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Original Contribution

EFFECTS OF AGING ON THE PLANTAR SOFT TISSUE PROPERTIES UNDER THE METATARSAL HEADS AT DIFFERENT IMPACT VELOCITIES

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Abstract—The plantar soft tissue properties under the metatarsal heads at different impact velocities in different age groups were measured. Each metatarsus of the left foot in healthy young adults ($n = 9$, 19 to 35 years old) and in healthy older persons ($n = 10$, 42 to 72 years old) was examined *in vivo* using a self-constructed loading-unloading device at low, medium and high impact status; the impact velocities of the device were about 2.5, 5 and 10 cm/s, respectively. The device comprised a 5- to 12-MHz linear-array ultrasound transducer, a miniature load cell and a fixation frame. From low to high impact status, the elastic modulus (*E*) in young adults significantly increased from about 300 kPa to about 500 kPa. However, the *E* in the older group did not show this trend. From low to high impact status, the energy dissipation ratio (*EDR*) of the metatarsus significantly increased from about 30% to about 60% in the young group and significantly increased from about 40% to about 70% in the older group. Most of the metatarsus in the older subjects had significantly greater *E* and *EDR* than those in the younger persons. (E-mail: chungli@ha.mc.ntu.edu.tw) © 2005 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Metatarsus, Biomechanics, Aging, Ultrasonography, Impact velocity.**

INTRODUCTION

In an active and healthy society, foot problems are becoming more prevalent in the aging population (Whitney 2003). Metatarsalgia, a well-recognized but loosely defined pathologic entity, is caused by excessive sports activities (Quirk 1996) and is frequently associated with the aging process (Edelstein 1988). Abnormal foot biomechanics caused by tissue changes under the metatarsal heads has been proposed to be a key risk factor for this lesion (Whitney 2003). Therefore, it is important to identify the plantar soft tissue properties under the metatarsal heads, because they can provide basic information about the material itself or indicate the presence of a disease (Brink 1995).

Features of viscoelasticity, including creep, stress relaxation and hysteresis can be seen in all biologic tissues (Fung 1993). The plantar soft tissues under the metatarsal heads, comprising a complex framework of the connective tissue and closely packed fat cells, are optimized for load-bearing during ambulation (Bojsen-Møller and Flagstad 1976). Healthy persons may voluntarily modify their walking velocity and the plantar soft tissues have to tolerate the ground reaction force at different impact velocities. It would be interesting to examine the plantar soft tissue behaviors at different impact velocities.

The plantar soft tissue thickness under each metatarsal head has been evaluated ultrasonographically (Gooding et al. 1986; Cavanagh 1999; Zheng et al. 2000) and roentgenographically (Dreeben et al. 1987). The elastic modulus of the metatarsus and of the soft tissues between the metatarsal heads is measured either by an ultrasonic indentation probe (Zheng et al. 2000) or by the method of integrating the contact pressure measurement technique into a magnetic resonance imaging system (Gefen et al. 2001), respectively. Klaesner et al. (2002) developed a 3-D indentor system to measure the tissue stiffness of the metatarsus; others used a durometer (Brink 1995). The hysteresis of the plantar soft tissue

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under each metatarsus in healthy young subjects has been measured by an ultrasound (US)-based loading-unloading device (Wang et al. 1999). However, how the soft tissue properties under the metatarsal heads react to different impact velocities has not been investigated.

Ultrasonography can provide dynamic information on the soft tissue structures in their physiological range of motion and is ideal for continuous monitoring of the plantar soft tissue thickness during a loading-unloading cycle. The present study developed an US-load-cell system to investigate the effects of aging on the plantar soft tissue properties under metatarsal heads at different impact velocities *in vivo*.

MATERIALS AND METHODS

A total of 19 healthy volunteers were recruited and were further divided into the young and the older groups. There were 4 women and 5 men in the younger group and 5 women and 5 men in the older group. The mean age and body mass index (BMI) were 24.0 ± 1.8 years (range: 19 to 35 years) and 23.0 ± 1.4 kg/m^2, respectively, in the young group. The mean age and BMI were 54.6 ± 3.3 years (range: 42 to 72 years) and 26.0 ± 1.5 kg/m^2, respectively, in the older group. These subjects did not have any foot problems within the recent 6 months. The above and subsequently presented data were all mean ± standard error of mean.

