Session 1: Total Ankle Replacement (SS)

Chair: Sorin Siegler, PhD (Drexel University)

Co-Moderators: Robin Queen, PhD (Virginia Tech)

9AM Keith Wapner, MD (Invited)

9:20AM *1-1:* Imsdahl, Sheri, et al. Anteroposterior Translational Malalignment of Ankle Arthrodesis in Cadaveric Gait Simulation

9:30AM *1-2:* Belvedere, Claudio, et al. Experimental evaluation of custom-made morphological approximations of the ankle articular surfaces

9:40AM *1-3:* Leardini, Alberto, et al. Flexibility in the ankle joint after implantation of custom-made artificial articular surfaces

9:50AM *1-4:* Sturnick, Daniel R., et al. Influence of tibial component position on altered kinematics following total ankle arthroplasty during simulated gait

10:00AM *1-5:* Saito, Guilherme H., et al. Differences in gait mechanics after total ankle arthroplasty and ankle arthrodesis

10:10AM *1-6:* Kraszewski, Andrew, et al. Differences in Mechanics During Stair Ascent After Ankle Arthrodesis and Total Ankle Arthroplasty

10:20AM *1-7:* Seo, Hansol, et al. Characterization of Ankle Joint Motions Patterns for Main Twelve Activities of Daily Living (ADLs) of Elderly

Experimental evaluation of custom-made morphological approximations of the ankle articular surfaces

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INTRODUCTION: Severe arthritis of the ankle joint is often treated by replacing the affected articular surfaces with prosthetic components aimed at replicating the joint natural mechanics. The resulting kinematics and flexibility in replaced ankles are influenced by the geometry of these artificial articulating surfaces. Current total ankle prosthesis designs nowadays offer only cylindrical or truncated-cone geometries with medially-oriented apex (TCM). A recent image-based study [1], proposed an original saddle-shaped, skewed, truncated cone with laterally-oriented apex (SSCL), differently to what proposed by Inman in 1976. The goal of this study was to experimentally compare the two traditional and the original designs in terms of their ability to replicate natural mechanical characteristics of the ankle joint.

METHODS: Ten cadaver specimens underwent a validated full process of custom design of these three geometries, including medical imaging, 3D modeling and printing of the three implantable sets of customized articular surfaces for tibiotalar joint replacement. Tests were performed on each specimen under cyclic loading, following an established technique [2,3] which implied measures of continuous torque across the ankle complex while tracking motion of the tibia, talus, and calcaneus by means of a stereophotogrammetric system for surgical navigation (Stryker Knee Navigation System, Stryker®, Kalamazoo, MI-USA). Torques in out-of-sagittal plane directions were applied in neutral and in the two extremes of flexion. 3D kinematics and flexibility at the overall ankle complex, as well as at the separate ankle and subtalar joints were thus determined. The performance of the three custom made artificial surfaces was compared with the natural joint surface.

RESULTS: Results showed that SSCL surfaces replicated the natural mechanical characteristics better that the cylindrical and the TCM, both at the ankle and subtalar joints, in all anatomical planes. In the large majority of the specimens and joints observed and torques applied, SSCL was superior on a statistical basis compared to the other two surface approximations, in particular for the responses in maximum dorsiflexion (see Figure below).

DISCUSSION: Originally, all these three implant sets were designed to match the specific morphology of each tested specimens, also according to the corresponding designing approach. Therefore this study may also represent a demonstration case also for possible future processes of ankle prosthesis designing and manufacturing on a patient-specific basis. The best replication of natural kinematics and flexibility was observed for the SSCL surface approximation, particularly in maximum dorsiflexion, which is in fact the joint position where the ankle articular surfaces are most congruent, and therefore where the contribution of the articular surfaces is expected to be the largest.

