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Kinematic Analysis of Sequential Partial-Midfoot Arthrodesis in Simulated Gait Cadaver Model

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Abstract

Background: Primary tarsometatarsal (TMT) arthrodesis is gaining popularity in the surgical treatment of Lisfranc injuries. However, few studies have evaluated biomechanical effects of TMT arthrodesis. The purpose of this study was to compare the kinematics of joints adjacent to the midfoot during simulations of stance before and after sequential arthrodesis of the first, second, and third TMT joints.

Methods: Ten midtibia cadaveric specimens were loaded on a 6-degree-of-freedom robotic gait simulator. Motion capture cameras were used to collect joint kinematics throughout simulations of the stance phase. Simulations were performed for the intact and sequential arthrodesis conditions of the first, second, and third TMT joints. The sagittal, coronal, and transverse plane rotational kinematics of the intact condition were compared to kinematics after each sequential arthrodesis condition.

Results: Sequential arthrodesis of the first and second TMT joints had no significant effect on ankle, subtalar, talonavicular, and first metatarsophalangeal joint motion during simulated stance when compared to the intact condition. In contrast, inclusion of the third TMT joint into the sequential arthrodesis significantly increased subtalar inversion ($P = .032$) in late stance and increased range of motion values in the ankle and subtalar joints by 2.1 degrees ($P = .009$) and 2.8 degrees ($P = .014$), respectively.

Conclusion: Sequential primary arthrodesis induced changes to ankle and adjacent joint kinematics during stance phase simulations, although not until the third TMT joint was included into the primary arthrodesis. The significant changes to kinematics due to arthrodesis of the first, second, and third TMT joints were small.

Clinical Relevance: The minimal changes in sagittal, coronal, and transverse plane rotational kinematics support the positive clinical outcomes reported in the literature for primary partial arthrodesis of Lisfranc injuries. The inclusion of the third TMT joint should be done judiciously.

Keywords: Lisfranc injury, primary arthrodesis, midfoot fusion, tarsometatarsal arthrodesis, joint kinematics

Introduction

Injuries to the tarsometatarsal (TMT) joint complex, referred to as Lisfranc injuries, are rare but can be associated with long-term disability such as painful posttraumatic osteoarthritis and residual deformity.[17,21,27] Historically, repair of Lisfranc injuries through open reduction and internal fixation (ORIF) has been the standard surgical method, and arthrodesis was considered only as a salvage procedure.[21,23] However, primary arthrodesis has recently been proposed as an alternative surgical treatment of these injuries.

Patients who have undergone primary arthrodesis have reported a successful return to sports or daily activities, and a high level of satisfaction.[14,22,26] Recent studies have demonstrated that individuals treated with primary arthrodesis have a much lower rate of additional surgery and comparable or superior patient-reported outcome scores than those treated with ORIF.[1,12,24] Thus, primary arthrodesis is

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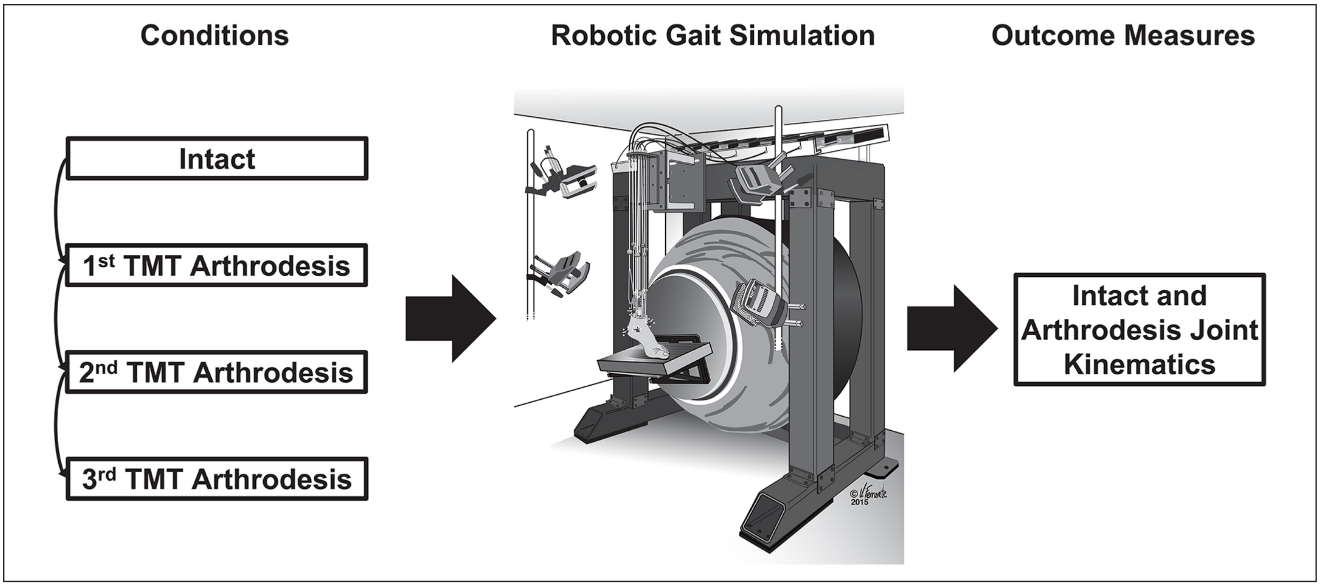

