Biomechanical consequences of subtalar joint arthroereisis in treating posterior tibial tendon dysfunction: A theoretical analysis using finite element method

Duo Wai-Chi Wong[a,b], Yan Wang[a,b], Tony Lin-Wei Chen[a], Aaron Kam-Lun Leung[a,b], Ming Zhang[a,b]*

[a] *Interdisciplinary Division of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong, China;*

[b] *The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, China*

Corresponding Author:

Prof. Ming Zhang

Interdisciplinary Division of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

Tel: (852) 2766-4939

Email: ming.zhang@polyu.edu.hk

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Abstract:

Subtalar joint arthroereisis (SJA) has been introduced to control the hyperpronation in cases of flatfoot. The objective of this study is to evaluate the biomechanical consequence of SJA to restore the internal stress and load transfer to the intact state from the attenuated biomechanical condition induced by posterior tibial tendon dysfunction (PTTD).

A three-dimensional finite element model of the foot and ankle complex was constructed based on clinical images of a healthy female (age 28 years, height 165 cm, body mass 54kg). The boundary and loading condition during walking was acquired from the gait experiment of the model subject. Five sets of simulations (conditions) were completed: intact condition, mild PTTD, severe PTTD, mild PTTD with SJA, severe PTTD with SJA. The maximum von Mises stress of the metatarsal shafts and the load transfer along the midfoot during stance were analyzed.

Generally, SJA deteriorated the joint force of the medial cuneonavicular and calcaneocuboid joints during late stance, while that of the metatarsocuneiform joints during early stance were over-corrected. Only the calcaneocuboid joint force at 45% stance demonstrated a trend of improvement. Besides, SJA exaggerated the increased stress of the metatarsals compared to the PTTD conditions, except that of the first metatarsal.

Our study did not support the hypothesis that SJA can restore the internal load transfer and midfoot stress. SJA cannot compensate the salvage of midfoot stability attributed by PTTD and could be biomechanically insufficient to restore the biomechanical environment. Additional procedures such as orthotic intervention may be necessary.

Keywords: posterior tibial tendon dysfunction; flatfoot; pes planus; extra-osseous talotarsal stabilization; sinus tarsi implant; talotarsal mechanism

Introduction

Subtalar joint arthroereisis (SJA) is an emerging minimally invasive surgical procedure, which is performed by inserting an implant into the sinus tarsi at the talotarsal joint to eliminate excessive ankle joint motion (Graham, Jawrani, Chikka, et al. 2012). The procedure has been used to treat flatfoot deformity (pes planus) and reported satisfactory clinical outcome (Graham, Jawrani and Chikka 2012). It can restore the alignment between the hindfoot and the forefoot during weightbearing (Ozan et al. 2015) and reduce the peak plantar pressure during walking (Fitzgerald and Vedpathak 2013). However, there were reports presenting negative results upon SJA. Bresnahan et al. (2013) showed that the surgery is not very effective to reduce foot pain and improve functions. Only half of the patients reported complete alleviation of foot pain (Graham, Jawrani and Chikka 2012). Besides, sinus tarsi pain is common for SJA that leads to high rate of implant removals (Saxena et al. 2016).

The biomechanical impact of SJA on soft tissue was previously evaluated by some cadaveric studies. In a maximally pronated foot position, SJA can reduce half of the posterior tibial tendon elongation, and one-third of the plantar fascia strain (Graham, Jawrani, et al. 2011a, Graham, Jawrani, et al. 2011b). However, Martinelli et al. (2012) found that the SJA cannot restore the normal joint pressure pattern at the ankle under a simulated midstance condition. Also, the peak plantar pressure of the midfoot was unable to restore to the intact state (Martinelli et al. 2012).

SJA aims to restrict excessive talotarsal joint motion (Graham 2010), but constraining joint motion non-physiologically may attenuate load transfer of the foot and yield undesirable compensatory mechanism, similar to that of the joint fusion procedure (Wang et al. 2015). The biomechanical consequence of the procedure should be noted. To this end, we aimed to evaluate the internal stress and load transfer of SJA after posterior tibial tendon dysfunction (PTTD), which is considered the root cause of talotarsal joint hyperpronation (Graham, Jawrani, et al. 2011a, Stovitz and Coetzee 2004). A finite element model was reconstructed from a representative subject and five conditions were simulated and compared: (1) intact condition, (2) simulated mild PTTD, (3) simulated severe PTTD, (4) simulated mild PTTD with SJA, and (5) simulated severe PTTD with SJA. We hypothesized that SJA would tend to restore the stress of the metatarsals and load transfer to the levels found in the intact condition.