A 5- to 12-MHz linear-array US transducer (HDI5000, Advanced Technology Laboratory, Bothell, WA, USA) with the area of 4.73 cm^2 was incorporated into an indenter that was equipped with a miniature load cell (LM-10KA, Kyowa Electronic Instruments Corp., Kyowa, Japan). They were then mounted on a device comprising a plastic fixation cover, stainless steel frame and a guiding linear bearing (Fig. 1). The hand-held indenter moved the transducer to and fro, to load and unload the metatarsus. Each subject was placed in the supine position with the ankle in neutral and the knee in straight positions. All of the subjects were examined by an experienced operator.

The skin was pretreated with alcohol, to facilitate US penetration into the plantar soft tissues. Then, the transducer was put along each toe ray and contacted the ball of the foot *via* a water bag. With the US transducer slightly detached from the skin and with the US couplant filled in between, the unloaded plantar soft tissue thickness under the metatarsal head (*UPTM*) was measured from the skin surface to the nearest metatarsal head cortex on the sonogram. Thereafter, the probe loaded the metatarsus rhythmically with low, medium and high impact status, according to the frequency of a metronome (quartz metronome SQ-77, Seiko S-Yard Co. Ltd., Tokyo, Japan) at 0.5 Hz, 1 Hz and 2 Hz, respectively. A beep sound was generated as soon as the compression force reached 98 N and then the applied force was relieved immediately. The averaged pressure, calculated from the total force divided by the area of the US transducer, was used to analyze the stress-strain relationship in the study. With a contact area of 4.73 cm^2, the maximum stress on the tested metatarsus applied by the US transducer was equivalent to 207 kPa. The water bag was open to the atmosphere. The tested metatarsus was about 5 cm below the water level and the water level in the bag was raised slightly (typically less than 0.5 cm) during the loading process. The pressure acting on the tested metatarsus by the water bag was about 500 to 550 Pa, which was about 0.25% of the maximum loading pressure applied by the US transducer. Therefore, it is considered that the pressure on the tested metatarsus applied by the water bag could be neglected during the examination.

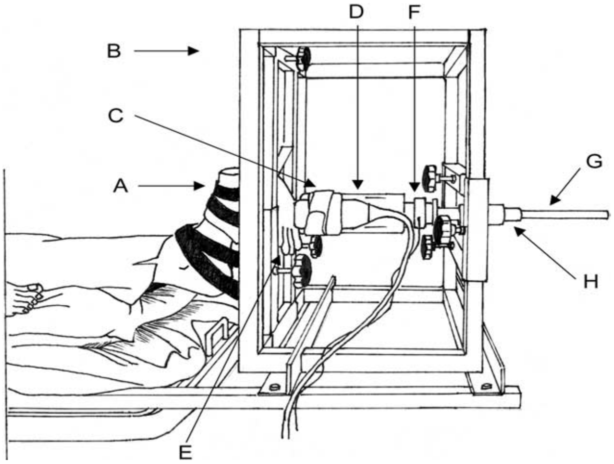

Fig. 1. Experimental design of this study. The tested left foot was placed in a plastic rim (A) of a stainless-steel frame (B) that allowed repeated loading-unloading examination. US transducer (C) contacted with the examined region through a water bag (E). The transducer was further connected with a load cell (F) *via* an adapter (D). A hand-held steel rod (G) could move the transducer freely in a bearing (H) at different maximum impact velocities. M-mode morphologies and piezoelectric signals were transmitted to the high-resolution US system and an IBM-compatible personal computer, respectively.

The impact velocity was defined as the rate of deformation of the water bag at the instant that the transducer contacted the skin. After the transducer touched the metatarsus, the plantar soft tissue started to deform in responding to the loading force of the transducer. The average loading rate was calculated by using the maximum deformation of the plantar soft tissue divided by the loading time interval (Wang et al. 1999). Moreover, the average force/time slope was given by the maximum compression force divided by the loading time interval (Klaesner et al. 2002).

