Finite Element Method Based Parametric Study of Gastrocnemius-Soleus Recession: Implications to the Treatment of Midfoot-Forefoot Overload Syndrome

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Finite Element Method Based Parametric Study of Gastrocnemius-Soleus Recession on Plantar Fascia Stress: Implications to the Treatment of Midfoot-Forefoot Overload Syndrome

Abstract

Gastrocnemius-soleus recession has been used to treat midfoot-forefoot overload syndrome and plantar fasciitis induced by equinus of the ankle joint. A controlled and selective amount of recession is imperative to maintain muscle strength and stability. The objective of this study was to conduct a parametric study to quantify the relationship between the level of recession and plantar fascia stress. A finite element model of the foot-ankle-shank complex was reconstructed from magnetic resonance and computed tomography images of a 63-year-old normal female. The model was validated by comparing modeled stresses to the measured plantar pressure distribution of the model participant during balanced standing. The midstance and push-off instants of walking stance were simulated with different levels and combinations of gastrocnemius-soleus recession resembled by different amounts of muscle forces. Halving the muscle forces at midstance reduced the average plantar fascia stress by a quarter while reducing two-third of the muscle forces at push-off reduced the average fascia stress by 18.2%. While the first ray of the plantar fascia experienced the largest stress among the five fasciae, the stress was reduced by 77.8% and 16.9% when the load was halved and reduced by two-third at midstance and push-off instants, respectively. Reduction in fascia stress implicates a lower risk of plantar fasciitis and other midfoot-forefoot overload syndromes. The outcome of this study can aid physicians to determine the amount of gastrocnemius-soleus recession towards patients with different levels of plantar fascia overstress. A detailed three-dimensional modelling on the plantar fascia is warranted in future study.

Keywords: gastrocnemius contracture; ankle equinus; Strayer procedure; Vulpius procedure; Baumann procedure; plantar fasciitis

Introduction

Gastrocnemius and soleus recession is a therapeutic intervention to treat foot pain due to the midfoot-forefoot overload syndrome induced by gastrocnemius or soleus equinus contracture of an ankle (Cychosz et al. 2015). It demonstrates a high level of patient satisfaction, low level of complication rate, and effectiveness in pain relief, particularly for patients with secondary plantar fasciitis and metatarsalgia (Maskill et al. 2010). While the association between gastrocnemius/soleus contracture and various foot pathologies has been on debates, the induced midfoot-forefoot overload syndrome has been linked to plantar fasciitis, metatarsalgia, posterior tibial tendon insufficiency, hallux valgus, and foot ulcer, etc (Hill 1995, Maskill et al. 2010).

The manifestation of midfoot-forefoot overload syndrome is attributed to the anatomical configurations between the plantar fascia and the Achilles tendon that attaches the gastrocnemius and soleus to the calcaneus. Based on corpse experiments, some researchers found that the distribution of plantar pressure would be mainly affected by triceps contracture of the lower limb, which would transfer plantar pressure from the hind foot to the forefoot (Abdulmassih et al. 2013, Ward et al. 1998), causing changes in the biomechanical environment of the lower extremity, and thus inducing other pathologies (Maskill et al. 2010). Myers (2014) pointed out that the plantar fascia and Achilles tendon were indeed 'linked'. The plantar fascia is attached to the periosteum of the calcaneus, which acts as a wrapping on the heel bone, runs posteriorly, and forms the collagenous network rooted by the Achilles tendon. There was a significant correlation between the thickness of plantar fascia and the Achilles paratenon (Stecco et al. 2013), while the tension of plantar fascia was also found to be positively correlated with the loading of Achilles tendon (Carlson et al. 2000). Thus, tightness or contracture of Achilles tendon or posterior leg muscles (gastrocnemius and soleus) was regarded as one of the risk factors of plantar fasciitis (Carlson et al. 2000, Nakale et al. 2018). More than 80% of plantar fasciitis patients presented equinus contracture problems (Patel and DiGiovanni 2011). Moreover, the high tension of plantar fascia caused by the equinus contracture induced excessive pressure and overload on the forefoot during gait that led to pain, deformity, and a spectrum of foot and ankle problems (Maskill et al. 2010, Schmal et al. 2018). Gastrocnemius-soleus recession was proven to relieve forefoot plantar pressure that alleviated the midfoot-forefoot overload syndrome (Greenhagen et al. 2010), while the effectiveness of the procedure on relieving plantar fascia tension requires further investigation.

