Compensatory Motion of the Subtalar Joint Following Tibiotalar Arthrodesis

An in Vivo Dual-Fluoroscopy Imaging Study

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Background: Tibiotalar arthrodesis is a common treatment for end-stage tibiotalar osteoarthritis, and is associated with a long-term risk of concomitant subtalar osteoarthritis. It has been clinically hypothesized that subtalar osteoarthritis following tibiotalar arthrodesis is the product of compensatory subtalar joint hypermobility. However, in vivo measurements of subtalar joint motion following tibiotalar arthrodesis have not been quantified. Using dual-fluoroscopy motion capture, we tested the hypothesis that the subtalar joint of the limb with a tibiotalar arthrodesis would demonstrate differences in kinematics and increased range of motion compared with the subtalar joint of the contralateral, asymptomatic, untreated ankle.

Methods: Ten asymptomatic patients who had undergone unilateral tibiotalar arthrodesis at a mean (and standard deviation) of 4.0 ± 1.8 years previously were evaluated during overground walking and a double heel-rise task. The evaluation involved markerless tracking with use of dual fluoroscopy integrated with 3-dimensional computed tomography, which allowed for dynamic measurements of subtalar and tibiotalar dorsiflexion-plantar flexion, inversion-eversion, and internal-external rotation. Range of motion, stance time, swing time, step length, and step width were also measured.

Results: During the early stance phase of walking, the subtalar joint of the limb that had been treated with arthrodesis was plantar flexed ($-4.7^\circ \pm 3.3^\circ$), whereas the subtalar joint of the untreated limb was dorsiflexed ($4.6^\circ \pm 2.2^\circ$). Also, during the early stance phase of walking, eversion of the subtalar joint of the surgically treated limb ($0.2^\circ \pm 2.3^\circ$) was less than that of the untreated limb ($4.5^\circ \pm 3.2^\circ$). During double heel-rise, the treated limb exhibited increased peak subtalar plantar flexion ($-7.1^\circ \pm 4.1^\circ$) compared with the untreated limb ($0.2^\circ \pm 1.8^\circ$).

Conclusions: A significant increase in subtalar joint plantar flexion was found to be a primary compensation during overground walking and a double heel-rise activity following tibiotalar arthrodesis.

Clinical Relevance: Significant subtalar joint plantar flexion compensations appear to occur following tibiotalar arthrodesis. We found an increase in subtalar plantar flexion and considered the potential relationship of this finding with the increased rate of subtalar osteoarthritis that occurs following ankle arthrodesis.

Tibiotalar osteoarthritis (OA) represents a substantial socioeconomic burden¹. The 2 main surgical options for the treatment of tibiotalar OA are tibiotalar arthrodesis²⁻⁴ and total ankle replacement⁵⁻⁷. Tibiotalar arthrodesis, which involves obtaining osseous fusion between the tibia and the talus, is the most common surgical treatment for end-stage OA, accounting for 80% of procedures^{8,9}. Arthrodesis has been shown to be effective for managing pain caused by end-stage

tibiotalar OA¹⁰. However, functional impairments persist following the procedure^{4,11}; notably, nearly 50% of patients are unable to return to their desired activities¹⁰. Regardless of early pain relief, tibiotalar arthrodesis is associated with progressive deterioration of hyaline cartilage in the surrounding joints, which may lead to secondary OA and dysfunction^{12,13}. As a result, many patients who are managed with tibiotalar arthrodesis experience increasing functional impairment

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following surgery^{14,15}. Subtalar OA is of particular concern; in 1 study, 100% of patients who had undergone tibiotalar arthrodesis exhibited radiographic evidence of subtalar OA at the time of a 20-year follow-up visit¹¹. However, the specific biomechanical factors responsible for subtalar OA following tibiotalar arthrodesis are poorly understood.

In vivo biomechanical studies have demonstrated that tibiotalar arthrodesis decreases ankle range of motion, which likely contributes to abnormal, inefficient gait^{3,4,16-21}. However, those studies involved the use of skin-based motion-capture techniques that do not quantify motion across the individual joints of the ankle (i.e., separating tibiotalar from subtalar joint motion). Notably, International Society of Biomechanics-recommended standards do not allow for separating hindfoot motion of the subtalar joint when using skin-marker motion analysis because of the inability to palpate landmarks on the talus²².

Dynamic imaging with high-speed dual fluoroscopy (also referred to as biplane radiography or biplane fluoroscopy) provides direct in vivo measurements of bone motion²³⁻²⁸. Dual fluoroscopy has been validated for the measurement of subtalar kinematics, with reported errors of <1 mm and <1°²⁷. One advantage of dual fluoroscopy is that it provides visualization of bone motion relative to patient-specific anatomy generated from segmented computed tomography (CT) scans or magnetic resonance images²⁵⁻³⁰. In the present study, we used dual fluoroscopy to measure in vivo subtalar motion in patients who had undergone unilateral tibiotalar arthrodesis. We hypothesized that the subtalar joint of the limb that had been treated with arthrodesis would demonstrate differences in subtalar kinematics and increased range of motion as compared with the contralateral, asymptomatic, untreated subtalar joint.

