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Short communication

Expanded butterfly plots: A new method to analyze simultaneous pressure and shear on the plantar skin surface during gait☆

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ABSTRACT

The current method of visualizing pressure and shear data under a subject's foot during gait is the Pedotti, or "butterfly" diagram. This method of force platform data visualization was introduced in the 1970s to display the projection of the ground reaction force vector in the sagittal plane. The purpose of the current study was to examine individual sub-components of the vectors displayed in Pedotti diagrams, in order to better understand the relationship between one foot region and another. For this, new instrumentation was used that allows multiple Pedotti diagrams to be constructed at any instant during the gait cycle. The custom built shear-and-pressure-evaluating camera system (SPECS) allows for simultaneous recordings of pressure and both components of the horizontal force vector (medio-lateral and antero-posterior) at distinctive regions under one's foot during gait. Data analysis of such recordings affirms three conclusions: (i) pressure and shear values on individual sites on the plantar surface of the foot are not associated in a linear manner, (ii) force vectors in the heel and forefoot regions exhibit horizontal force components that oppose one another, and similarly, (iii) force vectors in the frontal plane transecting the forefoot region also exhibit medial–lateral shear components that counteract one another. This approach sheds light on individual vectors that collectively sum to each vector displayed in a Pedotti diagram. The results indicate that shearing between the foot and the ground is not simply a passive event. The structures of the arches and/or muscular activities are major contributors to the observed interfacial stresses.

1. Introduction

Pedotti diagrams have been and continue to be used for analyzing the ground reaction forces acting on a foot during normal gait (Marasović et al., 2009; Johnson and Waugh, 1979; Kambhampati, 2007). Such diagrams (Fig. 1) are created with vectors that originate at the center of pressure between the foot and the ground, initially located under the heel but then progressing anteriorly during later stages of the stance phase of gait. The magnitude of each vector indicates the direction and total combined ground reaction force; therefore, only summed ground reaction forces may be observed and not the values at a specific foot region (Marasović et al., 2009).

As a historical note, Drs. Antonio Pedotti and Aurelio Cappozzo were directly involved with creating the first "Pedotti" diagrams. The latter researcher recently stated, "In my lab, the eight signals produced by the force plate were recorded during walking in different volunteers." Pedotti and Cappozzo then had to travel to another city to gain access to what was called a "hybrid computer" which was both "digital and analogic" and most importantly, had an A/D converter. Capozzo continues, "This made the production of the vector diagrams on a fluoroscopic screen possible (black and green image). The screen was then photographed and slides were produced." (Aurelio Cappozzo,

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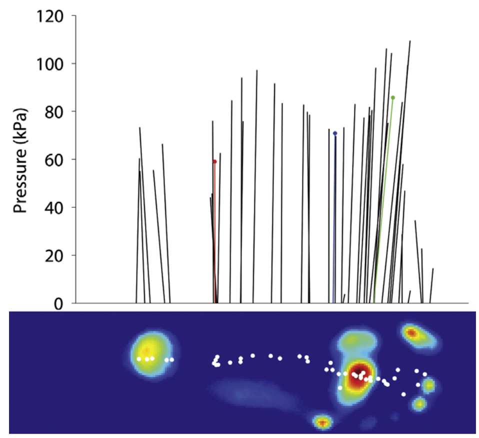

Fig. 1. A Pedotti diagram, illustrating total vertical force vectors experienced by the support surface, as resulting from shifting center of pressure during a step. The vectors in red, blue, and green indicate reaction forces occurring near heel strike, midstance, and toe-off instances, respectively. Vectors originate on the left side of the plot where heel strike occurs, and proceed towards the right, which shows vectors related to the metatarsal region. The image below the plot indicates the locations of the centers of pressure on the foot–ground interface. The image of the footprint shows the distribution of all pressure readings during the entire footstep. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

personal communication, July 24, 2013). Pedotti believes these diagrams could be very useful clinically speaking, "they constitute a synthetic and in many case [sic] clear documentation of gait dynamics with important information on global locomotion, muscle effort, deformities, asymmetries, adaptation, process, rehabilitation outcome and efficacy of devices, orthotics, or prosthetics." He also referenced other benefits including direct data, nonintrusive means of collection, easily repeatable in different conditions, and reduced costs (Antonio Pedotti, personal communication, July 18, 2013). By examining a Pedotti diagram, three general concepts are observed: (i) after heel strike, as the center of pressure moves anteriorly, both vertical and horizontal forces increase; conversely, preceding toe-off, both contact pressure (P) and shear stress (τ) appear to decrease in a linear manner, (ii) the horizontal components of Pedotti's vectors initially act posteriorly prior to mid-stance and then switch to anterior orientations; (iii) the emphasis remains on the sagittal plane. The purpose of this study was to investigate new concepts gained from observation of the Pedotti diagram in light of new instrumentation.

The plot created for this study, referred to as an Expanded Butterfly Plot (Figs. 2 and 3), uses points equally spaced (every 8 mm) along a chosen line across a given footprint. Each point has its own corresponding vector, with the vertical component as P and the horizontal component as τ.