Gastrocnemius-soleus recession may compromise the power, endurance, and stability of the foot and ankle (Lamm et al. 2005, Nawoczenski et al. 2015, Sammarco et al. 2006, Schmal et al. 2018) such that the level or degree of recession shall be controlled. Nawoczenski et al. (2015) found that patients after the procedure can have a one-fifth reduction in their peak ankle plantarflexion torque compared to that of their contralateral side and resulted in difficulties in participating endurance sports activities. Besides, Lamm et al. (2005) commented that the reduced muscle strength of the soleus jeopardized body balance during static stance. Different techniques of the gastrocnemius-soleus recession were introduced to strike for a better surgical outcome, including the Baumann, Strayer, Vulpius, Baker procedures, etc (Barske et al. 2012, Cychosz et al. 2015). A selective and controlled degree of the recession may minimize the compromised postoperative muscle weakness yet sufficiently alleviate midfoot or forefoot pressure, despite that current evidence is inconclusive (Barske et al. 2012).

To this end, the objective of this study is to construct a finite element (FE) model resembling the gastrocnemius-soleus recession procedure by reducing the respective muscle force; and to conduct a parametric analysis investigating the influence of the procedure on plantar fascia stress. Finite element method provides a versatile platform that could assess the biomechanical response of bones and soft tissue upon a different controlled set of boundary or loading conditions (Wang et al. 2016) and has been widely used in the evaluation of the foot and ankle pathology, trauma, surgery and implant design (Wong et al. 2018a, Zhang, Lv, Liu, et al. 2020, Zhang, Lv, Yang, et al. 2020). We hypothesized that the reduction in gastrocnemius and soleus forces induced by the recession procedure could reduce the plantar fascia stress. The outcome of this study could help facilitate a patient-specific decision-making process by advising different degrees of recession for different levels of plantar overload.

Materials and Methods

Geometry Reconstruction

A healthy female was recruited as the model participant. She was 63 years old, with body height and weight of 156 cm and 64 kg, respectively. She reported no musculoskeletal disorder, pain, and previous foot surgery. The study was approved by the Ethics Committee of Shanghai Pudong New Area Peoples' Hospital (No. 2019-15). Informed consent was obtained from the model participant.

Computed Tomography (CT) images of the left lower limb till the proximal tibia were taken from the model participant using the Discovery CT750HD (GE Healthcare, Chicago, USA) at

1-mm slice interval and 0.5-mm size pixel. Besides, Magnetic Resonance (MR) images were also acquired using the 3T MR scanner, Magnetom Skyra (Siemens Healthineers, Erlangen, Germany) at 1.25-mm slice interval and 0.68-mm size pixel. The ankle joint was put in a neutral position with a brace during the scan.

The CT and MRI images were integrated and processed by the medical image processing software (Mimics 15.0, Materialise, Leuven, Belgium), in which the geometry was subsequently reconstructed by a reverse engineering software (Geomagic 2015, 3D Systems, Rock Hill, USA). Except for the Achilles tendon model was established based on MRI images, other sections of the foot shank were built using CT images. The geometry of the FE model is shown in Figure 1. It encompassed the knee and ankle joints that included the tibia, fibula, the encapsulated soft tissue of the shank and foot, twenty-six-foot bones (talus, calcaneus, navicular, cuboid, 3 cuneiforms, 5 metatarsals, 14 phalanges), the gastrocnemius and soleus muscles (via Achilles tendon), 132 ligaments and 5 plantar fasciae.