Materials and Methods

Subject Recruitment and Screening

Approval from the institutional review board was granted, and patients completed informed consent for this retrospective cohort study. First, a database search identified all 334 patients who had undergone tibiotalar arthrodesis at our surgical center over a 6-year period. We then reviewed medical charts to exclude patients who had died, were >75 years old, and/or had comorbidities, including chronic pain, peripheral neuropathy, hemophilia, rheumatoid arthritis, stroke, muscular dystrophy, Charcot-Marie-Tooth disease, or a body mass index (BMI) of >35 kg/m². Fifty potential participants were identified, and 25 patients showed initial interest. When screened over the telephone, 4 of the interested individuals reported ankle pain that severely limited their daily activities and 11 stated they were unable to travel to our center for the study, leaving 10 participants. Once onsite, these 10 individuals underwent radiographic evaluation with weight-bearing radiographs of the foot and ankle (anteroposterior, hindfoot, lateral, and mortise) to screen for subtalar deformities or degeneration on the limb that had been treated with arthrodesis and for OA and/or deformities in the contralateral limb; no participants were excluded on the basis of radiographic evaluation. Finally, the 10 participants completed patient-reported outcome instruments (including the

Patient-Reported Outcomes Measurement Information System [PROMIS] Physical Function computerized adaptive test [PF-CAT]³¹ and a visual analog scale [VAS] for pain³²) to further screen for pain and poor physical function as these factors could confound kinematic results; no participants were excluded on the basis of PF-CAT or VAS scores.

To our knowledge, subtalar joint angles have not been quantified following tibiotalar arthrodesis; therefore, data from an appropriate population were not available to conduct a formal power analysis. Our sample of convenience (n = 10 patients) provided a Cohen d of 2.3. This value represents a large effect size, which we expected given that removal of tibiotalar motion likely would require compensatory changes in motion of the subtalar joint to provide functional motion of the ankle complex.

Dual-Fluoroscopy Motion Capture

A validated high-speed dual-fluoroscopy system was used to measure subtalar kinematics^{27,28}. The dual-fluoroscopy system consisted of 2 pairs of x-ray emitters and image intensifiers mounted to separate bases (Radiological Imaging Services). The 2 image intensifiers were positioned approximately 90° to one another with a 110-cm focal length. The dual-fluoroscopy system was positioned to capture oblique lateral images of the foot and ankle as participants contacted in-ground force plates during overground walking (OR-6 series; AMTI) (Fig. 1-A). Ground-reaction forces were simultaneously acquired as dual-fluoroscopy images were obtained to identify gait events (e.g., heel-strike, toe-off) and spatiotemporal parameters as well as to determine if there were force compensations between the treated and untreated limbs.

The energy settings of the dual-fluoroscopy system ranged from 62 to 78 kVp and from 1.4 to 2.2 mA; the settings were not uniform because of differences in limb size and osseous architecture as well as the presence or absence of metal. All participants completed 2 trials of overground barefoot walking and a double heel-rise activity (a bilateral balanced task to rise onto the toes); both activities were performed at a self-selected speed. Participants were provided with the opportunity to practice each activity before data capture. Walking was selected as a representative activity of daily living. The double heel-rise activity was chosen to accentuate potential compensations at the subtalar joint following tibiotalar arthrodesis. Total dual-fluoroscopy exposure time for each subject did not exceed 3 minutes, equivalent to an effective dose of 5.2×10^{-2} mSv (~9.4 days of background radiation).

CT and Model-Based Markerless Tracking

Quantification of in vivo joint kinematics from dual fluoroscopy images requires 3-dimensional (3D) surface representations of the joint anatomy. Accordingly, CT scans (SOMATOM Definition AS; Siemens Medical Solutions) were acquired for each participant from the middle part of the tibia through the entire plantar aspect of the foot with a 1.0-mm slice thickness, 450 ± 50.3 -mm field of view, and 512×512 acquisition matrix. Tube voltage and current averaged 90 kVp and 45 mA, respectively, using CAREdose (Siemens), which reduced radiation while maintaining image quality. Bilateral scans were acquired for patients with

Fig. 1

Fig. 1-A Dual-fluoroscopy (DF) setup. Participants performed overground walking at a self-selected speed as well as a double heel-rise. The DF image intensifiers (II #1 and II #2) processed images created by x-rays from the emitters (E #1 and E #2). Simultaneously, the force platforms (FP1 and FP2) quantified ground-reaction forces. The DF views show the ankle of a patient who is set to begin a double heel-rise trial. **Fig. 1-B** Medical imaging consisted of CT scans of the foot and ankle, which were segmented to reconstruct 3D surfaces representing the bones and digitally reconstructed radiographs. **Fig. 1-C** Digitally reconstructed radiographs were overlaid on the calibrated DF views frame by frame with markerless tracking methods. **Fig. 1-D** Subtalar kinematics were normalized from heel-strike to toe-off for walking.