2. Methods

Pressure and shear data were collected on volunteers during barefoot walking. Four separate recordings were taken for each subject. For the purposes of this article, we are using only the data from one subject as a means to explain Expanded Butterfly Plots. The volunteer walked for three consecutive strides across a 10-ft platform with the measuring device located directly in the center. During the second stride, the subject's foot made contact with the center of the measurement platform. The pressure and shear collection system, first described by Stucke et al. (2012), was custom built with the capability to optically measure the normal and tangential displacements of a surface stress sensitive film (S3F) (Fonov et al., 2007). The S3F film was mounted flush with the walking surface and on a 6-component force plate that can obtain ground reaction forces. Force platform measurements were used to validate and rescale the pressure and shear stress distributions, if necessary. Displacements in the S3F film were converted to P and τ distributions using a physical stress–strain model. The system described (in the paper by Stucke et al.,) is the same system that we are currently using. We have abbreviated the name of this particular device to SPECS (Shear-and-Pressure-Evaluating Camera

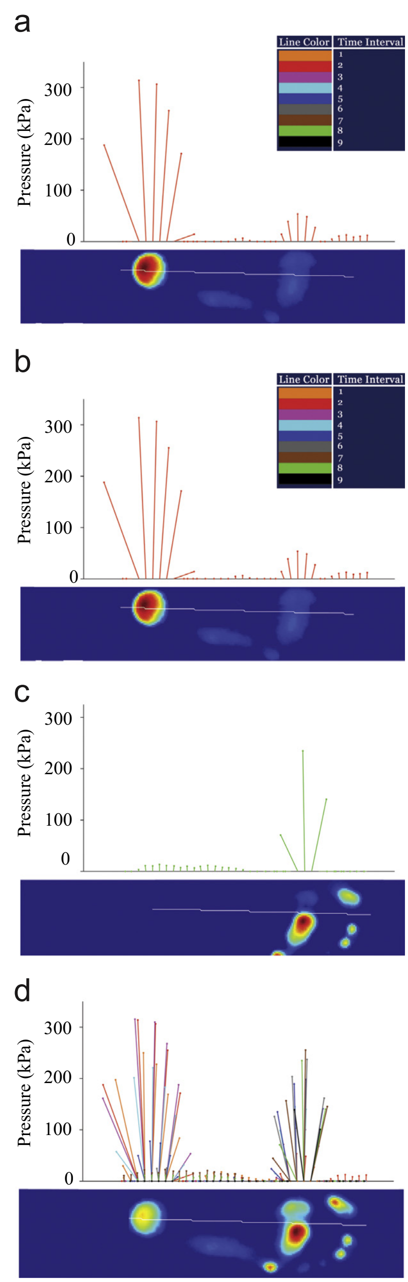

Fig. 2. Expanded Butterfly Plot of Pressure vs. Antero-Posterior shear stress (τ) along the midline of the foot, at times near: (a) heel strike; (b) midstance; (c) toe-off; and (d) cumulatively, from heel strike through toe-off. The footprint images below each plot show the vertical pressure recorded during the corresponding time interval. The midline used to make the plot is indicated in white. Each vector color is representative of a time frame corresponding to one instance in time, in increments of 10% of the total foot-platform contact time. Refer to the legend for the vector color chart. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

System). Pressure and shear stress data from the SPECS results in 187-long × 137-wide arrays. The resolution of each point in the array is 1.6 mm × 1.6 mm. SPECS collected data at 50 Hz, similar to the force platform that it is mounted on.

Research subjects were instructed to take a series of three steps, initiating with their left or right foot, contacting the SPECS platform with their next step, then stepping off. Ground reaction forces were collected at equal, consecutive time intervals every 0.02 s during the stance phase of gait, from heel strike (HS) through midstance (MS) to the completion of toe-off (TO). The output of the device consisted of three sets of data vectors: vertical pressure (P); anterior–posterior (AP) shear stress; and medial–lateral (ML) shear stress. Anterior, posterior, medial and lateral shear stresses were designated as τ_A, τ_P, τ_M and τ_L, respectively. All P and τ vectors were recorded for each assigned anatomical point on the foot that made contact with the device during gait.

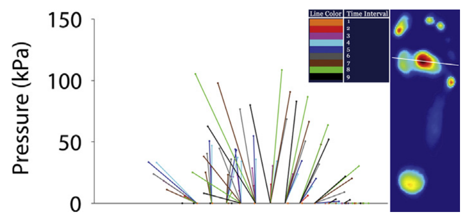

Fig. 3. Expanded Butterfly Plot of the forefoot line throughout stance phase, indicating: (a) Pressure vs. Medio-Lateral shear stress. Note that since these vectors fan outwards, they represent the situation where the transverse arch is flattening—thereby causing force vectors on the lateral side (right) to have both vertical and lateral components, and vectors on the medial side (left) to have both vertical and medial components. The legend indicates the time frame related to each vector, in increments of 10% of foot-platform contact time.