SIGNIFICANCE/CLINICAL RELEVANCE: These results demonstrate that replacing the natural ankle joint by custom-made surfaces in the shape of a saddle skewed truncated cone with apex laterally [1], produce a more natural mobility and stability behavior than those obtained by surfaces mimicking traditional total ankle designs, thus establishing the potential of this original geometry for novel total ankle replacement designs. In future publications, the design parameters, the full load transfer capacities, i.e. joint stiffness, the joint linear displacements, and the contact surfaces will be addressed.

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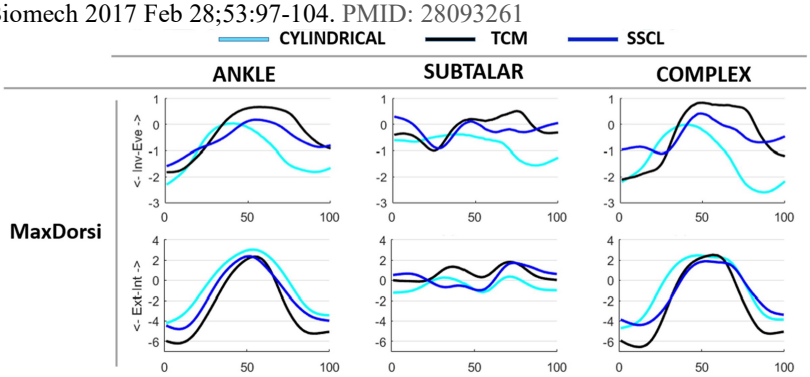
2. Leardini A, et al. J Biomech 1999 32 (2), 111-118. PMID: 10052915
3. Belvedere C, et al. J Biomech 2017 Feb 28;53:97-104. PMID: 28093261



Anteroposterior Translational Malalignment of Ankle Arthrodesis in Cadaveric Gait Simulation

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INTRODUCTION: Tibiotalar arthrodesis is a common surgical treatment for end stage ankle arthritis. Proper alignment is an important consideration, as malalignment can lead to complications that may require a revision surgery [1]. The biomechanical effects of malalignment are not well understood. The purpose of this study was to determine how anteroposterior (AP) translational malalignment of ankle arthrodesis affects the kinematics of the foot.

METHODS: Ankle arthrodesis was performed on nine cadaveric foot specimens with a custom device that could fuse the ankle neutrally and induce discrete malalignments of 3, 6, and 9 mm anteriorly (3A, 6A, 9A) and posteriorly (3P, 6P, 9P) (Figure 1). Gait was simulated for each specimen under each alignment using the robotic gait simulator (RGS) [2]. The RGS consists of a force plate mounted to a six degree-of-freedom robot that recreates the relative tibia to ground motion seen during the stance phase of gait. The target tibia kinematics and vertical ground reaction force were taken from *in vivo* data averaged across ten ankle arthrodesis subjects who were one year postoperative. Actuators were connected to nine extrinsic foot tendons to simulate muscle forces. An eight-camera motion capture system tracked reflective marker sets that were rigidly attached to the bones of interest. Bone kinematics were computed with a custom ten-segment foot model. The range of motion (ROM) and joint angle at each percent stance phase were determined for nine joints and one bone-to-bone relationship. Statistical analysis was performed with a linear mixed effects regression model that tested for differences in kinematics by condition. When omnibus testing was significant, pair-wise comparisons were carried out.

RESULTS: *ROM:* AP malalignment caused significant differences in sagittal plane ROM for two joints. Talonavicular ROM was significantly decreased for the 9P alignment (1.6°, p=0.014), and the 9A and 9P alignments significantly decreased the ROM of the first metatarsophalangeal joint (2.5°, p=0.0222 and 0.0313, respectively). *Joint Position:* There were several significant differences in joint position at various intervals within stance. The 6P and 9P alignments significantly inverted the talocalcaneal joint throughout stance phase and adducted it during late stance. Every posterior malalignment significantly plantar flexed the talocalcaneal joint in late stance, while the 6A and 9A alignments dorsiflexed it. During late stance, the 6P and 9P conditions also caused significant plantar flexion of the talonavicular joint. The 9A condition significantly dorsiflexed it, but this occurred at the very end of stance. Within the forefoot, differences in joint position were seen on the medial side of the foot. In early and late stance, the 6P and 9P alignments significantly inverted the first metatarsal relative to the talus. Both conditions also significantly adducted and plantar flexed the first metatarsal during the second half of stance phase. First metatarsal dorsiflexion relative to the talus was observed at the beginning and end of stance under the 6A and 9A alignments. Finally, the 6P and 9P alignments significantly everted the first metatarsophalangeal joint throughout stance phase.