Figure 1. Schematic of the protocol for stance phase simulations. All specimens underwent sequential arthrodesis of the medial 3 TMT joints using dorsal Lisfranc plates.

considered an effective surgical management strategy for Lisfranc injuries.

Despite positive outcomes observed clinically, the effect of primary arthrodesis for Lisfranc injuries on mechanics of adjacent joints remains unclear. Arthrodesis of joints with substantial motion during activity, such as subtalar or ankle joints, are known to result in significant changes to adjacent joint kinematics, which may promote degenerative changes with repeated use.[8,25] In contrast, motion in the first to third TMT joints is minimal because of the limited motion inherent in the medial and middle columns of the foot.[13,18] Therefore, advocates for arthrodesis in the setting of Lisfranc injures often assume that first to third TMT arthrodeses induce minimal changes to overall biomechanical changes in the foot. However, there is limited evidence to objectively support this widely held belief other than to confirm minimal motion within the midfoot joints.[13,16] Therefore, we sought to investigate the subsequent biomechanical effect of primary arthrodesis of the first, second, and third TMT joints.

In this study, our goal was to compare the kinematics of the ankle, subtalar, talonavicular, and first metatarsophalangeal (MTP) joints during simulations of stance before and after sequential arthrodesis of the first, second, and third TMT joints. We achieved this by simulating stance in cadaveric foot and ankle specimens using a robotic gait simulator to measure changes in joint kinematics following each sequential arthrodesis of the first 3 TMT joints. We hypothesized that the sequential arthrodesis of first, second, and third TMT joints would not significantly change the rotational kinematics of the ankle and adjacent joints.

Methods

Specimen Preparation

Ten midtibia cadaveric specimens (6 female; mean age, 77 years at the time of death; range, 68-83 years) with no history of foot and ankle surgery were used in this study with Institutional Review Board approval (IRB14010). Specimens were examined by fluoroscopy for any fractures and arthritic changes at the foot and ankle. In addition, a fellowship-trained foot and ankle surgeon manually evaluated the range of motion at the toes, subtalar joint, and ankle joint to confirm that specimens did not have any condition that would affect motion of the midfoot. Specimens were prepared by excising all soft tissue from 10 cm proximal to the ankle joint. The 9 extrinsic tendons were isolated from muscle tissue, and the proximal tibia was then potted in poly-methyl methacrylate to attach each specimen to the simulator. Bone pins were inserted into 12 bones of the foot and ankle: tibia; talus; calcaneus; navicular; first, second, and third cuneiforms; first, second, and third metatarsals; and the first phalanx. Fluoroscopic images were taken to ensure that the pins did not protrude through the bones and disrupt joints. A cluster of 4 retroreflective markers were then attached to each bone pin to track motion during the gait simulations.

The specimens were prepared for 4 total testing conditions (Figure 1). The conditions were prepped and tested on the simulator in sequential order: intact, arthrodesis of the first TMT joint (TMT1), arthrodesis of the first and second TMT joints (TMT12), and arthrodesis of the first, second, and third TMT joints (TMT123). Each joint was prepared for arthrodesis by excising soft tissue around the joint without denuding

Figure 2. Arthrodesis of the first, second, and third TMT joints using dorsal Lisfranc plates. The TMT joints were sequentially fused in a medial-to-lateral direction.

the articular surface of the joint or sectioning of the Lisfranc ligament. Simulated arthrodesis was performed through attachment of a dorsal Lisfranc plate (Gorilla Lisfranc Plate; Paragon 28, Englewood, CO) across the joint while it was being held in a neutral position. Each plate was secured by inserting 2.7-mm and 3.5-mm locking screws into the cuneiform and the corresponding metatarsal bones (Figure 2). Fluoroscopic images were taken in the axial and sagittal planes to ensure proper placement of the plate across the joint.

