JOURNAL OF BIOMECHANICS

Journal of Biomechanics 39 (2006) 2673–2689

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# Real-time subject-specific monitoring of internal deformations and stresses in the soft tissues of the foot: A new approach in gait analysis

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Accepted 18 August 2005

**Abstract**

No technology is presently available to provide real-time information on internal deformations and stresses in plantar soft tissues of individuals during evaluation of the gait pattern. Because internal deformations and stresses in the plantar pad are critical factors in foot injuries such as diabetic foot ulceration, this severely limits evaluation of patients. To allow such real-time subject-specific analysis, we developed a hierarchal modeling system which integrates a two-dimensional gross structural model of the foot (high-order model) with local finite element (FE) models of the plantar tissue padding the calcaneus and medial metatarsal heads (low-order models). The high-order whole-foot model provides real-time analytical evaluations of the time-dependent plantar fascia tensile forces during the stance phase. These force evaluations are transferred, together with foot–shoe local reaction forces, also measured in real time (under the calcaneus, medial metatarsals and hallux), to the low-order FE models of the plantar pad, where they serve as boundary conditions for analyses of local deformations and stresses in the plantar pad. After careful verification of our custom-made FE solver and of our foot model system with respect to previous literature and against experimental results from a synthetic foot phantom, we conducted human studies in which plantar tissue loading was evaluated in real time during treadmill gait in healthy individuals ($N = 4$). We concluded that internal deformations and stresses in the plantar pad during gait cannot be predicted from merely measuring the foot–shoe force reactions. Internal loading of the plantar pad is constituted by a complex interaction between the anatomical structure and mechanical behavior of the foot skeleton and soft tissues, the body characteristics, the gait pattern and footwear. Real-time FE monitoring of internal deformations and stresses in the plantar pad is therefore required to identify elevated deformation/stress exposures toward utilizing it in gait laboratories to protect feet that are susceptible to injury.


*Keywords:* Plantar pressure; Heel pad; Finite element model; Diabetes; Ulceration

## 1. Introduction

Traditionally, gait analysis involves kinematic and dynamic studies of whole body mechanics. Based on measurements from a force plate and motion tracking system, biomechanical models are embedded in the analysis of kinematic/dynamic data to allow evaluation of joint and muscle forces (Nigg and Herzog, 1994). However, no technology is presently available to provide real-time information on internal deformations and stresses in lower limb soft tissues of patients during evaluation of the gait pattern. Specifically, current gait analysis techniques consider the contact forces and pressures between the foot and ground, but internal deformations/stresses within the soft tissues of the foot are not addressed (Nigg and Herzog, 1994). Since internal deformations and stresses in the plantar pad are critical factors in foot injuries such as diabetic

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0021-9290/$ - see front matter 
doi:10.1016/j.jbiomech.2005.08.021

ulceration and overuse damage, this substantially limits evaluation of patients (Gefen, 2003a; Gefen and Linder-Ganz, 2004). For example, pathological stiffening of plantar tissues in the diabetic foot leads to intensified internal stresses in deep soft tissues under the second metatarsal head, which may be ~two-fold the interfacial stress at this site (Gefen, 2003a). Therefore, injuries in the diabetic foot may initiate in deep soft tissues which are presently not monitored in the evaluation of diabetic patients in the gait laboratory, or while fitting orthoses and footwear for these patients (Gefen, 2003a; Gefen and Linder-Ganz, 2004).

Finite element (FE) modeling is a well-established method for obtaining biomechanical characteristics of the foot, including internal deformation and stress magnitudes in its skeletal, ligamenteous, muscular, fat and other soft tissue components (Gefen et al., 2000; Giddings et al., 2000; Chen et al., 2001; Gefen, 2003a; Gefen and Linder-Ganz, 2004; Cheung et al., 2005). However, because FE analysis requires substantial time and bioengineering specialization for development of models of complex musculoskeletal structures such as the human foot, its use is currently limited to basic research of the foot and gait biomechanics. Accordingly, no attempts were reported for employing FE to real-time subject-specific analysis of the foot.

