) scores. Higher scores reflect better health. The SF-36 is well supported by evidence of reliability, validity, and responsiveness in a wide range of musculoskeletal disorders<sup>33</sup>. For the few patients who did not complete one-year SF-36 and AOS outcome measures, two or three-year data were used.

### Radiographic Analysis

All patients were followed with lateral standing, flexion, and extension radiographs of the ankle. Ankle motion was calculated by using the base plate of the tibial prosthesis as the tibial horizontal axis. For the Hintegra implant, the inferior aspect of the talar prosthesis was used as the horizontal axis of the talus, whereas for the STAR implant, a line was drawn from the anterior and posterior apices of the talar dome component to represent the talar horizontal axis. The difference in the angle between these measurements, in flexion compared with extension, was considered the total range of motion of the ankle joint.

### Statistical Analysis

The primary outcome measured was the kinetic gait parameter, the total sagittal ankle range of motion. Secondary outcomes included other kinematic and temporal-spatial gait parameters, SF-36 PCS and MCS scores, and AOS pain and disability scores.

Descriptive statistics were used to characterize the arthrodesis, arthroplasty, and control groups. These statistics included appropriate measures of

central tendency and dispersion. Preoperative and one-year postoperative patient-reported outcome measure scores were used to calculate the difference in scores for the arthroplasty and arthrodesis groups. For both the SF-36 and the AOS, independent sample t tests were used to compare mean changes in scores for patient groups. An α of <0.05 was considered significant.

Data extracted from the gait analysis included temporal-spatial, kinematic, and kinetic parameters. The temporal-spatial gait parameters included velocity, cadence, stride length, stance phase as a percentage of the gait cycle, and heel rise as a percentage of the gait cycle. The kinematic parameters included total sagittal ankle range of motion, ankle dorsiflexion, ankle plantar flexion, ankle coronal plane motion, tibial rotation, and tibial tilt at heel-off. The kinetic parameters included ankle plantar flexion moment, ankle moment at heel rise, and ankle power. Data were analyzed with use of separate one-way analysis of variance (ANOVA) for each gait parameter and functional score. The level of significance was fixed at  $p \leq 0.05$ . Post hoc analyses consisted of pairwise comparisons with Tukey-Kramer adjustments to control for multiple comparisons. To determine the risk of a Type-II error, if no significant differences were found, a power analysis was completed to calculate the sample size needed to find significance.

Residuals for all models were inspected for deviations from normality with use of quantile-quantile probability plots and the Kolmogorov-Smirnov test. Residuals with a p value of <0.05 were considered to have deviated significantly from a normal distribution and thus to have violated the assumptions of the ANOVA.

### Source of Funding

External funding from Integra and DePuy was utilized to fund the services provided by the gait laboratory for the gait analysis on both patient groups and the control group. Funds were used to pay for salaries and supplies.

### Results

Thirty-four patients were included in the study: seventeen underwent isolated ankle arthroplasties (nine with STAR prostheses and eight with Hintegra prostheses) and seventeen underwent ankle arthrodesis. Comparison was made with a control group of ten subjects matched for age, sex, and body mass index. Results presented include: preoperative demographic data,

TABLE II Kinematic Gait Parameters

Measurement	Arthrodesis Group	Arthroplasty Group	Control Group	P Value	Power of Study*
Total sagittal ankle range of motion ( <i>deg</i> )				<0.05†	0.899
Mean (and standard deviation)	13.7 ± 4.0	18.1 ± 4.6	27.9 ± 5.3		
95% CI†	11.6 to 15.8	15.8 to 20.5	24.1 to 31.6		
Ankle plantar flexion ( <i>deg</i> )				NS‡	0.513
Mean (and standard deviation)	6.9 ± 6.8	6.2 ± 4.8	16.0 ± 5.6		
95% CI†	3.4 to 10.4	3.7 to 8.7	12.0 to 20.0		
Ankle dorsiflexion ( <i>deg</i> )				<0.05#	0.893
Mean (and standard deviation)	6.8 ± 5.0	11.9 ± 5.2	11.9 ± 3.9		
95% CI†	4.2 to 9.4	9.3 to 14.6	9.1 to 14.6		
Ankle coronal plane range of motion (varus and valgus) ( <i>deg</i> )				NS‡	0.755
Mean (and standard deviation)	11.3 ± 3.5	13.8 ± 4.4	14.4 ± 4.0		
95% CI†	9.5 to 13.0	11.6 to 16.1	11.6 to 17.3		
Tibial rotation ( <i>deg</i> )				NS‡	0.643
Mean (and standard deviation)	9.1 ± 3.3	10.5 ± 3.2	10.6 ± 2.1		
95% CI†	7.4 to 10.9	8.9 to 12.2	9.1 to 12.1		
Tibial tilt at heel-off ( <i>deg</i> )				<0.05**	0.866
Mean (and standard deviation)	19.1 ± 4.6	23.1 ± 4.2	20.2 ± 3.7		
95% CI†	16.8 to 21.5	20.6 to 25.3	17.6 to 22.9		