Robotic Gait Simulator

A 6-degree-of-freedom robot was used to simulate the stance phase of healthy level walking in the cadaveric specimen before and after each sequential TMT joint arthrodesis condition. The previously validated robotic gait simulator incorporates a force plate trajectory developed from in vivo inputs from healthy human subjects to replicate ground reaction forces and kinematics in cadaveric specimens.[2,13] Briefly, a simulation began by first securing the potted tibia to a static mounting fixture on the robot frame. The proximal Achilles tendon was then secured to a linear actuator with an aluminum clamp, and the proximal ends of the 8 smaller tendons were grasped with a clove hitch knot reinforced with a screw and nut to attach to linear actuators, following a previously developed protocol.[2] The linear actuators applied physiologic muscle forces at times throughout the stance phase based on the literature and in vivo measurements.[2,13] The stance phase was simulated by rotating a force plate into position around the stationary tibia to re-create the in vivo ground reaction forces while the actuators were applying the corresponding muscle forces. An iterative fuzzy logic controller was then used to adjust the force plate trajectory and the forces of the Achilles and tibialis anterior tendons until optimized to replicate the in vivo ground reaction force inputs used as targets. All simulations were conducted at one-sixth the average time of in vivo stance and at one-quarter bodyweight (3.6 seconds and 175 N, respectively), which mitigated the risk of damaging specimens and has been validated to replicate the kinematics produced during full bodyweight loading.[2] An 8-camera motion capture system (Vicon Industries, Oxford, UK), with 4 MP resolution resulting in the joint rotation SD of ± 1.2 degrees, was fixed to the robot frame and oriented to track the retroreflective markers attached to the specimen bones throughout each simulation.

Simulations of the stance phase with the optimized trajectory were recorded 3 times per specimen for each condition to ensure repeatability of the condition while collecting marker position data. In total, the motion of the bones was collected during 3 stance phase simulations in 4 conditions, resulting in 12 simulations collected for each specimen. Following simulation of each condition, the specimen was loaded with a 100-N vertical ground reaction force and 100-N Achilles tendon force to simulate joint orientations during a standing pose at approximately one-quarter bodyweight. The marker clusters attached to bones were tracked for 1 second in the static standing pose to record the neutral position of each bone of interest. The axes of the motion capture coordinate system were directed medially, anteriorly, and superiorly defining plantar flexion, eversion, and adduction as positive values, respectively.[2,13]

Outcomes

For each condition, the main outcomes of interest were the joint rotational kinematics and the functional range of motion of 4 major joints of interest during simulated stance: the ankle, subtalar, talonavicular, and first MTP joints. Joint kinematics were determined by calculating the rotation in all 3 planes of motion of the more distal bone in the joint relative to the proximal bone throughout the simulation of stance. Changes in kinematics during simulations were calculated with respect to the standing pose and reported within the motion capture coordinate system defined. Range of motion was determined by calculating the difference

Table 1. Range of Motion of the First, Second, and Third TMT Joints During Robotic Simulations of Stance Cadaveric Foot and Ankle Specimens.[a]

