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Short Communication

# Prediction of plantar soft tissue stiffness based on sex, age, bodyweight, height and body mass index

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ABSTRACT

15% of Diabetes Mellitus (DM) patients suffer high risk of ulceration and 85% of the amputation involving DM population is caused by non-healing ulcers. These findings elucidate the fact that foot ulcer can result in major amputation especially to the DM and elderly population. Therefore, early diagnosis of abnormally stiffened plantar soft tissue is needed to prevent the catastrophic tissue damage. In order to differentiate between normal and pathological tissues, a threshold reference value that defines healthy tissue is required. The objective of this study is to perform a multivariate analysis to estimate the healthy plantar tissue stiffness values based on the individuals physical attributes such as bodyweight (BW), height and body mass index (BMI) as well as their age and sex. 100 healthy subjects were recruited. Indentation was performed on 2nd metatarsal head pad at 3 different dorsiflexion angles of 0°, 20°, 40° and the hallux and heel at 0°. The results showed the important influences of BW, height and BMI in determining the plantar tissue stiffness. On the other hand, age and sex only play minimal roles. The study can be further extended to increase the reliability and accuracy of the proposed predictive model by evaluating several other related parameters such as body fat content, footwear usage, frequency of sports participation, etc.



## 1. Introduction

Plantar soft tissue is the tissue embedded underneath the foot bones, formed by layers of skin, adipose cells and fascias. The different layers function as a total bulk and help to attenuate the ground impact transmitted from the ground to the foot. However, this substantial cushioning ability may degenerate eventually, due to natural causes (aging), disease (diabetes mellitus, DM) (Alcântara et al., 2002; Hsu et al., 2009; Kwan et al., 2010; Tong et al., 2003; Zheng et al., 2000) and other human factors (improper footwear and lack of foot care).

Stiffened tissue is found to be torn more easily (Cheung et al., 2005). Ulceration then occurs as the developed microscopic tears build up and evolve into a large discontinuity. In the United States, 85% of the non-traumatic amputation in diabetic population is preceded by foot ulcer (Apelqvist and Larsson, 2000). 15% of DM patients are subjected to high

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ulceration risk during their life time (Nather et al., 2010). These explain the fact that foot ulceration can lead to major amputation and there is a need for early diagnosis of abnormally stiffened plantar soft tissue, so as to reduce the risk of ulceration. In vivo measurement of tissue properties via non-invasive approach is favored.

Numerous assessment methods are practised (Chen et al., 2010), including simple loading-unloading apparatus with an ultrasound transducer (Chatzistergos et al., 2014; Wang et al., 1999; Zheng et al., 2000) , or a simple load cell (Chen et al., 2011) and optical coherence tomography based air-jet indentation systems (Chao et al., 2010). Nonetheless, the values attained are not conclusive, given the non-existence of standard experiment protocol. In addition to that, the stiffness value obtained remains meaningless unless it indicates tissue health; whether the tissue is at risk and precaution should be taken, or the tissue is healthy and no special attention is required. Therefore, it is necessary to create a database of healthy tissue stiffness values to serve as a baseline to distinguish between normal and pathological tissue. However, tissue stiffness is found to be affected by age and bodyweight (Hsu et al., 1998; Teoh et al., 2014; Zheng et al., 2012). Hence, the healthy threshold may not be just a fixed universal value that is applicable to all. Instead, the baseline should be adjusted and customized individually.

The study aims to perform predictive multivariate analysis on plantar tissue stiffness. The results may be useful in estimating the customized healthy threshold based on subject's attributes. This also provides a better understanding of the effect of age, sex, bodyweight (BW), height and body mass index (BMI) on plantar tissue stiffness.

## 2. Materials and methods

### 2.1. Subjects

One hundred subjects from the National University of Singapore (NUS) hospital were recruited (63.3±9.6 kg) for this study, and approval was obtained from the NUS Institutional Review Board (IRB). Consent was obtained from the subjects prior to testing. Subjects with foot lesions, diagnosed or symptomatic osteoarthritis in lower extremity joints, major medical conditions including diabetes, gout, or standing difficulty were excluded. The subjects had sedentary to moderately active lifestyle. Subject characteristics such as height, BW, and BMI are presented in Table 1.

**Table 1 – Demographic data of the participants.**

| | Male | Female | $p$ |
|---|---|---|---|
| Age | 64.6±2.9 | 64.6±2.9 | 0.946 |
| Weight | 68.9±8.4 | 57.7±7.1 | <0.05 |
| Height | 167.4±5.9 | 154.1±5.0 | <0.05 |
| BMI | 21.6±3.1 | 24.3±3.0 | <0.05 |

### 2.2. Experimental setup

The tissue indenter (Chen et al., 2011; Teoh et al., 2014, 2015) as shown in Fig. 1 consisted of two plates which was connected by a hinge joint. This set up allowed indentation of plantar soft tissue at various metatarsophalangeal joint (MTPJ) dorsiflexion angles. The motorized indentor comprised of a 5 mm diameter flat-tipped stylus, driven by a stepper motor (MYCOM, Singapore) and connected with a miniature compression load cell (FUTEK, USA). The data output was fed into the data acquisition module (Tokyo Sokki Kenkyujo, Japan).

### 2.3. Plantar tissue testing

Tests were conducted at three plantar regions, namely the hallux, 2nd sub-metatarsal head (MTH) and heel pad. Circular markings were drawn at these regions, to serve as visual references for alignment with the porthole where the indenter tip was located (Fig. 1). Loading on the foot was strictly maintained at 50% of BW by measuring the load on the other foot using a weighing scale to mimic the static stance of gait cycle.

Each indentation cycle comprised a loading and an unloading phase, associated with a maximum probe depth of 5.6 mm, a constant loading rate of 12.3 mm/s. Three cycles of preconditioning indentation were applied to each test site prior to data acquisition. During measurement, another three cycles of indentation were imposed on the 2nd sub-MTH pad with the MTPJ dorsiflexed at three different angles, i.e. 0°, 20°and 40°. The initial state was defined by the instant when the indenter tip just came into contact with the plantar tissue, corresponding to zero tissue deformation before the start of a test. This test protocol was also applied to the hallux and heel pad, but only for a 0° MTPJ configuration. The procedure described was applied to both feet of all subjects.

### 2.4. Plantar soft tissue assessment

Tissue behavior was characterized via stiffness constant ($K$), i.e.

$$K(\mathrm{N/mm}) = \frac{\mathrm{IndentationForce(N)}}{\mathrm{IndentationDepth(mm)}}$$

The mean and standard deviation of $K$ at different regions were calculated. Multivariate analysis was then performed on the plantar tissue stiffness data of 100 participants, allowing better apprehension of the influence of age, sex, height, BW and BMI on plantar tissue stiffness from a statistical and practical point of view. The selected factors are independent variables and the soft tissue stiffness is the dependent variables of a multiple linear regression of soft tissue stiffness versus age, sex, height, BW and BMI for each plantar region separately.

## 3. Results and discussion

The study was aimed to examine the influence of sex, weight, height, BMI and age on the plantar soft tissue stiffness at