Journal of Biomechanics 47 (2014) 3043–3049

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Quantification of plantar soft tissue changes due to aging in various metatarsophalangeal joint angles with realistic tissue deformation

Jee Chin Teoh [a], V.P.W. Shim [b], Taeyong Lee [c,*]

[a] Department of Biomedical Engineering, Faculty of Engineering, National University of Singapore, Singapore
[b] Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore, Singapore
[c] Department of Medical Biotechnology, Dongguk University, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Accepted 27 June 2014

Keywords:
Aging
Plantar soft tissue stiffness
Sub-metatarsal head (MTH)
Metatarsophalangeal joint
Indentation

ABSTRACT

The nonlinearity of plantar soft tissue is seldom examined because of the small extent of deformation induced during indentation for measurement purposes. Furthermore, in most indentation experiments, the metatarsophalangeal joint (MTPJ) angle is not well controlled, although it has been proven to have a significant stiffening effect on sub-metatarsal head (MTH) pads. Hence, the study aims to quantify changes in the mechanical properties of plantar soft tissue due to aging under an experimental condition which is similar to walking. This is done by subjecting the tissue to an appropriate level of deformation at various MTPJ angles. A custom-made in vivo tissue indenter was used to measure directly the force-indentation response of the plantar tissue of two healthy groups: “Young” ($n=25$, mean age 22) and “Elderly” ($n=25$, mean age 67) subjects. Tests were performed on the 2nd sub-MTH pad at angles of 0°, 20°, 40° MTPJ dorsiflexion, as well as at the hallux and heel pad at 0° MTPJ angle. At all three plantar sites tested, elderly subjects showed significantly higher tissue stiffness than the young ($p < 0.05$). However, the stiffening effect of MTPJ angle was not notably influenced by aging. In this work, tissue stiffness is quantified in stiffness constant (K) based on the proposed indentation technique. It is hypothesized that the increase in stiffness with age observed is probably due to compositional change in the plantar soft tissue.

1. Introduction

Walking is the most fundamental form of human locomotion. It was the main mode of transportation before the invention of machines and is once again promoted because of environmental friendliness and health benefit considerations. Although being one of the mildest forms of exercise, the ground reaction forces (GRF) exerted on the body can still be as large as 1.2 times of the body weight. This degree of loading intensifies even further to 2.5 times the body weight (Keller et al., 1996) during vigorous activities such as running and jumping, contributing to repetitive trauma to soft plantar tissue during shock attenuation. This significant GRF is primarily transmitted to and distributed over the hallux, metatarsal heads (MTH) and the calcaneus in the heel, since the foot is the only weight bearing interface between the human body and the ground. As a consequence, the plantar soft tissue beneath the bony structure plays an important role in attenuating the periodic internal stresses generated by the external GRF, specifically during heel strike and toe-off phases.

It has been noted that the substantial cushioning ability of plantar soft tissue diminishes as it stiffens and loses its viscoelasticity (Gefen, 2003). Indeed, stiffened tissues tend to break down easily when subjected to plantar stresses (Cheung et al.,2005). Ulceration then occurs as microscopic tears accumulate and evolve into a large lesion. In the USA, 85% of all non-traumatic amputations in diabetes patients arise from non-healing ulcers (Larsson, 1994). This finding advocates the necessity of early detection of degenerative plantar soft tissue to prevent problematic tissue rupture, especially to diabetic and elderly patients. Non-invasive in-vivo assessment that enables direct measurement of tissue mechanical response is therefore needed.

Plantar soft tissue is not a simple homogenous linear material, but a complicated multilayered composite. The total bulk of tissue composed of skin, adipose cells and fascia. The different layers work together as a whole. Because of this complicated layered geometry, plantar soft tissue has variable mechanical properties that depend on the extent of tissue deformation (Chao et al., 2010), as well as the configuration of the metatarsophalangeal joint (MTPJ) (Garcia et al., 2008). Thus, useful measurements of tissue stiffness should only be performed under a controlled environment with an appropriate degree of tissue deformation and MTPJ dorsiflexion. There are several existing in-vivo indentation systems, such as a simple loading–unloading device with an ultrasonic transducer (Wang et al., 1999),

---

[*] Correspondence to: Department of Medical Biotechnology, Dongguk University-Seoul, 30, Pildong-ro 1-gil, Jung-gu, Seoul 100-705, Republic of Korea. Tel.: +82 2 2260 3310; fax: +82 2 2260 8726.
E-mail address: tlee@dongguk.edu (T. Lee).

http://dx.doi.org/10.1016/j.jbiomech.2014.06.033
0021-9290/© 2014 Elsevier Ltd. All rights reserved.

tissue ultrasound palpation systems (Zheng et al., 2000) and optical coherence tomography based air-jet indentation systems (Chao et al., 2010), to characterize the biomechanical properties of plantar soft tissue. Numerous factors that affect the mechanical properties of plantar soft tissue have been closely studied using these techniques; these include aging (Kwan et al., 2010) which results in natural degeneration of an organism's functions over time. Nevertheless, none of these studies report of the ability to configure sufficient tissue deformation and flexibility of the MTPJ to mimic dynamic situations like walking (Chao et al., 2010; Kwan et al., 2010; Sun et al., 2011; Zheng et al., 2000).

Therefore, the objective of this study is to investigate the effects of aging on plantar soft tissue stiffness at various degrees of MTPJ dorsiflexion, and with tissue deformation similar to normal gait conditions. It is hypothesized that natural aging causes stiffening of the plantar soft tissue and this stiffness change may vary at different MTPJ configurations.