Joint	Plane	Intact, degrees	First TMT Arthrodesis, degrees	P_{12}	First-Second TMT Arthrodesis, degrees	P_{13}	First-Second-Third TMT Arthrodesis, degrees	P_{14}
First TMT	Sagittal	3.1 ± 1.2	2.0 ± 1.1	.056	1.8 ± 0.7	.001*	2.3 ± 0.8	.130
	Coronal	3.0 ± 1.2	2.4 ± 1.5	.176	1.7 ± 0.7	.001*	1.9 ± 0.6	.013*
	Transverse	5.2 ± 2.1	2.1 ± 1.0	.002*	2.8 ± 2.4	.021*	2.2 ± 1.0	.004*
Second TMT	Sagittal	3.8 ± 1.6	3.1 ± 2.0	.227	2.9 ± 1.3	.164	2.0 ± 1.1	.013*
	Coronal	3.7 ± 2.7	3.0 ± 1.9	.239	2.5 ± 1.1	.113	2.1 ± 1.0	.059
	Transverse	4.1 ± 2.3	3.6 ± 2.9	.291	3.2 ± 2.3	.173	2.5 ± 1.5	.037*
Third TMT	Sagittal	6.3 ± 2.6	4.5 ± 1.8	.003*	5.4 ± 3.3	.313	4.1 ± 1.6	.037*
	Coronal	4.5 ± 1.8	4.9 ± 2.6	.370	3.5 ± 1.7	.129	3.0 ± 0.9	.028*
	Transverse	5.2 ± 2.5	3.5 ± 1.2	.047	4.6 ± 2.7	.289	2.6 ± 1.0	.005*

Abbreviation: TMT, tarsometatarsal.
[a]Values reported as the mean ± SD of TMT range of motion simulations of stance. Paired *t* tests were performed between the arthrodesis conditions and intact conditions: P_{12}, *P* value comparing the first TMT arthrodesis condition to the Intact condition; P_{13}, *P* value comparing the first-second TMT arthrodesis condition to the intact condition; P_{14}, *P* value comparing the first-second-third TMT arthrodesis condition to the intact condition.
[*]Significant difference ($P < .05$) from the intact condition.

between the maximum and minimum joint rotations throughout the simulation of stance. Range of motion for the first, second, and third TMT joints were also calculated and reported for each condition to characterize motion of the TMT joints during stance in the intact and arthrodesis conditions. The calculated joint kinematics and range of motion were averaged across the 3 simulations collected for each condition.

Statistical Analysis

Statistical analyses were conducted to determine if joint kinematics and range of motion values during simulated stance changed during sequential arthrodesis conditions compared to the intact condition. Bias-corrected 95% CIs of the arthrodesis conditions and the intact condition were calculated for all joint rotational kinematics in each condition. Statistical significance for joint kinematics was determined when the 95% CIs did not overlap between conditions.[11] Range of motion was analyzed for the major joints of interest using Wilcoxon signed-rank tests to compare between the sequential arthrodesis conditions and the intact condition. Post hoc analysis was conducted using the Tukey-Kramer method to investigate multiple pairwise comparisons.

A sample size of 10 was based on previous studies that reported joint kinematics, which is the primary outcome in this study.[2,25] A power analysis was made presuming a paired *t* test with mean and 95% CI data average across the stance phase and a significance level of .05.[2] The analysis indicated that 80% power is achievable with 10 specimens and an effect size of $d = 1$, where a 2-degree difference in kinematics was detectable.

Results

Rotational motion was measured within the first 3 TMT joints during simulations of stance and was reduced with sequential arthrodesis conditions. For the intact condition, the motion of the first 3 TMT joints ranged from 3.0 to 6.3 degrees within each plane (Table 1). On average, the third TMT demonstrated the most motion overall compared to the first and second TMT, although motion for each of the 3 joints were similar. The primary plane of motion for the first and second TMT joint was the transverse plane, while the greatest range of motion in the third TMT joint occurred in the sagittal plane. Range of motion values of the first TMT joint were significantly reduced in the transverse joint ($P = .002$) after first TMT joint arthrodesis. Sequential arthrodesis of the second TMT joint further reduced sagittal ($P < .001$) and coronal ($P < .001$) range of motion in the first TMT joint. Further sequential arthrodesis of the third TMT joint reduced sagittal ($P = .013$) and transverse ($P = .037$) range of motion in the second TMT joint, as well as reducing range of motion in the sagittal ($P = .037$), coronal ($P = .028$), and transverse ($P = .005$) planes in the third TMT joint.

