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Short communication

An instrumented tissue tester for measuring soft tissue property under the metatarsal heads in relation to metatarsophalangeal joint angle

Wen-Ming Chen [a], Victor Phyau-Wui Shim [b], Seung-Bum Park [c], Taeyong Lee [a,*]

[a] Division of Bioengineering, National University of Singapore, Block E3A #07-15, 7 Engineering Drive 1, Singapore 117574, Singapore
[b] Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore, Singapore
[c] Footwear Biomechanics Team, Footwear Industrial Promotion Center, South Korea

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ABSTRACT

Identification of the localized mechanical response of the plantar soft tissue pads underneath the metatarsal heads (i.e., sub-MTH pad) to external loading is key to understand and predict how it functions in a gait cycle. The mechanical response depends on various parameters, such as the external load (direction and rate), the sub-MTH tissue properties (anisotropy and viscoelasticity), and the configuration of the metatarsophalangeal (MTP) joint overlying the tissue. In this study, an instrument-driven tissue tester that incorporates a portable motorized indentor within a special foot positioning apparatus was developed for realistic *in vivo* mechanical characterization (i.e. tissue stiffness and force relaxation behavior) of the local sub-MTH pad with the MTP joint configured at various dorsiflexion angles associated with gait. The tester yields consistent results for tests on the 2nd sub-MTH pad. Measurement errors for the initial stiffness (for indentation depths ≤ 1 mm), end-point stiffness, and percentage force relaxation were less than 0.084 N/mm, 0.133 N/mm, and 0.127%, respectively, across all test configurations. The end-point tissue stiffness, which increased by 104.2% due to a 50° MTP joint dorsiflexion, also agreed with a previous investigation. *In vivo* tissue's force relaxation was shown to be pronounced (avg. = 8.1%), even for a short holding-time interval. The proposed technique to facilitate study of the dependence of the local sub-MTH pad and tissue response on the MTP joint angle might be preferable to methods that focus solely on measurement of tissue property because under physiologic conditions the sub-MTH pad elasticity may vary in gait, to adapt to drastically changing mechanical demands in the sub-MTH region of the terminal stance-phase, where MTP joint dorsiflexion occurs.

1. Introduction

The plantar soft tissue in the pads underneath the metatarsal heads (MTHs) is an optimal load-bearing structure (Bojsen-Moller and Flagstad, 1976), particularly for cushioning the highest sub-MTH ground reaction forces (GRF) exerted in the terminal stance-phase of gait (Cavanagh, 1999). Identification of the mechanical response of the sub-MTH pad to external loading is essential for clinicians or users who wish to distinguish between normal and pathological tissue functions. Both *in vivo* and *in vitro* studies have observed stiffening (Gefen et al., 2001; Klaesner et al., 2002; Pai and Ledoux, 2010), hardening (Piaggesi et al., 1999), or diminished energy dissipation (Hsu et al., 2007; Hsu et al., 2000) of the sub-MTH pad in neuropathic diabetic foot. Many believe that such altered tissue properties that accompany diabetes may severely compromise its cushioning capacity with the consequence of elevated peak plantar pressure at the sub-MTH region, where ulcers are most common (Boulton et al., 1983).

Indentation tests offer a convenient way for direct *in vivo* investigation of the mechanical responses of the soft tissue, and commonly involve applying a known deformation (i.e., indentation) directly to the living subject's tissue, e.g. the amputee residual tissue covering long bones (Silver-Thorn, 1999; Vannah et al., 1999) and the heel pad (Rome and Webb, 2000), where the naturally immobile skeleton acts as a rigid foundation. However, the intrinsically small MTH has great mobility in the plantar–dorsal direction, which often limits the maximum indenting force to be directly applied at a desired loading rate using general-purpose indentors. Previously, for sub-MTH pad indentation, large tissue deformation similar to that during actual gait was not always achieved (Zheng et al., 2000; Kwan et al., 2010). Moreover, poor instrument alignment is inherent to hand-held devices (Kawchuk and Herzog, 1996; Zheng and Mak, 1999) and limited measurement reliability in trial-and-error procedures (Klaesner et al., 2001; Wang et al., 1999) often makes interpretation of data even difficult.

