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Short communication

A novel gait platform to measure isolated plantar metatarsal forces during walking

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ABSTRACT

A new gait platform described in this report allows an isolated measurement of the vertical and shear forces under an individual metatarsal head during barefoot walking. The apparatus incorporated a customized tactile force sensor and a high-speed camera system, which enabled easy identification of a single anatomical landmark at the forefoot's plantar surface that is in contact with the sensor throughout stance. After calibration, the measured peak forces under the 2nd MTH showed variability of 3.7%, 9.2%, and 8.9% in vertical, anterior–posterior, and medial–lateral directions, respectively. The device therefore provides information about the magnitude and timing of such local metatarsal forces, and has been shown to be of significant research and clinical interest. Its ability to achieve this with a high degree of accuracy ensures its potential as a valuable research tool.

1. Introduction

The ball of the forefoot supports a significant portion of the body's weight during human locomotion. The highest ground reaction force (GRF) has been estimated to be beneath the foot's plantar metatarsal sites, including five metatarsal heads (MTHs) and the underlying protective fat pads, serving as pivot points during push-off (Hicks, 1955). These localized loadings produce high pressures on MTHs, which could cause problems to a pathological foot. Excessive pressure (i.e., arising from vertical force) and shear stresses (i.e., arising from shear force) at MTHs have been shown to be associated with metatarsalgia in rheumatoid arthritis (Roy, 1988), and have been implicated in the development of ulcers in the insensate foot (Cavanagh et al., 1993) and other forefoot structure abnormalities (Sanders et al., 1992). It is therefore important to be able to accurately determine the localized forces acting on MTHs, in order to prevent tissue damage in the pathological foot.

There is still a lack of suitable systems capable of measuring the three-dimensional forces acting on localized anatomical sites such as the plantar MTHs. Force sensor technology is still far from miniaturization to the point where it can accurately relate force distribution data to specific anatomical sites (e.g., the 2nd MTH). Davis et al. (1998) presented a method whereby strain-gauged force sensors were arranged in an array to measure the plantar force distribution. Recently, Mackey and Davis (2006) developed a similar optical based force sensor array. Gross plantar force patterns obtained, however, can only be "mapped" onto a portion of the foot (Yavuz et al., 2009). Subtle variations within individual MTH often cannot be distinguished. Today, many researchers have theoretically estimated the local GRF acting at foot areas of concern based on the local plantar pressure distribution and the global GRF (Abuzzahab Jr. et al., 1997; Uccioli et al., 2001; Giacomozzi et al., 2008). However, its accuracy can be significantly compromised due to the fact that the vertical and the shear force components may not have a simple linear relationship at the foot–ground interface (Yavuz et al., 2007).

This study describes the construction of a gait platform-type apparatus, and a pilot study to obtain the vertical, anterior–posterior (AP), and medial–lateral (ML) GRF components acting at the 2nd MTH during walking.

2. A new gait platform system

A mini tactile force sensor capable of detecting the forces at three orthogonal directions at the foot–ground interface was developed. The sensor was incorporated into a gait platform,

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which enabled direct visual observation of the forefoot's plantar surface using a high speed camera. This set-up ensured easy identification of a single anatomical landmark (e.g., 2nd MTH) at the forefoot's plantar surface in contact with the force sensor.

2.1. *Force sensor design*

The force sensor was designed by utilizing the shear-web principle and strain-gauge based techniques (Fig. 1). It was fabricated using a single piece of aluminum bar (2024-T351), with a flat top sensing surface that measured a square contact area of 1.9 × 1.9 cm^2. During operation, the load applied at the sensing surface produced a nearly uniform strain field at each shear web structure located at the sensor body, onto which a set of miniature 90° Tee strain gauge rosettes (Vishay J2A-13-S254R-350) were bonded. The sensor was instrumented with a total of five sets of gauge rosettes, positioned accordingly to capture the three orthogonal forces independently. The first set (A1/A2) sensed the vertical force component. The subsequent second and third sets (B1/B2, C1/C2) measured the AP force component, and finally the fourth and fifth sets (D1/D2, E1/E2) measured the ML force component. This arrangement provided three sensor channels measuring the normal force, the AP and ML shear forces at the foot's plantar surface (Fig. 1B). Signals from each strain gauge set were fed into a Wheatstone-bridge circuit with temperature compensation. Signal conditioning included five precision instrumentation amplifiers (Tokyo Sokki Kenkyujo CO., Ltd.) for differential signal processing. Sensor outputs were collected at a sampling rate of 100 Hz and stored in a portable scope recorder (Yokogawa SL1400).