Arthrodesis of the first TMT joint and the combined arthrodesis of the first and second TMT joints did not influence adjacent joint kinematics in the foot during simulations of the stance phase. The TMT1 and TMT12 conditions did not produce significant changes in the kinematic patterns for the ankle, subtalar, talonavicular, or first MTP joints compared with the intact condition (Figures 3 and 4). Additionally, the range of motion values for each joint during the simulations were also similar from the intact condition compared to the TMT1 and TMT12 conditions (Table 2). With little motion produced in the first and second TMT joints to begin

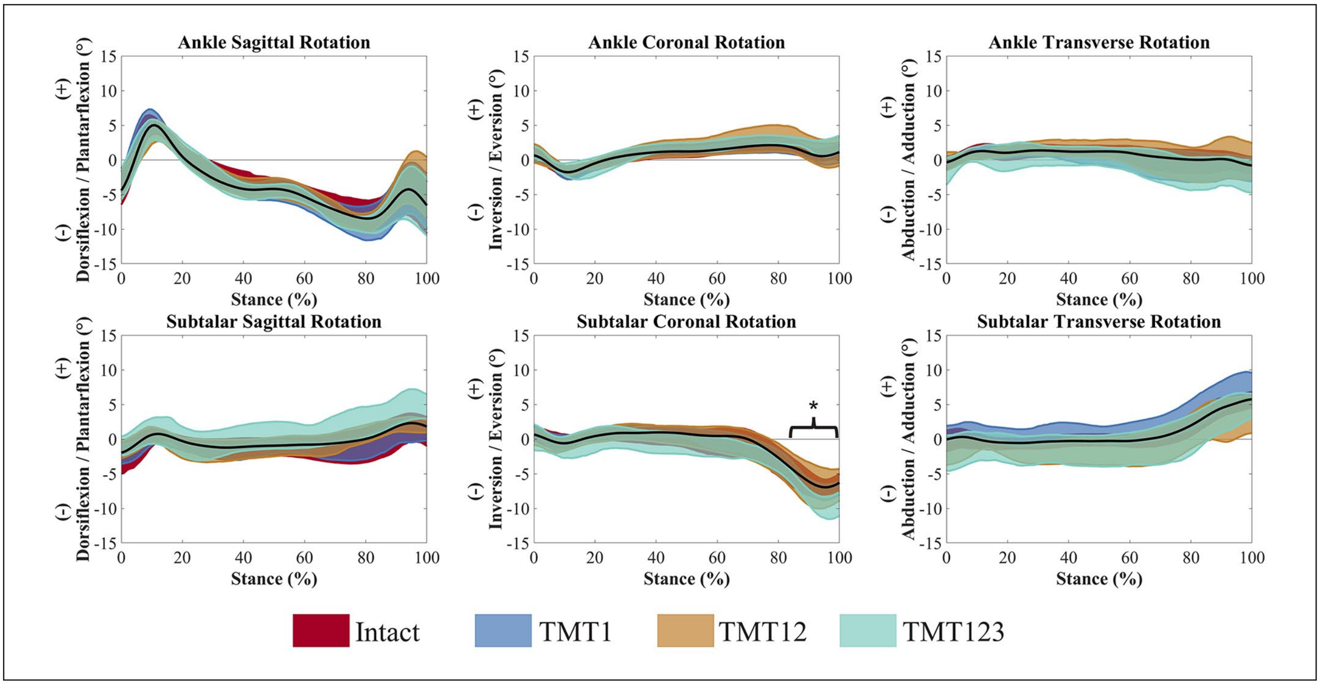

Figure 3. Bias-corrected 95% CIs of the intact and sequential arthrodesis conditions of the ankle and subtalar joint rotational kinematics. The average rotational kinematics during the intact condition are denoted with a bold black line. *Statistical significance of the intact and the TMT123 condition. There were no significant differences between the intact condition and with the TMT1 and TMT2 conditions.