The geometry was input to Hypermesh 13.0 (Altair, Troy, USA) for mesh creation. The bones, muscles (Achilles tendon), and the encapsulated soft tissues were meshed with 4-node three-dimensional stress tetrahedrons units (C3D4), while the plantar fascia and ligaments were modeled as 2-node truss units (T3D2). The ground support was meshed with an 8-node reduced integrated hexahedral elements (C3D8R). We assigned an overall mesh size of 2 mm for the bone and the encapsulated soft tissue. The mesh quality was verified by the Element Quality Check module of the Hypermesh software. Although we did not conduct a mesh convergence test, we adopted a more conservative mesh size compared to an existing simulation research which passed the mesh convergence test. A total of 80311 nodes, 455104 solid elements, and 137 truss units were used in the FE model.

Material Properties

As shown in Table 1, the material property of bones was assumed isotropic and linearly elastic (Cheung and Nigg 2008, Cheung et al. 2005, Morales-Orcajo et al. 2016, Ramlee et al. 2014). The muscles and encapsulated soft tissues were modeled as being hyperelastic and a second-order polynomial expression of strain potential energy was adopted, whereas the coefficients of the constitutive equation were calculated by the experimental data from Lemmon et al. (Lemmon et al. 1997b).

Loading and Boundary Conditions

The midstance and push-off instants were simulated in the FE model since the gastrocnemius and soleus were not activated until midstance. Throughout the simulation, the proximal end of the tibia, fibula, and encapsulated soft tissue were restrained, while the ground reaction forces and inclination were applied on the ground plate (Figure 1). The vertical ground reaction forces were 608 N (95% body weight) and 736 N (115% body weight), respectively at midstance and push-off instants (Yu et al. 2016). The muscle forces of gastrocnemius and soleus via the Achilles tendon were 550 N and 1100 N, respectively at midstance and push-off instants. Gastrocnemius and/or soleus recession was resembled by a parametric study with a detailed simulation scheme using a different combination of gastrocnemius and soleus muscle forces shown in Table 2. The coefficient of friction between the ground and plantar soft tissue was 0.6 (Dai et al. 2006) and that at the articular joint was assumed frictionless. The angle between the foot and ground was set to be 11° (Lieberman et al. 2010).

Validation

The model participant was invited to perform a balanced standing trial, in which the plantar pressure was measured by a TPScan System (Biomecha, Goyang, Korea). A specific set of simulations on balanced standing was further conducted with ground reaction force (GRF) and Achilles tendon force of 320 N (50% body weight) and 240 N (75% GRF), respectively (Whitney and Kendrick 2003). Validation was conducted by comparing the FE predicted plantar pressure distribution, including the peak plantar pressure, rearfoot, and forefoot contact area, with the physical measurement. Besides, the predicted navicular descending distance by the FE method was compared to that of existing studies (Giuliani et al. 2011).

Results

Validation

The validation results demonstrated good agreement between the outcome of FE simulation and plantar pressure measurement, as shown in Figure 2. The peak plantar pressures of the prediction and measurement were 0.262 MPa and 0.253 MPa, respectively. Moreover, the contact area of the forefoot was 20.17 cm^2 and 20.97 cm^2 for the FE prediction and pressure measurement, respectively, while that of the rearfoot was 39.83 cm^2 and 38.63 cm^2. Regarding the navicular descending distance, that of the FE prediction was 8.1 mm, which was generally acceptable compared to that between 7.3 mm to 9.0 mm reported in existing literature (Giuliani et al. 2011). We viewed our FE simulation adequately reliable according to the validation findings.

Stress of Plantar Fascia

The average stress of the plantar fascia at midstance and push-off upon different triceps surae load is shown in Figure 3, in which the raw data are tabulated in Table 3.