\*The value shown is  $(1 - \beta)$ , with the number of subjects required for each group ( $n = 932$  for ankle plantar flexion,  $n = 34$  for ankle coronal plane range of motion [varus and valgus], and  $n = 74$  for tibial rotation) to detect a significant difference and to avoid a Type-II error. †There was a significant difference between the arthrodesis group and the control group, between the arthroplasty group and the control group, and between the arthrodesis group and the arthroplasty group. ‡95% CI = 95% confidence interval. §NS = not significant. #There was a significant difference between the arthrodesis group and the control group and between the arthrodesis group and the arthroplasty group. \*\*There was a significant difference between the arthrodesis group and the arthroplasty group.

baseline outcome data parameters, postoperative gait analysis measurements, postoperative outcome scores, and radiographic measurements.

The treatment groups and the control group had a similar body mass index (see Appendix). There were more

men in the arthrodesis group. Typically, patients who undergo arthroplasty are older than patients who undergo arthrodesis. This trend was true in our study; thus, the age of patients in the control group was an intermediate age between the two patient populations. Preoperative SF-36 and AOS scores were

TABLE III Kinetic Gait Parameters

Parameters	Arthrodesis Group	Arthroplasty Group	Control Group	Power of Study*
Power ( <i>watts</i> )				0.556
Mean (and standard deviation)	0.69 ± 0.36	0.99 ± 0.69	2.25 ± 0.47	
95% CI†	0.43 to 0.95	0.73 to 1.25	1.90 to 2.58	
Ankle extension moment ( <i>Nm/kg</i> )				0.152
Mean (and standard deviation)	0.64 ± 0.22	0.67 ± 0.35	1.11 ± 0.13	
95% CI†	0.58 to 0.75	0.49 to 0.85	1.02 to 1.21	
Ankle moment at heel rise ( <i>Nm/kg</i> )				0.152
Mean (and standard deviation)	0.61 ± 0.23	0.67 ± 0.31	1.07 ± 0.11	
95% CI†	0.49 to 0.73	0.51 to 0.84	0.99 to 1.15	

\*The value shown is  $(1 - \beta)$ , with the number of subjects required for each group ( $n = 43$  for power and  $n > 1000$  for both ankle extension moment and ankle moment at heel rise) to detect a significant difference and to avoid a Type-II error. †95% CI = 95% confidence interval.

