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Discrete sensors distribution for accurate plantar pressure analyses

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ABSTRACT

The aim of this study was to determine the distribution of discrete sensors under the footprint for accurate plantar pressure analyses. For this purpose, two different sensor layouts have been tested and compared, to determine which was the most accurate to monitor plantar pressure with wireless devices in research and/or clinical practice. Ten healthy volunteers participated in the study (age range: 23–58 years). The barycenter of pressures (BoP) determined from the plantar pressure system (W-inshoe®) was compared to the center of pressures (CoP) determined from a force platform (AMTI) in the medial-lateral (ML) and anterior-posterior (AP) directions. Then, the vertical ground reaction force (vGRF) obtained from both W-inshoe® and force platform was compared for both layouts for each subject. The BoP and vGRF determined from the plantar pressure system data showed good correlation (SCC) with those determined from the force platform data, notably for the second sensor organization (ML SCC= 0.95; AP SCC = 0.99; vGRF SCC = 0.91). The study demonstrates that an adjusted placement of removable sensors is key to accurate plantar pressure analyses. These results are promising for a plantar pressure recording outside clinical or laboratory settings, for long time monitoring, real time feedback or for whatever activity requiring a low-cost system.

1. Introduction

New wireless plantar pressure systems have been developed in recent years, aiming mainly at providing low-cost systems for mobile gait analysis, activity monitoring and rehabilitation [1–5]. They may be classified into two groups, according to the number and organization of the sensors throughout the insole. In the first group, the insoles are entirely wrapped in a matrix of sensors [6–10], so as to be able to analyze the pressures exerted under the whole foot, regardless of sensor placement. In the second group, the insoles are composed of few sensors usually located along specific anatomical landmarks [4,11,12]. The main issue, there, consists in defining an optimal placement so as to avoid errors incurred by the position of the sensors in conjunction with these landmarks [13]. Howell et al. [3] suggested a methodology to decide where best to place twelve sensors throughout the insole of a new low-cost plantar pressure system. For this purpose, a 32-sensor insole was created and tested to determine the locations most relevant to ground reaction force and ankle moment calculations [14]. Authors used the information obtained from the 32-sensor insole incorporated in a model shoe that was similar for all the subjects, to determine the location of the 12 sensors during a walking task. From the plantar pressures recorded, a mean location was defined for the sensors. Authors observed good results when they compared those obtained with the insole with those from the force platform. However, two important shortcomings have to be mentioned in this method: (1) Subjects must have the same feet size or the same sensors distribution may be reproduced in a scaled model for bigger or smaller feet. In that case, the scale process is never detailed but should take into account a possible allometry from one size to another as a function of age. (2) Only one configuration has been created, and so the feet shape differences between all subjects are not taken into account. Authors analyzed the ground reaction force and the ankle moment to determine the insole accuracy for uses outside of a laboratory. The center of pressures (CoP) monitoring is also equally important to study the subject's balance in order to detect any pathology [15–17], or to be used during rehabilitation to prevent fall risks [18–20], or to evaluate the effects of a surgery [21,22] outside of a laboratory. However, the CoP is computed by means of a force platform which is a heavy and expensive device, limiting the analyses to few non-consecutive stance phases. Low-cost embedded systems analyzing plantar pressures had been developed for that reason, making it possible to

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determine the barycenter of pressures (BoP) and to compute the vertical ground reaction force (vGRF) during dynamic tasks outside laboratory settings, like clinical applications in patients in podiatrist's offices for example. The CoP and BoP, as the vGRF, allow one to analyze the recovery after a lower limb surgery, the severity of the pathology creating an important lower limb asymmetry [23–26]. The interest of the low-cost portable systems using discrete sensors is to allow a plantar pressure survey over several consecutive steps in research and/or clinical practice, or even in everyday life. The aim of this study is to determine an adjusted and individualized layout of removable sensors to accurately analyze plantar pressure. For this purpose, the BoP and vGRF obtained from a plantar pressure system (W-inshoe®, MEDICAPTEURS©, France) are compared to the CoP and vGRF obtained from a force platform, which is the criterion measure. A first sensor layout was designed according to Cavanagh et al. [27], then a second one was drawn to limit the number of sensors to three located under the heel so as to take into account the calcaneus anatomy on the one hand, and on the other hand to add a sensor under the metatarsus to increase the definition under a poly-articulated area. Then, results obtained from both sensor layouts are discussed to determine which is the most accurate to analyze plantar pressure.