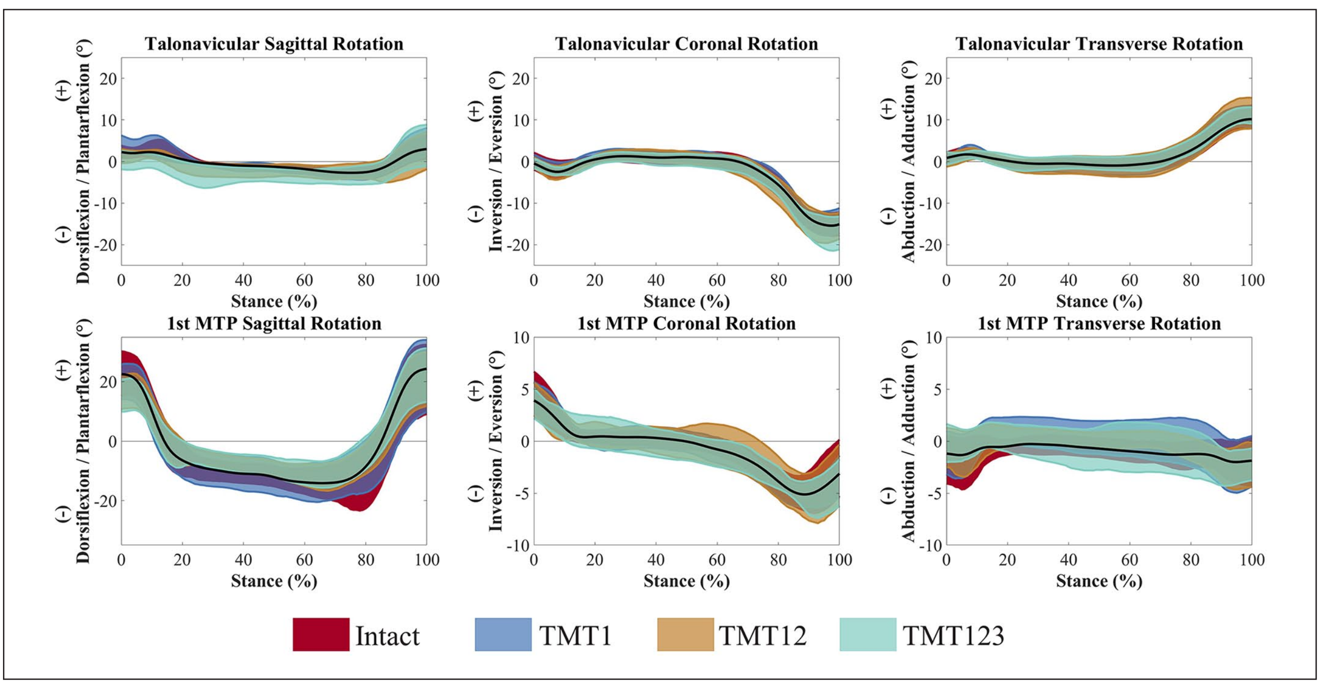

Figure 4. Bias-corrected 95% CIs of the intact and sequential arthrodesis conditions of the talonavicular and first MTP joint rotational kinematics. The average rotational kinematics during the intact condition are denoted with a bold black line. There were no significant differences in kinematics between the intact condition and any of the arthrodesis conditions for these joints.

Table 2. Range of Motion Values in the Ankle, Subtalar, Talonavicular, and First MTP.[a]

	Joint Range of Motion During Stance Phase Simulations							
	Plane	Intact, degrees	First TMT Arthrodesis, degrees	P_1	First-Second TMT Arthrodesis, degrees	P_{12}	First-Second-Third TMT Arthrodesis, degrees	P_{123}
Ankle	Sagittal	15.0 ± 4.5	15.1 ± 3.7	.68	14.7 ± 2.7	.79	15.7 ± 3.0	.61
	Coronal	4.4 ± 3.0	4.5 ± 2.4	.89	5.0 ± 3.1	.60	5.4 ± 2.3	.38
	Transverse	4.7 ± 1.9	5.1 ± 2.3	.30	5.8 ± 2.9	.73	6.8 ± 2.9	.009*
Subtalar	Sagittal	5.4 ± 1.9	5.1 ± 1.6	.63	8.5 ± 2.7	.80	6.9 ± 2.6	.09
	Coronal	9.1 ± 1.5	10.1 ± 2.1	.14	9.6 ± 3.3	.49	11.9 ± 2.2	.01*
	Transverse	7.7 ± 2.1	8.1 ± 3.3	.93	7.7 ± 2.2	.93	8.3 ± 2.6	.49
Talonavicular	Sagittal	8.4 ± 4.3	9.7 ± 4.1	.67	10.5 ± 4.6	.67	10.0 ± 5.8	.61
	Coronal	17.7 ± 4.5	19.1 ± 3.9	.44	18.1 ± 4.7	.86	20.0 ± 5.9	.30
	Transverse	12.5 ± 3.1	13.7 ± 3.1	.16	14.2 ± 5.2	.39	14.9 ± 5.2	.05
First MTP	Sagittal	48.0 ± 5.6	47.0 ± 7.8	.49	42.2 ± 9.9	.09	40.1 ± 10.1	.08
	Coronal	10.3 ± 3.8	10.7 ± 3.6	.86	10.9 ± 4.0	.37	10.8 ± 3.2	.64
	Transverse	6.3 ± 2.4	5.7 ± 2.9	.44	5.8 ± 2.6	.52	6.3 ± 2.4	.97