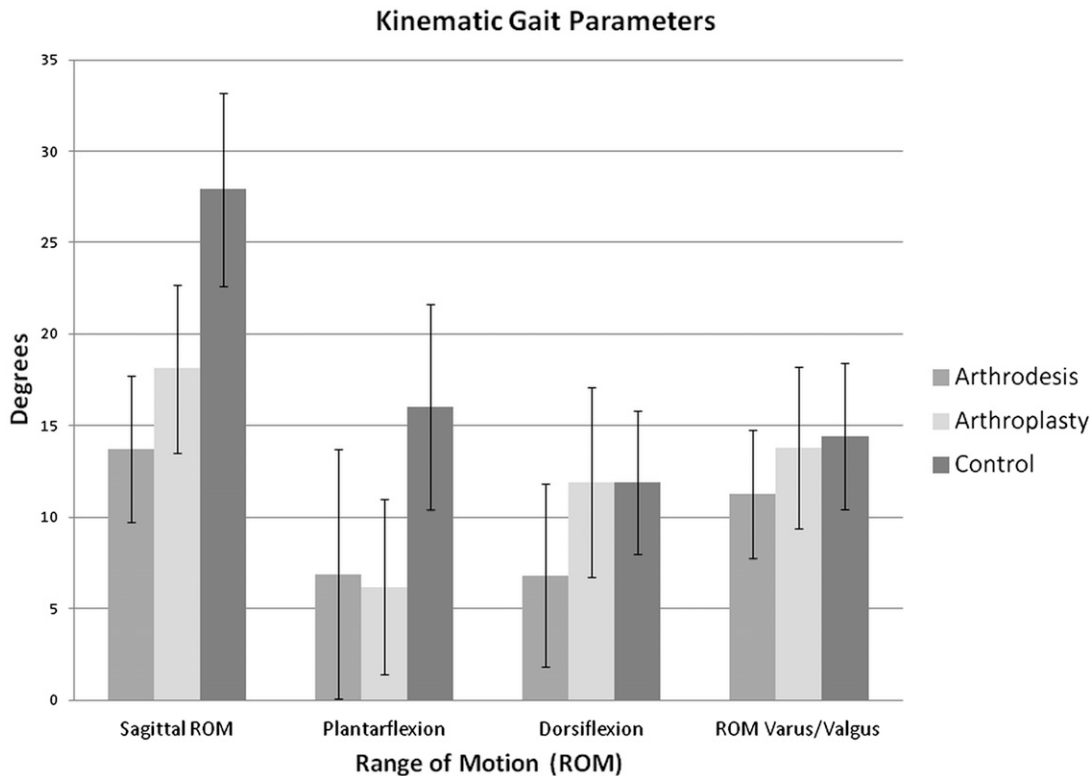


Fig. 1  
Ankle kinematic gait parameters: range of motion. Error bars represent one standard deviation.

not significantly different between the two patient groups (see Appendix).

Seven patients (41%) who had undergone arthroplasty and one patient (6%) who had undergone arthrodesis had undergone Achilles tendon lengthening by gastrocnemius slide (Strayer procedure) as part of their procedure. Concurrent procedures were performed in four patients (24%) who had undergone arthroplasty: three patients underwent a lateral base closing-wedge osteotomy of the calcaneus, and one patient underwent lateral base closing-wedge osteotomy of the calcaneus, dorsiflexion osteotomy, first metatarsal osteotomy, and plantar fascia release.

#### *Gait Analysis: Temporal Parameters*

Gait was evaluated at a mean follow-up (and standard deviation) of  $1.60 \pm 0.65$  years for patients who had undergone arthrodesis and  $1.27 \pm 0.62$  years for patients who had undergone arthroplasty ( $p = 0.15$ ). Temporal-spatial gait parameters for patients in the arthrodesis group at follow-up, patients in the arthroplasty group at follow-up, and patients in the control group were similar (Table I).

#### *Gait Analysis: Kinematic Parameters*

There were significant differences in kinematic variables among groups (Table II). The control group had the largest mean sagittal plane range of motion (and standard deviation) ( $27.9^\circ \pm 5.3^\circ$ ); when compared with the control group

or the arthrodesis group, the arthroplasty group had an intermediate outcome ( $18.1^\circ \pm 4.6^\circ$ ;  $p < 0.05$  for both comparisons); and when compared with the control group, the arthrodesis group had the least amount of motion ( $13.7^\circ \pm 4.0^\circ$ ;  $p < 0.05$ ) (Fig. 1). The main difference between the two patient groups came from improved dorsiflexion in the arthroplasty group (Fig. 2). The mean dorsiflexion (and standard deviation) was  $11.9^\circ \pm 5.2^\circ$  for the arthroplasty group but only  $6.8^\circ \pm 5.0^\circ$  for the arthrodesis group ( $p < 0.05$ ); the control group had dorsiflexion equal to that of the arthroplasty group ( $p = 1.00$ ). Conversely, neither patient group was using normal plantar flexion motion; the mean plantar flexion motion (and standard deviation) was  $6.2^\circ \pm 4.8^\circ$  for the arthroplasty group and  $6.9^\circ \pm 6.8^\circ$  for the arthrodesis group. Also, the plantar flexion motion (and standard deviation) was limited compared with the control group ( $16.0^\circ \pm 5.6^\circ$ ) (Fig. 2).

