Journal of Biomechanics 49 (2016) 3022–3025

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

The influence of sex, body mass and body mass index on plantar soft-tissue stiffness in healthy people in their 60s

Jee Chin Teoh [a], Dong Yeon Lee [b], Taeyong Lee [c,*]

[a] Department of Biomedical Engineering, National University of Singapore, Singapore
[b] Department of Orthopaedic Surgery, Seoul National University Hospital, Seoul, South Korea
[c] College of Science & Industry Convergence, Ewha Womans University, Seoul, South Korea

ARTICLE INFO

Article history:
Accepted 26 May 2016

Keywords:
Plantar soft-tissue stiffness
Indentation
Sex
Body mass
Body mass index

ABSTRACT

Foot abnormality has become a public health concern. Early detection of pathological soft tissue is therefore an important preventive measure, especially in older people who generally have a higher risk of foot pathology. However, the interpretation of plantar tissue stiffness data – whether to normalize the data or to separate the data on the basis of sex– remains questionable. The objective of this study was to assess the influence of sex and physical attributes such as body mass (BM) and body mass index (BMI) on plantar soft-tissue stiffness, and to evaluate whether it is necessary to isolate the differences in sex, BM and BMI in the data analysis. One hundred healthy subjects in their 60s were recruited for the experiment. Localized force response was obtained underneath the second metatarsal head (MTH) pad at three different dorsiflexion angles of 0°, 20°, 40° and the hallux and heel at 0°. No significant relationship was found between the independent variables and plantar stiffness. From the experimental results, it can be deduced that BM and BMI are weakly associated with plantar tissue stiffness, and that there is no significant difference in stiffness between male and female participants. No difference was found between left and right foot measurements. This suggests that normalizing of plantar tissue stiffness by BM and BMI is not necessary in healthy people in their 60s. The data can be pooled and treated equally regardless of sex.

1. Introduction

Plantar soft tissue is a composite material composed of fatty and specific connective tissues located between the skin dermis and the bony segment of the foot. It plays an important role in absorbing the periodic internal stresses generated by the external ground reaction force (GRF), specifically during heel-strike and toe-off phases. The viscoelastic property of plantar soft tissue may become reduced due to several causes such as aging (Teoh et al., 2014) and accelerated tissue glycation resulting from diabetes mellitus (DM) (Hsu et al., 2009; Kwan et al., 2010; Zheng et al., 2000). The stiffened plantar soft tissues break down easily, and these microscopic tears will congregate and develop into a large ulcer (Cheung et al., 2005). In fact, foot ulceration is one of the major causes of hospitalization among DM patients. According to a previous study (Nather et al., 2010), 15% of the DM population are threatened by high ulceration risk during their lifetime. Non-invasive, in-vivo assessment that enables direct measurement of the tissue's mechanical response is therefore needed to prevent problematic tissue rupture, especially in diabetic and older populations.

In some studies, measurement of tissue stiffness was implemented under non-weight-bearing conditions (Chao et al., 2010; Klaesner et al., 2001; Zheng et al., 2000) to eliminate the effect of body mass (BM) on plantar soft tissue. However, it is questionable whether the removal of the influence of BM during assessment may inappropriately alter the in-vivo behavior of plantar soft tissue, since the cushioning ability is normally achieved when the tissue is loaded. Therefore, in order to better study the realistic behavior of plantar soft tissue, the tissue should be loaded during data acquisition.

The prime argument is how to correctly interpret the stiffness data. It is uncertain whether to normalize the tissue stiffness by BM or by body mass index (BMI). In addition to that, pooling of data from different sex may disguise any sex-related difference. It has been noted that males differ from females in a number of foot-shape characteristics (Wunderlich and Cavanagh, 2001) and gait features (Cho et al., 2004). This implies that the stiffness data may need to be considered separately. The purpose of this study is to provide a direction for the interpretation of plantar tissue data.

* Corresponding author. Tel.: +82 2 3277 2795; fax: +82 2 3277 2846.
E-mail address: tlee@ewha.ac.kr (T. Lee).