In both instants, the average plantar fascia stress decreased with reducing triceps surae load (or gastrocnemius-soleus recession). At midstance, the average plantar fascia stress decreased from 1.47 MPa to 0.62 MPa when the triceps surae load decreased from 550 N to 0 N. At push-off, the average plantar fascia stress decreased from 3.58 MPa to 2.98 MPa when the triceps surae load decreased from 1100 N to 550 N. The results at both instants appeared to demonstrate a positive linear relationship between the average plantar fascia stress and the triceps surae load.

Figure 4 demonstrated the stress of each plantar fascia ray when the triceps surae load was reduced. For both midstance and push-off instants, the first ray remained the largest load-bearing fascia among the five fasciae, while the fifth ray sustained the lowest load. The load difference between the first and the fifth rays decreased when the triceps surae load was reduced. The differences were 2.23 MPa and 0.221 MPa when the triceps surae loads were 1100 N and 0 N, respectively. As the triceps surae force increases, the stress of the plantar fascia increases accordingly.

The stress of first ray increased by 127.4% under the action of triceps surae muscle strength. In comparison, when only the gastrocnemius muscle was loaded, the stress in the first ray increased by 128.3%. With a P value of the two sets of data are both under 0.05, it can be concluded that there are no significant differences in the plantar fascia stress under different gastrocnemius and soleus loading combinations.

Discussion

Our FE prediction showed that the gastrocnemius-soleus recession (resembled by the reduction of muscle force) reduced the stress of the plantar fascia and supported our hypothesis. While the first ray of the plantar fascia sustained the largest stress among the five fasciae, the stress of the first ray fascia was reduced by 77.8 % when the triceps surae load was halved at midstance; and was reduced by 16.9% when the triceps surae load was reduced by 22.2% at push-off. The reduced plantar fascia stress could implicate reduced risk of plantar fasciitis, in addition to the midfoot-forefoot overload syndrome and other foot pathologies.

Gastrocnemius equinus refers to the insufficient dorsiflexion at the ankle joint (Mulhern et al. 2018). A minimum of 10-degree ankle dorsiflexion is imperative to facilitate foot clearance during push-off (Paley 2003, Root et al. 1977), whilst the limited dorsiflexion resulted in localized high pressure at the forefoot region (Armstrong et al. 1999). Moreover, the ankle equinus was compensated by subtalar and midtarsal joint pronation, and the unlocking of the midtarsal joints (Lamm et al. 2005). These compensatory motion produced a hypermobile first ray and subsequently deteriorated to other forefoot deformities (Doty and Coughlin 2013, Wong et al. 2014). While gastrocnemius-soleus recession aims to treat the equinus, the procedure was proven safe and efficient with a ‘fair’ level of evidence (Barske et al. 2012, Cychosz et al. 2015). The advantage of this procedure was that the magnitude of the muscle strength could be preserved or gradually restored overtime (Lamm et al. 2005, Sammarco et al. 2006). Moreover, Delp and Zajac (1992) found that the lengthening of soleus and gastrocnemius tendon by 1.2 cm and 1.5 cm, respectively, could halve the respective muscle forces.

Given the implications of the plantar fascia and the Achilles tendon in gastrocnemius equinus, the FE model has been used to evaluate the biomechanical relationship among these structures. Cheung et al. (2006) conducted a parametric analysis to investigate the effect of Achilles tendon loading on the tension of the plantar fascia while Cheng et al. (2008) further investigated the contribution of windlass mechanism on their relationships. Interventions to relieve plantar fascia stress were evaluated by finite element analysis, including both orthotic interventions (e.g. insole and tapping) and surgical interventions (e.g. fascia release) (Chen et al. 2020, Cheung, An, et al. 2006, Hsu et al. 2008). Recently, the geometry of the plantar fascia was improved to three-dimensional for better simulation on the complex scenario, such as sports activity (Chen et al. 2019).