DISCUSSION: AP malalignment did not substantially affect joint ROM but did cause significant differences in joint position throughout stance phase. Differences were seen in the talocalcaneal, talonavicular, and first metatarsophalangeal joints, and the first metatarsal relative to the talus. In general, the 6P and 9P alignments had the greatest effect on foot kinematics. Aberrant motion may lead to altered joint loading and facilitate cartilage degeneration. These findings may thus have important implications for the postoperative health of these joints. This study had several limitations. Simulations were performed at 25% body weight and 1/6th the speed of physiological gait to maintain fixation of the fusion device. The 9A and 9P conditions were only achieved with eight and seven specimens, respectively, which decreased statistical power. Also, because the two extreme malalignments were difficult, they were always done last so testing was only partially randomized.

SIGNIFICANCE: AP malalignment of ankle arthrodesis altered the kinematics of three joints and one bone-to-bone relationship within the foot. The most widespread effects were seen when the talus was displaced 6 mm or more in the posterior direction. *In vivo*, this may lead to changes in joint loading, which could negatively impact patient outcomes.

FIGURES AND TABLES:

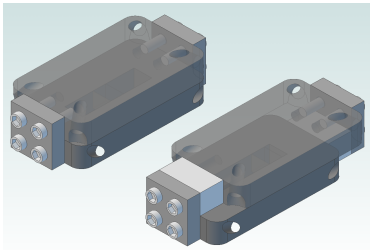

Figure 1: Fusion device in neutral and 9P alignments.

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Flexibility in the ankle joint after implantation of custom-made artificial articular surfaces

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INTRODUCTION: In total ankle replacement the resulting joint kinematics and flexibility are influenced by the geometry of the artificial articulating surfaces. Current total ankle prosthesis designs offer only cylindrical (CYL), or truncated-cone geometries with medially-oriented apex (TCM), according to what proposed by Inman in 1976. Differently from the latter, an original saddle-shaped, skewed, truncated cone with laterally-oriented apex (SSCL) has been recently proposed [1]. An extensive experimental study compared the effects of these different surfaces, defined with a custom-made approach, in terms of their ability to replicate natural mechanical characteristics of the ankle joint.

METHODS: Ten cadaver specimens underwent a validated full process of custom design and experimental tests of these three artificial surfaces [2]. This included CT scans of the specimen, 3D bone modeling, surface designing and printing in ABS. Tests were performed on each specimen and for each of the three sets of customized articular surfaces implanted sequentially in the tibiotalar joint. In these conditions, torque across the ankle complex under cyclic loading was measured with a torque sensor, synchronized with a stereophotogrammetric system for surgical navigation (Stryker Knee Navigation System, Stryker®, Kalamazoo, MI-USA) for motion at the tibio-talar and sub-talar joints. Torques in out-of-sagittal plane directions were applied in neutral joint position and in the two extremes of flexion. In the joint rotation vs torque plots for the tibio-talar joint, regression lines were calculated over relevant data from the three repetitions in the loading run of the cycle; therefore these represent the correlation between torque and corresponding rotation at the joint.

RESULTS: Flexibility plots (see Figure below) showed that all three artificial surfaces replicated well the corresponding patterns in the natural joint; this was observed for both for the Int/Ext and Inv/Eve rotations. Interestingly, tibio-talar joints after replacements were stiffer than the natural in max Dorsiflexion and neutral joint positions, more lax in max Plantarflexion, which is in fact the joint position where the ankle is less congruent. In a large number of specimens the ratio between rotation and torque at the regression lines was in favor of the SSCL, thus replicating the corresponding patterns in the natural joint better than CYL and TCM, both at the ankle and subtalar joints, in both out-of-sagittal anatomical planes.