unilateral arthrodesis so that the untreated limb could be evaluated as an internal control. The CT images were segmented semi-automatically (Amira v6.0; Visage Imaging) to generate 3D surfaces representing the tibia, talus, calcaneus, and combined tibiotalar fusion (Fig. 1-B). Segmentations were processed to

generate digitally reconstructed radiographs, which were input to model-based markerless tracking^{23,24} to quantify in vivo kinematics as detailed elsewhere²⁷ (Fig. 1-C). Only 1 trial of each activity was analyzed because of laborious data-processing procedures, and, thus, intertrial variability was not assessed.

Dynamic Subtalar Kinematics and Range of Motion

Coordinate systems were established with use of a landmark-based approach for the tibia, talus, and calcaneus²⁷. For the untreated limb, the talus and calcaneus were aligned with respect to the tibial coordinate system. For the limb that had been treated with tibiotalar arthrodesis, a modified approach was implemented with use of the intact features on the distal side of the talus along with the long-axis alignment of the tibial shaft. For the treated limb, the calcaneus coordinate system was aligned with the tibiotalar fusion coordinate system. A weight-bearing neutral position of the ankle was determined on the basis of a static standing dual-fluoroscopy trial.

During all completed tasks, dynamic joint angles were calculated for the subtalar joint with use of previously validated techniques²⁷. Three-dimensional bone trajectories were smoothed with a fourth-order bidirectional low-pass Butterworth filter with a 10-Hz cutoff frequency prior to joint-angle calculations. Subtalar joint angles were reported for motion in the sagittal plane (with positive values indicating dorsiflexion and negative values indicating plantar flexion), frontal plane (with negative values indicating inversion and positive values indicating eversion), and transverse plane (with negative values indicating internal rotation and positive values indicating external rotation). Walking tasks were normalized and reported as percent stance wherein heel-strike and foot-off were calculated on the basis of the ground-reaction forces (Fig. 1-D). Double heel-rise tasks were normalized with use of 2 inflection points at the beginning and end of activity completion as defined by the second derivative (where accelerations equaled 0) for the dorsiflexion-plantar flexion subtalar joint angles and were reported as percent activity. Subtalar range of motion was calculated for all activities as the within-trial kinematic maximum minus the minimum.

Statistical Analysis

All statistical tests were performed in MATLAB (MathWorks). The Kolmogorov-Smirnov test³³ revealed that the data were

normally distributed, and, thus, parametric tests were employed. The mean and 95% confidence interval (CI) were plotted to visualize group profiles (for the operatively treated and contralateral, untreated limbs) with respect to normalized percent stance for subtalar kinematics and ground-reaction forces. Differences in subtalar range of motion were evaluated between the operatively treated and contralateral, untreated limbs with use of the paired Student t test.

Statistical parametric mapping (SPM) was applied to conduct a time-domain-dependent analysis for joint angles at each instant of normalized percent stance. The advantage of SPM is that it performs temporal comparisons to report cluster-based p values³⁴⁻³⁷. A previous implementation of SPM (1d version 0.4, MATLAB-based open source software: www.spm1d.org) was applied³⁸⁻⁴². With use of paired t tests, SPM evaluated whether kinematics and ground-reaction forces were statistically different between the operatively treated and contralateral, untreated limbs.

Results

In total, 10 patients with unilateral tibiotalar arthrodesis were included (Table I). The mean age was 53.2 years (range, 34 to 62 years), and the mean BMI was 28.6 kg/m² (range, 22.6 to 34.3 kg/m²). Five patients had had tibiotalar arthrodesis on the right side, and 5 had had it on the left side. The mean time from surgery to testing (and standard deviation) was 4.0 ± 1.8 years, with all participants having had the procedure at least 18 months (range, 1.6 to 7.1 years) previously.

Dynamic Subtalar Kinematics

During walking, the side that had been treated with tibiotalar arthrodesis showed increased plantar flexion ($-4.7^\circ \pm 3.3^\circ$) and decreased eversion ($0.2^\circ \pm 2.3^\circ$) at the subtalar joint in stance phase compared with the contralateral, untreated limb, which showed dorsiflexion ($4.6^\circ \pm 2.2^\circ$) ($p = 0.001$) and eversion ($4.5^\circ \pm 3.2^\circ$) ($p = 0.001$) (Fig. 2). During walking, no significant differences were found between the sides in terms of subtalar internal or external rotation. During the double heel-rise task, the subtalar joint on the side that had been treated

