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Discrete sensors distribution for accurate plantar pressure analyses

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A B S T R A C T

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.

Keywords:

Wireless sensors
Plantar pressure
Placement
Gait
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]. Au-

thors 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.

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/cm²) and the manufacturer checked sensor homogeneity. Each sensor was 0.15 mm thick with

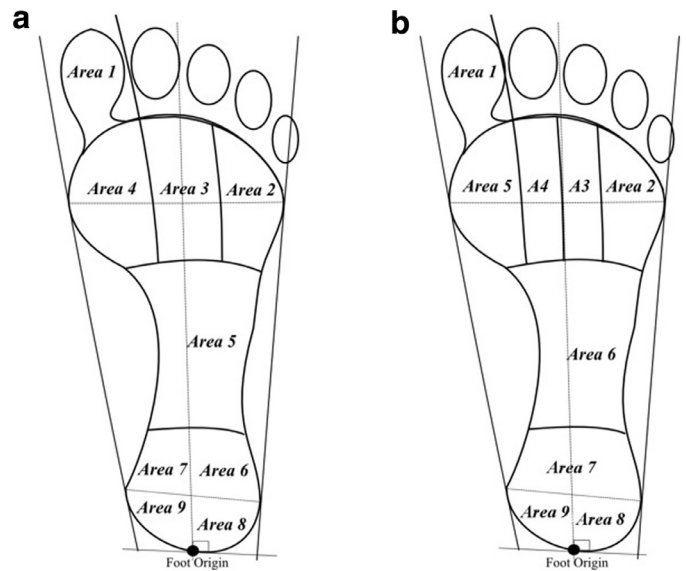


Fig. 1. Footprint areas determination. (a) The first and (b) second sensor layout.

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

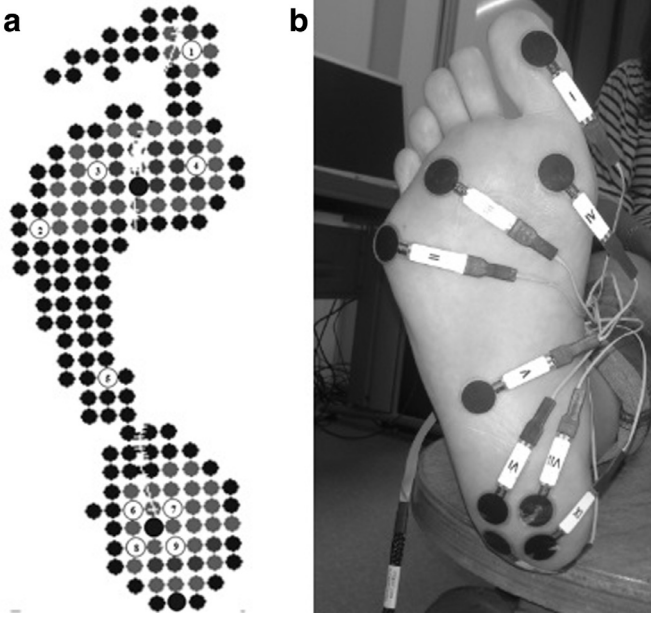


Fig. 2. Sensor layout. (a) Win-pod® footprint model printed at a 1/1 scale with the 9 peak pressure locations; (b) locations of the 9 W-inshoe® sensors taped directly under the foot.

locations of the nine sensors were then transferred to the foot origin to precisely locate each sensor under the foot during dynamic tasks.

2.3.3. Sensor layout

The peak pressure locations determined from the Win-Pod's footprint were printed at a 1/1 scale, and served as a model to locate the 9 W-inshoe® sensors on the peak pressure locations (Fig. 2a). Nine ink pads, their size fitting that of the sensors, were taped at the peak plantar pressure locations. For an easier placement of the subject's foot on the footprint with the nine ink pads, and to avoid errors of sensor locations, a system was used to fix the footprint in a reference position. The subjects were asked to put their feet one after the other on the system with the footprint model. Each ink pad left a mark under the foot so as to determine the positions of the 9 sensors. Then, the 9 W-inshoe® sensors were taped on each mark directly under the foot to avoid any constraint due to insole or shoe (Fig. 2b).

2.3.4. Validation of the W-inshoe® sensor layout

The subjects, equipped with the W-inshoe®, performed walking trials on a 10 m walkway including the AMTI force platform. After trials at self-selected speed (familiarization), a start mark was placed, enabling the subjects to strike the force platform after 4 steps. This procedure permitted a better reproducibility between trials [28]. Only trials with the foot fully positioned on the force platform were accepted for analysis. Six trials per foot were recorded. It took around thirty minutes to set up and perform patient testing: ten minutes to record and print the footprints; ten minutes to fix the sensors under the feet and ten minutes to record data.

