EXPERIMENTAL STUDIES AND EFFECTIVE FINITE ELEMENT MODELLING OF FOOT DEFORMATION IN STANDING

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ABSTRACT

In this work, a full scale subject specific FE foot model is developed to simulate the deformation of human foot under a standing position similar to a Navicular Drop Test. The model used a full bone structure and effective embedded structure method to increase the modelling efficiency. Navicular drop tests have been performed and the displacement of the navicular bone is measured using 3D image analysing system. The experimental results show a good agreement with the numerical models and published data. The model is verified by comparing the numerical data for simple standing against subject specific navicular drop test. The detailed deformation of the navicular bone and factors affecting the navicular bone displacement and measurement are discussed.
Keywords: FE modelling, Navicular Drop Test.

INTRODUCTION

Navicular Drop Test (NDT) measures navicular drop height with or without the subject's body weight pushing down on the medial longitudinal arch. It is one of the most commonly used clinical methods for evaluating the foot structure change with different conditions, such as foot structure (e.g. flat feet), the effect of medical conditions, effect of design, etc. (Rathi et al 2015). People of different genders, age, and medical condition will have different Navicular Drop (ND) (Shrader J A, 2005). Typically foot pronation is associated with higher NDT result (larger than 10mm means excessive foot pronation). On the other hand low NDT result (lower medial longitudinal arc) is linked to soft tissue damage, which will reduce the support ability. Under such a condition, extrinsic muscles have to compensate for the reduced function, causing unbalanced condition in the body alignment and overuse syndrome, including patellar tendinitis and plantar fasciitis, and sore knee and sore lower back (Neumann DA, 2010).

NDT is widely used to evaluate the medical condition or the effect of medical devices or treatment. Bandholm et al (2008) used a ruler and digital photography testing the navicular drop during quiet standing with neutral and loaded. The works show that subjects with medial tibial stress syndrome demonstrated a significantly larger navicular drop (mean _1 SD, 7.7 ± 3.1 mm). NDT is also a way to help the footwear design especially for medial purpose of foot orthosis, where the height of navicular bone is an index indicating the improvement from the foot orthosis. In the work by Lee et, al (2015), the effect of elastic tapes and non-elastic tapes was investigated by measuring navicular drop height of flat foot. A significant difference in navicular height under non-elastic tape and elastic tape was observed. Non-elastic has significant higher navicular height than the elastic tape (46.07 ±5.74mm vs. 40.14 ±7.00mm), while the control group of barefoot has the lowest navicular height (34.29 ±7.57mm). Based on the data, it was concluded that non-elastic tape application is considered to be the most effective intervention for subjects with flat foot. In another research, the NDT was used as an index of the effect of low dye taping for preventing excessive pronation at the subtalar joint of the foot over time (Rathi et al, 2015). During the test, a pre-assessment of navicular drop and plantar pressures was performed after 20 mins exercises. The researchers considered that the increased height of NDT result as a mean to prevent the excessive pronation in hyperpronated foot. Ferber et al (2011) used an Arch Height Index Measurement System to see the effect of heat-mouldable semi-custom foot orthotic device. Escalona-Marfil (2014) also studied the navicular height affected by three different midfoot supports.

Due to the importance of navicular height/drop measurement in clinical field or footwear designing, many advanced methods are used to obtain these data (Bandholm et al, 2008; Ferber and Benson, 2011; Escalona-Marfil et al, 2014). Classic manual test of NDT is involved measuring the height of the navicular when standing with the foot placed in the subtalar neutral, and again when the subject was in relaxed standing by a piece of paper and a pen. Among these tests, the motion capture system is an active method which measures the NDT through the continuously captured images by multiple cameras while the foot is load in standing, running or other movement. For example, in the work by Ferber et al (2011), retroreflective markers with an eight-camera motion analysis system (Vicon Motion Systems Ltd, Oxford, UK) was used. In the case, the arch height/navicular height is always measured in dynamical state i.e. walking or running and standing. Compare to the manual and medical image methods, the imaging based system is more efficient. However, there are issues as the marker can only be put on the skin surface, which may cause some variation between the skin movement and the bones. While the advantage of FE lies in its ability in predicting the whole system deformation. FE modelling has been widely used in modelling the deformation of foot under different conditions: standing, running, jumping and landing at inversion or aversion conditions (Gu et al, 2011; Guiotto et al, 2014; Shu et al, 2016). Most of the cases, the focus are on other structure/components such as the heel pad, metatarsals, etc. In this work, a full scale subject specific FE foot model is developed to simulate the deformation of human foot under a standing position in order to further understand NDT. The models used a subject specific full bone structure and effective embedded structure method to increase the modelling efficiency. Navicular drop tests have been performed and the displacement of the navicular bone is measured using 3D camera and image analysing system.

