# Using Ultrasound to Assess Microchambers and Macrochambers Tissue Properties After Walking at Different Speeds and Durations

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Yih-Kuen Jan
University of Illinois, Urbana-Champaign


Chi-Wen Lung
Asia University


Jianguo Bau
National Taiwan University


Ben-Yi Liau
Feng Chia University

# Using Ultrasound to Assess Microchambers and Macrochambers Tissue Properties After Walking at Different Speeds and Durations

Wei-Cheng Shen[1], Yih-Kuen Jan[2,3,4], Chi-Wen Lung[2,5], Hsin-Chieh Chen[6], Cheng-Tsung Li[5], Jian-Guo Bau[6], and Ben-Yi Liau[6](✉)

[1] Department of Digital Media Design, Asia University, Taichung, Taiwan
[2] Rehabilitation Engineering Lab, University of Illinois at Urbana-Champaign, Illinois, USA
[3] Kinesiology and Community Health, University of Illinois at Urbana-Champaign, Illinois, USA
[4] Computational Science and Engineering, University of Illinois at Urbana-Champaign, Illinois, USA
[5] Department of Creative Product Design, Asia University, Taichung, Taiwan
[6] Department of Biomedical Engineering, Hungkuang University, Taichung, Taiwan
byliau@hk.edu.tw

**Abstract.** Exercise has been shown to improve health in people with diabetes. However, various walking speeds and durations in daily life may increase plantar pressure, thereby increasing risk for diabetic foot ulcers. Plantar thickness and stiffness have been demonstrated to be associated with plantar pressure. The pads under the heel and metatarsal heads include microchambers and macrochambers for absorbing impact forces during weight-bearing activities. The objective of this study was to investigate the effect of different walking intensities on the changes of biomechanical properties of plantar soft tissues. The healthy participants were tested in a 3 × 2 factorial design, including three walking speeds (1.8, 2.7, and 3.6 mph) and two durations (10 and 20 min). B-mode ultrasound images were obtained at the first metatarsal head to quantify plantar soft tissue thickness and stiffness before and after walking. Our results showed that the walking duration factor causes a significant effect on the macrochambers thickness. In addition, the speed factor caused a downward trend of the macrochambers stiffness with a lower walking speed.

**Keywords:** Diabetic foot ulcer · Ultrasound · Weight-bearing · Metatarsal heads

## 1 Introduction

The plantar soft tissue in diabetes had a risk of developing ulcers, it was the most recognized complication in people with diabetes mellitus (DM) [1]. In diabetes tissue glycation, the fat pad increased collagen fibril density causes it to stiffen risk of developing foot ulcers [2]. The American Diabetes Association (ADA) recommends that people with DM daily exercise or at least not allowing more than 2 days to elapse between


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exercise sessions have 150 min/week of physical activity [1]. An appropriate intensity of exercise can provide necessary physical stress to maintain tissue health. However, if the intensity is too low, it would decrease the tolerance of tissues to subsequent stresses, or if the intensity too high, it would lead to tissue injury [3]. But most weight-bearing physical may decrease tissue thickness and increased plantar pressure [4]. Other studies showed the increasing pressure demonstrated to be a major risk factor for diabetic foot ulcers, measure the stiffness in plantar soft tissue has been used to detect the endured pressure at plantar tissue [5, 6].

Plantar soft tissue stiffness and thickness are critical biomechanical variables to understand stress concentrations that may contribute to tissue injury [7]. The plantar soft tissue of diabetic was generally increased the stiffness and thickness decrease [8]. it can be caused by damaged motor neurons of the foot musculature or blood flow reduction [9]. The research revealed that walking speed is one of affected skin blood flow increase [10], and make it decrease the stiffness[11]. Also, soft tissue thickness decrease makes functional on difficult to cushioning capacities, cause the rising pressure [12].