The motion of the ankle in the coronal plane (varus and valgus) was similar in all groups ( $p = 0.07$ ). Tibial rotation was also not significantly different among the groups ( $p = 0.32$ ). The range of tibial tilt (and standard deviation) was only different ( $p < 0.05$ ) between patient groups ( $23.1^\circ \pm 4.2^\circ$  for the arthroplasty group and  $19.1^\circ \pm 4.6^\circ$  for the arthrodesis group), whereas control group values were intermediate between the two treatment groups when they were compared with the arthrodesis group ( $p = 0.79$ ) and the arthroplasty group ( $p = 0.21$ ).

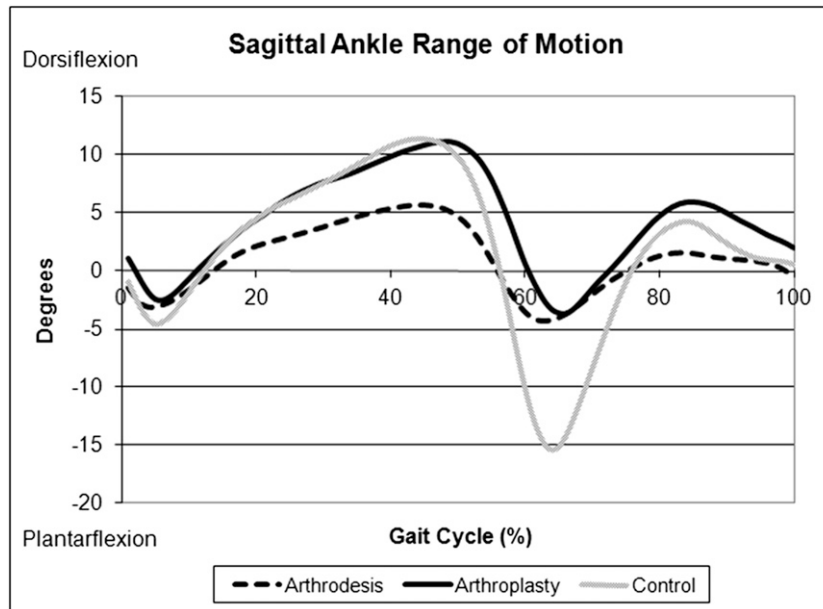


Fig. 2  
Ankle range of motion: sagittal plane.

#### Gait Analysis: Kinetic Parameters

Ankle kinetic variables are shown in Table III. The mean ankle power (and standard deviation) was greatest in the control group ( $2.25 \pm 0.47$  W/kg) and was less in the patient groups ( $0.69 \pm 0.36$  W/kg in the arthrodesis group and  $0.99 \pm 0.69$  W/kg in the arthroplasty group) (Fig. 3). A similar pattern was observed for ankle plantar flexion (extension) moment (Fig. 4) and ankle moment at heel rise.

#### Patient-Reported Outcome Measure Data

Clinical outcomes were evaluated at a mean follow-up (and standard deviation) of  $1.70 \pm 0.72$  years for patients who had undergone arthrodesis and  $1.02 \pm 0.10$  years for patients who had undergone arthroplasty ( $p < 0.05$ ). Changes in preoperative to postoperative AOS scores, in which a lower score indicates a better result, were not significantly different between the two patient groups. The pain score decreased by a