Abbreviations: MTP, metatarsophalangeal; TMT, tarsometatarsal.
[a]Values are given as the mean ± SD of the range of motion of each joint during stance phase simulations. *P* values are given for comparisons between the intact condition and the TMT arthrodesis conditions. P_1 denotes comparisons between the intact and first TMT Arthrodesis conditions, P_{12} denotes comparisons between the intact and first-second TMT arthrodesis conditions, and P_{123} denotes comparisons between the intact and first-second-third TMT Arthrodesis conditions.
*Statistically significant ($P < .05$) differences between intact and arthrodesis conditions.

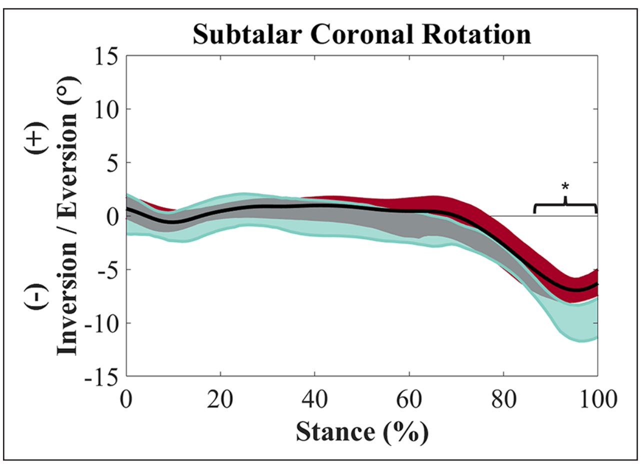

Figure 5. Bias-corrected 95% CIs of the subtalar joint coronal rotation for the intact and TMT123 arthrodesis condition, isolated from the other arthrodesis conditions to visualize the differences. The average rotational kinematics during the intact condition are denoted with a bold black line. *Statistical significance between the 2 conditions.

with, any redistribution of joint motion from the arthrodeses was not large enough to cause a significant change in motion at the ankle and adjacent joints during stance.

In contrast, arthrodesis of the first, second, and third TMT joints was influential enough to produce significant changes in adjacent joints when compared to the intact condition. Subtalar inversion was significantly increased ($P = .032$) in comparison to the intact condition during late stance, indicating a slightly more inverted hindfoot during push-off with the TMT123 condition (Figures 3E and 5). There were no significant changes to kinematics of the ankle, talonavicular, and first MTP joints (Figures 3 and 4). The TMT123 condition also produced significant changes to the range of motion values for joints during the simulations of the stance phase. For this condition, the subtalar joint range of motion increased by 24% ($P = .009$) in comparison to the intact condition (Table 2). In addition, transverse rotation in the ankle significantly increased by 43% ($P = .014$). Results from this condition indicate the decrease in mobility of the third TMT joint resulting from the arthrodesis, along with arthrodesis of the first and second TMT joints, significantly influenced the ankle and adjacent joint mechanics, although the changes detected were minimal.

Discussion

The objective of this biomechanical study was to quantify the effects that sequential arthrodesis of the first, second, and third TMT joints have on adjacent joint motion during simulated gait. Our results suggest that sequential arthrodesis of the first and second TMT joints did not change ankle and adjacent joint motion compared to the intact condition. Conversely, the ankle and subtalar joints experienced some significant alterations in joint kinematics and range of motion values after including the third TMT joint in the sequential arthrodesis. Although minimal from a clinical perspective, the normal range of motion values in the third TMT joint during stance were greater than those of the first and second

TMT joints, which may have created slight compensation in the adjacent joints following the arthrodesis.