Soft tissue is a multilayer embodying, anisotropic, and viscoelastic properties to withstand large structural deformations [13]. This multilayer tissue include microchambers and macrochambers [6]. Microchambers contain predominantly elastic fibers and equal amount of collagen and elastic fibers are identified in the macrochambers [14]. The microchambers function to maintain most of the macrochamber tissue beneath the plantar and prevent excessive deformation of the deep pad structure [15]. The macrochambers play a significant role in the resiliency, i.e., the tissue's property to recover its shape after deformation and are supposed to play a cushioning role in the walking [3].

This study can provide a foundation to understand the effect of different walking exercises including different time duration and different speeds on the changes of mechanical property of plantar tissue in people at risk for foot ulcers. This study is to observe the effect of different walking intensities on the microchambers and macrochambers thickness and stiffness properties of plantar soft tissue to the best of our knowledge. Thus, initial work is essential to analyze healthy people's reactions, which can provide a foundation for understanding the effect of diabetes on the response. Therefore, the current study aimed to investigate the effect mechanism of different walking speeds and durations on microchambers and macrochambers thickness and stiffness of plantar soft tissue properties, from multiple skin surface indentation tests in non-diabetics.

## 2 Method

### 2.1 Plantar Soft Tissue

Ultrasonography can provide information on the soft tissue structures in their plantar soft tissue thickness [11, 16]. Also it can be used to assess soft tissue stiffness [17].In this study, skin epidermal plus dermal thickness was obtained using a 12 MHz B-mode ultrasound (ArtUs EXT-1H, Lithuania) . Images (7 mm depth, 9 mm width) were acquired using a linear ultrasound. A gel pad was used to control the contact interference area between the probe and skin. Using a custom-built motor indenter device, loadcell and B-mode ultrasound images were measured at the first metatarsal heads to hold the similar pressure value quantify plantar soft tissue thickness after walking. Thickness and stiffness are measures with the same equipment. It includes a gel pad, ultrasound probe, loadcell, and stepper motor. Gel pad to limit the area of ultrasound contact with the skin, ultrasound probe for soft tissue image RF data, the acquired load cell signal was recorded using LabVIEW software (DAQ, National Instruments Austin, TX, USA), and stepper motor can monitor pressure value, and a stepping motor to regulate the advancing speed and distance of ultrasound probe (Fig. 1).

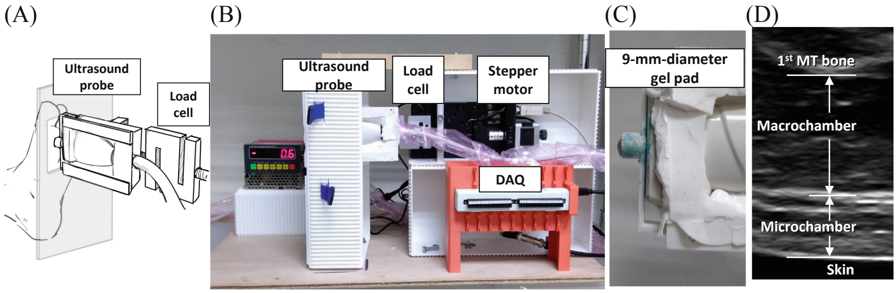


**Fig. 1.** (A) Experimental at the first metatarsal head, (B) Indentation system, (C) The ultrasound probe with gel pad, (D) Macrochamber and microchamber beneath 1$^{st}$ Metatarsal head.

The majority of skin structural deformation of the foot sole occurred within the first metatarsal [18], choose first metatarsal for the experimental location. A 9-mm-diameter indenter gel pad probe was used in this study. A load cell linear actuator was assembled on a load cell holder. We controlled the linear displacement of the indenter using a step motor driver. The rate was calculated by using the maximum deformation and the plantar pressure force to obtain Young's modulus obtained by motor applying cyclic compressions on the first metatarsal head [3, 12].