Using a custom image analysis code written for the MATLAB software platform, it was possible to detect a complete footprint and to analyze any point, line, or surface region that that was defined within it. Two representative lines were selected for analysis: the midline was drawn in a posterior–anterior direction from the mid heel to the second toe; and the forefoot line was drawn in a medial–lateral direction across the forefoot, from the first metatarsal head towards the fifth. Pressure and shear values were recorded for nine evenly spaced time frames during stance phase, each value corresponding to a specific point on the designated line. The reason for choosing the two specified lines to produce Expanded Butterfly Plots is that we believe that these two regions exhibit opposing forces indicative of a musculoskeletal arch. The presence of a longitudinal arch is widely accepted, whereas the idea of a transverse arch that passes across the metatarsals remains a hypothesis. SPECS has the capability to produce the data required for this type of analysis.

To generate an Expanded Butterfly Plot (Fig. 2), selected points of interest were first laid out along the *x*-axis. For each selected time frame and point, P and τ values were plotted to produce a combined pressure-shear vector. Vector magnitudes with respect to the *y*-axis indicate P magnitudes; simultaneously, vector displacements with respect to the *x*-axis indicate τ values. The horizontal component for each vector shown is of the same scale as the vertical component.

Given that the resolution of the final pressure and shear data arrays corresponds to one value for every 1.6 mm $\times$ 1.6 mm area on the contact surface, by choosing to measure at every fifth data point along a said line (midline, and the forefoot line), Expanded Butterfly Plots are essentially displaying P and τ vector clusters that are originating 8 mm apart (5∗1.6 mm) relative to the next point on the foot–ground surface.

3. Data analysis

SPECS has the capability to track localized frame-by-frame variations in P and τ, thus allowing us to display data in the form of Expanded Butterfly Plots. The Expanded Butterfly Plots for P and AP τ data along the midline of the foot (Fig. 2) were visually simplified to clearly indicate step data occurring at key time frames. Note that these displays reflect the stress response of the surface on which the subjects were stepping. A posterior force under the heel and an anterior force under the forefoot therefore represent a situation where the foot's longitudinal arch may be "spreading" (or flattening) during weight support. Fig. 2a displays a single data collection frame near HS, for which the vectors are plotted in red. The Expanded Butterfly Plot in Fig. 2b displays another frame, wherein vectors in blue correspond to P and τ values near MS. Green vectors indicate values near TO, as shown in Fig. 2c. The last plot in Fig. 2 shows 9 frames evenly spaced throughout the entire stance phase of the step. Each of the 9 vector colors corresponds to a specific time frame between HS and TO, ranging from 10% to 90% of the total foot-platform contact time. Three main differences were observed between an Expanded Butterfly Plot and a Pedotti diagram: (i) pressure and shear values were not always increasing or decreasing linearly, (ii) vectors of the Expanded Butterfly Plot were not always moving in the same direction, indicating forces tending to either "bunch" or "stretch" skin on the plantar surface of the foot, and (iii) values at any point or line could be evaluated, expanding on the Pedotti diagram approach that averages P and τ values throughout the entire foot.

By observing the position of certain vector colors, the progression of distinct points on the foot–ground interface could be interpreted at various instances. The left side of the plots in Fig. 2 displays vectors representing data along the midline passing though the heel and the right side vectors represent the forefoot and toe regions. For many test subjects, Expanded Butterfly Plots of the foot midline show that vectors between the heel and forefoot regions were relatively small or nonexistent; indicating that the arch of the foot made little or no contact with the ground. This contrasts the Pedotti diagrams whose vectors begin at the center of pressure of the foot, allowing vectors to be seen in the middle of the foot where ground contact may not be present.

Values along a line passing though the forefoot are shown in Fig. 3. These values are not plotted in a Pedotti diagram, as that particular diagram was not used to represent data from individual points, nor represent a medial–lateral orientation. Fig. 3 is an Expanded Butterfly Plot of P and ML τ, at evenly spaced points along the forefoot line. Observation of the plot shows vectors pointing inward towards the center of the forefoot. This pattern of τ vector directions indicates a pinching effect that can lead to bunching of the skin. In areas where similar colored vectors are pointing outward, a spreading effect is produced, causing tissue to stretch radially. These patterns are clearly present in the data from the single volunteer and step included in this article.

4. Conclusion

Ground reaction forces that are measured simultaneously and at individual points gives opportunity for evaluating P and τ data at specific locations on the plantar surface during gait. Using an Expanded Butterfly Plot helps to provide visual clarity to the SPECS data and allows for observation of bunching or stretching of the skin in specified locations, not found in current means of interpreting ground reaction forces. A clinical application of this method is to observe the ground reaction forces of patients with diabetic neuropathy. The understanding of bunching and stretching distributions and their effect on plantar soft tissue may help to predict skin breakdown and ulceration.

Conflict of interest statement

Bertec Corporation and Innovative Scientific Solutions Inc. have ownership of the intellectual property associated with measuring pressure and shear.

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