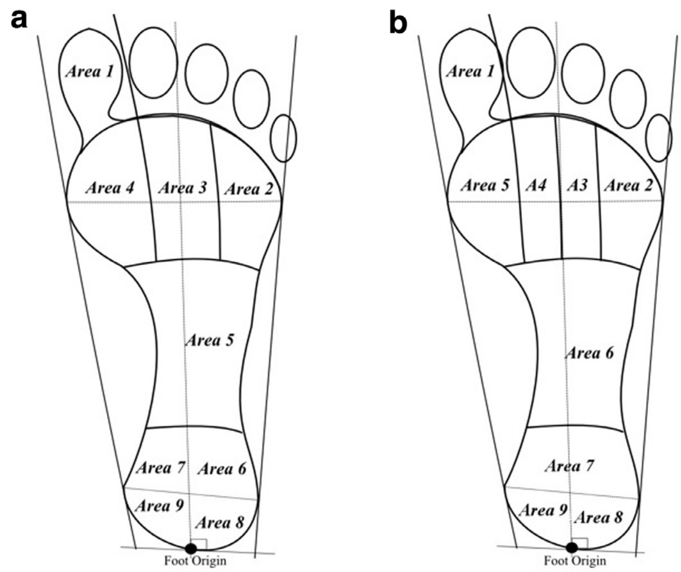

Fig. 1. Footprint areas determination. (a) The first and (b) second sensor layout.

2. Materials and methods

2.1. Materials

2.1.1. The plantar pressure system

The W-inshoe® is a wireless embedded system including 9 force sensor resistors. The sensors are 0.5 mm thick and the diameter of the active surface is 14.3 mm. The pressure and temperature ranges are 9.8–785 kPa and −40 °C to +85 °C, respectively. The 9 sensors are connected to a wireless Bluetooth transmitter attached to the subject's ankle. The transmitter's dimensions are 65 mm × 45.5 mm × 18.3 mm for a weight of 50 g. Data, sampled at a rate of 100 Hz, are transmitted to the computer and treated with the W-inshoe® software (MEDICAPTEURS©, France). The sensors are calibrated individually in the range of 0 to 600 kPa using a calibration press (MEDICAPTEURS©, France) that applies progressively increased forces to the sensor. The forces applied and the corresponding digital outputs of the sensors are recorded to determine the relationship between them. The linearity of the calibration press is verified regularly by means of a system (MARK-10, series 5 force gauges) certified by the manufacturer.

2.1.2. The force platform

One AMTI force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA), sampled at a rate of 1000 Hz, was used to calculate the center of pressure (CoP) under each foot. Three passive reflective markers were placed along each foot: (1) on the first metatarsal head; (2) on the fifth metatarsal head; (3) at the heel. A Vicon motion analysis system (Vicon, Oxford metric's, Oxford, United Kingdom) with eleven infrared cameras, sampled at a rate of 200 Hz, was used to determine the positions of the reflective markers. The measurement uncertainty of AMTI and W-inshoe® sensors is about 1% each.

2.1.3. The pressure platform

One portable pressure platform, Win-pod® (MEDICAPTEURS©, France), was used to record the subject's footprint. The Win-pod® system allows one to analyze the plantar pressures (PP) during postural or dynamic tasks. The pressure platform dimensions were 530 mm × 600 mm × 45 mm, for a weight of 6,8 kg. It included a 48 × 48 sensors matrix (i.e., 4 sensors/cm^2) and the manufacturer checked sensor homogeneity. Each sensor was 0.15 mm thick with an 8 mm × 8 mm diameter. Data, sampled at 100 Hz, was transmitted to the computer and treated with the Win-pod® software.

2.2. Subjects

Ten healthy volunteers (4 women, 6 men) ranging from 23 to 58 years ($\bar{x} = 38 \pm 12$) participated in this study. Subjects reported no medical history related to their lower limbs (for example surgery, pes cavus or pes planus). All subjects gave informed consent prior to participating in the study.

2.3. Experimental protocol

To validate the methodology used to locate the sensors of the W-inshoe® system, a three-step protocol was created. Step 1 consisted in dividing the footprint recorded by Win-pod® into 9 areas according to Cavanagh et al. [27]. Step 2 consisted in adjusting the placement of the 9 W-inshoe® sensors under each foot and for each subject. Step 3 consisted in comparing the results obtained with the W-inshoe® system and the AMTI force platform during the same walking trials to validate the method and determine the most accurate sensor placement.

2.3.1. Footprint areas determination

Each subject's footprints were recorded, using the Win-pod® pressure system, during a walking test at spontaneous speed. A program had been developed to map the subject's footprints into 9 areas according to Cavanagh et al. [27]. Two configurations to place the sensors had been created. These were: the heel (divided into 4 areas for the first sensor layout and 3 areas for the second sensor layout); the midfoot; the forefoot (divided in 3 areas for the first sensor configuration and 4 areas for the second) and the Hallux (Fig. 1a and b). They represented successively 30% (heel); 35% (midfoot); 20% (forefoot) and 15% (lesser toes) of the length of the foot.

2.3.2. Sensors location

The footprint recorded with the Win-pod®, helped determine the peak plantar pressure of each defined areas. First, the coordinates of their locations were expressed at the Win-pod® origin from the program. The coordinates of the foot origin were also expressed at the Win-pod® origin (Fig. 1a and b). Second, the