In the 1980s, Huiskes (1982) pointed out that under quasi-static loading, both the cortical bone and cancellous bone could be regarded as having linear elasticity and isotropic properties. Same attempts have been used in relevant studies based on the assumption of isotropic, uniform and continuous linear elastic bodies (Chen et al. 2017). It has been proved without result in significant deviations, and can greatly save modeling costs and calculation time. We did not subdivide the cortical bone and the cancellous bone either and before carrying out our research we did validate its accuracy.

Although it has been a common approach to simplify the geometry of the plantar fascia, it is controversial whether it shall be simplified (Wang et al. 2016). Existing studies often simplified the plantar fascia as truss units validated by cadaveric experiments (Liang et al. 2011). There were attempts to reconstruct a three-dimensional anatomically plantar fascia based on MRI images for FE analysis (Chen et al. 2015). However, the detailed geometrical model requires a detailed constitutive equation for the material properties. Existing studies failed to address the tension-only and anisotropy characteristics of plantar fascia bundles (Chen et al. 2015), which may overestimate the stress under bending and twisting circumstances. Besides, validating a three-dimensional model of the plantar fascia is challenging and lacking. For a validation experiment using cadavers, exposure is required to install sensors and thus may overlook the interaction between the bulk soft tissue and the plantar fascia since some soft tissue are removed. Taking these into account, we decided to simplify the plantar fascia into truss units. It is calling for research to establish the detailed constitutive material property model for the plantar fascia to facilitate a more detailed reconstruction and simulation.

There were some other limitations in this study. External validity has been a challenging task since constructing and validating a single FE model for the complex foot-and-ankle requires strenuous amount of work, whereas some studies switched to enhance the internal validity by accounting for inter-trial variability (Wong et al. 2020) or sensitivity analysis on the insertion site of ligaments (Wong et al. 2018b). In terms of the simplification of model configurations, apart from the plantar fascia, the ligaments and musculotendon units were also simplified in addition to the applied mechanical loading and behaviour of muscles. The simulation was also confined to a particular loading case at midstance instant. Simulation for the whole walking stance could facilitate a complete loading profile for analysis.

Conclusions

Our FE prediction showed that the gastrocnemius-soleus recession resembled by the reduction of muscle forces could reduce plantar fascia stress. Halving the muscle forces at midstance reduced the average fascia stress by a quarter while reducing two-third of the muscle forces at push-off reduced the average fascia stress by 18.2%. The reduction in plantar fascia stress implicated a lower risk of plantar fasciitis and other midfoot-forefoot overload syndromes.

Besides, it was found that gastrocnemius release has similar surgical effect as the triceps surae release for patients with plantar fasciitis from the biomechanical point of view. A detailed three-dimensional modelling on the plantar fascia is warranted in future study.

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Tables

Table 1 Material properties used in the FE model

Component	Young's modulus E（MPa）	Poisson's ratio v	Density（kg/m^3）	Cross-sectional area（mm^2）	Reference
Bone	7300	0.3	1500	——	(Morales-Orcajo et al. 2016)
Plantar fascia	350	——	937	58.6	(Morales-Orcajo et al. 2016)
Ligament	260	——	937	18.4	(Morales-Orcajo et al. 2016)
Ground	17000	0.1	5000	——	(Morales-Orcajo et al. 2016)
Encapsulated soft tissue	Hyperelastic (2nd order polynomial strain energy potential model) C_{10} = 0.08556, C_{01} = −0.05841, C_{20} = −0.039, C_{11} = −0.02319, C_{02} = 0.00851, D_1 = 3.65273, D_2 = 0				(Lemmon et al. 1997a)
Muscle	C_{10} = 8.57000, C_{01} = 12.1000, C_{20} =936.000, C_{11} = 718.000, C_{02} =480.000, D_1 =0.00413, D_2 = 0				(Reeves et al. 2005)

Table 2. Simulation scheme presenting different combination of gastrocnemius and soleus forces at midstance and push-off