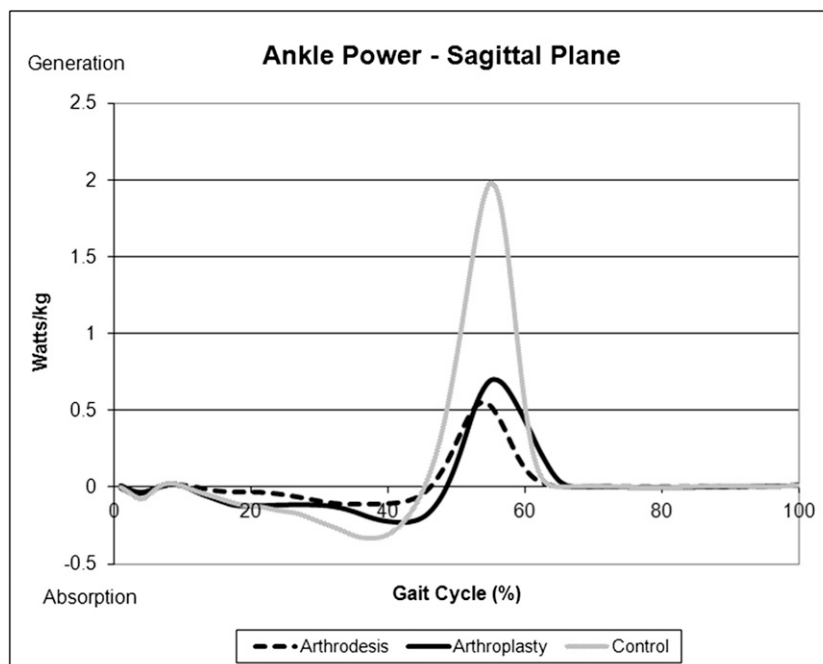


Fig. 3  
Ankle power: sagittal plane.



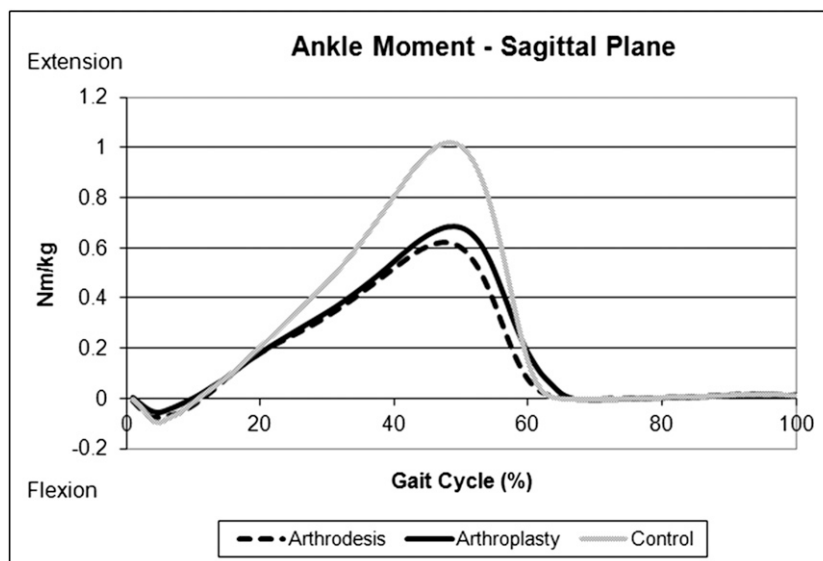


Fig. 4  
Ankle moment: sagittal plane.

mean (and standard deviation) of  $25.6 \pm 15.7$  points for the arthroplasty group compared with  $28.4 \pm 22.4$  points for the arthrodesis group ( $p = 0.68$ ). The disability score decreased by a mean (and standard deviation) of  $32.5 \pm 20.4$  points for the arthroplasty group compared with  $31.5 \pm 20.0$  points for the arthrodesis group ( $p = 0.88$ ). Similarly, comparing the amount of improvement in the SF-36 PCS and MCS scores, in which a higher score indicates a better result, did not reveal any significant differences between the two treatment groups. Patients who had undergone arthroplasty showed an improvement of 9.7 points in the PCS score, whereas scores of patients who had undergone arthrodesis improved by 9.6 points ( $p = 0.98$ ). MCS scores showed limited change in both patient groups: scores changed by 0.1 point for the arthroplasty group and 1.9 points for the arthrodesis group ( $p = 0.59$ ).

#### Radiographic Parameters

One-year radiographic assessment demonstrated that all ankle replacement implants were appropriately sized and in good alignment in sagittal and coronal planes. Lateral flexion and extension views revealed an average total arc of motion of  $21^\circ$  (range,  $9^\circ$  to  $33^\circ$ ).