Inclusion of the third TMT joint, the most mobile of the first 3 TMT joints, in the sequential arthrodesis was the point at which hindfoot kinematics began to significantly change. The midtarsal axis functions in conjunction with the subtalar joint during stance, where it has been suggested that the midtarsal joint becomes rigid when the subtalar joint is more inverted. This notion was further supported by Blackwood et al[3] who reported a decrease in sagittal midtarsal motion associated with increased subtalar inversion. Although the impact of the slightly inverted heel position after primary arthrodesis cannot be determined with the current study, decreased eversion motion may impair foot adjustment on the ground in some patients, which may account for persistent discomfort and inability to return to previous activity levels after surgery reported in some patients described in previous clinical studies.[14,22]

A pattern of increasing motion from the first to third TMT joints was observed, which supports the column theory that characterizes the lateral side of the midfoot as being more flexible than the medial columns.[10] The third TMT joint had double the sagittal plane motion of the first and second TMT joints, and the greater loss of motion of the third TMT joint following sequential arthrodesis may have led to compensational adjacent joint motion observed in the TMT123 condition. Although previous computational studies have reported alterations in hindfoot kinematics with the arthrodesis of the fourth and fifth TMT joints,[28] the relationship between hindfoot kinematics and the laterality of TMT arthrodesis has not been reported in a cadaveric model. Additional research needs to be conducted; however, this observation raises questions about the long-held assumption that the middle column is a "nonessential" joint where a loss of motion has minimal impact on overall foot function.[5,16]

Another interesting finding was an increase in transverse plane motion at the ankle joint following sequential arthrodesis of the first, second, and third TMT joints. Given that transverse plane motion is the predominant motion in the native TMT joints, this finding could be indicative of compensatory motion occurring at the ankle joint. An abnormal talar rotation within the ankle mortise may lead to bony impingement at the ankle joint, and a recent study using weightbearing computed tomography demonstrated an association between abnormal talar rotation and ankle degenerative changes.[9] Therefore, it may be reasonable to investigate ankle radiographs in the long-term follow-up of the primary arthrodesis patients, especially in cases of ankle pain after primary arthrodesis.

Although the findings of this study show a change in the kinematics of some adjacent joints after arthrodesis of the first, second, and third TMT joints, the differences observed in this analysis were small in magnitude. Despite statistical significance, it is unclear whether a 1- to 2-degree change in kinematics following arthrodesis represents a clinically meaningful difference that would result in further complications. Because previous studies that have reported successful clinical outcomes of primary arthrodesis were mostly based on short-term follow-up,[20] the long-term consequences of such a change is unknown. Given the adjacent joint changes observed following the third TMT joint arthrodesis in the current study, there may be some utility in carefully evaluating whether patients truly require sequential arthrodesis of the third TMT rather than routine inclusion of the entire medial and middle column in primary arthrodesis to minimize potential complications associated with these findings.

This study also shares valuable insight into the compensatory motion present within the first MTP joint after arthrodesis of the TMT joint complex. In previous studies based on static cadaveric examination, the dorsiflexion motion in the first MTP joint was increased after arthrodesis of the first TMT joint.[19] Conversely, in our study with simulated gait, no difference was found between the motion of the first MTP during intact and arthrodesis conditions during stance. We believe that this may have been due to inverted hindfoot position during late stance phase, which unloaded medial forefoot pressure, resulting in no compensatory increase in first MTP joint motion in our study.[7]

There were limitations associated with this study that should be considered. First, the representation of a fusion was limited because a true bony fusion cannot be achieved in a cadaver model. An additional fixation screw could have been used to improve fixation[4,6,15]; however, arthrodesis of the first, second, and third TMT joints resulted in a 40% reduction in range of motion, which was deemed sufficient for the cadaveric representation of the procedures. Additionally, a Lisfranc injury was not created for the purposes of testing the arthrodesis condition in this study. The decision was made to keep the ligament intact to better simulate the stability achieved by the fusion construct within our cadaveric model. Also, although some kinematic changes were detected, real patients may compensate differently based on the sensations they have after arthrodesis. Therefore, there could be more significant changes and compensation in patients following sequential arthrodesis based on their proprioception. Finally, because of the repeated measures design of the study and the interest in studying the sequential arthrodesis of the first to third TMT joints, it is possible that some of the significant differences seen after arthrodesis of the third TMT joint resulted from repeated testing of the specimens without randomization of the order.

In conclusion, sequential primary arthrodesis induced changes to ankle and adjacent joint kinematics during stance phase simulations, although not until the third TMT joint was included into the primary arthrodesis. This cadaveric model supports the favorable clinical outcomes for primary partial arthrodesis in Lisfranc injuries reported in the literature. However, because inclusion of the third TMT joint in the sequential arthrodesis significantly altered adjacent joint kinematics, primary arthrodesis in the third TMT joint should be carefully evaluated although the influence of this change needs further investigation.

Declaration of conflicting interests

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