THE EFFECT OF THE PLANTAR PLATE ON PLANTAR APONEUROSIS STRAIN: 3D FINITE ELEMENT MODELING OF FOOT AND ANKLE

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Experimental measurements of stresses and strains for the Lower Extremity Injuries (LEI) are invasive, and therefore, predictions require physiologically accurate 3D Finite Element (FE) models of the foot and ankle. Previous FE models of foot and ankle in the literature neglect the function of the plantar plate, and therefore, these models underestimate the Plantar Aponeurosis (PA) strain. In this study the effect and function of the plantar plate on PA strain and other biomechanical parameters of foot and ankle are studied. The Soft Tissue (ST) and PA are analysed as hyperelastic materials supplemented by material sensitivity analysis. The plantar plate is contributing towards more accurate prediction of PA strain (1-1.4% at full body weight during balanced standing). Material properties of ST also highly affect the PA strain, and it is a primary feature in validating FE models.

KEY WORDS: finite element analysis, foot and ankle, hyperelastic material

INTRODUCTION: Injury of the Plantar Aponeurosis (PA) is a common injury among athletes and accounts for 10% of running injuries. In addition to highly active populations, 10% of the overall population are affected at some time during their lives by Lower Extremity Injuries (LEI's) especially Plantar Fasciitis (PF) (Riddle DL, 2004; Taunton et al., 2002). Excessive strain in the PA causes micro tearing resulting in the pain. Since high strain values are being experienced by patients diagnosed with PF, there is a need for accurate Finite Element (FE) models that can predict the high PA strain measured in experiments. Previous FE models of foot and ankle in the literature (Tao et al., 2009a and Cheung et al., 2006) neglect the function of plantar plate, and therefore, these models underestimate the PA strain. One simple representative model of the foot is a simply supported arch Figure 1 (B) in which there is a "pin" condition at the calcaneus and "roller" at the metatarsal heads. This "roller" condition under the metatarsal heads was neglected in the literature which then requires that the soft tissue deform significantly in shear following extension of the arch.

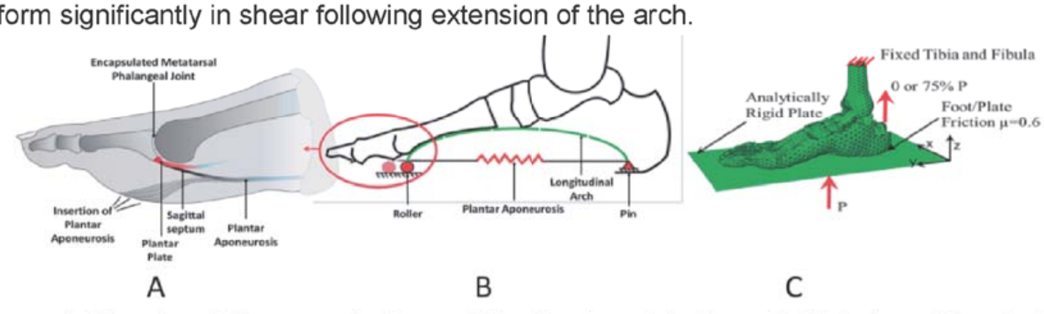


Figure 1: Structural Representations of the Foot and Ankle. A. Metatarsal heads (1-4) in contact with the plantar plate, and the PA is connected to the Plantar Plate through sagittal septum, B. The plantar plate acts as a "roller", C. 3D FE model of balanced standing with all boundary conditions and loadings

In this study the function of the plantar plate is considered. The plantar plate releases the transverse and rotational degrees of freedom between the bone and ST at the metatarsal heads (up to fourth metatarsal), and the vertical degree of freedom is constrained only. This model represents the frictionless contact behaviour between the metatarsal heads and the plantar plate by using "compression only" zero length springs.

MODEL DEVELOPMENT METHOD: The 3D model of the 30 bones (28 foot bones and the distal segments of the tibia and fibula) and ST of the foot and ankle was obtained through coronal MRI of the unloaded right foot supine male volunteer subject (age 26, height 172 cm, weight 62 kg) at 1.5 mm intervals (Tao et al., 2009a). ANSYS 9.0 (ANSYS, Inc., Canonsburg, PA, USA) was used to build the geometry of the model including bone and ST geometries. This was later imported into ABAQUS Commercial finite element software for the Finite Element Analysis (FEA)。

Table 1 Material properties used in Finite Element (FE) model

Materials	Elastic Modulus (MPa)	Poisson's Ratio	Cross Sectional area (mm^2)
Bone (Wearing et al., 2003)	7300	0.3	-
Cartilage (Shepherd and Seedhom, 1999), (soft contact in all joints)	10	0.4	-
Ligament (Tao et al., 2009b)	260	-	18.4

Neo Hookean hyperelastic material models (with material constants D1, C10 and C01) are used for the PA (Pavan et al., 2011) and ST (Lemmon et al., 1997). A material sensitivity analysis is also performed by changing the stiffness of the ST to study the sensitivity of the developed FE model for the ST stiffness given in Table 2.