DISCUSSION: Originally, three implant sets were designed according to corresponding different concepts and particularly also to match the specific morphology of each specimen. The best replication of natural flexibility was observed for the SSCL surface approximation, particularly at the extremes of the range of flexion.

SIGNIFICANCE/CLINICAL RELEVANCE: These results demonstrate that replacing the natural ankle joint by custom-made surfaces in the shape of a saddle skewed truncated cone with apex located laterally [1], produce a more natural joint flexibility than those obtained by surfaces mimicking traditional total ankle designs, i.e. CYL or TCM, thus establishing the potential of the SSCL geometry for novel total ankle replacement designs. In future work, the effect of friction at the articulating surfaces will be addressed more carefully. The present study may also represent a demonstration case also for possible future processes of ankle prosthesis designing and manufacturing on a patient-specific basis.

REFERENCES:

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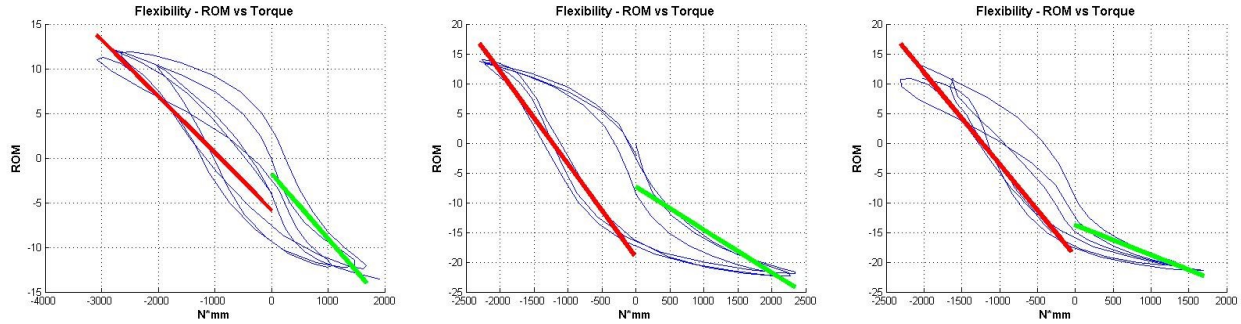
2. Belvedere C, et al. J Biomech 2017 28;53:97-104. PMID: 28093261

Figure 1: Flexibility curves of the tibio-talar joint in Int/Ext rotation from the neutral joint position in a typical specimen: in the natural (left), and after implant of the TCM (centre) and SSCL (right) articular surface approximations; the regression lines are also shown.



Differences in gait mechanics after total ankle arthroplasty and ankle arthrodesis

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INTRODUCTION: In the past, ankle arthrodesis was considered the gold-standard treatment for end-stage ankle arthritis. However, with the development of modern total ankle arthroplasty (TAA) designs and a better understanding of surgical techniques, TAA has become a reliable treatment for end-stage ankle arthritis. Both treatment options are effective in providing pain relief and function improvement. However, patients following TAA demonstrate more normalized gait and a more normal ground reaction force curve than patients after ankle arthrodesis. In addition, patients after ankle arthrodesis compensate for loss of sagittal range of motion through the ankle by increasing motion at the subtalar joint, conceivably leading to early degeneration of the adjacent joints. It is unclear if this similarly occurs in TAA patients, since the gains in motion after TAA compared to ankle arthrodesis are rather modest in previous gait studies. This study aims to quantitate the three-dimensional foot and ankle kinematics and calculate the moments at the joints to determine power that is generated during the task of walking on level ground.