2. Materials and methods

2.1. Subjects

25 young subjects (aged 22.1 ± 1.6 years) from the National University of Singapore (NUS) and 25 elderly subjects (aged 66.9 ± 5.8 years) from local senior citizen centers were recruited 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. Subject characteristics such as height, weight, and body mass index are presented in Table 1. Factors that might alter the stiffness measurement, i.e. weight and body mass index were found to be not significantly different between the two experimental groups ($p > 0.05$) using independent t-test.

Table 1
Demographic characteristics of the two experimental groups tested.

	Young ($n=25$)	Elderly ($n=25$)
Age (years)	22.1 ± 1.6	66.9 ± 5.9
Gender (female: male)	14:11	13:12
Height (cm)	164.9 ± 8.0	160.1 ± 8.4
Weight (kg)	56.5 ± 8.4	56.9 ± 9.1
BMI (kg/m^2)	20.8 ± 2.3	21.8 ± 2.8

2.2. Experimental setup

The tissue indenter consisted of two foot positioning plates and a motorized indenter (Chen et al., 2011), as shown in Fig. 1. The two plates were connected by a hinge joint which allowed indentation of plantar soft tissue at various MTPJ dorsiflexion angles, in order to encompass the range of MTPJ motion corresponding to normal walking. A cylindrical porthole was drilled into the forefoot plate to accommodate the indentor. Since the tissue assessment would be done under weight bearing condition, bulging of plantar soft tissue into the porthole was expected if no material was present in the hole or if there was gap between the probe tip and the porthole. To solve this issue, the hole was filled by the probe entirely and the probe tip was adjusted to be complete leveled with the surface of the forefoot plate.

The motorized indentor comprised of a 5 mm diameter flat-tipped stylus (Chen et al., 2011), driven by a stepper motor (MYCOM, Singapore). A miniature compression load cell (FUTEK, USA) was located at the lower-end of probe tip, with the output feeding into the data acquisition module (Tokyo Sokki Kenkyujo, Japan).

The indentation cycles were designed to induce significant tissue deformation at the selected plantar sites. Each cycle comprised a loading and an unloading phase, associated with a maximum probe indentation depth of 5.6 mm, a constant loading rate of 9.2 mm/s and a holding time of 85 ms (Chen et al., 2011) at maximum deformation. Based on previous studies, the deformation characteristics were reported to be about 45.7% (7 mm) (Cavanagh, 1999) and 53.9% (10.3 mm) (Wearing et al., 2009) of unloaded tissue thickness at sub-metatarsal head (MTH) pad and heel respectively. Thus, the indentation depth was set at a higher value, i.e. 5.6 mm, to better mimic tissue deformation during actual gait. However, the indentation depth could not be set too high, else it might cause uneasiness and even pain to the participants. The arbitrary holding time of 85 ms was chosen, as this only affects the force relaxation characteristic, which was not a parameter examined in this study.

2.3. Plantar tissue testing

Tests were conducted at three plantar regions, namely the hallux, 2nd sub-MTH and heel, which are the major load transmission points and have even been

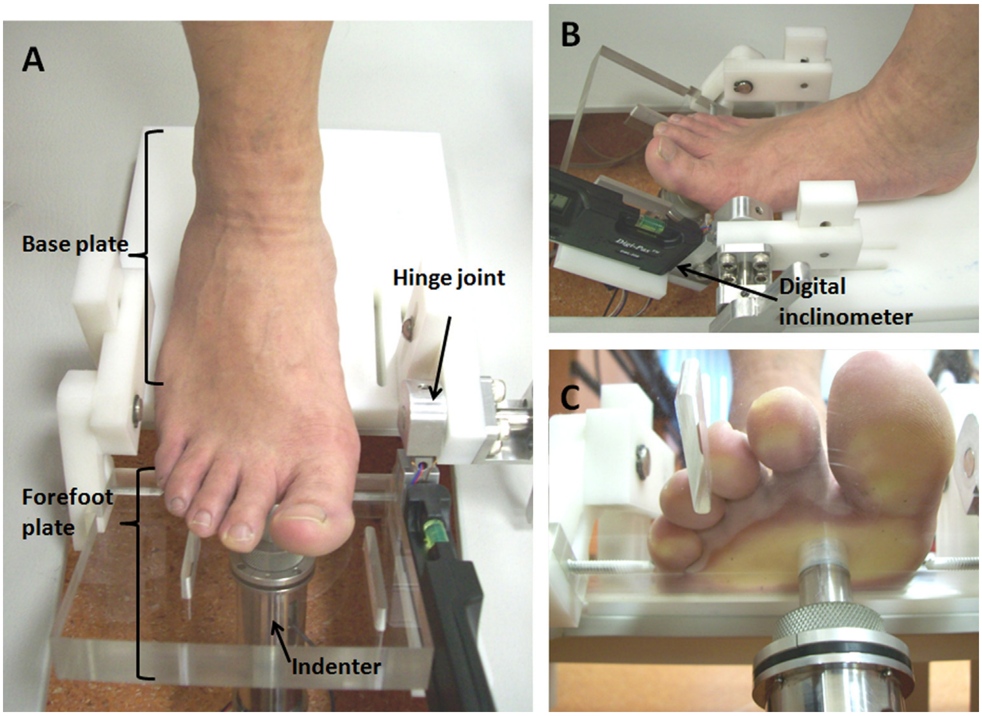

Fig. 1. (A) Top view (B) side view (C) bottom view of experimental set up, with 2nd MTH pad at 40° MTPJ dorsiflexion. The hinge joint connecting the forefoot and base plates enables the MTPJ to be dorsiflexed between 0° and 90°. The integrated indenter on the forefoot plate indents the plantar site and measures directly the force applied to the deformed tissue via a load cell mounted at the other end of the probe tip.