TABLE I Demographic Characteristics

Case	Treated Side	Sex, Age (yr)	Height (cm)	Body Mass (kg)	BMI (kg/m ²)	Years Postop.
1	Right	F, 40	170.5	91.8	31.6	7.1
2	Right	M, 62	178.0	80.5	25.4	3.1
3	Left	F, 57	170.0	71.0	24.6	2.4
4	Left	M, 56	187.5	92.0	26.2	3.3
5	Right	M, 54	173.0	67.5	22.6	4.8
6	Left	M, 55	170.0	99.0	34.3	4.9
7	Right	F, 58	169.0	92.5	32.4	5.9
8	Right	M, 54	173.5	98.5	32.7	1.9
9	Left	F, 62	161.0	78.5	30.3	1.6
10	Left	F, 34	168.0	74.0	26.2	5.1

Fig. 2

Fig. 3

Fig. 2 Line graph showing subtalar kinematics (dorsiflexion-plantar flexion, inversion-eversion, and internal-external rotation) during walking for the limbs treated with arthrodesis (red) and the contralateral, untreated limbs (blue). Results are normalized as the percent of stance cycle (with 0% indicating initial heel contact and 100% indicating toe-off). Portions of the stance cycle during which differences were significant (*) as evaluated with statistical parametric mapping are shown with a horizontal bar. The shaded regions indicate the 95% confidence intervals. **Fig. 3** Line graph showing subtalar kinematics (dorsiflexion-plantar flexion, inversion-eversion, and internal-external rotation) during the double heel-rise activity for the limbs treated with arthrodesis (red) and the contralateral, untreated limbs (blue). Results are normalized as the percent of the entire heel-rise activity. Portions of the heel-rise activity during which differences were significant (*) as evaluated with statistical parametric mapping are shown with a horizontal bar. The shaded regions indicate the 95% confidence intervals.

TABLE II Maximum Differences in Subtalar Joint Angles Between the Limbs with and without Arthrodesis*

	Walking			Double Heel-Rise		
	P Value	% Stance	Maximum	P Value	% Activity	Maximum
Dorsiflexion-plantar flexion	0.001	0.1-32.3	9.3° ± 2.8°	0.001	11.2-92.8	7.3° ± 2.4°
Eversion-inversion	0.001	5.3-36.5	4.3° ± 2.7°	0.001	0-38.3, 68.3-99.4	7.0° ± 2.5°
External-internal rotation	NS	—	—	0.001	16.8-40.5	5.4° ± 2.1°

*To calculate differences between the groups, statistical parametric mapping (SPM) first identified time points in the activity or stance phase during which kinematics were significantly different. During walking, time-point regions were reported as a percentage of stance (% Stance), whereas during the double heel-rise task, time-point regions were reported as a percentage of the activity (% Activity). Reported p values of <0.05 indicate regions where joint angles differed significantly (bold). Maximum differences in subtalar joint angles during walking and double heel-rise tasks were reported as the mean and standard deviation within these significant regions. SPM results for walking did not result in significant external-internal rotation joint angle differences; therefore, maximum differences and regions are denoted as not significant (NS).

with tibiotalar arthrodesis showed increased plantar flexion, decreased eversion, and increased internal rotation as compared with the untreated limb (Fig. 3). During double heel-rise, the treated limb exhibited increased peak subtalar plantar flexion ($-7.1^\circ \pm 4.1^\circ$) compared with the untreated limb ($0.2^\circ \pm 1.8^\circ$). Significantly different regions of joint angles were reported as a percentage of the stance or activity phase and were noted in the sagittal, frontal, and transverse planes, with maximum differences of 4.3° to 9.3° between limbs (Table II).

Range of Motion

During walking, the subtalar range of dorsiflexion-plantar flexion was $7.3^\circ \pm 2.8^\circ$ for the limb that had been treated with arthrodesis, compared with $5.2^\circ \pm 1.9^\circ$ for the untreated limb ($p = 0.03$), but no differences were observed in terms of inversion-eversion or internal-external rotation range of motion (Table III). Similarly, during the double heel-rise task, the subtalar range of dorsiflexion-plantar flexion was $7.8^\circ \pm 3.2^\circ$ for the limb that had been treated with arthrodesis, compared with $2.5^\circ \pm 0.9^\circ$ for the untreated limb ($p = 0.001$), with no differences in the other rotation directions.

Ground-Reaction Forces and Spatiotemporal Parameters

SPM paired t tests revealed no significant differences in ground-reaction forces (see Appendix Figure A1). During overground walking, patients walked at an average self-selected

walking speed of 0.92 ± 0.16 m/s. There were no differences in step length, step width, stance time, or swing time (see Appendix Table A1).