Methods

Model Subject

A healthy female subject (age 28 years, height: 165 cm, weight: 54 kg) was recruited as the model subject. She reported no musculoskeletal disorder, pain and did not have any previous foot surgery. Ethical approval was obtained from the university. The subject signed the informed consent statement after receiving an oral and written description of the experiment prior to the experiment.

Geometry Reconstruction

Coronal magnetic resonance images were taken from the model subject using a 3T scanner (TrioTim, Siemens Medical Solutions, Erlangen, Germany) at 1-mm intervals and a 0.625-mm resolution. The right foot was put in a neutral and nonweightbearing condition using an ankle-foot orthosis during the scanning.

The geometry of the osseous structures and the encapsulated soft tissue was reconstructed using the software MIMICS v10 (Materialise, Leuven, Belgium) and RAPIDFORM XOR2 (INUS Technology Ltd., Seoul, Korea). Based on the constructed osseous geometry, the ligaments, muscles, and fascia were built by connecting the insertion points using trusses, surfaces, or connectors. Because it was difficult to segment and model the cartilage, the cartilaginous layers were represented by non-linear contact stiffness and frictionless contact was assigned between the bone articular surfaces (Athanasiou et al. 1998). The model was verified by colleagues with expertise in anatomy.

The sinus tarsi implant chosen in this study was HyProCure® (GraMedica, Macomb, USA), which was classified as a self-locking wedge device (Needleman 2005). The model geometry was built based on the dimensions suggested in the product catalog. Then, the implant was scaled to fit the sinus tarsi of the model subject to eliminate any possible effects of size mismatch. The implant was then assembled and aligned with the ankle at the medial anchorage of the canalis according to the product instructions (Graham 2014). Figure 1 illustrates the geometry of the intact foot and the ankle model.

Mesh Creation

The mesh creation process was carried out using the FE software ABAQUS 6.11. Osseous structures, the encapsulated soft tissue, and the implant were meshed using linear tetrahedral elements (C3D4), whereas the ligaments were represented by quadrilateral elements (S4R). The mesh was refined locally to accommodate small part geometries, contact regions, and abrupt geometrical changes. A mesh convergence test and validation processes were performed previously (Wong et al. 2016, Wong et al. 2015, Wong et al. 2014). The results demonstrated that the fineness of the mesh size was adequate and the prediction results were generally agreeable with the results of physical experiments (Wong et al. 2016, Wong et al. 2015, Wong et al. 2014).

Boundary and Loading Conditions

The boundary and loading conditions were acquired from the gait analysis of the model subject. Gait analysis was carried out using a motion capture system (MX-40, Vicon, Oxford Metrics, UK) and a force platform (OR6, AMTI, USA), with the model subject walking at a comfortable self-selected speed. The ground reaction force (GRF) and the tibial inclination angle were recorded and applied to the ground plate in the simulation, whereas the proximal end of the foot was fixed. The coefficient of friction between the foot and the ground plate was 0.6 (Zhang and Mak 1999). Muscle forces were estimated by the maximum capacity (Arnold et al. 2010) and the electromyography profile of the muscles during walking (Perry and Burnfield 1993). The Achilles tendon force was adopted from literature (Fröberg et al. 2009).

Simulated Conditions and Data Analysis

Four featured time instants were extracted for analysis. They were identified by the occurrence of the first GRF peak (25% stance), the GRF valley (45% stance), the heel-off instant (60% stance), and the second GRF peak (75% stance).

Mild PTTD was simulated by unloading the tibialis posterior on the intact model. To simulate severe PTTD, in addition to the unloading, the stiffness values of some stabilization structures were reduced by half, including those of the spring ligament, the short plantar ligament, and the medial portions (1st to 3rd columns) of the long plantar ligament and the plantar aponeurosis (Arangio et al. 2004). Subtalar arthroereisis was then performed under the mild and severe PTTD conditions. In all, five sets of simulations/conditions were completed.

The FE analysis was carried out using the commercially available FE software ABAQUS 6.11 (SIMULIA, Dassault Systèmes, USA) with the standard (quasi-static) solver. The load transfers through the midfoot and the medial column were studied, which were represented by the contact force magnitudes across the joints. In addition, the von Mises stress of the metatarsal shafts was extracted for analysis.

Validation

Validation was conducted by the plantar pressure measurement (F-scan® System, Tekscan, USA) of the model subject during walking. The agreement between the plantar pressure measurement and the finite element prediction would be evaluated by comparing the peak plantar pressure.

Results

Load Transfer (Joint Force)

Figure 2 shows the percentage change in the load transfer under PTTD and SJA conditions relative to the intact condition (0% represents the intact condition). The PTTD and operative conditions responded differently at different joints and different time instants. Table 2 indicates whether load transfer restoration was achieved postoperatively in comparison to the intact condition. Among the 40 sets of outcomes, only three cases supported the restoration trend of the joint forces. In general, SJA performed under both mild and severe TPTD conditions reduced and deteriorated the joint force of the medial cuneonavicular joint, increased and deteriorated the joint force of the calcaneocuboid joint during late stance, and increased and over-corrected the joint force of the first and second metatarsocuneiform joints during early stance.