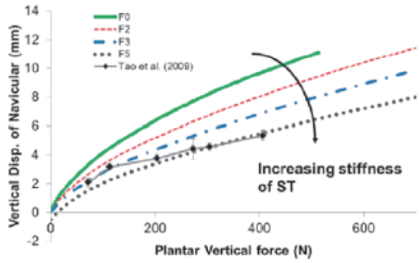
Table 2: Neo-Hookean Hyperelastic material models with sensitivity analysis models

Materials	Model Source	D1	C10	C01
PA	(Pavan et al., 2011)	0	3.009	0
Soft Tissue F0	(Lemmon et al., 1997)	0.750	0.026	0
Soft Tissue F2	(Cheung et al., 2005)	0.475	0.042	0
Soft Tissue F3	(Cheung et al., 2005)	0.321	0.062	0
Soft Tissue F5	(Cheung et al., 2005)	0.203	0.099	0

RESULTS AND DISCUSSION: Three validations are conducted to show the function of the plantar plate and ST stiffness. The first validation is the plantar vertical force and vertical displacement relation of the navicular as shown in Figure 2 which was experimentally measured in-vivo by Tao et al. (Tao et al., 2009a) via x-radiography. It is evident that the modelling of the internal boundary condition of plantar plate with hyperelastic material model for the ST and PA decreases the shear in the ST and increases the navicular drop.

The second validation is the plantar vertical force and vertical displacement relation of the foot as shown in Figure 3. The models of both Tao et al (Tao et al., 2009a) and Cheung et al (Cheung et al., 2006) which lack the function of the plantar plate are plotted also in

Figure 3 for comparison. This analysis shows that the plantar plate does not affect the vertical stiffness measure, since the model of Cheung et al (Cheung et al., 2006) (which neglects the effect of plantar plate) and the "F0" model conducted in this study are similar in prediction.



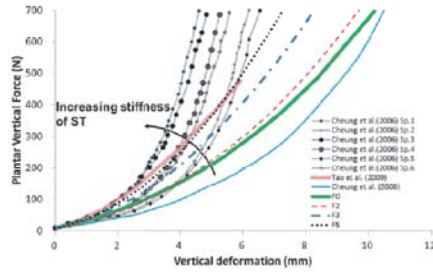


Figure 2: In-vivo Navicular displacement vs plantar vertical force

Figure 3: In-Vitro Plantar vertical force vs vertical deformation

The third validation is the plantar vertical force and PA strain relation as shown in Figure 4 which shows the largest effect of the plantar plate and the result is an excellent prediction of PA strain. In-vitro force versus PA strain experiments were conducted by Cheung et al and Kogler et al (Cheung et al., 2006; Kogler et al., 1995) in which the tibia was fixed, and the full body weight of 700 N is applied to specimens without Achilles tendon forces. These experimental results indicate that an accurate PA strain at the full body weight is between 0.5 and 2.5% strain. Simulating the effect of the plantar plate in this research yields a 1.4% strain which is in line with the experimental results (Cheung et al., 2006; Kogler et al., 1995), and this is in contrast with the model of Cheung et al (Cheung et al., 2006) which predicts a maximum value of 0.8-0.9% strain at full body weight neglecting the effect of the plantar plate.

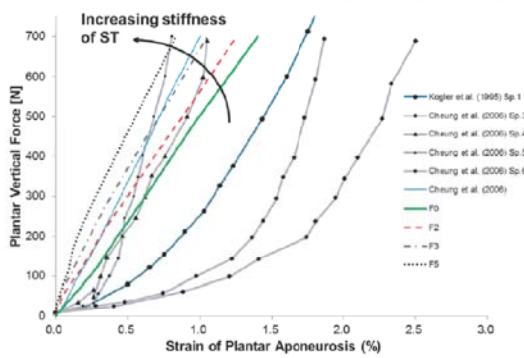


Figure 4 Plantar vertical force vs PA strain

The first and second validations are also providing significant information about the effect of ST material properties. The FE model of Tao et al (Tao et al., 2009a) in Figure 3 uses a linear elastic ST modulus of 0.45MPa. Likewise, Cheung et al (Cheung et al., 2006) in Figure 3 and 4 uses a hyperelastic material with an initial modulus of 0.185MPa. It is evident from the validations that the FE models with stiffer ST (i.e. larger than Lemmon et al. (Lemmon et al., 1997)) tend to better match the experimental results of navicular vertical displacement and foot vertical deformation, and this stiffening effect may produce by the skin which is typically neglected in the literature.

The high PA strain in this study is achieved also by adopting a hyperelastic PA material property that was recently reported by Pavan et al. (Pavan et al., 2011). The PA stiffness from Pavan et al's (Pavan et al., 2011) study agrees with the experimental results given by

Kitaoka et al. (Kitaoka et al., 1994). The models by Tao and Cheung et al (Tao et al., 2009a and Cheung et al., 2006) use a PA linear elastic modulus of 350MPa which is much higher than the initial modulus from Pavan et al (Pavan et al., 2011).

CONCLUSION: The PA connects at the calcaneous and the metatarsal phalangeal joints by sagittal septum to the plantar plate, and it provides both stiffness and stability to the foot by acting as a horizontal tie for the longitudinal arch of the foot. The PA strain prediction in the literature was low because the effect of the plantar plate was neglected. In this study the ST and PA are analysed as hyperelastic materials calibrated from data in the literature and supplemented by material sensitivity analysis. The accurate modelling of plantar plate in this study is one of the major features contributing towards the better prediction of PA strain (1-1.4% at full body weight during balanced standing), and it acts like a "roller" which prevents the excessive shear strain of the ST during arch extension. Soft tissue material properties also highly affect the PA strain, and it was shown that stiffer hyperelastic material models better match the experimental range of PA strain.

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