To quantify the elastic properties of soft tissues, we used the effective Young's modulus (E). It is a traditional material constant for response to the stiffness of soft tissue property [19].To extract effective Young's modulus E, the equation was defined as below:

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$$\boldsymbol{E} = \frac{(1-\boldsymbol{v}^2)}{2\boldsymbol{a}\cdot\boldsymbol{k}(\boldsymbol{v},\boldsymbol{a}/\boldsymbol{h})}\frac{\boldsymbol{P}}{\boldsymbol{w}} \quad (1)$$

Where $\boldsymbol{v}$ is Poisson's ratio; $\boldsymbol{a}$ is the indenter radius; $\boldsymbol{k}$ is a scaling factor dependent on the Poisson's ratio, indenter radius (4.5 mm), and soft tissue thickness; $\boldsymbol{h}$ is the soft tissue thickness; $\boldsymbol{P}$ is the force of pressure loading (indentation); $\boldsymbol{w}$ is the depth of indentation. Generally, 0.45 is set as the Poisson's ratio for biological soft tissues [20]. The $\boldsymbol{k}$ value was obtained from the information extracted from the publication of Hayes and colleagues [21].

### 2.2 Data Acquisition

A 3 × 2 factorial design, including 3 speeds (1.8 mph, 2.7 mph, and 3.6 mph) and 2 durations (10 and 20 min), was used in this study. A total of 6 walking protocols was tested in this study. The participant received the 1.8 mph protocol in the first week, the 2.7 mph protocol in the second week, and the 3.6 mph protocol in the third week. The order of duration (10 and 20 min) was randomly assigned. Each protocol was separated by 7 ± 2 days. The tissue strain ratios of plantar foot were then used to quantify plantar thickness and stiffness.

Each participant completed a provided informed written consent before the study's onset. Healthy participants between 18 and 28 were recruited from the student at the Asia University. The exclusion criteria included active foot ulcers, diabetes, vascular diseases, hypertension, and inability to walk 20 min independently or walk at the speed of 3.6 mph independently. Subjects were free from recent lower limb injury or presence of lower limb pain, as well as any sensitivities to adhesives or gels. All examinations were performed in the Rehabilitation Engineering Lab at the Asia University. and room temperature was maintained at 24 ± 2 °C. Our laboratory has validated the plantar tissue feasibility of the test plan [11, 22, 23].

### 2.3 Experimental Procedures

For each participant, all experiment process was done during a single laboratory visit lasting approximately one hour. Set the plantar postures for control of the foot dorsum and set relax 15-min by lifting replacing the left foot onto the sit while relaxing, then neutral for the foot was stand on the ultrasound tube box. The operator adjusts each participant's left plantar position as required to access the necessary plantar sole place test. All participants were reminded to relax all lower limb muscles to avoid any confounding effects of active muscle-mediated skin structural deformation. The same operator performed specific components of the experimental procedure across all subjects to reduce variability.

### 2.4 Statistical Analysis Method

The significant differences in each parameter among the three speeds (1.8, 2.7, and 3.6 mph) were tested using one-way analysis of variance (ANOVA). The paired sample *t*-test was used to evaluate the variation of two durations (10 and 20 min) and the between the speeds. It examines the interaction between the speed and duration factors on macrochambers and microchambers stiffness thickness. All statistical tests were performed using SPSS 22 (IBM, Somers, NY, USA) at the significance level of 0.05.

## 3 Results

Among the one-way factors of speed, there were no significant difference exist between different speeds. However, thickness and stiffness of the macrochamber trend to downward more than that of the microchamber. Including the walking speed rate at the same time factor, the thickness of the macrochamber is lower at 2.7 mph than that at 1.8 and 3.6 mph (Table 1). Moreover, the stiffness of the soft tissue continues to decrease with walking time and speed. Regarding the walking duration, there is a significant difference in the plantar macrochambers thickness between 10 min and 20 min in 3.6 mph (109 ± 8.4% v.s. 121.7 ± 6.1%, $P = 0.047$) (Table 2 and Fig. 2).