2.2. *Sensor calibration*

Each of the three sensor channels was independently calibrated using an Instron machine (Model 5848). A loading and unloading cycle of 4 Hz and up to 200, 50, and 50 N were applied along the vertical, AP, and ML axes, respectively. Cross-talk effects within the sensor were checked by sequentially loading the specific channels and recording the outputs from the other channels.

Fig. 2 shows the individual loading and unloading plots for vertical (Channel A), AP (Channel BC), and ML (Channel DE) force components. A simple linear regression equation was sufficient to determine the respective calibration factors for each channel. The correlation coefficients (R^2 value) were greater than 0.999 for all channels. Cross-talk effects were found to be less than 0.6% in all cases.

In order to determine whether the sensor has adequate frequency response to transient force fluctuations during gait, the sensor was driven with a mechanical sinusoidal wave vibrator (Beta Corp.). The amplitude response of the sensor was found to be constant within 2% up to 50 Hz of sinusoidal vibration.

2.3. *Construction of the new gait platform*

The sensor was mounted flush onto a transparent acrylic (polymethyl methacrylate) gait plate, which could accommodate the foot of the human subject (Fig. 3). Beneath the gait plate, a reflective mirror was positioned at 45° to the vertical direction, permitting direct visualization of the plantar aspect of the forefoot using a Photron Fastcam Super 10 K (Tokyo) high-speed camera, placed at right angle to the platform. The mirror has a laser cut rectangular opening to accommodate the sensor body. As shown in Fig. 3B, the image captured clearly indicates the sensor location in relation to a particular anatomical landmark (e.g., the 2nd MTH). The high-speed camera was set to record images at 100 frames per second (fps) with a resolution of 512 × 480 pixels, providing real-time images of the forefoot plantar surface during walking. The assembled platform (load cell and gait platform) was embedded in a straight, 7-m long, 1-m wide walkway. The entire surface of the walkway was covered with a slip-resistance material. Visual checks ensured that the gait platform and walkway did not alter the normal gait during subject walking.

3. Pilot study using the gait platform

A 26-year-old male subject, height of 169 cm and body weight of 65.1 kg, with no foot pathology volunteered for the pilot trial using the gait platform. Informed consent was obtained according to the procedures of the National University of Singapore Institutional Review Board.

Prior to data collection, the location of the subject's 2nd MTH was identified with a black ink dot after palpating the underlying metatarsal and its tuberosity. Nevertheless, this marked location would be blocked by the sensor itself whenever the 2nd MTH came into contact with the force sensor (see camera's view in Fig. 3B), making identification of a single MTH difficult. Furthermore, maintaining a consistent placement of the foot in relation

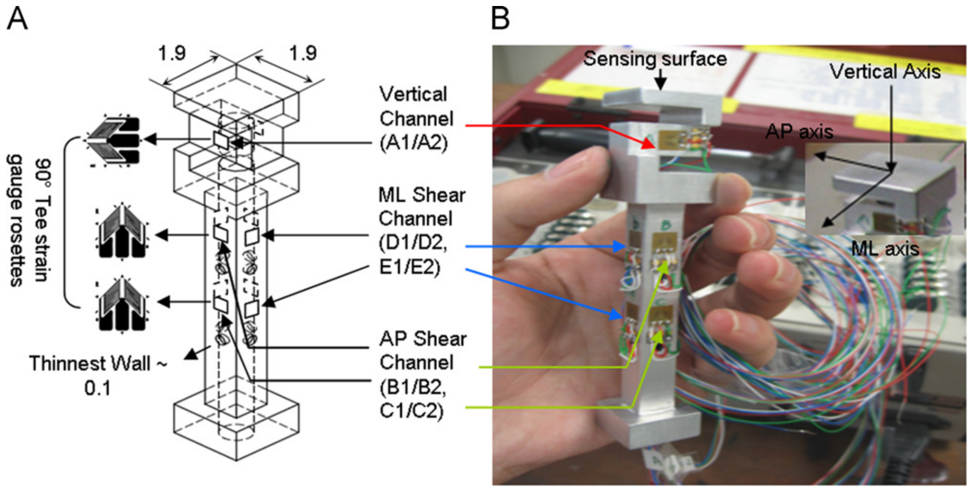

Fig. 1. (A) Schematic diagram of sensor showing the positions of the strain gauges and (B) photograph showing the attachment of strain gauges to the front surfaces of the sensor body. Gauges (not shown) are also bonded to the rear surfaces. The positions of the vertical and shear channels are also shown.