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Short communication

Simultaneous shear and pressure sensor array for assessing pressure and shear at foot/ground interface

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Abstract

Foot ulceration is a diabetic complication estimated to result in over $1 billion worth of medical expenses per year in the United States alone. This multifaceted problem involves the response of plantar soft tissue to both external forces applied to the epidermis and internal changes such as vascular supply and neuropathy. Increasing evidence indicates that a combination of elevated external forces (pressure and shear) and altered tissue properties is key to the etiology of foot ulcers. The overall goal of this research is to develop a platform-type hardware system that will allow a clinician to measure three-dimensional stress tensors (i.e. pressure and shear patterns) on the plantar surface and identify areas of concern. Experimental results have demonstrated that an optical approach can provide clear indication of both shear and pressure from 50 to 400 kPa with a frequency response of 100 Hz, a stress measurement accuracy of 100 Pa and a spatial resolution of 8.0 mm. Initial evaluation of the system shows strong correlation between (i) applied shear and normal stress loads and (ii) the optical phase retardance computed for each stress axis of the polymer-based stress-sensing elements. These special sensing elements are designed to minimize the need for repeated calibration procedures—an issue that has plagued other attempts to develop multisensor shear and pressure systems.

Keywords: Shear; Pressure; Gait; Sensors; Optical

1. Introduction

In the etiology of foot ulcers in diabetic patients, factors such as peripheral neuropathy, dry skin and/or vascular problems are often major contributing causes for skin ulceration (Boulton, 1990). However, current opinion is divided as to the principal biomechanical causes of ulcer formation; repetitive loads, shear and pressure all are cited as potentially detrimental. In several studies (Ctercteko et al., 1981; Sims et al., 1988; Stokes et al., 1975), the investigators concluded that elevated plantar pressures constituted a major biomechanical factor in the etiology of skin ulceration. Pollard and Le Quesne, (1983), however, showed that diabetic neuropathic ulceration occurred at sites of maximal shear under the foot. Unfortunately, the studies that have focused on the nature of shear forces under the feet (Pollard et al., 1983; Tappin and Robertson, 1991) were limited by instrumentation capable only of unidirectional shear measurement (e.g., medio-lateral). This limitation inevitably results in an underestimation of maximum shear stress, since this quantity is a vector addition of medio-lateral and anterior–posterior components.

Historically, shear measurement capability has lagged behind the development of pressure platforms. Biomechanical skin stresses are certainly dictated by both pressure and shear. The probability of skin site breakdown may depend not only on pressure and shear at that site, but on the nature of skin stresses at adjacent sites. Stress couples that cause skin torsion may

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contribute to ulcer risk in a manner different to stresses (Perry et al., 2002) that act toward each other ("bunching") or away from each other ("stretching"). New hardware quantifying shear and pressure either already exists at major research institutions (Akhlaghi and Pepper, 1996; Lord et al., 1992; Razian and Pepper, 2003; Tappin and Robertson, 1991) or occupies research and development efforts in companies that market pressure platforms. What our new system offers is a true measurement of the three-dimensional (3D) stress tensor at every area of contact with the sole of the foot. Because of its optical basis, this system also offers better noise immunity than electro-mechanical systems, and has the ability for auto-calibration by simply activating the instrument, collecting the zero-load data and measuring the optical phase retardance. The stress–optic linkage response accounts for calibration over the entire stress range of the instrument, which is nearly an order of magnitude greater than the highest anticipated gait load.

It is likely that clinics treating patients with bedsores will also benefit from systems that can provide both pressure and shear data. Dinsdale (1974) showed that a pressure as low as 45 mmHg, combined with shear, could cause a decubitus ulcer. In the absence of shear, the required level of pressure was 290 mmHg. With approximately 1 million patients per year experiencing pressure ulcers according to the National Decubitus Foundation, there is a substantial need to evaluate the interface between skin and support surfaces more effectively. This need also extends to those at risk for skin breakdown when wearing a prosthetic limb and in patients with known peripheral vascular disease (Czerniecki et al., 1990).

2. Materials and methods

2.1. Optical testing system

Several single-sensor systems were developed for testing purposes. Furthermore, a 16-element sensor array complete with a modulated laser input section, polarization-maintaining fiber-optic coupling, 32 photodetectors, 32 transimpedance amplifiers, sequential data acquisition system and offset homodyning signal analysis was assembled and tested (Figs. 1 and 2). The optical components were mounted into an aluminum housing and coupled with a polarization-maintaining optical fiber to a modulated laser input section (Fig. 2).

Initially, the laser light is linearly polarized in a vertical state (0°). This polarization state (Azzam and Bashara, 1979) is sinusoidally modulated from 0° to 120°, at a frequency appropriate for gait response. Because of the number of sampling channels (33 channels), expected gait duration, data acquisition

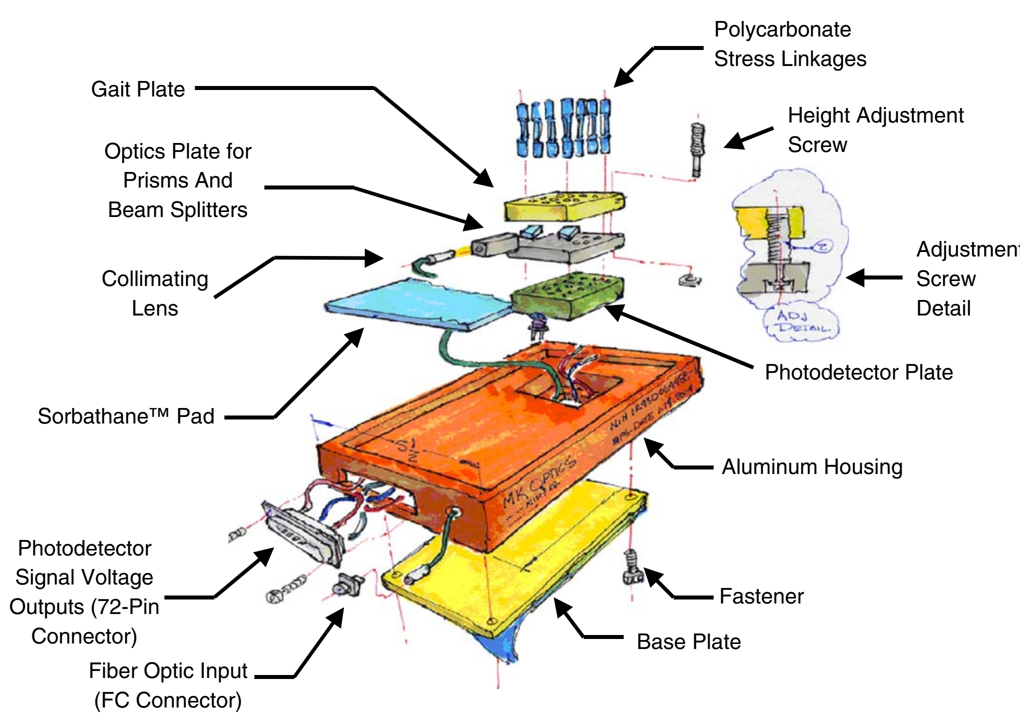

Fig. 1. Exploded view of sensor assembly. This drawing includes (i) machined, extruded polycarbonate rod stress sensor linkage (shown at the top) and (ii) 2 mm prism and 2 mm custom cube beam splitter (small squares beneath the stainless-steel gait plate with holes to allow linkage contact with sole of the foot).