2.4. Data collection and analysis

The force platform, the Vicon systems and the W-inshoe® were synchronized using an Arduino system. Data recorded by the force platform, the Vicon and the W-inshoe® systems were computed for comparison. Data recorded by the force platform was used to compute the coordinates of the CoP in medial-lateral (x) and

anterior-posterior (y) directions (Eqs. (1) and (2)). Data recorded by the W-inshoe® system was used to calculate the BoP in x and y directions (Eqs. (3) and (4)) when the subject's foot was in contact with the force platform.

$$X_{CoP} = -\frac{My}{vGRF} \quad (1)$$

and

$$Y_{CoP} = \frac{Mx}{vGRF} \quad (2)$$

Where (X_{CoP} , Y_{CoP}) is the instantaneous position of the CoP in the medial-lateral (x) and anterior-posterior (y) directions, (Mx , My) are the ground reaction forces momentum and $vGRF$ is the vertical ground reaction force.

$$X_{BoP} = \frac{\sum_{i=1}^n x_i \cdot vGRF_i}{vGRF} \quad (3)$$

and

$$Y_{BoP} = \frac{\sum_{i=1}^n y_i \cdot vGRF_i}{vGRF} \quad (4)$$

Where (X_{BoP} , Y_{BoP}) is the instantaneous position of the BoP; (x_i , y_i) is the position of the center of sensor i in the medial-lateral (x) and anterior-posterior (y) directions; $vGRF_i$ is the vertical ground reaction force applied to the sensor i ; and n is the number of sensors.

The positions of the three markers obtained by the Vicon motion analysis system were used to determine the positions of the foot regarding the force platform during the recordings. It enabled us to align the CoP (computed in the platform reference) and the BoP (computed in the foot reference).

The $vGRF$ profiles obtained by both systems were compared. Data of all analyzed steps were re-sampled to 100Hz by means of an interpolation procedure.

2.5. Statistical analysis

Statistical analyses were performed using the STATISTICA software (STATISTICA V12, StatSoft, Maison-Alfort, France). The Spearman's correlation coefficient (SCC) was computed to determine the correlation between the CoP and BoP curves. Two repeated-measures Anova were performed to find out the differences between CoP and BoP displacements in medial-lateral (ML) and anterior-posterior (AP) directions. To detect with accuracy any difference throughout the stance phase, ten windows were created -composed of ten frames each- to break down the signals. To quantify errors between both systems, the root mean square error (RMSE) was calculated for the whole stance phase. As for the $vGRF$ curves analysis, the mean SCC and the normalized root mean square error (NRMSE) were computed to compare our results with those obtained in previous studies. The $vGRF$ data were divided in ten windows to perform repeated-measures Anova from RMSE values to follow errors between both curves throughout the stance phase. A Bonferroni post-hoc test was done to determine if any difference appeared between the RMSE values calculated at each window ($p < 0.005$).

3. Results

3.1. CoP and BoP displacements

3.1.1. First sensor layout

The SCC and the RMSE values in the AP and ML directions between the AMTI force platform and the W-inshoe® systems are presented in Table 1, showing the results of both sensor layouts. The SCC results showed a good correlation in the ML direction, and a higher correlation in the AP direction. The repeated-measures Anova showed differences for 1% to 40% of the stance

Table 1
CoP and BoP comparison for the first and second sensor layout.

	First sensor layout		Second sensor layout	
	Medial-lateral axis (x)	Anterior-posterior axis (y)	Medial-lateral axis (x)	Anterior-posterior axis (y)
Mean SCC	0.91 ± 0.04	0.97 ± 0.02	0.95 ± 0.02	0.99 ± 0.01
Mean rmse (mm)	5.5 ± 2	15.5 ± 3	4.1 ± 1	12.5 ± 2

phase (ML = 7.5 mm ± 4.7 mm; AP = 24.7 mm ± 6.6 mm), and no difference was obtained for 41% to 100% of the stance phase (ML = 3.6 mm ± 1.7 mm; AP = 9.3 mm ± 4.8 mm) in the ML and AP directions. The RMSE results showed a 5.5 ± 2 RMSE in the ML direction and a 15.5 ± 3 RMSE in the AP direction.