#### Discussion

A functional outcome comparison with use of gait analysis demonstrated better kinematic gait parameters for the ankle arthroplasty cohort compared with the arthrodesis cohort at one year following surgery. Sagittal plane range of motion was significantly better in patients who underwent ankle arthroplasty; however, temporal and kinetic parameters were similar for the two treatment groups. Neither treatment group had completely normalized gait parameters. However, the ankle kinematics observed one year following ankle arthroplasty in this study were a marked improvement over gait

patterns reported following arthroplasties using first-generation total ankle prostheses<sup>5,17</sup>.

Normal ankle plantar flexion, which contributes to ankle push-off, was not achieved in either patient group. The fact that both patient groups were limited in plantar flexion motion is an interesting observation that could help to improve the design of future implants, techniques for implantation, patient rehabilitation, and expectations. Patients who underwent arthroplasty had more motion than they used during gait, with an average of  $21^\circ$  of sagittal plane range of motion on radiographs and an average of  $17^\circ$  observed during steady-state walking on gait analysis. These results are similar to the  $17.9^\circ$  of ankle sagittal plane range of motion reported by Brodsky et al.<sup>18</sup> in fifty patients at a mean duration of forty-nine months following arthroplasty. However, from our control data, approximately  $28^\circ$  of sagittal plane range of motion is necessary for normal gait. It is our observation that neither of the arthroplasty designs used in this study effectively reproduces the posterior malleolus of the ankle. This deficiency appears to be common to the design of most current three-component ankle arthroplasty systems. It is possible that the lack of posterior support prevents patients from using their functional ankle plantar flexion during the terminal portion of the stance phase. Other possibilities include a weak gastrocnemius-soleus complex caused by long-term disuse and/or lengthening at the time of surgical intervention.

A sole gait study, published by Piriou et al.<sup>34</sup>, compared patients who had undergone arthroplasty with those who had undergone arthrodesis. They compared two equally sized groups of patients who had undergone arthroplasty or arthrodesis, concluding that the arthroplasty group had a slower gait, with ground reaction forces approaching those of normal controls. However, the study was underpowered and was limited by a short six-month follow-up period for some subjects, unmatched controls, limited kinetic analysis, and kinematic

results from the sagittal plane only. Their results differ somewhat from our findings, in which patients who had undergone arthroplasty walked at a speed similar to that of patients who had undergone arthrodesis. Both the study by Piriou et al.<sup>34</sup> and the current study demonstrated that ankle motion and forces were not completely normalized by either procedure, but were closer to normal with arthroplasty.

The mean ankle power (and standard deviation) observed in patients who had undergone arthroplasty in our study at one year following surgery ( $1.0 \pm 0.7$  W/kg) was similar to that observed by Brodsky et al.<sup>18</sup> in fifty patients at a mean of forty-nine months following arthroplasty with the STAR prosthesis ( $1.0 \pm 0.4$  W/kg). The fact that patients after undergoing arthroplasty have less than half the power generation of control ankle joints in both studies is interesting and worthy of future studies, which might consider evaluation of calf muscle strength in conjunction with gait analysis. The limitation in power generation might be related to the apparent lack of posterior support at toe-off and/or weakness of the gastrocnemius-soleus complex causing disruption in the terminal coupling mechanism between the ankle and the knee. Because ankle power is the product of the ankle moment and ankle angular velocity, greater ankle plantar flexion would be associated with greater ankle power. Consideration of implant design modification to include a posterior support may improve ankle power generation at toe-off. Altering the technique in which components are implanted may be able to skew the improvements in sagittal plane motion into a more functional arc.

Ankle plantar flexion moments in both of our study groups were not comparable with those of the control group. The lack of ankle plantar flexion moment was accompanied by a lack of plantar flexion motion. Our study was not designed to establish the cause of the lack of plantar flexion motion or lower power generation. Long-standing weakness of the ankle plantar flexion muscle complex due to painful ankle arthritis might be a key factor in achieving further normalization of ankle power generation at toe-off. Future studies may consider one of two avenues to improve these parameters: addressing implant design changes to improve posterior hindfoot sagittal plane stability during the late-stance phase of gait to improve ankle power, or investigating the effect of long-standing ankle osteoarthritis on ankle plantar flexor weakness and considering alterations in rehabilitation protocols to improve ankle strength and power. Ankle plantar flexion weakness in the involved ankle one year after arthroplasty has been documented compared with the uninvolved ankle<sup>35</sup>.