METHODS: Ten patients who previously underwent TAA with a modern fixed-bearing ankle replacement (Salto Talaris - Tornier or INBONE 2 - Wright Medical Technology) and ten patients who previously underwent ankle arthrodesis were recruited for participation in the study. Patients were matched for age, sex, BMI, time from surgery and pre-operative diagnosis. A minimum of 1-year follow up was required for inclusion. The modified Oxford multi-segment foot model was applied to determine hindfoot, midfoot, and forefoot kinematics (Figure 1). A standard 6-degree of freedom marker set was simultaneously applied with the modified Oxford multi-segment foot kinematics measurements to determine hindfoot kinetics (Figure 2). Each participant performed the gait analysis at their self-selected walking speed.

RESULTS: In the sagittal plane, motion of the tibia in relation to the axis of the foot was significantly higher in the TAA group (20.9 ± 4.9 vs 14.6 ± 2.8 degrees, $p = .003$). Forefoot-tibia motion was also significantly higher in the TAA group (26.7 ± 6.5 vs 20.0 ± 5.4 degrees, $p = .024$). Differences in forefoot-hindfoot motion and hindfoot-tibia motion between groups were not significant. In the frontal plane, the arthrodesis group presented a significantly greater forefoot-hindfoot motion (7.4 ± 1.3 vs 7.2 ± 1.4 degrees, $p = .015$). No other statistically significant difference was observed in the frontal plane between groups. No significant differences were observed in ankle moment when comparing the TAA and the arthrodesis group (-1.3 ± 0.3 vs -1.2 ± 0.2, $p = .505$). Ankle power was greater in the TAA group (2.0 ± 0.6) in comparison to the arthrodesis group (1.3 ± 0.4), but the difference was not significant ($p = .104$).

DISCUSSION: Hindfoot-tibia motion in the sagittal plane was similar between groups, suggesting that following ankle arthrodesis patients have an increased motion at the subtalar joint. However, no significant differences were observed in forefoot-hindfoot motion between groups. Furthermore, the TAA group did not show significant improvement in ankle moment and ankle power. TAA have shown to provide improved clinical outcomes on uneven surfaces and stairs, whereas the present study was performed on level ground. Gait analysis of patients performing more demanding tasks such as ascending and descending stairs may demonstrate different results.

SIGNIFICANCE/CLINICAL RELEVANCE: Compensatory increased motion at the subtalar joint may explain the high rates of subtalar joint arthritis observed following ankle arthrodesis. Gait comparison of ankle moment and power on uneven surfaces and stairs should be the focus of future research.

Figure 1: Markers for multi

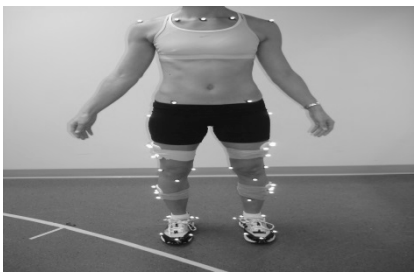

Figure 2: Six degree of freedom kinematic marker set

Characterization of Ankle Joint Motions Patterns for Main Twelve Activities of Daily Living (ADLs) of Elderly

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INTRODUCTION: As we enter the Ageing Society, the decrease of activities of daily living (ADLs) ability performance of the elderly is inevitable as the proportion of the elderly population increases significantly. This results in the loss of quality of life by forming the difficulties of independent living. As a result, the development of aged-friendly products considering the convenience of everyday life is increasing rapidly. Prior to this development, analysis of joint motion by various motions enables systematic description and quantitative evaluation of human motion. The purpose of this study was to analyze the characterization of ankle joint motions patterns for main twelve ADLs of elderly

METHODS: Following Institutional Review Board approval, 25 healthy males elderly (height: 170.1±4.5cm, weight: 68.8±9.5kg, age: 72.2±4.3) and 25 healthy females elderly participated. At the time of the experiment, twelve ADLs were selected based on Katz 's ADLs index, and the ADLs that generated the ankle joint motions on the anterior-posterior and medial-lateral. A 3-axis IMU sensor (Seedtech) was used to kinematic measure the ankle joint motions for main ADLs. The IMU sensor had an angle and an angular acceleration value and is attached to the tibia, instep, medial malleolus, and heel such that the local x axis is parallel to the sagittal plane vertical vector and the local y axis is parallel to the coronal plane vertical vector. The range of motion (ROMs) data were analyzed on the basis of major ankle motions. Depending on the results of the ROMs, the representative patterns between ankle joint motion patterns for the ADLs was quantified using the k-means clustering methods and similarity of patterns was analyzed using the cross-correlation methods (MATLAB R2016b Software). The closer the result of the similarity is to '1', the higher the similarity.