The mean impact velocity corresponding to low, medium and high impacts of the young subjects was

2.36 ± 0.09 cm/s (range: 1.46 to 3.62 cm/s), 5.47 ± 0.14 cm/s (range: 4.02 to 6.64 cm/s) and 10.5 ± 0.3 cm/s (range: 6.76 to 12.6 cm/s), respectively. The mean impact velocity corresponding to low, medium and high impacts of the older subjects was 2.42 ± 0.10 cm/s (range: 1.34 to 3.8 cm/s), 5.26 ± 0.13 cm/s (range: 3.27 to 6.71 cm/s) and 9.92 ± 0.22 cm/s (range: 7.06 to 13.1 cm/s), respectively. The average loading rate corresponding to low, medium and high impacts of the young subjects was 1.09 ± 0.05 cm/s (range: 0.71 to 1.68 cm/s), 1.87 ± 0.05 cm/s (range: 1.26 to 2.45 cm/s) and 2.88 ± 0.08 cm/s (range: 2.12 to 3.74 cm/s), respectively. The average loading rate corresponding to the low, medium and high impacts of the older subjects was 0.98 ± 0.04 cm/s (range: 0.47 to 1.42 cm/s), 1.75 ± 0.06 cm/s (range: 1.21 to 2.58 cm/s) and 2.89 ± 0.12 cm/s (range: 2.03 to 4.78 cm/s), respectively. The force/time slope at the low, medium and high impacts of the young subjects was 227 ± 13 N/s (range: 118 to 490 N/s), 357 ± 12 N/s (range: 265 to 490 N/s) and 566 ± 21 N/s (range: 392 to 817 N/s), respectively. The force/time slope at the low, medium and high impacts of the older subjects was 206 ± 9.6 N/s (range: 111 to 338 N/s), 351 ± 15 N/s (range: 181 to 649 N/s) and 550 ± 20 N/s (range: 329 to 817 N/s), respectively.

Each metatarsus of the left foot in every subject was monitored continuously during loading-unloading tests by motion-mode (M-mode) at a sampling rate of 100 Hz (Fig. 2). We examined the metatarsus with a slower impact velocity first and then increased the velocity sequentially. Each metatarsus had a 10-min interval free-of-loading between each measurement (Fung 1993). The load cell signals were magnified by an amplifier (INA128/UAF42, Texas Instruments, Austin, TX, USA), in which frequency above 10 Hz was filtered. The signals were digitized by an analog-to-digital converter card (PCI-9118 DG, AD Link Technology Inc., Taipei, Taiwan) and were then transmitted to an IBM-compatible personal computer. A pulse generator was used to synchronize the load cell and the tissue thickness information. By carefully calibrating the system with an impulsive motion, the time lag between the load cell signals and the ultrasonic M-mode was found to be about 20 ms (Shau et al. 1999).

The elastic modulus (E) of the plantar soft tissue under the metatarsal head was defined as:

$$E = \frac{P_{\max}}{\left(\dfrac{UPTM - PTM_{\max}}{UPTM}\right)}, \qquad (1)$$

where $P_{\max}$ and $PTM_{\max}$ represented the maximum stress and plantar soft tissue thickness measured at maximum stress, respectively. The denominator of the above formula represented the maximum strain.