Scheme No.	At midstance		At push-off	
	Gastrocnemius Force (N)	Soleus Force (N)	Gastrocnemius Force (N)	Soleus Force (N)
1	0	0	275	275
2	0	110	275	385
3	110	0	385	275
4	0	220	275	495
5	110	110	385	385
6	220	0	495	275
7	0	330	275	605
8	110	220	385	495
9	220	110	495	385
10	330	0	605	275
11	0	440	275	715
12	110	330	385	605
13	220	220	495	495
14	330	110	605	385
15	440	0	715	275
16	0	550	275	825
17	110	440	385	715
18	220	330	495	605
19	330	220	605	495
20	440	110	715	385
21	550	0	825	275

Table 3. The plantar fascia stress for each ray at midstance and push-off under each simulation scheme.

Scheme No.	At midstance					At push-off				
	1st ray	2nd ray	3rd ray	4th ray	5th ray	1st ray	2nd ray	3rd ray	4th ray	5th ray
1	0.708	0.660	0.669	0.598	0.488	3.955	3.262	3.003	2.604	2.082
2	0.874	0.811	0.829	0.786	0.685	4.110	3.402	3.132	2.711	2.164
3	0.877	0.814	0.833	0.801	0.790	4.113	3.408	3.137	2.715	2.165
4	1.046	0.979	1.006	0.957	0.890	4.258	3.544	3.262	2.817	2.237
5	1.049	0.982	1.009	0.979	0.905	4.260	3.551	3.268	2.818	2.239
6	1.053	0.984	1.012	0.984	0.911	4.261	3.556	3.270	2.822	2.241
7	1.226	1.156	1.203	1.087	0.927	4.303	3.694	3.397	2.914	2.313
8	1.229	1.160	1.205	1.098	0.987	4.309	3.696	3.399	2.917	2.314
9	1.232	1.163	1.209	1.108	1.009	4.402	3.698	3.402	2.921	2.314
10	1.235	1.166	1.211	1.117	1.089	4.407	3.703	3.403	2.929	2.316
11	1.413	1.342	1.396	1.178	1.099	4.541	3.831	3.520	3.020	2.391
12	1.415	1.343	1.399	1.190	1.108	4.547	3.833	3.524	3.023	2.396
13	1.417	1.346	1.401	1.245	1.189	4.549	3.837	3.526	3.025	2.397
14	1.420	1.348	1.404	1.267	1.199	4.553	3.842	3.529	3.026	2.397
15	1.422	1.350	1.406	1.270	1.218	4.555	3.845	3.530	3.029	2.390
16	1.604	1.524	1.591	1.310	1.238	4.676	3.971	3.643	3.116	2.446
17	1.606	1.526	1.592	1.347	1.259	4.680	3.974	3.644	3.116	2.448
18	1.608	1.529	1.595	1.349	1.267	4.683	3.977	3.648	3.117	2.450
19	1.611	1.530	1.596	1.356	1.279	4.688	3.979	3.649	3.119	2.453
20	1.614	1.533	1.599	1.378	1.290	4.691	3.983	3.653	3.121	2.455
21	1.617	1.535	1.601	1.382	1.291	4.698	3.989	3.658	3.126	2.458

Figure Legends

Figure 1. The geometry, and boundary and loading conditions of the FE model.

Figure 2. Validation of the FE model: (a) boundary and loading condition for the simulation of balanced standing for validation; (b) Predicted plantar pressure distribution by FE method; (c) Measured plantar pressure distribution using TPScan System.

Figure 3. The average stress of plantar fascia upon different triceps surae load at midstance and push-off. The error bars indicate the standard deviations over the five rays of plantar fascia.

Figure 4. Plantar fascia stress of each ray upon different triceps surae force at: (a) midstance; and (b) push-off instants. The error bars indicate the standard deviations over the combinations of gastrocnemius and soleus forces for the dedicated triceps surae force.