RESULTS: During the selected ADLs, the ankle joint motion of the dorsi/plantar flexion was relatively higher than that of the inversion/eversion and the adduction/abduction. In particular, it showed the maximum ROMs in the 'Sit down Cross-Legged and Stand up' motion (dorsi/plantar flexion: 96.9±9.2°, inversion/eversion: 57.1±8.9°, adduction/abduction: 58.9 ±11.0°), and 'Sit down and Stand up on Chair' motion with little motion of the ankle joint showed the minimum range of motion. (dorsi/plantar flexion: 16.7±2.9°, inversion/eversion: 11.6±2.5°, and adduction/abduction: 11.9±2.8°) ($p < 0.05$). In the main motions of the ankle joint, equally, the similarity between 'Lying on the bed' motion and Sit down squatting and Stand up motions pattern was the highest, and the value was 0.94. The overall similarity value of each ADLs was 0.5 or less.

DISCUSSION: According to the results, there is a statistically significant difference of the ankle joint motions for main twelve ADLs of elderly. Compared with previous studies on the young adults, the ROMs of the elderly ankle joints of the 'normal walking' and 'stair up/down' showed a lower tendency. In the 'Sit down Cross-Legged and Stand up' and 'Sit down squatting and Stand up' motions, which had relatively large motion, the elderly ROM tended to be higher than the young adults. The low similarity results of the overall ankle motion patterns in the twelve ADLs may serve as a basis for qualitatively describing the ADL behavior according to each pattern. And the characteristic range of ankle joint motions according to these ADLs performance is expected to utilized by reflecting on elderly-friendly products development and care.

SIGNIFICANCE/CLINICAL RELEVANCE: The characteristic range of ankle joint motions according to these ADLs performance is expected to utilized by reflecting on elderly-friendly products development and care.

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Influence of tibial component position on altered kinematics following total ankle arthroplasty during simulated gait

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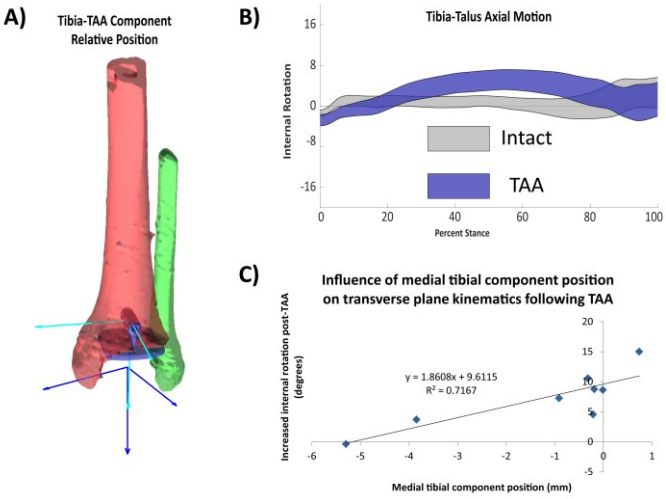
INTRODUCTION: Malposition of total ankle arthroplasty (TAA) components has been shown to affect periarticular ligament balance and joint contact mechanics in previous biomechanical studies. However, it is unclear how component position influences ankle joint motion. The objective of this study is to assess the effect of component position on ankle joint kinematics following TAA during simulated gait.