3.1.2. Second sensor layout

The SCC results showed a better correlation in the ML and AP directions (Table 1). The repeated-measures Anova showed differences for 11% to 31% of the stance phase (ML = 6.3 mm ± 4 mm; AP = 14.8 mm ± 4.7 mm), no difference was obtained for 1% to 10% and 32% to 100% of the stance phase (ML = 3.5 mm ± 2 mm; AP = 11 mm ± 5.7 mm) in the ML and AP directions. The RMSE results showed a 4.1 ± 1 RMSE in the ML direction and a 12.5 ± 2 RMSE in the AP direction.

3.2. vGRF curves

3.2.1. First sensor layout

The SCC results showed a good correlation with a value higher than 0.85 (SCC = 0.90 ± 0.08). The normalized root mean square error (NRMSE) between both vGRF curves showed that the force recorded by the force platform was higher than the force recorded by the pressure sensors system. Indeed, the average NRMSE is about 50% (NRMSE = 50% ± 2%). The repeated-measures Anova done from RMSE values showed differences between the ten windows ($p < 0.0001$). To determine more precisely where these differences were located, a Bonferroni post-hoc was done. Results showed no difference for 21% to 90% of the stance phase (RMSE = 444 ± 36N).

3.2.2. Second sensor layout

The SCC results showed a better correlation between the vGRF curves obtained by both systems (SCC = 0.91 ± 0.08). This placement allows a moderate decrease of the NRMSE to 46% (NRMSE = 46% ± 1%). The repeated-measures Anova showed differences between the ten RMSE values ($p < 0.0001$) but the Bonferroni post-hoc test showed no difference between the RMSE values for 11% to 90% of the stance phase (RMSE = 390 ± 35N).

4. Discussion

The aim of this study was to adjust the layout of removable sensors spread over insoles, in order to analyze plantar pressure accurately while outside of a laboratory. For this purpose, two sensor layouts were created and compared. The BoP was compared to the CoP, which acted as standard measure. Then, the vGRF obtained from both W-inshoe® and force platform were compared.

4.1. CoP and BoP curves

The second sensor layout showed better results with a higher correlation between the CoP of the force platform and the BoP of the W-inshoe® systems (SCC = 0.95 in the ML direction and SCC = 0.99 in the AP direction) than the first (SCC = 0.91 in the ML direction and SCC = 0.97 in the AP direction). In the ML direction the correlation is lower than in the AP direction for both layouts,

with a lesser difference for the second one. This was observed in previous studies [13,29]. However it must be noted that the SCC obtained in the ML direction in the present study is higher than those obtained previously (Pearson CC greater than 0.7) [13,29], in particular for the second sensor organization.

The second sensor layout allowed a decrease in RMSE values (RMSE = 4.1 ± 1 mm in the ML direction and RMSE = 12.5 ± 1 mm in the AP direction) as compared to the first (RMSE = 5.1 ± 1 mm in the ML direction and RMSE = 15.5 ± 3 mm in the AP direction). Furthermore, it permitted to obtain RMSE values that were lower than those reported by Chesnin et al. [13] that were by 5.6 ± 3 mm in the ML and by 13.7 ± 5.9 mm in the AP directions. These first results confirm the relevance of our method, notably concerning the second sensor layout, especially if we consider that the adjusted layout of 9 sensors allows results similar to those obtained with either a 24 sensor insole [13] or even with a 99 sensor one [29], notwithstanding the fact that the insoles were put in shoes that seem to induce higher AP RMSE while in the present study the sensors were taped directly under the foot. Looking at the BoP and CoP differences over time, the repeated-measures Anova enabled to specify the analysis over the different phases of the foot contact. The second sensor layout allowed narrowing differences between BoP and CoP curves (11% to 31% of the stance phase) compared to the first (1% to 40% of the stance phase). Nevertheless, differences persisted during the heel loading in the ML and AP directions (11% to 31% of the stance phase) for the second sensor layout with a BoP vs. CoP RMSE higher than during the next phases. At that moment, the heel fat pad located under the calcaneus suffers from a deformation in the 3 dimensions. Wearing et al. [30] showed a decrease by half of the heel pad thickness in the sagittal plane during gait while the unloaded heel pad thickness is 18.9 mm and decreases to 8.6 mm as a minimum during the ground contact. Our sensors being taped under the foot, their displacements relatively to the foot origin may be due to soft tissue deformation under the heel and may explain the differences between the CoP and BoP during the first part of the stance phase.