Discussion

In the present study, we applied dual fluoroscopy to measure in vivo subtalar motion in patients who had undergone unilateral tibiotalar arthrodesis. We hypothesized that the subtalar joint of the limb that had been treated with arthrodesis would demonstrate kinematic differences and increased range of motion when compared with the contralateral, asymptomatic, untreated ankle. We found that, during double heel-rise, the subtalar joint in the limb that had been treated with arthrodesis exhibited increased plantar flexion, reduced eversion, and increased internal rotation. Only sagittal plane range of motion was significantly increased during walking and double heel-rise activities. Collectively, these findings suggest that tibiotalar arthrodesis induces compensatory changes in the subtalar joint.

In healthy individuals, the subtalar joint is theorized to provide internal-external rotation and inversion-eversion motion^{26,43}. A recent dual-fluoroscopy study demonstrated that the subtalar joint in healthy individuals provides 6-degrees-of-freedom motion (i.e., dorsiflexion-plantar flexion, inversion-eversion, internal-external rotation, and medial-lateral, anteroposterior, and superoinferior translation)²⁶. As a

TABLE III Subtalar Joint Ranges of Motions During Walking and Double Heel-Rise*

	Walking			Double Heel-Rise		
	Arthrodesis	No Arthrodesis	P Value	Arthrodesis	No Arthrodesis	P Value
Dorsiflexion-plantar flexion	7.3° ± 2.8°	5.2° ± 1.9°	0.03	7.8° ± 3.2°	2.5° ± 0.9°	0.001
Eversion-inversion	5.2° ± 2.3°	7.1° ± 1.6°	0.09	3.8° ± 1.4°	3.4° ± 1.4°	0.47
External-internal rotation	7.8° ± 3.0°	6.3° ± 2.2°	0.27	6.2° ± 2.9°	3.8° ± 1.6°	0.06

*The values are given as the mean and standard deviation. The range of dorsiflexion-plantar flexion was significantly increased in the limb with arthrodesis during both activities. Bold text indicates significant findings.

combined hindfoot complex, the tibiotalar and subtalar joints work together to collectively provide additional range of motion and stability. We found that the subtalar joint in the limb that had been treated with tibiotalar arthrodesis underwent significantly more plantar flexion, which may be an expected compensation as the tibiotalar joint typically provides the sagittal plane motion required for the toe to clear the ground during gait. Therefore, the complex interplay between the tibiotalar and subtalar joints is likely driving the altered subtalar kinematics when tibiotalar motion is eliminated following tibiotalar arthrodesis.

Direct comparisons of our data are not possible because, to our knowledge, no other studies have quantified *in vivo* subtalar joint kinematics in patients who have been managed with arthrodesis. Our findings agree with those of Sturtnick et al., who used a cadaver model and robotic simulator to quantify dynamic subtalar kinematics following tibiotalar arthrodesis during simulated walking and reported increased plantar flexion, inversion, and internal rotation in early stance⁴⁴. Additional cadaver studies have demonstrated that tibiotalar arthrodesis changed hindfoot kinematics most dramatically with respect to range of motion and talar movement measures in comparison with intact ankle or total ankle replacement specimens⁴⁵⁻⁴⁷. We cannot compare the reported measurements of subtalar kinematics with previous gait analyses of patients who had been managed with tibiotalar arthrodesis because prior studies quantified motion of the tibia relative to the calcaneus^{4,20} (due to the inability to track the talus with markers adhered to the surface of the skin).

Despite having complete fusion of the tibiotalar joint in 1 limb, our patients did not exhibit asymmetries between the treated and untreated limbs with respect to step length, step width, and stance or swing time during the low-demand experimental tasks that were performed in the present study (see Appendix Table A1). We surmise that compensatory motion at the subtalar joint is used as a mechanism to maintain gait symmetry. Our participants had an average self-selected walking speed of 0.92 ± 0.16 m/s, which was 16% to 41% lower than that for previously reported control groups without orthopaedic injuries or surgery^{48,49} but was similar to that of other patients who had undergone arthrodesis^{3,50-52}. Beyaert et al., in a study on the effects of walking speed in patients following unilateral tibiotalar arthrodesis, reported a decrease in vertical ground-reaction force when patients were forced to walk at a speed that was faster than their preferred speed⁵⁰. We observed no differences in ground-reaction forces at the preferred walking speed for our participants (see Appendix Figure A1), but it is possible that these forces would change if we had asked our participants to increase their walking speed.

