Assessment of Sub-metatarsal Pad Elasticity in vivo in Relation to Gait

INTRODUCTION:
The primary function of the plantar soft tissue that pads underneath the metatarsal heads (i.e., sub-MTH pad) is known to distribute the highest sub-MTH ground reaction forces experienced in gait. The elastic response of the sub-MTH pad to external loading is one of the keys to understanding, as well as predicting, its behavior. In-vivo tissue deformation measurements of the sub-MTH pad have been largely performed previously, and have yielded a fundamental understanding of the mechanical characteristics of this load-bearing soft tissue. Other have made measurements based on indentations, but poor instrument alignment intrinsic to hand-held devices, small deformations atypical of gait, limited measurement reliability using trial and error procedure, and inability to account for inappropriate boundary conditions often make interpreting the data difficult. Realistic mechanical characterization of the sub-MTH pad could further be complicated by the metatarsophalangeal (MTP) joint configurations due to specialized anatomical structures. It has been shown that the initially soft and pliable sub-MTH pad becomes increasingly “tightened” during MTP joint dorsiflexion, which is believed to be an important tissue property adaption to the drastically changing sub-MTH loading conditions (i.e., combined loading of vertical and shear forces) during push-off phase of walking. The present study introduces a custom device, the sub-Metatarsal Pad Elasticity Acquisition Instrument (MPEAI), to allow a more robust, instrument-driven, in-vivo tissue response of the sub-MTH pad to be obtained.

METHODS:
Construction of the MPEAI: The sub-Metatarsal Pad Elasticity Acquisition Instrument (MPEAI) consists of a special hinged forefoot positioning apparatus integrated with a portable motorized indenter. The apparatus permits the accommodation of the local sub-MTH pad and reproduction of the MTP joint configurations generated by individuals in actual walking. The integrated indenter can directly probe the tissue’s mechanical response inducing rate-controlled deformation to the exposed soft-tissue pad in a way that similar to that experienced in gait.

Gait analysis: Subject-specific gait variables of the 2nd ray were first collected. Five healthy subjects with no congenital/acquired foot pathologies participated. Two sets of retro-reflective marker clusters, each equipped with 3 markers forming a T-shape, were attached to the base of the 2nd metatarsal bone and its articulated proximal phalanx of each equipped with 3 markers forming a T-shape, were attached to the motion system (Oxford) for calculating the MTP joint angles, while the dorsiflexed approximately up to 81.5% of its ROM in gait. Peak anteroposterior (AP) shear force occurs later when the MTP joint dorsiflexed approximately up to 55% of its ROM in gait. Following gait analysis, the subject was instructed to place the 2nd MTH’s tissue pad onto the cylindrical opening port situated in the transparent forefoot plate, with the rear foot resting above the base plate of the MPEAI in a balanced posture. This port was just large enough to accommodate the local sub-MTH pad (See Fig. 2B). Rotation of the forefoot plate along the built-in hinge joint allow control of the MTP joint, which was set to the angle determined through gait analysis and measured by a digital inclinometer. The hinge axis could be manipulated in bi-axial directions for approximation of the axis of rotation of the MTP joint. A motorized indenter was then secured perpendicular to the opening port where the sub-MTH pad had been fully exposed. The hemispherical probing tip of the indenter was 5 mm in diameter, and was driven by a linear actuator and stepper motor (MYCOM). A miniature compression load cell (Model LLB200, FUTEK) in line with the actuator recorded the magnitude of the reaction forces exerted by the local tissue at a sampling rate of 1,000 Hz. After establishment of the initial contact at the tip/tissue pad boundary, a sequence of indentation cycles was defined by the motor controller. One cycle is the complete loading and unloading, which exhibits a triangular axial-displacement wave profile with a maximum probing depth $\delta$ (avg. = 5.6 mm) and a constant loading rate $\sigma$ (avg. = 9.2 mm/s) (Inset of Fig. 2A). The selection of $\delta$ and $\sigma$ was based on a previous study that described the actual deformation characteristics of sub-MTH pad during walking using in-floor ultrasound [1]. For each subject, the soft-tissue pad underneath the 2nd MTH was individually tested with the MTP joint configuration at six different dorsiflexion angles of 0°, 10°, 20°, 30°, 40°, and 50°, a set that merely covers the actual 2nd MTP joint angles measured in walking.

RESULTS:
As is shown in Fig 2, all the tissue response curves obtained could be considered to consist mainly of loading and unloading phases, and both of which were nonlinear in nature. At alternating phases during which the local deformation peaked, considerable compression of the tissue indicated some stress relaxation over a shot-time period of around 85 msec at the initial portion of the unloading curve.

Fig. 2 Typical tissue reaction force patterns (A) obtained for a sub-metatarsal pad (B) due to localized large tissue deformation induced by a probing indenter. Tissue responded differently depending on the various MTP joint configurations in testing.

Moreover, with the current ‘gait-relevant’ loading protocol, the sub-metatarsal pad showed very distinctive tissue responses at various naturally occurring joint configurations. Notably, the end-point stiffness (= peak tissue reaction force $\delta$)detected at 30°, 40°, 50° MTP joint angles were 101.7% higher on average than those measured at 0°, 10°, 20° MTP joint angles. From the gait analysis, it is also interesting to note that the combined loading of vertical and shear forces acting at the sub-MTH pad were consistently higher when MTP joints were within the range of 30 – 50 degrees.

DISCUSSION:
With the use of the current MPEAI, we demonstrated that the sub-MTH pad elasticity is dependent on the MTP joint angle. It might be important to relate such tissue property adaptations to the dramatically changing sub-MTH loading during push-off, the fact that the sub-MTH pad should not only be capable of best distributing the highest sub-MTH loading through considerable large elastic deformation [1], but also of protecting itself from those potentially injurious excessive tissue distortion during walking [2,3].