METHODS: Eight mid-tibia cadaveric specimens were utilized in this IRB approved study. The stance phase of gait was simulated both pre- and post-TAA in each specimen using a six-degree of freedom robotic platform. Ground reaction forces and tibial kinematic from in vivo data were replicated while physiologic tendon force profiles were applied to each extrinsic ankle tendons by linear actuators instrumented. Ankle kinematics was measured from reflective markers attached to bones via surgical pins. TAAs were completed using a common fixed-bearing total ankle system following the manufacturer recommended protocol (Salto Talaris, Integra LifeSciences). Using reconstructed CT data, 3D tibial component position relative to a standard ankle joint reference was characterized (Figure 1A). The effect of tibial component position on absolute differences in ankle kinematics (pre – post TAA) was assessed using linear regression with a level of significance set to $p = 0.05$.

RESULTS: Differences in ankle joint kinematics were only identified in the transverse plane, where internal talar rotation was significantly increased following TAA compared to the native condition (Figure 1B). The medial position of TAA tibial components was found to be positively associated with increased internal talar rotation (Figure 1C; $\beta = 1.861$ degrees/mm, $R^2 = 0.72$, $p = 0.008$). No other measurements of tibial component position (anterior-posterior/inferior-superior position, sagittal/frontal/transverse plane angle) were found to be significantly associated with altered ankle kinematics following TAA (All $\beta < 0.1$ and $p > 0.05$).

DISCUSSION: A large proportion (72%) of altered transverse plane kinematics following TAA was explained by medial tibial component position. While previous studies evaluated the effects of tibial component varus/valgus and anterior/posterior slope malposition on clinical outcomes, this is the first report to identify the influence of medial-lateral position on ankle kinematics. Medial-lateral position of the tibial component is often a neglected parameter during operative procedures, where implants are usually positioned in order to preserve bone stock of the medial malleolus. However, little attention is given to the position of the center of the tibial component in relation to the center of the tibial axis. Further understanding the relationship between implant position and resultant joint function is a specific goal of future research.

SIGNIFICANCE/CLINICAL RELEVANCE: This study suggests that the medial-lateral position of the tibial implant may have an influence on final ankle kinematics. This finding could have clinical implications for techniques implemented during surgical procedures and for the development of new instrumentation systems.



Differences in mechanics during stair ascent after ankle arthrodesis and total ankle arthroplasty