* Corresponding author. Tel.: +65 6516 1471; fax: +65 6872 3069.
E-mail address: bielt@nus.edu.sg (T. Lee).

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Accurate mechanical characterization of the sub-MTH pad can be further complicated by metatarsophalangeal (MTP) joint configurations particular to structurally specialized tissue frameworks. Early cadaveric-dissection observations (Bojsen-Moller and Flagstad, 1976) have shown that the initially soft and pliable tissue pad can become increasingly "tightened" during MTP joint dorsiflexion. Such tissue "tightening" may significantly restrict skin mobility against shear forces (Bojsen-Moller and Lamoreux, 1979) and increase the compressive stiffness of the sub-MTH pad (Garcia et al., 2008). However, this unique joint-angle-dependent tissue property has not yet been fully elucidated due to experimental technique limitations.

The purpose of this study is to devise a new instrument-driven, *in vivo* tissue tester called the sub-Metatarsal Pad Elasticity Acquisition Instrument (MPEAI), which enables extraction of the localized mechanical response of the plantar soft tissue pad underneath an individual MTH (i.e. the 2nd sub-MTH pad) in relation to the MTP joint angle.

2. Materials and methods

The MPEAI consists of a special hinged foot positioning apparatus integrated together with a portable motorized indentor. This apparatus permits accommodation of the local sub-MTH pad and reproduction of MTP joint configurations generated by individuals during actual walking. The integrated indentor can directly probe the mechanical response of the sub-MTH pad by inducing rate-controlled tissue deformation, in a way that is similar to that experienced in gait.

2.1. Multiple DOF foot positioning apparatus

A multiple degree-of-freedom (DOF) apparatus was devised for gait-related foot positioning and orientation. This is achieved using a kinematic linkage that consists of three linear translators and one hinge joint for connection to the base and forefoot plates (Fig. 1). A cylindrical porthole is drilled into the rear-half of the transparent acrylic (polymethyl methacrylate) forefoot plate. The hole size was optimized (i.e. 15 mm in diameter) in order to best encircle an individual MTH adjacent to the tissue pad. The base of the porthole is internally threaded, so that a portable indentor can be firmly mounted to it.

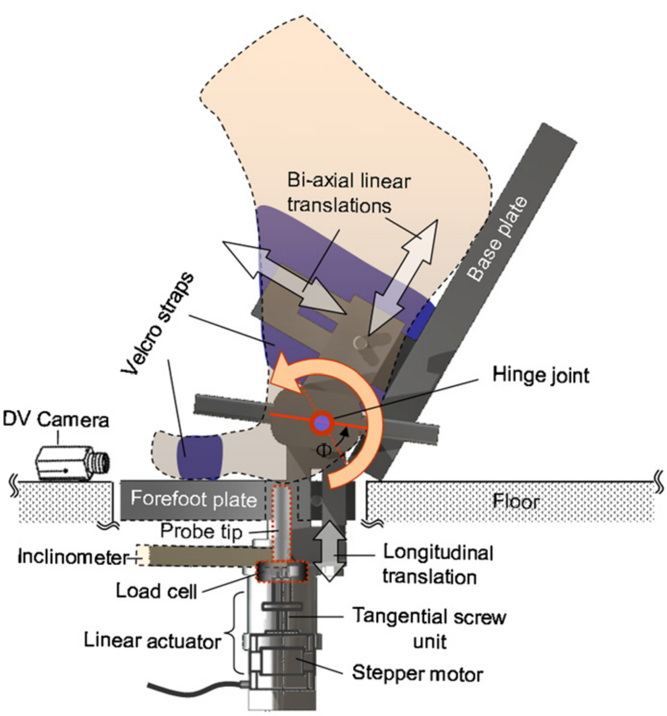

Fig. 1. Schematic diagram of the sub-Metatarsal Pad Elasticity Acquisition Instrument (MPEAI), showing details of probe tip, accommodation of sub-MTH pad, and inside components of actuator to drive probe tip.