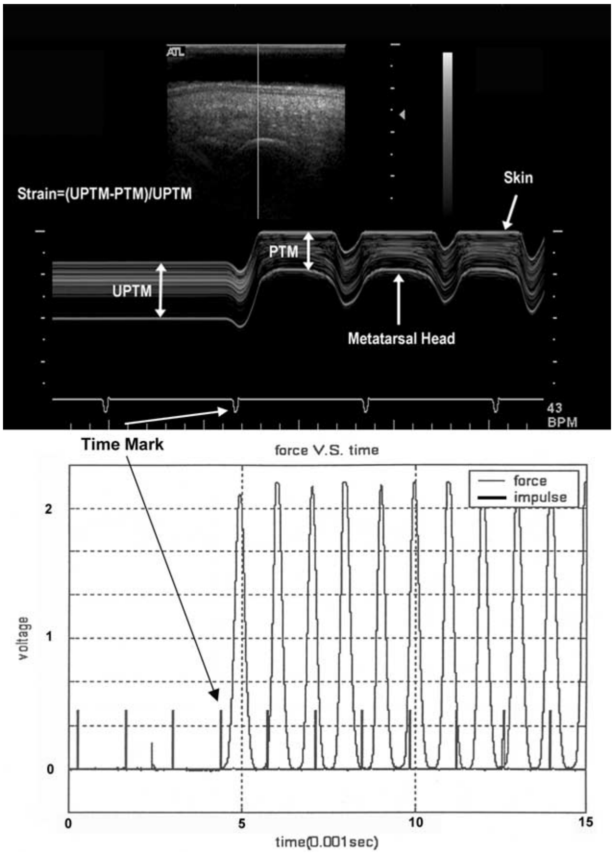

Fig. 2. B- and M-mode images of the plantar soft tissue under left third metatarsus (top) in a 57-year-old healthy man. The vertical line of the upper panel represented the US scanning line of the M-mode (bottom). The two sinusoid lines in the lower panel are the skin and cortex of the metatarsal head at different times in loading-unloading cycles. *UPTM* was measured from the skin to the nearest cortex. Plantar soft tissue thickness under the metatarsal head (*PTM*) during a loading-unloading cycle could be easily measured from M-mode. Time marks produced by a pulse generator were used to synchronize load cell signals (lower panel) in the IBM-compatible personal computer and the US image.

In terms of stress-strain relationship, the metatarsus showed a nonlinear looping curve (Fig. 3). The upper loading curve and the lower unloading curve formed a closed area that represented the dissipated energy. Thus, the energy dissipation ratio (*EDR*), indicating the shock absorbency of plantar soft tissues under the metatarsal heads, was given as:

$$EDR = (\text{bounded area}/\text{area under the loading curve}) \times 100\% \qquad (2)$$

The area was estimated by the numerical integration-based trapezoid rule using Microsoft Excel (Microsoft Corp., Redmond, WA, USA).

Reliability was determined by a test-retest procedure. We repeated the measurement with the three dif-

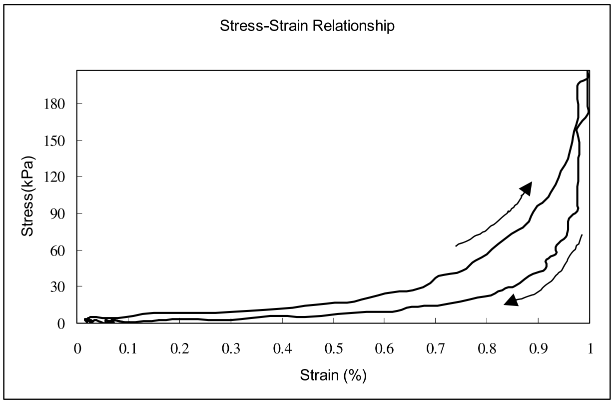

Fig. 3. An example of the stress-strain curve of plantar soft tissue under the fourth metatarsus in a 20-year-old healthy woman. The x-axis and y-axis represented the strain and stress, respectively. The upper loading curve (↗) and the lower unloading curve (↙) formed a closed area. *EDR* is defined as the ratio of this closed area to the area formed by the loading curve, the vertical line and the x-axis.

ferent impact statuses on the plantar soft tissue under the second metatarsal head of the left foot in five healthy individuals at intervals of 10 min, 2 h and 1 week after the first measurement. The coefficient of variation (CV) was then calculated from the 20 measurements at each impact status and ranged from 1 to 3% for the *UPTM* and *E*. The CV for the *EDR* ranged from 2.56 % to 8.45 %. Mann–Whitney *U* test was used to compare the age, BMI, *UPTM*, *E*, *EDR*, maximum strain, impact velocities, loading rates and force/time slopes between the two groups. The relationship between the BMI, *UPTM* and the mechanical properties was analyzed by the Pearson correlation. Repeated measurements were conducted to compare differences of *E* and *EDR* of the plantar soft tissues under the metatarsal heads among different impact statuses. Fisher's exact test was used to evaluate the gender distribution between the two groups. A *p* value of less than 0.05 was regarded as statistically significant.