FE MODELS AND METHOD

Figure 1(a) shows the procedure used to build the FE foot model from medical images. The geometry of foot model is based on scan of a 25 years old health male (265mm foot length) by computer tomography. As shown in Figure1(a), CT image is converted into STL files through 3D rendering. Geometry of each bone and the foot shape is then imported into Abaqus. Coronal CT images were taken with space intervals of 2 mm in the neutral unloaded position. The images of 28 bones (i.e. talus, calcaneus, cuboid, navicular, 3 cuneiforms, 5 metatarsals, and 14 components of the phalanges) and an encapsulated volume were segmented using MIMICS 16.0 (Materialise, Leuven, Belgium) to obtain the boundaries of the skeleton and exterior surfaces of the assembly model in STL format. Then Solidworks (SolidWorks Corporation, Massachusetts) was used to convert all volume into solid parts in the format of .STEP.

In the model (Figure 1(b)), the bone structure is considered as an embedded region in the whole foot thorough a boundary condition constraint. The foot interacts with a rigid base and a force equivalent of the body weight was applied on the tibia and fibula. The structure of human bones predominate the deformation of foot under the standing load. the function of retaining the bone structure by connective tissue (tendon, ligament and fascia) is simplified by using the constraint of ‘‘embedded region’’. This constraint on foot bones avoids the collapse of foot bone structure, namely, the foot arch. In the other hand, this change reduces the stress contraction on bones from traction of the tendon, ligament, and fascia in order to avoid convergence problem. The vertical displacement of navicular bone is collected and compared with the result of biomechanical test of NDT (navicular drop test) and other methods.

Navicular drop test was used to verify the deformation of foot model under the standing load. In the test, three reflective markers were sticked on the navicular bone, heel, and first metatarsophalangeal joint (Figure 2). The subject transferred the body weight from the back foot entirely to the front foot while standing in a line. High speed camera recorded the foot from unloaded to full load at 500HZ. The displacement of the marker on navicular bone was read. The true distance of navicular drop was calculated from imaging calibration.

RESULTS AND DISCUSSION

Figure 3 shows the simulated deformation of the foot under bodyweight. When the vertical displacement of arch point on navicular bone reaches 7.8mm, the ground reaction force is equal to the body weight of the subject. As shown in Figures 3(a&b), the general foot deformation and the contour of the vertical deformation is slightly different, as the structure undergoes both vertical and lateral deformation. Figures 3(c&d) shows the vertical displacement of the bone structure and the navicular bone. The contour of the navicular bone has undergone certain degree of rotation but the main movement is downward. The average of the vertical displacement is 8.2mm.

As shown in Figure 4, the physical NDT (navicular drop test) on the same subject by high speed camera shows a reasonable agreement between the experimental and numerical result. This suggests that the modeling with simplified approach of treating the bone structure as an embedded system in the foot model is accurate under static standing loading condition. This will make it easier to use the model in biomechanics-led shoe sole development for optimizing material selection and pressure distribution. Further comparison between FE data and published data (Nielsen et al, 2009; Picciano AM, 1993; Moul, 1998) of NDT result as shown in Figure 4 also shows a good agreement.

Research works have shown that the ND can be influenced by many factors (such as age, gender, medical conditions, and external structure in contact with the foot). In the statistic model by Nielsen et al, 2009, it is found that the ND is loosely correlated to the length of the foot, and the relationship is different between the data for female and male subjects. This is an interesting factor but difficult to research purely base on experimental works. The validated model offers a potential means to establish the effect of foot length and angle on the ND of the subjects. Another issue to be studied is on the potential effects of the skin on the variation or distribution of the NDT based on the markers.

CONCLUSIONS

A new modelling approach has been evaluated in this work, in which the bone structure is treated as an embedded system within a homogenized foot host region. The model is verified by comparing the numerical data for simple standing against subject specific navicular drop test. Future work is to verify this approach through sensitive tests with a parametric FE model and tests on a larger number of cohorts.

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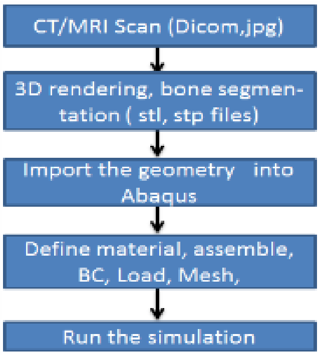
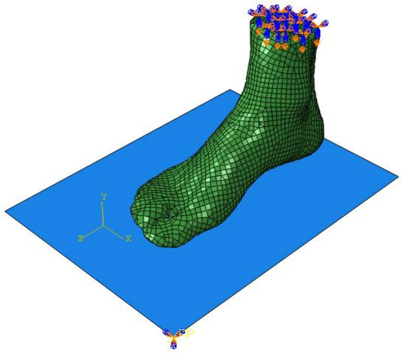
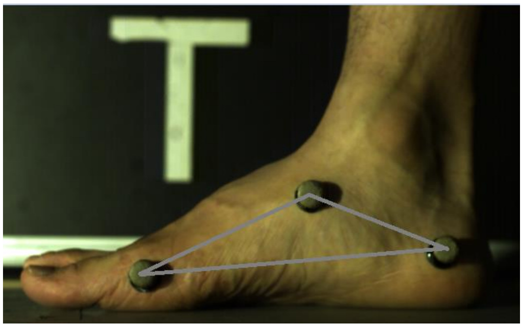