The goal of this study was to develop a practical real-time method for monitoring deformations and stresses in soft tissues of the plantar foot of individual subjects during gait. Real-time feedback on the internal loading of the plantar pad, synchronized with generally accepted measurements of foot kinematics and dynamics, will eventually allow immediate orthotic interventions and footwear modifications in the clinical setting, to reduce internal stress concentrations and avoid excessive deformations in the plantar tissues.

The method proposed herein couples analytical modeling of the foot with FE analysis of the heel and metatarsal head regions in the plantar pad. This method allows visualization and quantitative analysis of time-dependent deep soft tissue deformations/stresses during the stance phase of gait in individuals, as related to the individual's measured contact pressure pattern and foot kinematics. The monitored deformations/stresses provide important new information on the foot mechanics, which is potentially helpful for diagnosis and prognosis of patients, and may allow better fitting of orthoses or footwear based not only on foot–shoe contact pressures, but also on internal plantar tissue mechanics. For example, this method may be useful in providing additional information when evaluating the risk for diabetic foot ulceration and in prescribing footwear or orthoses to minimize deformations and stresses in the vulnerable deep soft tissues of the plantar pad (Gefen, 2003a; Gefen and Linder-Ganz, 2004).

## 2. Methods

### 2.1. Rationale

Biomechanical analysis of the foot was so far carried out using either analytical modeling or numerical (commonly FE) modeling. In analytical modeling, structural analysis is employed, so that bones are modeled as rigid rods, and connective soft tissues such as ligaments are modeled as elastic springs or viscoelastic spring–damper systems (Paul, 1966; Kim and Voloshin, 1995; Gefen, 2003b; Erdemir and Piazza, 2004). Structural analysis allows solving complex rod/spring/damper structures where the degree of reality of representation of the foot depends on the number of degrees of freedom in joints, representation of tendon-muscular loading system, number of ligaments included in the model, two-dimensional (2D) or three-dimensional (3D) construction, and consideration of dynamic (inertial) effects (Paul, 1966; Kim and Voloshin, 1995; Gefen, 2003b; Erdemir and Piazza, 2004). Structural models typically allow fast computation time, and can be parametric in dimensions and viscoelastic mechanical properties of tissues, so that individual subject feet and gait can be robustly analyzed. Although the general mechanical characteristics of the foot, such as forces transferred through the hindfoot or forefoot or extent of foot sagging, can be predicted from analytical structural modeling (Kim and Voloshin, 1995), local tissue deformations and stresses cannot be obtained due to the geometrical simplicity. On the other hand, numerical FE modeling allows accurate 3D reconstruction of the real foot anatomy including most hard/soft tissue components, and subsequent predictions of the distributions of internal tissue deformations and stresses (Gefen et al., 2000; Giddings et al., 2000; Chen et al., 2001; Gefen, 2003a; Gefen and Linder-Ganz, 2004; Cheung et al., 2005). Constraining and loading such a realistic FE foot model is more representative of foot–shoe or foot–ground contact in real-life stance phase events, as tissue motion or loading can be defined individually for every musculoskeletal component in the model (e.g. regions of the plantar pad, certain bones, etc.) (Gefen et al., 2000). The major drawback of FE modeling when employed for subject-specific analysis is the substantial time and bioengineering specialization that are needed to tailor the FE model to the individual anatomy and tissue mechanical properties. Apparently, this factor so far limited FE foot models to be employed for basic research (Gefen et al., 2000; Giddings et al., 2000; Chen et al., 2001; Gefen, 2003a; Gefen and Linder-Ganz, 2004; Cheung et al., 2005) rather than for subject evaluation.

Merging the analytical and numerical approaches in a single foot model offers several advantages. Specifically, it allows one to focus on regions of interest in the foot, e.g. the plantar pad regions susceptible to diabetic ulceration, and obtain detailed deformation/stress