RESULTS

Gender distribution and BMI were not significantly different between the two groups. Significant difference ($p < 0.001$) of the age distribution was observed between the two groups. The mean *UPTM* had a decrease trend from the first to the fifth metatarsus in both groups, with values of 1.36 ± 0.05, 1.23 ± 0.06, 1.13 ± 0.05, 1.09 ± 0.06 and 0.89 ± 0.03 cm in the younger group and 1.40 ± 0.05, 1.31 ± 0.06, 1.21 ± 0.05, 1.16 ± 0.03 and 1.07 ± 0.06 cm in the older group. There was no significant difference of the thickness between the two groups. The impact velocities, loading rates and force/time slopes were not significantly different between the two groups, either.

The *E* in most of the metatarsus in the young persons had a significant increase trend from low to high impact status. However, the *E* of the metatarsus in the older individuals measured at different impact statuses did not share the same tendency (Fig. 4). The second to fifth metatarsus in the older persons were stiffer than those in the younger persons at low and medium impact status. The first metatarsus in the older subjects had greater tissue stiffness than that in the younger subjects at the three different impact conditions (Table 1).

The maximum strain in the young subjects had a significant decrease trend from low to high impact status. The maximum strain in the older subjects measured at different impact status did not show the same trend. Almost all the plantar soft tissues under the metatarsal heads in the older persons deformed less than those in the young subjects at the three impact statuses (Table 2).

The *EDR* in almost all the metatarsus increased significantly from low to high impact status (Fig. 5). Under the same impact status, the older subjects had significantly greater *EDRs* than the young subjects in a majority of the metatarsus. At the low impact status, there was no significant difference of the *EDR* in the second to fourth metatarsus between the two groups. The *EDR* of the fifth metatarsus measured at the high impact status was not significantly different between the two groups. The detail information is listed in Table 3.

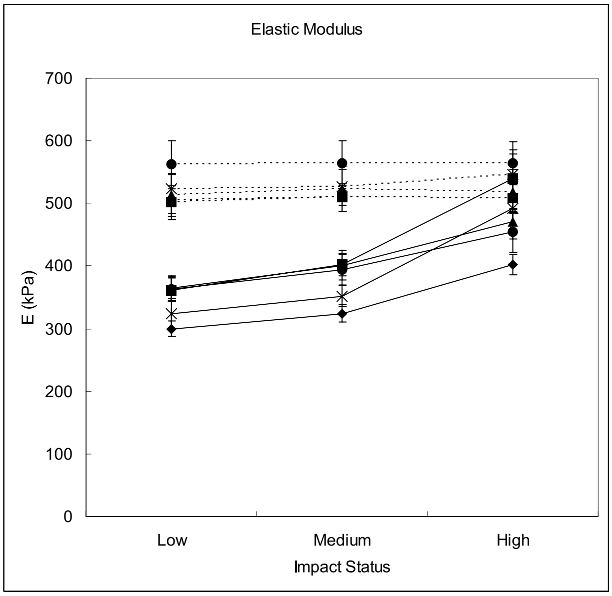

Fig. 4. *E* of the young and older groups at different impact status. The *E* of the five metatarsals (◆ = the first metatarsus; ■ = the second metatarsus; ▲ = the third metatarsus; ● = the fourth metatarsus; × = the fifth metatarsus) in the young subjects (—) increased with increasing impact velocity. However, stiffness of the older group (· · ·) lost the rate sensitivity. The metatarsus in the older group had greater tissue stiffness than those in the young group, except at high-impact status. Data are presented as mean ± one standard error of the mean.

Table 1. Elastic modulus of the plantar soft tissues under the metatarsal heads at different impact status in the two groups

	Impact status	Young	Older	p value*
MT1 (kPa)	Low	300 ± 12	509 ± 21	0.003
	Medium	324 ± 14	505 ± 20	0.003
	High	402 ± 16	511 ± 32	0.042
	p value†	0.021	0.992	–
MT2 (kPa)	Low	362 ± 19	500 ± 26	0.001
	Medium	402 ± 18	502 ± 28	0.021
	High	539 ± 46	494 ± 22	0.720
	p value†	0.003	0.803	–
MT3 (kPa)	Low	365 ± 20	517 ± 34	0.003
	Medium	401 ± 24	527 ± 37	0.012
	High	471 ± 19	547 ± 32	0.063
	p value†	0.010	0.462	–
MT4 (kPa)	Low	363 ± 20	564 ± 35	<0.001
	Medium	394 ± 24	568 ± 36	0.001
	High	455 ± 33	545 ± 37	0.114
	p value†	0.032	0.826	–
MT5 (kPa)	Low	324 ± 24	528 ± 29	0.004
	Medium	352 ± 17	530 ± 33	0.006
	High	492 ± 48	557 ± 31	0.376
	p value†	0.536	0.694	–

Data are presented as mean ± standard error of mean. MT1–5 = the plantar soft tissue under the first to the fifth metatarsus. * Mann-Whitney U-test for estimation of differences between the two groups; † repeated measurement test for estimation of differences within subjects.