(a) Procedure

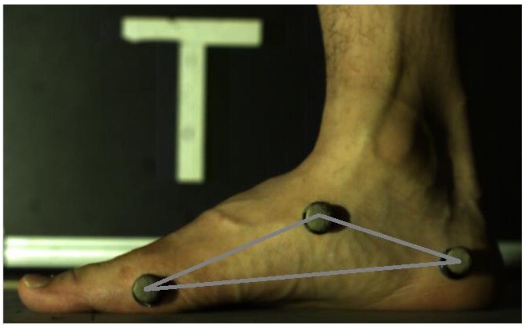


(b) FE model

Figure 1. Procedure of building the foot model and FE model.

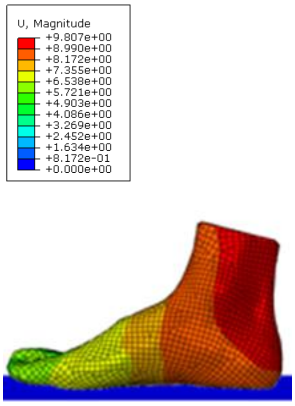


(a) unload

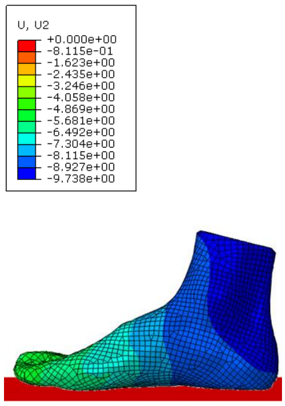


(b) loaded

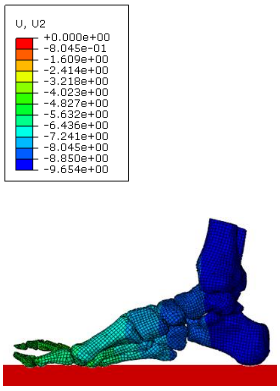
Figure 2. Navicular drop of foot at standing loading condition.



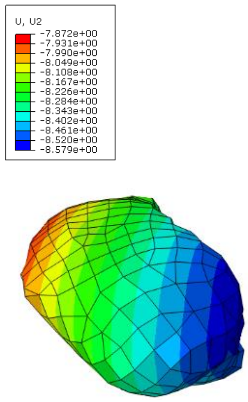
(a) General deformation field of the foot.



(b)Vertical displacement (U2) only.



(c)Vertical displacement (U2) of the bony structure.



(d) Vertical displacement (U2) of the navicular bone.

Figure 3. Deformation of the foot and Navicular Drop of foot at standing condition

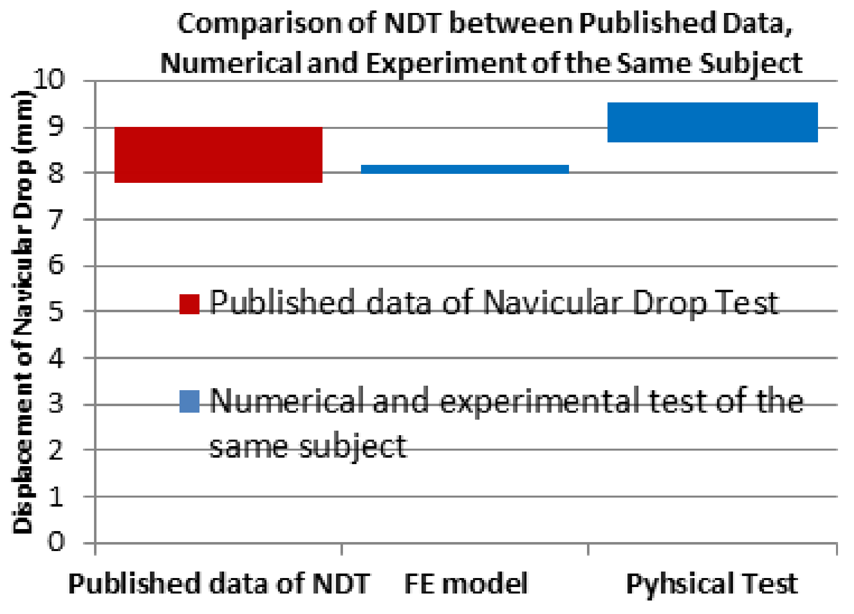


Figure 4. Comparison of NDT between Published data, numerical and experiment of the same subject. (Picciano AM et al, 1993; Moul JL, 1998)