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INTRODUCTION: Ankle arthrodesis, once the standard treatment for end-stage ankle arthritis, today competes with modern total ankle arthroplasty (TAA) which is considered a reliable treatment. Both are effective in providing pain relief and functional improvement. However, patients following TAA demonstrate more normalized gait than patients after ankle arthrodesis {1}; in addition, patients after ankle arthrodesis compensate for loss of ankle sagittal range of motion through increased movement in neighboring joints. Previous studies examined level walking, but not stair navigation. Our objective was to investigate ankle and foot mechanics during stair ascent between ankle replacement and arthrodesis patients.
METHODS: Institutional IRB approval was obtained. A total of 20 patients were recruited and gave informed consent: Ten previously underwent TAA with a modern fixed-bearing ankle replacement (Salto Talaris - Integra Lifesciences or INBONE 2-Wright Medical Technology) and ten patients who previously underwent Fusion. Patients were matched for age, sex, BMI, time from surgery and pre-operative diagnosis. A minimum of 1-year follow-up was required for inclusion. They underwent instrumented 3D motion analysis during a short three-stair ascent at a comfortable speed five times. For the surgically affected limb, sagittal ankle range-of-motion (ROM) (deg), peak moment (Nm/kg), and peak power (W/kg) were calculated during stance along with modified Oxford foot kinematics {2} in the sagittal and frontal planes: hindfoot-to-tibia, forefoot-to-tibia, forefoot-to-hindfoot, and hindfoot-to-lab. Cycle time (s) of the affected limb was included as a proxy for climbing speed. Comparisons were conducted with Mann-Whitney tests for independent samples; significance was set at $p<0.05$.
RESULTS: We report the results from 17 patients: 9 TAA vs 8 Fusion; three patients could not complete the stair trials with a reciprocal gait pattern and were excluded from analysis. Ankle ROM (25±7 vs 17±5 °, p=.021) and peak ankle plantarflexion power (2.3±0.5 vs 1.4±0.2 W/kg, p=.002) were significantly higher in TAA than Fusion patients (see Figure 1), but peak moment was not significantly different between groups. Oxford foot ROM outcomes were not significantly different between groups for either plane of motion. Climbing speed (1.5±0.3 vs 1.6±0.2 sec, p=.236) was not different.
DISCUSSION: The merits of ankle replacement and fusion are debated among surgeons. TAA patients showed 64% greater peak plantarflexion ankle power despite that Fusion patients ascended 6% faster. Power is a product of the joint's moment and angular velocity (rad/s) – thus one or both could contribute to the observed difference. Further analysis found both ankle plantarflexion angular velocity and moment were greater on average in TAA patients at the time of peak ankle power, but only angular velocity (164±34 vs 117±23 °/s, p=.011) was significantly different. Still, it is likely both account for the power difference. Higher TAA angular velocity is attributable to their greater ankle ROM.
SIGNIFICANCE/CLINICAL RELEVANCE: Even though previous studies demonstrated similar functional outcomes during level walking between TAA and arthrodesis, TAA patients potentially have improved performance walking on stairs. Future research should compare TAA and arthrodesis during specific daily activities, and not only during level walking.
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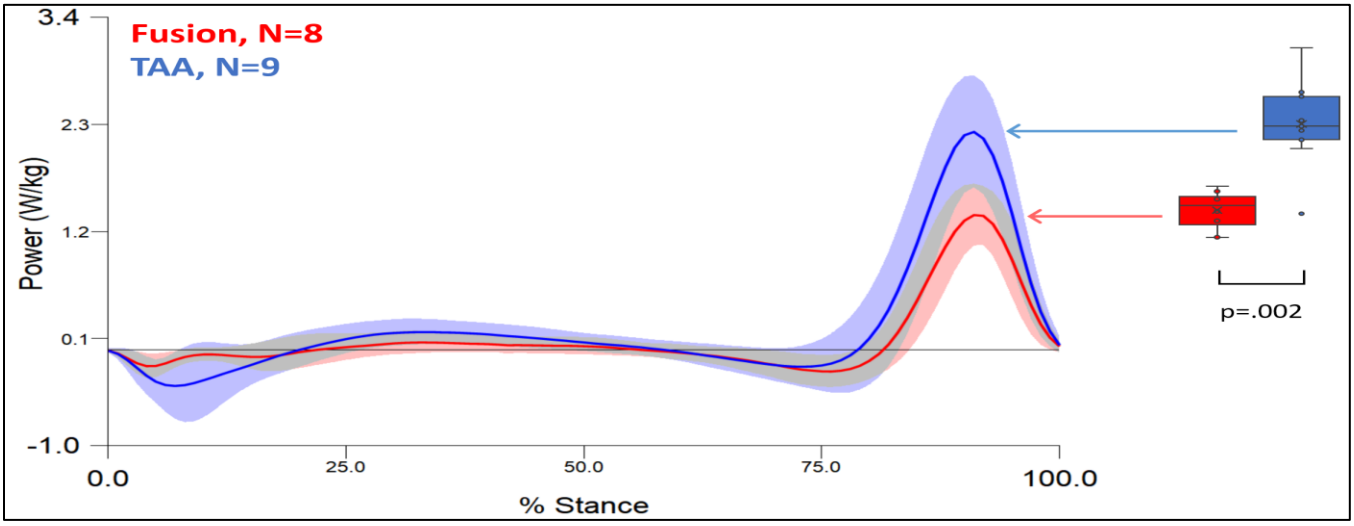

Figure 1. Average ankle flexion power across stance ± standard deviation bands: Fusion (red) and TAA (blue). Box plots show group distributions of late-stance peak values, p-value given.