Placement of a test subject's foot on the device is shown in Fig. 1, whereby the built-in hinge axis can be manipulated in bi-axial directions (i.e. antero-posterior and superio-inferior) for approximation of the MTP joint axis, which is assumed to pass through the medial aspect of the 1st MTH and the lateral aspect of the 5th MTH. In this way, rotation of the base plate around the hinge joint would permit control of MTP joint dorsiflexion within a range of 0–90°. This range of motion is sufficient to capture MTP joint configurations for simulation of a static stance-phase (Leardini et al., 2007). The joint angle Φ is measured by a digital inclinometer.

2.2. Portable motorized indentor

A motorized indentor was developed; it contains a closed-housing linear actuator comprising a 500-step per revolution stepper motor (MYCOM) and a 1.25 mm pitch tangential screw unit to drive a 5 mm diameter hemispherically tipped probe (Fig. 1). The indentor can be completely integrated into the positioning apparatus by a snap-lock mechanism via the testing port through which the sub-MTH pad is fully exposed (Fig. 2). Such a design ensures that the probe tip is consistently perpendicular to the tissue pad, regardless of testing conditions corresponding to different MTP joint configurations. The MPEAI can be mounted flush with the floor.

A microchip-based controller (MNC-100 Indexer Unit) and a driver are used to prescribe the desired displacement profiles accurately. As is shown in Fig. 3A, this facilitates smooth and continuous movement of the probe tip. A miniature compression load cell (FUTEK) embedded between the actuator and the lower-end of the probe tip records the magnitude of the local reaction force exerted on the tissue (Fig. 1). Load cell outputs were fed into a signal-conditioning module and a data acquisition board (National Instruments, SCXI 1520/1314 and PXI-6052E). To avoid tissue damage/pain during testing, a closed-loop control program for overload protection was written in LabVIEW (National Instruments). The indentation process automatically terminates when the indenting force magnitude exceeds 19 N. This corresponds to a nominal stress of 435 kPa at indentor-soft tissue interface, approximating the peak plantar pressure that occurs at the sub-MTH region during normal walking (Hayafune et al., 1999). A schematic diagram of the entire MPEAI system is shown in Fig. 1. Force and displacement data were collected at a sampling rate of 1000 Hz.

3. Use of MPEAI

For the pilot trial, MPEAI was used to assess the mechanical responses of the 2nd sub-MTH pad of two normal subjects. The location of the 2nd MTH of the right foot was first identified by palpating the underlying metatarsal tuberosity and was marked by an ink ring, which defines the bounds of the plantar MTH region. With the help of an assistant the soft-tissue pad can be positioned and sited within the testing port, making it readily visible to a camera aimed at the side of the forefoot plate (Fig. 1). After correction of joint axis misalignment, the foot was secured by Velcro straps (3M) and an appropriate distance with respect to the contralateral foot maintained to simulate a balanced stance-phase. The indentor can be operated in manual mode by moving the tip axially at a speed of approximately 1 mm/s. Such adjustments, coupled with visual guidance and force feedback, enabled initial contact between the indentor tip and the soft-tissue pad to be established easily and with confidence (Fig. 2). Generally, subjects can sense a threshold indenting force of approximately 0.2 N upon initial contact.

Following the initial set-up, a sequence of pre-defined indentation cycles was used to induce large deformation to the local sub-MTH pad. One cycle corresponds to complete loading and unloading, and exhibits a trapezoidal axial-displacement profile with a maximum probe depth δ (avg. = 5.6 mm), a constant loading/unloading rate η (avg. = 9.2 mm/s), and a holding time t_r (avg. = 85 ms) at the maximum deflection δ_{max} (Fig. 3A). Selection of δ and η was based on a previous study that elicited detailed deformation characteristics of the 2nd sub-MTH pad during walking, via use of an in-floor ultrasound technique (Cavanagh, 1999). A volume reconstruction of the computer tomography scan images of the subjects' right feet in non-weight-bearing