The present study had limitations. We evaluated participants at a self-selected walking speed (0.92 ± 0.16 m/s); faster walking speeds could induce larger kinematic compensations at the subtalar joint. A typical walking speed for similarly aged healthy adults reportedly ranges from 1.10 to 1.55 m/s^{48,49}. Still, we believe that our conclusions are valid because it is likely that our participants also walk slower in their daily lives. Future

investigators could consider examining more-demanding activities. Next, the angle of the fusion and orientation of the talus relative to the floor were not acquired; future investigators could use radiographs to evaluate these metrics. Our study provides insight into the kinematic role of the subtalar joint following tibiotalar arthrodesis, but we acknowledge that a longitudinal study will be required to evaluate relationships of compensatory kinematic motion with other clinical metrics, including radiographic findings and patient-reported outcomes. Furthermore, a kinematic analysis of the contralateral, untreated limb compared with healthy individuals could evaluate possible compensations in the contralateral limb that are not seen in healthy individuals without a history of foot and ankle surgery. Finally, no preoperative or pretreatment analysis was conducted in these patients to evaluate joint stiffness, health, or status prior to tibiotalar arthrodesis. A preoperative assessment could lend itself to the identification of comorbidities contributing to surgical outcomes. Last, we utilized a small convenience sample that may have introduced sampling bias, and thus our results may not be representative of the entire population of patients who had undergone tibiotalar arthrodesis. We recognize that a larger sample size is likely needed to determine the clinical relevance of subtalar kinematics quantified with use of dual fluoroscopy. Still, our sample size was adequate to test our primary hypothesis. In addition, our primary outcome data adhered to a normal distribution.

In conclusion, we found that for low-speed activities, a significant increase in subtalar joint plantar flexion appears to be a primary kinematic compensation following tibiotalar arthrodesis. Future research should analyze longitudinal changes in subtalar joint kinematics after tibiotalar arthrodesis to better characterize the potential impact of excessive motion, surgical technique, and final positioning of the tibiotalar arthrodesis on the development of subtalar joint OA.

Appendix

Supporting material provided by the authors is posted with the online version of this article as a data supplement at [jbjs.org \(http://links.lww.com/JBJS/F735\)](http://links.lww.com/JBJS/F735). ■