Von Mises Stress of Metatarsal Shafts

The stress distribution (von Mises stress) of the metatarsal shafts during late stance (75% stance) is shown in Figure 3. PTTD, both mild and severe, exposed the metatarsals to higher stress, whereas SJA further exaggerated the increased stress distribution. Figure 4 and Figure 5 present the maximum von Mises stress of the metatarsal shafts under the five sets of simulated conditions at different time instants. In general, SJA increased the maximum von Mises stress of all the metatarsals, except the first metatarsal. The increase in stress was more prominent in the second metatarsal, accounting for approximately half of the total stress increase at 60% stance, and one-fourth at 75% stance.

Validation

At first GRF peak, the peak plantar pressure for both measurement and prediction located at the heel region. The predicted and measured peak plantar pressures were 0.49 MPa and 0.46 MPa respectively. The peak pressure shifted to the hallux region at the second GRF peak, with the values of 0.52 MPa and 0.46 MPa for the prediction and measurement. The outcome of the experimental measurement and finite element prediction were generally agreeable in terms of the plantar pressure pattern and peak values.

Discussion

Subtalar joint arthroereisis (SJA) aims to fix the flatfoot deformity by controlling the hyperpronation of the talotarsal joint (Graham 2010, Graham, Jawrani, Chikka, et al. 2012, Stovitz and Coetzee 2004). Though clinical and cadaveric studies have successfully demonstrated patient satisfaction and joint realignment, a number of reports have indicated undesirable outcomes, failure, or complications that required implant removal or re-operation (Corpuz et al. 2012, van Ooij et al. 2012). The objective of this study was to evaluate SJA from a biomechanical perspective with respect to the internal load transfer and stress, which are indicative of the functioning ability after the procedure and the risk of failure (Wong et al. 2015). Finite element analysis can provide a versatile platform to investigate the biomechanics of foot and ankle and has been widely used in both design and clinical applications (Cheung et al. 2009, Ni et al. 2016, Wang et al. 2016). The results of this study can assist physicians in their decision-making process, as well as facilitate the optimization of implants and surgical protocols.

Our study did not support the hypothesis that SJA can restore the internal stress and load transfer. On the contrary, SJA may worsen the problems caused by PTTD. Our predictions showed that the metatarsal shafts were further stressed and that the load transfer across the midfoot generally deviated further from normal levels. The osseous structures could be forced to bear higher stress because of the weakening of the soft tissue in PTTD (Arangio et al. 2004), which has been affirmed by existing cadaveric studies (Graham, Jawrani, et al. 2011a, Graham, Jawrani, et al. 2011b). Although SJA is expected to regulate the load transmitted to the hindfoot and the forefoot at the talotarsal joint (Bresnahan et al. 2013), the midfoot stability endangered by PTTD may interrupt the load transfer to the forefoot. SJA cannot compensate the salvage of midfoot stability by PTTD and PTTD-induced ligament failure. Besides, some studies indicated that SJA fails to restore the normal intra-articular ankle joint pressure pattern (Martinelli et al. 2012). The reduced peak plantar pressure and increased contact area contributed by the procedure (Fitzgerald and Vedpathak 2013) could also produce a negative effect because a normal foot should exhibit less contact area and concentrated pressure than a flatfoot (Chuckpaiwong et al. 2008). Clinically, the rate of patients who reported pain or complications could range from 5% to 46% (van Ooij et al. 2012). Some categories of patients did not demonstrate considerable functional improvement or demonstrated only small improvement postoperatively (Bresnahan et al. 2013).

The use of SJA on flatfoot may be theoretically indecisive since SJA targets on hyperpronation but not the deformity complex (Graham, Jawrani, et al. 2011a, Graham, Parikh, et al. 2011). The biomechanical consequence of interfering and restraining joint motion by an implant on load transfer of the foot was not comprehensively evaluated, not mentioning to account for the variations of the flatfoot and other PTTD-induced deformities. In fact, one of the technical manuals of SJA states that flatfoot with stage IIA

PTTD could have a higher risk of failure (Graham 2014). Our findings did ratify this statement, despite that the manual regards the statement as a nonevidence-based pessimistic claim (Graham 2014). In addition, our study anticipated a deterioration in the load transfer along the first column, which corresponded to the fact subtalar arthroereisis is contraindicated in cases of first ray instability (Graham 2014).