The *UPTM* of the fourth metatarsus (r = 0.584, p = 0.018) and its *EDR* measured at the medium impact status (r = 0.578, p = 0.03) had fair correlation with the BMI. The *E* of all the metatarsals did not correlate with the BMI. Fair correlation could be seen between the *UPTM* of the second metatarsus and its *E* measured at low impact status (r = 0.527, p = 0.002). Fair correlation was also observed between the *UPTM* of the third metatarsus and its *EDR* measured at low impact status (r = 0.456, p = 0.05).

Table 2. The maximum strain of the plantar soft tissues under the metatarsal heads at different impact status in the two groups

	Impact status	Young	Older	p value*
MT1 (%)	Low	69.2 ± 2.6	41.4 ± 1.6	0.003
	Medium	64.2 ± 2.8	41.1 ± 1.6	0.003
	High	51.8 ± 2.0	41.2 ± 1.8	0.008
	p value†	0.006	0.829	–
MT2 (%)	Low	58.4 ± 3.1	47.7 ± 6.9	0.011
	Medium	52.2 ± 2.3	42.6 ± 2.4	0.021
	High	40.8 ± 3.5	42.1 ± 2.4	0.661
	p value†	< 0.001	0.287	–
MT3 (%)	Low	58.0 ± 3.0	41.7 ± 2.4	0.003
	Medium	53.0 ± 3.3	40.9 ± 2.4	0.012
	High	44.4 ± 1.6	41.4 ± 2.6	0.549
	p value†	0.001	0.308	–
MT4 (%)	Low	58.1 ± 3.0	38.0 ± 2.2	< 0.001
	Medium	53.7 ± 3.4	37.7 ± 2.0	0.001
	High	47.2 ± 3.5	37.7 ± 2.0	0.036
	p value†	< 0.001	0.803	–
MT5 (%)	Low	65.0 ± 4.5	40.0 ± 1.8	0.004
	Medium	59.2 ± 2.8	40.1 ± 2.0	0.004
	High	43.0 ± 4.6	38.8 ± 2.2	0.497
	p value†	0.114	0.593	–

Data are presented as mean ± standard error of mean. MT1–5 the plantar soft tissue under the first to the fifth metatarsus. * Mann–Whitney *U*-test for estimation of differences between groups; † repeated measurement test for estimation of differences within subject.

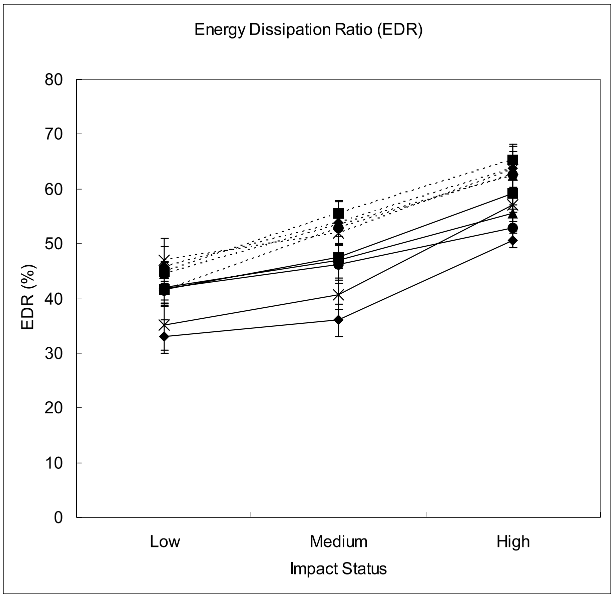

Fig. 5. *EDR* of the young and older groups at different impact status. The *EDRs* of the five metatarsals (◆ = the first metatarsus; ■ = the second metatarsus; ▲ = the third metatarsus; ● = the fourth metatarsus; × = the fifth metatarsus) in the young subjects (—) and the older subjects (· · ·) increased with increasing impact velocity. The older group had greater *EDRs* than those in the young group. Data are presented as mean ± one standard error of mean.