**Table 1.** Measure the walking speed of thickness and stiffness.

| Duration | | Speed | | | One-way ANOVA | Fisher LSD Post hoc | | |
|---|---|---|---|---|---|---|---|---|
| | | 1.8 mph (Mean ± SE) | 2.7 mph (Mean ± SE) | 3.6 mph (Mean ± SE) | *P* value | 1.8 mph vs. 2.7 mph | 1.8 mph vs. 3.6 mph | 2.7 mph vs. 3.6 mph |
| **Thickness** (%) | | | | | | | | |
| Macro | 10 min | 107.5 ± 6.1 | 95.5 ± 13.2 | 109.0 ± 8.4 | 0.576 | 0.404 | 0.912 | 0.348 |
| | 20 min | 116.2 ± 4.6 | 107.3 ± 9.4 | 121.7 ± 6.1 | 0.384 | 0.395 | 0.594 | 0.182 |
| Micro | 10 min | 92.0 ± 14.5 | 82.4 ± 10.7 | 98.4 ± 14.5 | 0.546 | 0.370 | 0.333 | 0.939 |
| | 20 min | 97.1 ± 9.7 | 90.8 ± 7.0 | 92.6 ± 16.7 | 0.792 | 0.598 | 0.928 | 0.538 |
| **Stiffness** (%) | | | | | | | | |
| Macro | 10 min | 134.0 ± 35.3 | 92.9 ± 28.8 | 89.5 ± 27.7 | 0.949 | 0.755 | 0.843 | 0.909 |
| | 20 min | 128.0 ± 36.7 | 84.6 ± 59.8 | 118.9 ± 56.4 | 0.827 | 0.569 | 0.904 | 0.652 |
| Micro | 10 min | 99.1 ± 27.4 | 76.8 ± 22.2 | 73.0 ± 35.4 | 0.694 | 0.652 | 0.406 | 0.695 |
| | 20 min | 110.6 ± 25.6 | 135.3 ± 48.2 | 88.0 ± 37.4 | 0.692 | 0.659 | 0.685 | 0.404 |

**Note:** %, normalized with before excise value. Data was presented as mean ± standard errors.

## 4 Discussion

This study demonstrated that the 3.6 mph walking durations (10 and 20 min) significantly affected plantar tissue thickness and the walking speed of 1.8 and 2.7 mph did not and walking at 2.7 mph for 10 min resulted in a decreased thickness macrochambers tissue. It showed a trend that plantar tissue stiffness after walking at 2.7 and 3.6 mph for the same duration was lower compared to walking at 1.8 mph. This finding is significant because walking durations of 20 min can increase plantar tissue thickness compared to slow walking durations of 10 min. This study suggests people at risk for foot ulcers should walk at the speed (3.6 mph) rather than walk slowly (1.8 mph) and keep more duration (20 min).

The result of this study found 2.7 mph walking 10 min may decrease the plantar thickness. The thickness decrease represents the macrochambers attenuate to shape deformation ability [3], this phenomenon might indicate that the soft tissue universal received more pressure. This phenomenon disappears after 20 min of exercise.

**Table 2.** Measure the duration of thickness and stiffness.

| Parameter | Layer | Speed | Duration | | Paired *t*-test |
|---|---|---|---|---|---|
| | | | 10 min | 20 min | *P* value |
| | | | (Mean ± SE) | (Mean ± SE) | |
| **Thickness** (%) | Macro | 1.8 mph | 107.5 ± 6.1 | 116.2 ± 4.6 | 0.093 |
| | | 2.7 mph | 95.5 ± 13.2 | 107.3 ± 9.4 | 0.079 |
| | | 3.6 mph | 109.0 ± 8.4 | 121.7 ± 6.1 | **0.047*** |
| | Micro | 1.8 mph | 92.0 ± 14.5 | 97.1 ± 9.7 | 0.655 |
| | | 2.7 mph | 92.9 ± 28.8 | 76.8 ± 22.2 | 0.686 |
| | | 3.6 mph | 89.5 ± 27.7 | 73.0 ± 35.4 | 0.690 |
| **Stiffness** (%) | Macro | 1.8 mph | 134.0 ± 35.3 | 99.1 ± 27.4 | 0.167 |
| | | 2.7 mph | 92.9 ± 28.8 | 76.8 ± 22.2 | 0.686 |
| | | 3.6 mph | 89.5 ± 27.7 | 73.0 ± 35.4 | 0.690 |
| | Micro | 1.8 mph | 128.0 ± 36.7 | 110.6 ± 25.6 | 0.801 |
| | | 2.7 mph | 84.6 ± 59.8 | 135.3 ± 48.2 | 0.339 |
| | | 3.6 mph | 118.9 ± 56.4 | 88.0 ± 37.4 | 0.464 |