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References

- Buckwalter JA, Saltzman C, Brown T. The impact of osteoarthritis: implications for research. *Clin Orthop Relat Res*. 2004 Oct;427(Suppl): S6-15.
- Ahmad J, Raikin SM. Ankle arthrodesis: the simple and the complex. *Foot Ankle Clin*. 2008 Sep;13(3):381-400, viii.
- Mazur JM, Schwartz E, Simon SR. Ankle arthrodesis. Long-term follow-up with gait analysis. *J Bone Joint Surg Am*. 1979 Oct;61(7):964-75.
- Thomas R, Daniels TR, Parker K. Gait analysis and functional outcomes following ankle arthrodesis for isolated ankle arthritis. *J Bone Joint Surg Am*. 2006 Mar;88(3): 526-35.
- Brunner S, Barg A, Knupp M, Zwicky L, Kapron AL, Valderrabano V, Hintermann B. The Scandinavian Total Ankle Replacement: long-term, eleven to fifteen-year, survivorship analysis of the prosthesis in seventy-two consecutive patients. *J Bone Joint Surg Am*. 2013 Apr 17;95(8):711-8.
- 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 Dec 18;95(24):e191.1-10.
- Anderson T, Montgomery F, Carlsson A. Uncemented STAR total ankle prostheses. Three to eight-year follow-up of fifty-one consecutive ankles. *J Bone Joint Surg Am*. 2003 Jul;85(7):1321-9.
- Maffulli N, Longo UG, Locher J, Romeo G, Salvatore G, Denaro V. Outcome of ankle arthrodesis and ankle prosthesis: a review of the current status. *Br Med Bull*. 2017 Dec 1;124(1):91-112.
- Terrell RD, Montgomery SR, Pannell WC, Sandlin MI, Inoue H, Wang JC, SooHoo NF. Comparison of practice patterns in total ankle replacement and ankle fusion in the United States. *Foot Ankle Int*. 2013 Nov;34(11):1486-92. Epub 2013 Jun 17.
- Ajis A, Tan KJ, Myerson MS. Ankle arthrodesis vs TTC arthrodesis: patient outcomes, satisfaction, and return to activity. *Foot Ankle Int*. 2013 May;34(5): 657-65. Epub 2013 Mar 6.
- Fuchs S, Sandmann C, Skwara A, Chylarecki C. Quality of life 20 years after arthrodesis of the ankle. A study of adjacent joints. *J Bone Joint Surg Br*. 2003 Sep; 85(7):994-8.
- Coester LM, Saltzman CL, Leupold J, Pontarelli W. Long-term results following ankle arthrodesis for post-traumatic arthritis. *J Bone Joint Surg Am*. 2001 Feb;83(2): 219-28.
- Easley ME, Montijo HE, Wilson JB, Fitch RD, Nunley JA 2nd. Revision tibiotalar arthrodesis. *J Bone Joint Surg Am*. 2008 Jun;90(6):1212-23.
- Schuh R, Hofstaetter J, Krismer M, Bevon R, Windhager R, Trnka HJ. Total ankle arthroplasty versus ankle arthrodesis. Comparison of sports, recreational activities and functional outcome. *Int Orthop*. 2012 Jun;36(6):1207-14. Epub 2011 Dec 16.
- Pedowitz DI, Kane JM, Smith GM, Saffel HL, Comer C, Raikin SM. Total ankle arthroplasty versus ankle arthrodesis: a comparative analysis of arc of movement and functional outcomes. *Bone Joint J*. 2016 May;98-B(5):634-40.
- Flavin R, Coleman SC, Tenenbaum S, Brodsky JW. Comparison of gait after total ankle arthroplasty and ankle arthrodesis. *Foot Ankle Int*. 2013 Oct;34(10):1340-8. Epub 2013 May 13.
- Malerba F, Benedetti MG, Usueli FG, Milani R, Berti L, Champlon C, Leardini A. Functional and clinical assessment of two ankle arthrodesis techniques. *J Foot Ankle Surg*. 2015 May-Jun;54(3):399-405. Epub 2014 Nov 26.
- van Engelen SJ, Wajner QE, van der Plaats LW, Doets HC, van Dijk CN, Houdijk H. Metabolic cost and mechanical work during walking after tibiotalar arthrodesis and the influence of footwear. *Clin Biomech (Bristol, Avon)*. 2010 Oct;25(8):809-15. Epub 2010 Jun 22.
- Waters RL, Barnes G, Husserl T, Silver L, Liss R. Comparable energy expenditure after arthrodesis of the hip and ankle. *J Bone Joint Surg Am*. 1988 Aug;70(7): 1032-7.
- Bruening DA, Cooney TE, Ray MS, Daut GA, Cooney KM, Galey SM. Multisegment foot kinematic and kinetic compensations in level and uphill walking following tibiotalar arthrodesis. *Foot Ankle Int*. 2016 Oct;37(10):1119-29. Epub 2016 Jun 27.
- Nichols JA, Foreman KB, Barg A, Saltzman CL, Anderson AE. Ankle strength, muscle size, and adipose content following unilateral tibiotalar arthrodesis. *J Orthop Res*. 2019 May;37(5):1143-52. Epub 2019 Mar 28.
- Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, Witte H, Schmid O, Stokes I. Standardization and Terminology Committee of the International Society of Biomechanics; International Society of Biomechanics. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *J Biomech*. 2002 Apr;35(4):543-8.
- Bey MJ, Kline SK, Tashman S, Zauel R. Accuracy of biplane x-ray imaging combined with model-based tracking for measuring in-vivo patellofemoral joint motion. *J Orthop Surg Res*. 2008 Sep 4;3:38.
- Bey MJ, Zauel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. *J Biomech Eng*. 2006 Aug;128(4):604-9.
- Campbell KJ, Wilson KJ, LaPrade RF, Clanton TO. Normative rearfoot motion during barefoot and shod walking using biplane fluoroscopy. *Knee Surg Sports Traumatol Arthrosc*. 2016 Apr;24(4):1402-8. Epub 2014 Jun 6.
- Roach KE, Wang B, Kapron AL, Fiorentino NM, Saltzman CL, Bo Foreman K, Anderson AE. In vivo kinematics of the tibiotalar and subtalar joints in asymptomatic subjects: a high-speed dual fluoroscopy study. *J Biomech Eng*. 2016 Sep 1;138(9).
- Wang B, Roach KE, Kapron AL, Fiorentino NM, Saltzman CL, Singer M, Anderson AE. Accuracy and feasibility of high-speed dual fluoroscopy and model-based tracking to measure in vivo ankle arthrokinematics. *Gait Posture*. 2015 May;41(4):888-93. Epub 2015 Mar 21.
- Kapron AL, Aoki SK, Peters CL, Maas SA, Bey MJ, Zauel R, Anderson AE. Accuracy and feasibility of dual fluoroscopy and model-based tracking to quantify in vivo hip kinematics during clinical exams. *J Appl Biomech*. 2014 Jun;30(3): 461-70. Epub 2014 Feb 25.
- Fiorentino NM, Kutschke MJ, Atkins PR, Foreman KB, Kapron AL, Anderson AE. Accuracy of functional and predictive methods to calculate the hip joint center in young non-pathologic asymptomatic adults with dual fluoroscopy as a reference standard. *Ann Biomed Eng*. 2016 Jul;44(7):2168-80. Epub 2015 Dec 8.
- Roach KE, Foreman KB, Barg A, Saltzman CL, Anderson AE. Application of high-speed dual fluoroscopy to study in vivo tibiotalar and subtalar kinematics in patients with chronic ankle instability and asymptomatic control subjects during dynamic activities. *Foot Ankle Int*. 2017 Nov;38(11):1236-48. Epub 2017 Aug 11.
- Hung M, Baumhauer JF, Brodsky JW, Cheng C, Ellis SJ, Franklin JD, Hon SD, Ishikawa SN, Latt LD, Phisitkul P, Saltzman CL, SooHoo NF, Hunt KJ. Orthopaedic Foot & Ankle Outcomes Research (OFAR) of the American Orthopaedic Foot & Ankle Society (AOFAS). Psychometric comparison of the PROMIS Physical Function CAT with the FAAM and FFI for measuring patient-reported outcomes. *Foot Ankle Int*. 2014 Jun;35(6):592-9.
- Huskisson EC. Measurement of pain. *Lancet*. 1974 Nov 9;2(7889):1127-31.
- Öner M, Deveci Kocakoç İ. JMASM 49: a compilation of some popular goodness of fit tests for normal distribution: their algorithms and MATLAB codes (MATLAB). *J Mod Appl Stat Methods*. 2017;16(2):547-75.
- Warmerhoven J, Harrison A, Robinson MA, Vanrenterghem J, Bargary N, Smith R, Cobley S, Draper C, Donnelly C, Pataky T. A force profile analysis comparison between functional data analysis, statistical parametric mapping and statistical non-parametric mapping in on-water single sculling. *J Sci Med Sport*. 2018 Oct;21(10): 1100-5. Epub 2018 Mar 21.
- Nieuwenhuys A, Papageorgiou E, Desloovere K, Molenaers G, De Laet T. Statistical parametric mapping to identify differences between consensus-based joint patterns during gait in children with cerebral palsy. *PLoS One*. 2017 Jan 12;12(1): e0169834.
- Bangerter C, Romkes J, Lorenzetti S, Krieg AH, Hasler CC, Brunner R, Schmid S. What are the biomechanical consequences of a structural leg length discrepancy on the adolescent spine during walking? *Gait Posture*. 2019 Feb;68:506-13. Epub 2018 Dec 28.