DISCUSSION

Cavanagh (1999) has used ultrasonography to study the deformation of the soft tissue underneath the second metatarsal head during walking in five healthy subjects with the average age of 36.6 years. The maximum strain measured at the maximum force of around 160 N was 45.7%. In-shoe peak plantar pressure at the metatarsal heads of young persons, evaluated at a walking speed of 1.66 m/s with capacitance-based pressure-measuring insoles, ranged from 185 kPa to 198 kPa (Rozema et al. 1996). In this study, the maximum strain of the second metatarsus in the young group was 58.4 ± 3.1%, 52.2 ± 2.3% and 40.8 ± 3.5% at low, medium and high impact status, respectively. The maximum tissue deformation was close to that in the previous report. The maximum stress on each metatarsus was 207 kPa in each test, which was similar to the above in-shoe peak plantar walking pressure. Thus, the experimental design in the study can simulate the physiological walking condition.

Table 3. Energy dissipation ratio of the plantar soft tissues under the metatarsal heads at different impact status in the two groups

	Impact status	Young	Older	p value*
MT1 (%)	Low	33.0 ± 3.0	51.6 ± 3.4	0.020
	Medium	36.0 ± 2.9	61.8 ± 2.5	0.003
	High	50.6 ± 1.3	70.4 ± 4.3	0.004
	p value†	0.018	0.003	–
MT2 (%)	Low	41.6 ± 3.1	48.1 ± 2.4	0.113
	Medium	47.6 ± 2.2	61.8 ± 2.7	0.001
	High	59.2 ± 3.5	70.7 ± 3.5	0.043
	p value†	0.001	< 0.001	–
MT3 (%)	Low	42.1 ± 3.0	46.6 ± 2.7	0.447
	Medium	46.9 ± 3.2	58.8 ± 1.8	0.016
	High	55.6 ± 1.5	68.6 ± 2.4	<0.001
	p value†	0.015	< 0.001	–
MT4 (%)	Low	41.8 ± 3.0	41.7 ± 3.7	0.743
	Medium	46.2 ± 3.4	57.9 ± 3.5	0.055
	High	52.8 ± 3.5	71.4 ± 2.0	< 0.001
	p value†	0.022	< 0.001	–
MT5 (%)	Low	35.1 ± 4.6	52.9 ± 3.6	0.016
	Medium	40.6 ± 2.7	57.7 ± 3.6	0.048
	High	57.0 ± 4.7	67.9 ± 3.8	0.194
	p value†	0.491	0.014	–

Data are presented as mean ± standard error of mean. MT1–5 = the plantar soft tissue under the first to the fifth metatarsus. * Mann–Whitney *U*-test for estimation of differences between groups; † repeated measurement test for estimation of differences within subject.

In agreement with the previous reports concerning the *UPTM* in the young persons (Wang et al. 1999) and the effects of aging on the heel-pad stiffness (Hsu et al. 1998), the *UPTM* decreased progressively from the first to the fifth metatarsus in both groups and the plantar soft tissues in the older persons stiffened. Although the *UPTM* and the BMI were not significantly different between the two groups, yet there is a trend for a thicker *UPTM* and a greater BMI in the older subjects. An increase of body fat distribution in the plantar soft tissues may cause the increase of the *UPTM* in the older persons. The increased fatty content in the sole of the foot may lead to increased pressure in the sealed fibrous compartment and, finally, result in the harder plantar soft tissues in the older persons (Prichasuk et al. 1994).

A simple linear elasticity model (Fung 1993) describes the elastic modulus of a material as:

$$\sigma(t) = E\varepsilon(t) \tag{3}$$

Both the stress, $\sigma(t)$, and strain, $\epsilon(t)$, are functions of time. Typically, as the stress rate increases, the strain for the soft tissue decreases. This results in an increase of the elastic modulus E with the increase of the stress rate. It has been reported that the elastic modulus in the metatarsus of healthy persons about 22-years-old measured with an US indentation system ranged from 40 to 50 kPa at a loading rate of 0.1 to 0.2 cm/s (Zheng et al. 2000). In that study, the stiffness increased significantly from about 300 kPa to 500 kPa in the young adults as the loading rate increased from 1 cm/s to 3 cm/s. It is obvious that the young metatarsus stiffens as the loading rate increases, indicating its rate-dependency.