One major shortcoming of this study was that deformity complex was not considered, since our theoretical analysis aimed to evaluate PTTD-induced hyperpronation only. Normal foot with some modification or a PTTD foot was often assumed to be the flatfoot-related surrogate model (Arangio et al. 2004, Graham, Jawrani, et al. 2011a, Graham, Jawrani, et al. 2011b, Martinelli et al. 2012). Modelling a flatfoot is an ongoing challenge because a flatfoot is often accompanied by other deformities and problems (Graham, Jawrani and Chikka 2012), for example, the tarsal tunnel syndrome, hallux valgus, and postural abnormalities. A representative model is difficult to be selected particularly for single-subject design and confronting factors is difficult to be controlled. Yet, FE analysis with single-subject design is a common approach but should confine to nonclinical tool to complement clinical research and decisions (Wang et al. 2016). We believe that this is the first work that has studied PTTD and subtalar arthroereisis using an anatomically detailed model simulating the walking stance. One advantage of this study is that the intact condition was considered for comparison. We believe that some previous studies were ambiguous in terms of whether the outcome was positive or negative because of the lack of reference for comparison (Fitzgerald and Vedpathak 2013, Graham, Jawrani, et al. 2011a, Graham, Jawrani, et al. 2011b, Graham, Parikh, et al. 2011).

The study had some other limitations. In addition to the simplifications and assumptions considered in the model construction and simulation, external validity has long been a drawback of FE analysis (Ren et al. 2016). A single-subject model is often used with specific sets of loading cases because of the strenuous work involved in creating a single model, particularly that of the foot and ankle complex (Wang et al. 2016, Wong et al. 2016). Because of the complexity, a standalone document on the methods used could not be reproduced, and we relied heavily on references to our previously published work to address methodological issues. While the use of the model and the model subject was justified and they were previously considered to be representative (Wong et al. 2016, Wong et al. 2015, Wong et al. 2014). The validations of the model pertained to the intact condition. Therefore, validations of a flatfoot model and a model with SJA remain necessary.

Conclusion

Our study did not support the hypothesis that SJA can restore internal load transfer and stress to normal levels. SJA may not be able to fully compensate the salvage of midfoot stability attributed by PTTD and could be biomechanically insufficient to treat PTTD. Additional procedures or orthosis may be necessary. Further investigations should be made on the flatfoot deformity complex.

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Table 1. Material properties used in the FE model

Component	**Material Property**		**Source**
Bone	E = 7300 MPa; ν = 0.3		Nakamura et al. (1981)
Ground plate	E = 30 GPa; ν = 0.3		Wong et al. (2015)
Plantar fascia	K = 182.2 - 232.5 Nmm^{-1} (depend on the column)		Kitaoka et al. (1994)
Ligaments	E = 264.8 MPa; cross-section area = 18.4 mm^2		Siegler et al. (1988)
Encapsulated soft tissue	Second-order polynomial strain energy potential model		Lemmon et al. (1997)
	C_{10} = 0.08556 Nmm^{-2};	C_{20} = 0.03900 Nmm^{-2};	
	C_{01} = -0.05841 Nmm^{-2};	C_{02} = 0.00851 Nmm^{-2};	
	C_{11} = -0.02319 Nmm^{-2};	D_1 = 3.65273 mm^2N^{-1}	
Skin	First-order Ogden model μ = 0.122 kPa; α = 18		Gu et al. (2010)

E: Young's modulus; ν: Poisson's ratio; K: elastic stiffness

Table 2. Summary on whether joint forces were restored after SJA for mild PTTD (M) and severe PTTD (S).

%Stance	(a) Calcaneo-cuboid		(b) Talo-navicular		(c) Medial cuneo-navicular		(d) 1st metatarso-cuneiform		(e) 2nd metatarso-cuneiform	
	M	S	M	S	M	S	M	S	M	S
25	ǂ	ǂ	×	×	×	×	ǂ	ǂ	ǂ	ǂ
45	✓	✓	⊙	⊙	×	×	ǂ	×	ǂ	ǂ
60	×	×	✓	×	⊙	×	×	⊙	×	×
75	×	×	⊙	ǂ	×	×	ǂ	ǂ	ǂ	×

✓: Partial or full restoration; ×: Deterioration; ǂ: Overcorrection; ⊙: No apparent difference (<5%) postoperatively

Figure Captions

Figure 1. Finite element model of the foot and ankle complex and the sinus tarsi implant. The figure was reproduced and modified from an existing article under the Creative Common Attribution.

Figure 2. Percentage change in the load transfer under PTTD and SJA conditions relative to the intact condition during stance.

Figure 3. Stress distribution (von Mises stress) of metatarsal at 75% stance.

Figure 4. Maximum von Mises stress of the metatarsal shafts under intact, mild PTTD, and SJA conditions stance.

Figure 5. Maximum von Mises stress of the metatarsal shafts under intact, severe PTTD, and SJA conditions stance.