4.2. vGRF curves

The vGRF profiles obtained by the W-inshoe® system show typical patterns, i.e. the double-peak-curve, with the first peak occurring at the weight acceptance and the second at the push-off (Fig. 3) for both sensor layouts. These observations are confirmed with a high correlation between both systems for the first (SCC = 0.90) and second (SCC = 0.91) layout. These results are higher than those reported by Chesnin et al. [13] (PCC > 0.70), and close to those reported by Crea et al. [1] (PCC = 0.88 ± 0.03). In addition, the NRMSE results obtained in the present study are lower for the second layout (NRMSE = 46%) compared to the first (NRMSE = 50%) and lower than the NRMSE reported by Crea et al. [1] (NRMSE = 80%). These NRMSE differences may be due to differences in method. Indeed, Crea et al. [1] have created insoles composed of several sensors which were then fitted in a shoe. In the present study, sensors were taped directly under the foot. The good results obtained by the second sensor layout, concerning the measure of the normal ground reaction force component, confirm that adjusting the layout of the 9 W-inshoe® sensors from the peak

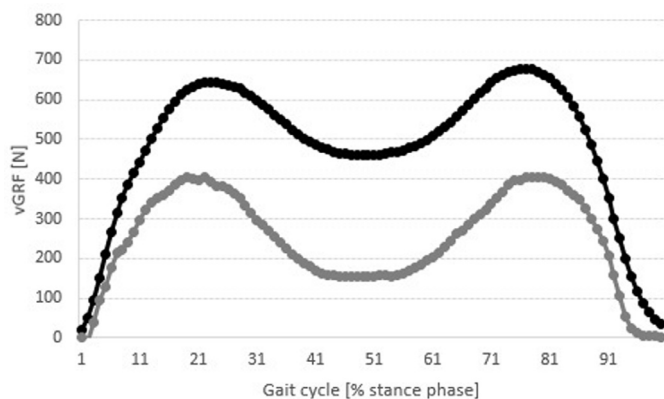


Fig. 3. Comparison between the insole vGRF profiles (grey line) and the AMTI vGRF profiles (black line) of Subject #1.

pressure leads to valuable plantar pressure measures with a low number of sensors, while the previous studies regarding the topic had used 24 to 99 sensors per insole. Moreover, the individualized distribution of the sensors under each foot enabled to avoid any difference due to anatomic asymmetry and to keep the measures under both feet accurate. It is important to adapt the layout to each foot, in order to take its shape into account. Indeed, the layout can be modified according to pathologies like lower-limb arthritis or diabetes [31–40], in order to detect foot problems before functional limitations develop or to decrease joint pain [41–45]. It can be adapted, more generally, to the feet of patients who have suffered from a lower limb surgery [46–49]. These results are promising in terms of sensor layout methodology for gait analysis outside clinical or laboratory settings, or whenever a low-cost system must be used. Besides, there is room for further improvements, to make the procedure simpler and faster. We validated this process with sensors taped under the foot. It enables to avoid the forces due to the bending of an insole and to consider that both sensor and platform surfaces are aligned during the recordings of a vertical ground reaction force. However, the shoe or insole materials at the foot-to-ground interface make the comparison between sensor and force platform signals critical, while the 3D deformations of the structure induce changes in sensor orientation and layout. One has to assume that sensor sticking is a valuable means to reduce these artifacts or to evaluate the effects of intermediate structures on local plantar pressures. The originality of this procedure is twofold: 1- this procedure may be used with more or less sensors. 2- Four to five times cheaper than other plantar pressure systems, the win-shoe also simplify the data treatment for real time feedback. It is a potential for development of other applications dedicated to clinical and daily life surveys. It may be used for long time locomotor disorders monitoring. To enlarge the investigation possibilities, we can mention that the procedure we validated for plantar pressure analysis can be adapted to measure pressure in different configurations such as grasping or seating while the sensors can be located in various supports like gloves or seats.

5. Conclusion

The aim of this study was to determine an adjusted placement for insole sensors in order to analyze plantar pressure accurately. Results show good correlation between the data of the AMTI force platform and those computed from the 9 sensors of the W-inshoe® system, notably regarding the second sensor layout, while their distribution under the foot followed the peak pressure locations identified through the Win-pod® pressure platform. This layout al-

lows results that are more similar, even better sometimes, than those from previous studies using insoles integrating many more sensors (24 to 99 sensors), compared to a low-cost system like the W-inshoe®. Taping the sensors under the foot enables the shape of both feet to be taken into account, and is an argument to better evaluate the effect of intermediate structures at the foot-to-ground interface like insole or shoe.

Conflict of interest

No conflict of interest.

Funding

None

Ethical approval

Not required

Acknowledgments

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