Klaesner et al. (2002) measured the tissue stiffness of the metatarsus in healthy persons about 56 years old and the elastic modulus ranged from 81 to 228 kPa. Their force/time slopes ranged from 20 to 30 N/s, using a device that consisted of a load cell mounted on a cylindrical stylus. In the present study, the plantar soft tissue stiffness measured at higher force/time slopes (range: 111 N/s to 817 N/s) ranged from 500 to 568 kPa, which was greater than those in the above report. It is noted that the E increased as the force/time slope increased from 20 N/s to 111 N/s. Nevertheless, the plantar soft tissue stiffness did not increase with further increase in force/time slope in the older persons.

Findings concerning the dissipated energy in the human heel pad, measured from 0.06 cm/s to 1.0 m/s, ranged from 23.7% to 95% (Bennett and Ker 1990; Hsu et al. 1998; Kinoshita et al. 1996). Wang et al. (1999) had measured the *EDR* of the metatarsus in healthy subjects about 30 years old at the loading rate of 0.06 cm/s and the value was about 30%. The *EDR* in plantar soft tissues under the metatarsal heads also increased as the impact velocity increased in all our subjects, indicating its rate-dependent characteristics. The plantar soft tissue deforms less in high-impact velocity, resulting in a steeper loading curve, and finally leads to the increased *EDR* in higher-impact velocity. Unlike the elastic modulus, simply determined from the beginning and the end-loaded condition, the *EDR* records the loading-unloading process and can reflect the nonlinear tissue properties. This advantage may describe effects of aging on the metatarsus more clearly than the tissue stiffness.

Under the same impact status, all the metatarsals in the older group had greater *EDRs* than those in the younger group. This observation was similar to that in the senescent heel pad (Hsu et al. 1998). The aging metatarsus becomes stiffened at each instantaneous point during the loading process. Slow tissue recovery may also occur during the unloading process of the aging metatarsus. The increase of *EDR* in the older persons may be caused by a steeper loading curve and a poor rebound unloading curve. It has been reported that a decrease of the water component plays a role in senescent foot tissue properties (Kuhns 1949). A gradual change of collagen and a decrease in the elastic fibers may also contribute to the aging of tissues (Haut and Haut 1997).

The E and *EDR* in most of the metatarsals did not correlate with the BMI in the study. The findings were similar to those in the study for the measurement of the heel-pad mechanical properties in elderly subjects and diabetic patients (Hsu et al. 2000) but were contrary to those in the study for plantar soft tissues properties in young persons (Wang et al. 1999). More investigation for the plantar soft tissue mechanical properties may be necessary to reach a conclusion about the relationship between the plantar soft tissue biomechanics and the BMI. The *E* and *EDR* had been normalized with the initial thickness and, therefore, no correlation between them and the *UPTM* could be expected.

In this study, we used the averaged pressure, calculated from the total force divided by the contact area of the US transducer, to analyze the stress-strain relationship of the metatarsus. The pressure distribution may be different from site to site and may be changed during the compression process, because of the underlying bones. The calculated *E* may be affected by the boundary conditions and further study is warranted.

The present study demonstrates that individuals in different age groups may have different plantar soft tissue responses to varied impact velocities. The tissue properties are also different between the different age groups. Effects of aging on plantar soft tissues under metatarsal heads are stiffened soft tissue, loss of tissue response to different impact velocities and high dissipated energy. These changes may impair the tissue reaction to a sudden or repetitive stress and eventually lead to the development of metatarsalgia in the aging people. Therefore, adequate footwear is suggested for aging persons. Because US is widely available, the facility in this study can be easily built to measure the plantar soft tissue properties. This noninvasive technique can be an adjunct in examining the forefoot biomechanics and bridge the gap between podiatric science and the proper design of foot orthotics. A prospective study for evaluating the relationship between the altered tissue properties and the development of forefoot problems can be done in the future, after measurement of the healthy forefoot mechanical properties.

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