It has been theorized that the development of ipsilateral arthritis in the subtalar and midtarsal joints following ankle arthrodesis is the result of abnormal gait kinematics. This study did observe an improved tibial tilt in the arthroplasty group compared with the arthrodesis group, consistent with the findings by Beyaert et al.<sup>30</sup> The ankle motion in the coronal plane (varus or valgus) was not significantly different and is comparable with results reported in the literature<sup>36</sup>. Post hoc

power calculations suggest that a sample size of thirty-four participants would be sufficient to detect a significant difference and to avoid a Type-II error. Nevertheless, the normalization of coronal plane motion (evaluated as ankle range of motion in varus or valgus) and improvement in ankle sagittal movement observed following arthroplasty suggests that more normal hindfoot or midfoot kinematics are restored. It has not been established whether this will decrease stresses on adjacent joints, thereby slowing the progression of arthritis.

#### *Limitations and Bias*

The strict exclusion criteria employed in this study to minimize potential bias resulted in the inclusion of a limited percentage of the total number of patients undergoing these two procedures during the study period. This strategy was necessary, as the validity of our conclusions hinged on ensuring that patients' gait patterns were attributed to the surgical procedures alone. We were unable to randomize patients to treatment groups; therefore, equivalence at baseline was not assured. Although the treatment groups were not matched for age and sex, they were equivalent on the basis of key variables. The control group was matched for sex and weight to the two treatment groups and was an intermediate age between the two patient populations. The younger age of the patients in the arthrodesis group was a potential confounder in this study and would likely have biased the outcome in favor of better sagittal range of motion and greater power following arthrodesis. Thus, the moderately better outcome observed following arthroplasty would likely be even greater if adjusted for patient age.

The sample size of our study was small and may be prone to bias. This is a universal problem in gait studies, which generate a massive amount of raw data for each subject. Nevertheless, our study was sufficiently powered to determine significant differences in sagittal plane motion, dorsiflexion, and tibial tilt at heel-off.

With respect to patient-reported outcome measure data, it is an established concept that when comparing two groups and using change in patient scores, if a group starts with lower scores, then there is more room for improvement. In our study, the patients in the arthrodesis group started out with slightly lower, but not significantly lower, patient-reported outcome scores, which may bias the study toward greater improvement in the arthrodesis group.

Our radiographic measurements are limited in that we cannot conclusively say from our study whether the unused 4° of sagittal motion is in the plantar flexion range or just part of the unused dorsiflexion range that is outside of the functional range necessary for steady-state walking.

#### *Generalizability*


Our results can be generalized to patients with end-stage ankle arthritis who are between forty and eighty years of age and are choosing between ankle arthroplasty and arthrodesis. Although we employed strict exclusion criteria, this exclusion process



was necessary to isolate differences in gait patterns due to the surgical procedure alone; the relative expectations of patients who have other joint replacements and/or other lower-limb trauma can likely be extrapolated.

In conclusion, the current investigation demonstrated that neither ankle arthroplasty nor arthrodesis replicated normal ankle function, and there were no differences in ankle power, moments, or temporal gait parameters between the two patient groups. However, gait mechanics were normalized to a greater extent following ankle arthroplasty compared with those following arthrodesis, sagittal joint motion was maintained in the arthroplasty group, and ankle kinematics one year following ankle arthroplasty were markedly improved compared with those following arthroplasty with first-generation total ankle prostheses. These results will help with the design of future implants, will form the basis for modification of surgical technique, and will help clinicians educate patients on the expected improvements following ankle arthroplasty or ankle arthrodesis.

## Appendix

 A figure showing an illustration of the marker placement for gait analysis and tables showing the preoperative patient demographic characteristics and preoperative patient data

are available with the online version of this article as a data supplement at [jbjs.org](http://jbjs.org). ■

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