ANISOTROPIC COMPRESSIVE AND SHEAR PROPERTIES OF HEEL PADS IN WALKING AND RUNNING HUMANS

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INTRODUCTION

Heel pads are believed to bear weight, to cushion impact, to stabilize feet, and to return elastic energy. However, to perform these multiple roles, the pad has to be compliant and stiff, damped and resilient. These conflicting demands present a paradox for heel pad design. To date, only compressive properties of the stabilized heel pads have been examined (in vivo pendulum tests: Kinoshita et al., 1993; Cavanagh et al., 1984; in vitro tests: Bennett and Ker, 1990; Aerts et al., 1995). It is unclear how the pads behave mechanically in barefoot walking and running humans. In this study, I used synchronous kinetic and kinematic data to characterize the mechanical behavior of heel pads in moving subjects. I hypothesized that: (1) Heel pads are subject to **both** compressive and shear loading during impact, and the resultant pad stiffness depends on the shear component. (2) Heel pads show **anisotropic** properties to achieve multiple mechanical roles in locomotion.

METHODS

During walking and running, a significant impact is generated because the momentum of the foot changes after heel strike. It is well accepted that the characteristics of this impact are solely determined by the foot inertia and the mechanical properties of the heel pad (Whittle, 2000). In this study, I treated impact as a natural and non-invasive perturbation event during which I can examine the mechanical response of heel pads in moving humans.

Heel pads of three healthy adults were examined in the Vertebrate Movement Lab of Duke University. Each subject walked or ran at various speeds on the trackway, within which a force plate (9281C, Kistler) was mounted to record the ground reaction forces at 3000Hz in three orthogonal directions. The foot was filmed at 1000 frames/sec using a high-speed video camera. Kinetic and kinematic data were collected simultaneously using a motion measurement system Motus 2000 (Peak Performance Technologies, Inc). Displacement of a skin-mounted marker overlying the heel bone was digitized using Motus, and was used to describe the deformation of the pad. When the pad deforms, the impact energy [E_I] put into the pad is either stored as strain energy [E_S] or dissipated as heat [E_D]. E_D can be calculated mathematically as $E_D = E_I - E_S$, and normalized as percentage of impact energy [$E_{D\%}$]. E_S is calculated as the area under the load-deformation curve. E_I, which is also the kinetic energy of the foot prior to impact, can be calculated as $E_I = 1/2\, m_{eff} v_0^2$, where m_{eff} is effective foot mass and v_0 is impact velocity. When the mass decelerates, the change of momentum imparts an impulse to the ground. So m_{eff} can be estimated from the impulse-momentum equation, $\int_0^t F dt = m_{eff}(v_0 - v_t)$. Forces and displacement of vertical and horizontal directions were treated separately as compressive and shear.

RESULTS AND DISCUSSION

Among 41 steps analyzed, v_0 ranged 0.7-1.8 m/s, m_{eff} ranged 4-6 Kg (cf. 3.6 Kg estimated by Ker *et al.*, 1989), and impact energy ranged 0.2-3.2 J. Load-deformation curves of the pad under impact loading were J-shaped, i.e. pad stiffness increased with deformation.

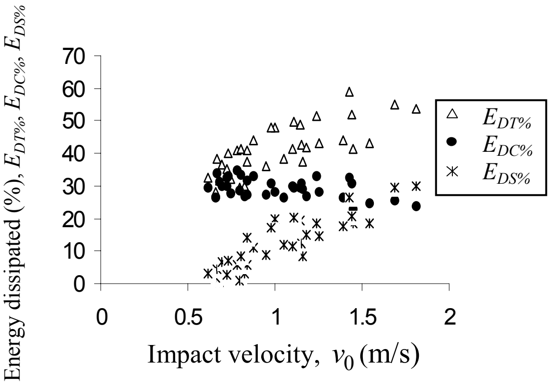

***Figure1:** Relationship between energy dissipation in compression [$E_{DC\%}$], shear [$E_{DS\%}$], and total [$E_{DT\%}$] versus impact velocity [v_0].*

<u>Energy dissipation.</u> The relationship between energy dissipated ($E_{DC\%}$, $E_{DS\%}$, $E_{DT\%}$) and impact velocity [v_0] is shown in Fig.1. $E_{DC\%}$ slightly decreases with v_0, which is consistent with previous studies (Ker, 1996); while $E_{DS\%}$ increases with v_0. The net effect is an increase of total energy dissipated [$E_{DT\%}$] with v_0. The mechanical consequences of this anisotropy are that when humans run faster, the pad becomes more resilient in compression to help lift the foot (Ker, 1996), but more damped in shear to cushion braking and prevent the foot from rebounding backward.

<u>Stiffness.</u> Resultant stiffness of the pad, normalized as a fraction of its compressive stiffness, is plotted against the impact angle as shown in *Fig.* 2. The results suggest that when the pad is subject to more shear, the pad as a whole becomes more compliant. The data for initial shear stiffness also exhibit anisotropy. The shear stiffness is greater when shear is rearward (35.59 $N/°$) as compared to forward (6.68 $N/°$). Mechanical consequences of this anisotropy are that the pad is more compliant to cushion braking in the forward direction. Greater stiffness of the pad in a rearward direction conversely restricts foot motion at heel strike and potentially stabilizes the foot.

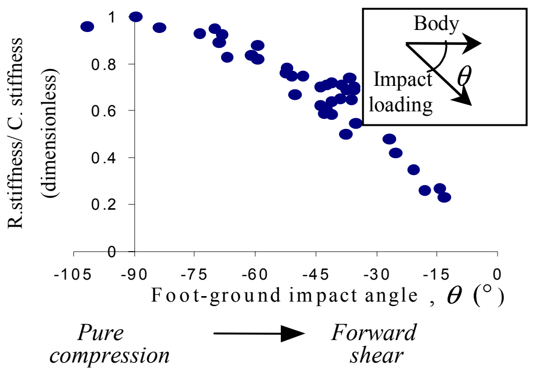

***Figure 2:** Resultant stiffness-compressive stiffness ratio versus foot-ground impact angle θ (°). When $\theta = 90$, the loading is in pure compression; $\theta < 90$: forward shear; $\theta > 90$, rearward shear.*

SUMMARY

Mechanical properties of heel pads were examined in walking and running humans. The results suggest that at each step the heel pads are subject to both compression and shear. When the shear force is greater, the pad as a whole becomes more compliant. The results also suggest that the heel pad has anisotropic properties—it is compliant and damped in forward shear, stiff in rearward shear, and resilient in compression. Such anisotropic properties allow heel pads to perform multiple mechanical functions.

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