http://dx.doi.org/10.1016/j.jbiomech.2016.05.032
0021-9290/

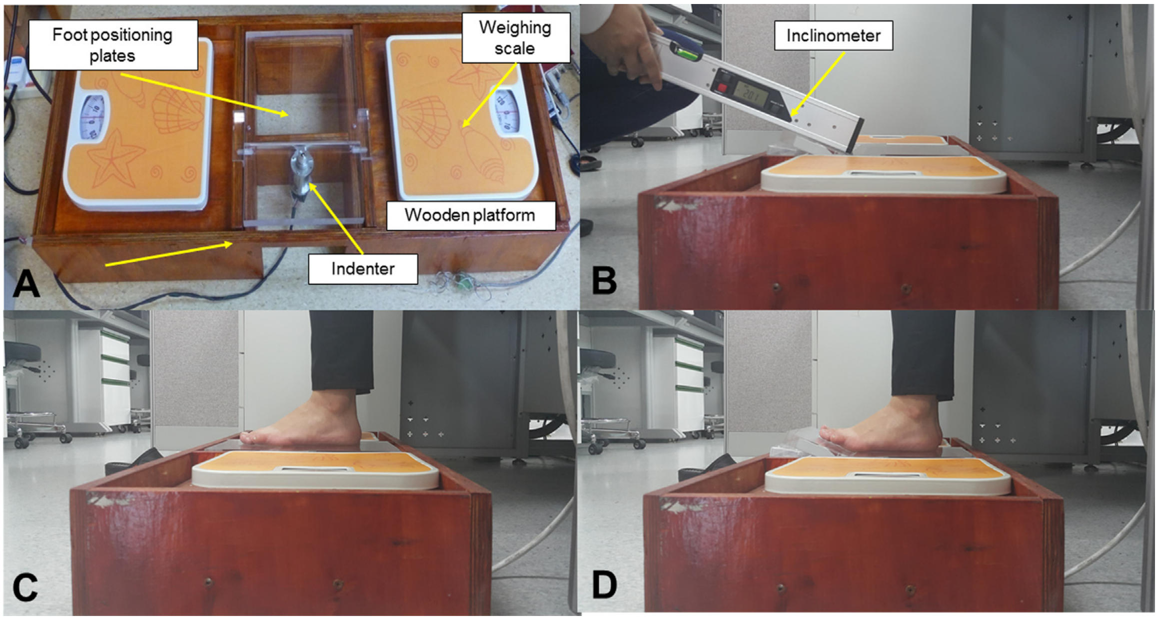

Fig. 1. (A) Overview of the indentation system, and (B) the rotation of the forefoot plate to change the metatarsophalangeal joint (MTPJ) configuration from 0° (C) to 20° and 40° (D).

Table 1
Demographic data of the participants.

	Male	Female	*P*-value
Age (years)	64.6 ± 2.9 (60–69)	64.6 ± 2.9 (60–69)	0.946
Mass (kg)	68.9 ± 8.4 (55.0–86.5)	57.7 ± 7.1 (39.5–70.2)	< 0.05
Height (cm)	167.4 ± 5.9 (153.1–177.6)	154.1 ± 5.0 (139.5–165.0)	< 0.05
BMI (kg/m^2)	21.6 ± 3.1 (17.37–28.11)	24.3 ± 3.0 (18.37–31.83)	< 0.05

BMI, body mass index.

The investigation aims to determine whether BM and BMI are correlated with tissue stiffness and to review the influence of sex difference on the stiffness assessment. It is hypothesized that the absolute value of the stiffness constant, *K*, needs to be normalized and separated by sex when plantar tissue stiffness is analyzed, in order to offset the influence of BM, BMI and sex.

2. Materials and methods

2.1. Subjects

One hundred healthy subjects (50 males and 50 females) aged 60–69 years were recruited with approval from the NUS Institutional Review Board (IRB). Consent was obtained from the subjects prior to testing. Subject characteristics are presented in Table 1. Subjects with foot lesions, diagnosed or symptomatic osteoarthritis in lower-extremity joints, major medical conditions such as diabetes or gout, or difficulty in standing were excluded.

2.2. Plantar tissue testing

The tissue indenter consisted of two foot-positioning plates and a motorized indenter (Chen et al., 2011) as shown in Fig. 1A. The device accuracy has previously been investigated (Klaesner et al., 2001) and found to be accurate and reliable, with a mean error $< 1\%$. The forefoot plate was rotated to the desired inclination with the help of an inclinometer, as shown in Fig. 1B. Indentation tests were conducted at three plantar regions: i.e. (1) the second sub-metatarsal head (MTH) at a 0° angle to the metatarsophalangeal joint (MTPJ) (as shown Fig. 1C) and extended MTPJ at 20° and 40°(Fig. 1D); (2) the hallux; and (3) the heel at 0° MTPJ configuration. Subjects were then instructed to stand on the indentation platform. Loading on the foot had to be maintained at 50% of body mass to mimic the static stance of the gait cycle.

Each indentation cycle comprised a loading phase and an unloading phase, associated with a maximum probe indentation depth, a constant loading rate of 9.2 mm/s, and a holding time of 85 ms at maximum deformation. The indentation depth was fixed at 5.6 mm such that the deformation is large enough to characterize the tissue behavior in the normal gait condition (Teoh et al., 2015). The initial state corresponding to zero tissue deformation is defined by the instant when the indenter tip is leveled with the base plate. The procedure described was applied to both feet of all subjects.

Tissue stiffness was characterized via the stiffness constant (*K*), i.e.

$$K(\mathrm{N/mm}) = \frac{\text{Indentation force (N)}}{\text{Indentation depth (mm)}}$$

Data were modeled by a normal distribution model. The goodness-of-fit was examined with D'Agostino–Pearson test. *t*-tests were used to identify significant differences in stiffness between male and female subjects on the hallux and heel pad. Meanwhile, two-way ANOVA was used to analyze the data obtained from the sub-MTH pad at various MTPJ angles. Pearson correlation was used to assess the relationship between BM and BMI with plantar soft-tissue stiffness.

3. Results

All data were normally distributed ($P > 0.05$) except in the case of sex which was a categorical variable fixed at 50 males and 50 females. No significant difference in stiffness was found between the left and right feet. Age was regarded as a controlled parameter. As shown in Table 2, the highest stiffness values were recorded at the heel pad: 4.009 ± 1.111 N/mm on the left and 3.991 ± 1.243 N/mm on the right. Meanwhile, the hallux showed the lowest stiffness constant of 1.012 ± 0.0486 N/mm and 0.932 ± 0.403 N/mm on the left and right feet respectively. The second sub-MTH pad had moderate tissue stiffness. The tissue was stiffened as the MTPJ dorsiflexion angle was increased from 0° to 40°.

The male and female participants varied significantly in mass, height and BMI, as shown in Table 1, but were similar in age. There was a low correlation coefficient for both BM and BMI with plantar tissue stiffness (Table 3A and B). This showed that BM and BMI are unlikely to be the cause for the variations in stiffness.

Females showed lower plantar tissue stiffness in all the plantar sites tested, except at the hallux, but the difference was small (Table 2). The largest difference was found at the second sub-MTH pad, with a variation of 20% when the MTPJ was flexed to 40°.