37. Mundt M, Thomsen W, David S, Dupré T, Bamer F, Potthast W, Markert B. Assessment of the measurement accuracy of inertial sensors during different tasks of daily living. *J Biomech*. 2019 Feb 14;84:81-6. Epub 2018 Dec 19.
38. Pataky TC. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin*. 2012;15(3):295-301. Epub 2011 Jul 14.
39. Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech*. 2010 Jul 20;43(10):1976-82.
40. Pataky TC, Robinson MA, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech*. 2013 Sep 27;46(14):2394-401. Epub 2013 Jul 31.
41. Pataky TC, Robinson MA, Vanrenterghem J. Region-of-interest analyses of one-dimensional biomechanical trajectories: bridging 0D and 1D theory, augmenting statistical power. *PeerJ*. 2016 Nov 2;4:e2652.
42. Pataky TC, Vanrenterghem J, Robinson MA. Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J Biomech*. 2015 May 1; 48(7):1277-85. Epub 2015 Mar 13.
43. Krähenbühl N, Horn-Lang T, Hintermann B, Knupp M. The subtalar joint: a complex mechanism. *EFORT Open Rev*. 2017 Jul 6;2(7):309-16.
44. Sturnick DR, Demetracopoulos CA, Ellis SJ, Queen RM, Kolstov JCB, Deland JT, Baxter JR. Adjacent joint kinematics after ankle arthrodesis during cadaveric gait simulation. *Foot Ankle Int*. 2017 Nov;38(11):1249-59. Epub 2017 Aug 24.
45. Valderrabano V, Hintermann B, Nigg BM, Stefanyshyn D, Stergiou P. Kinematic changes after fusion and total replacement of the ankle: part 1: range of motion. *Foot Ankle Int*. 2003 Dec;24(12):881-7.
46. Valderrabano V, Hintermann B, Nigg BM, Stefanyshyn D, Stergiou P. Kinematic changes after fusion and total replacement of the ankle: part 2: movement transfer. *Foot Ankle Int*. 2003 Dec;24(12):888-96. Epub 2004 Jan 22.
47. Valderrabano V, Hintermann B, Nigg BM, Stefanyshyn D, Stergiou P. Kinematic changes after fusion and total replacement of the ankle: part 3: talar movement. *Foot Ankle Int*. 2003 Dec;24(12):897-900.
48. Andriacchi TP, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *J Biomech*. 1977;10(4):261-8.
49. Bohannon RW, Williams Andrews A. Normal walking speed: a descriptive meta-analysis. *Physiotherapy*. 2011 Sep;97(3):182-9. Epub 2011 May 11.
50. Beyaert C, Sirveaux F, Paysant J, Molé D, André JM. The effect of tibio-talar arthrodesis on foot kinematics and ground reaction force progression during walking. *Gait Posture*. 2004 Aug;20(1):84-91.
51. Frigg A, Schäfer J, Dougall H, Rosenthal R, Valderrabano V. The midfoot load shows impaired function after ankle arthrodesis. *Clin Biomech (Bristol, Avon)*. 2012 Dec;27(10):1064-71. Epub 2012 Sep 10.
52. Piriou P, Culpan P, Mullins M, Cardon JN, Pozzi D, Judet T. Ankle replacement versus arthrodesis: a comparative gait analysis study. *Foot Ankle Int*. 2008 Jan; 29(1):3-9.