**Note:** %, normalized with before excise value. Data was presented as mean ± standard errors

Our previous study demonstrated that the walking speeds significantly affected plantar tissue stiffness and the walking durations did not [11], combined with the findings from this study, the trend of stiffness also supports the research. The other study showed the decreased stiffness macrochambers tissue represents means increased cushioning capacities [12]. And this study showed that walking duration was significantly affected plantar tissue thickness at 3.6 mph, this may indicate that in the walking duration (10 and 20 min), the thickness of the soft tissue changed can affect the plantar more significantly than the stiffness.

Several issues still have to be clarified in the future work. The stress increase caused by wearing shoes or different shoe-wearing habits is different. In this study, the subjects themselves are accustomed to walking shoes, which should be limited in the future. Besides, for the subjects exhibiting different walking posture at 3.6 mph speed, the walking posture may change the soft tissues' compression conditions, but this depends on the subjects' own exercise habits. It should consider that how to reduce the difference between the subjects' moving postures. In this study, we developed a method for quantifying the plantar foot's mechanical properties and analyzed the differences in skin and fat mechanical properties with speed and duration. This study suggests that the possibility of the soft tissue buffer capacity attenuation is related to mechanical property changes in the walking duration time. This study can be used to help preserve healthy plantar tissues in diabetic patients.

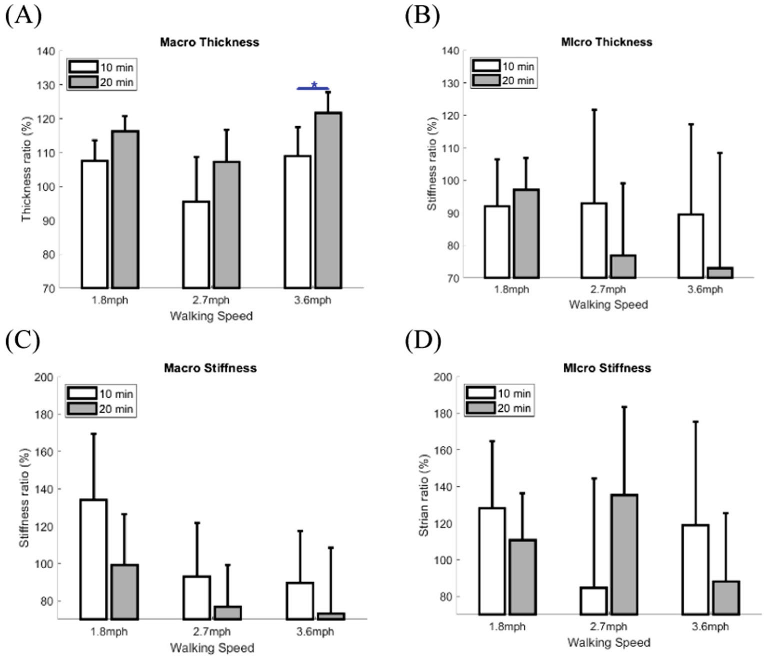


**Fig. 2.** Percentage change of soft tissue (A) thickness of macrochambers after walking, (B) thickness of microchambers after walking, (C) stiffness of macrochambers after walking, (D) stiffness of microchambers after walking.

## 5 Conclusions

The results of this study demonstrated that the walking duration (10 and 20 min) significantly affected plantar macrochambers tissue thickness and the walking speed (1.8, 2.7, and 3.6 mph) did not. Our results showed that the walking duration factor causes a significant main effect on the macrochambers thickness. In addition, the speed factor caused a downward trend of the macrochambers stiffness. This study suggests that people at risk for foot ulcers should walk at speeds at 3.6 mph with duration 20 min.

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