Application of Smart Sock System for Testing of Shoe Cushioning Properties

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Abstract

Appropriate choice of shoes with required cushioning characteristics is rather an urgent problem for people from very different groups, such as sportsmen, elderly people, people with foot disorders and locomotion problems. Present research is devoted to further development of wireless DAids™ Pressure Sock System and its application for shoe cushioning estimation. In particular, a new version of pressure sensors with improved sensitivity and working range is designed and tested. Based on above-mentioned developments, the possibility of shoe cushioning testing using DAid™ Pressure Sock System was studied. For this purpose, gait records of several test subjects who used sets of shoes with different cushioning properties, as well as bare walking, were made. Data analysis showed that the developed system gives the possibility to recognize different shoe cushioning. Several approaches to data processing to increase the sensitivity of such recognition are discussed. The comparison showed the potential ability of the developed system to test wirelessly shoe cushioning in real outdoor conditions. Such ability also provides the possibility to monitor and estimate degradation of cushioning quality of shoes under deterioration and environment.

Keywords

Textile sensors • Smart socks • Cushioning control

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1 Introduction

It is known that cushioning ability of shoes is one of the factors which have essential influence on lower feet loading level. For example, according to [1] midsole degradation of running shoes can lead to increase of heel impact loading forces up to 20–30%. These data were obtained by using force platforms. Data obtained with smart insoles [2] showed an increment of loading impact forces due to midsole degradation up to 100%. So, appropriate choice of shoes midsoles and periodic monitoring of their cushioning characteristics can be rather an urgent problem for people from very different groups, such as sportsmen, elderly people, people with foot and locomotion disorders.

Existing devices which can provide shoe cushioning estimation are quite complicated and expensive and most of them are only for indoor application and cannot be used for outdoor shoe tests. Moreover, as clear from results [1, 2], force platforms can give strongly underestimated data comparatively with in-shoe pressure monitoring.

Reported in [3, 4] DAid™ Pressure Sock System is in-shoe low cost device developed for outdoor monitoring of human gate and running. Comprehensive tests of this system showed its applicable accuracy for monitoring of temporal parameters of locomotion. Present paper is devoted to analysis of the possibility to use DAid™ Pressure Sock System for shoe cushioning ability estimation. Different types of sensor designs are developed and compared to improve system sensitivity and accuracy for plantar pressure measurement. Two data analysis methods of shoe cushioning estimation are proposed and compared as well.

2 Pressure Sensors Tests

2.1 Materials and Methods

Three types of pressure sensors ("filled", "ribbed" and "curved line", referred further as type A, B and C, correspondently) (Fig. 1) were designed and produced using

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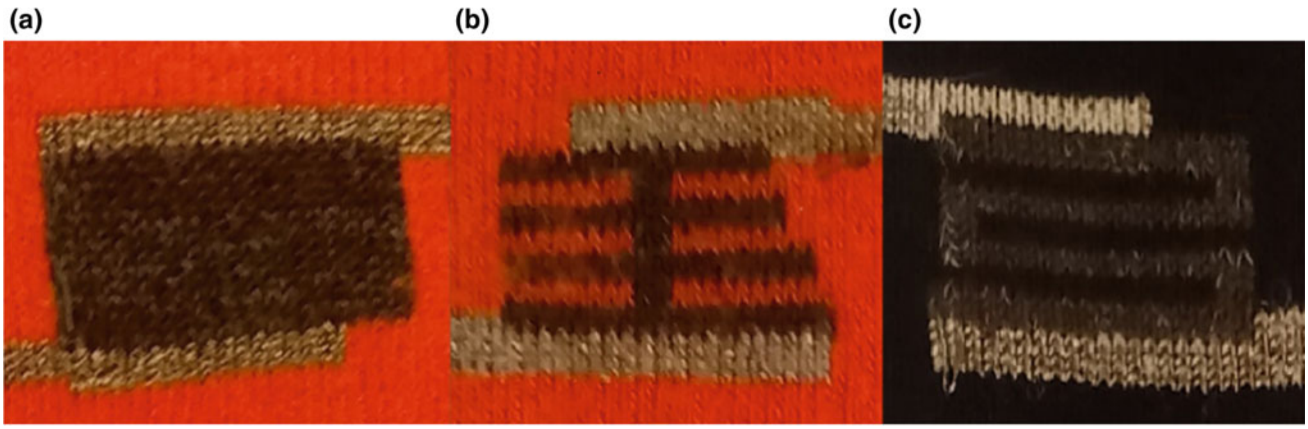
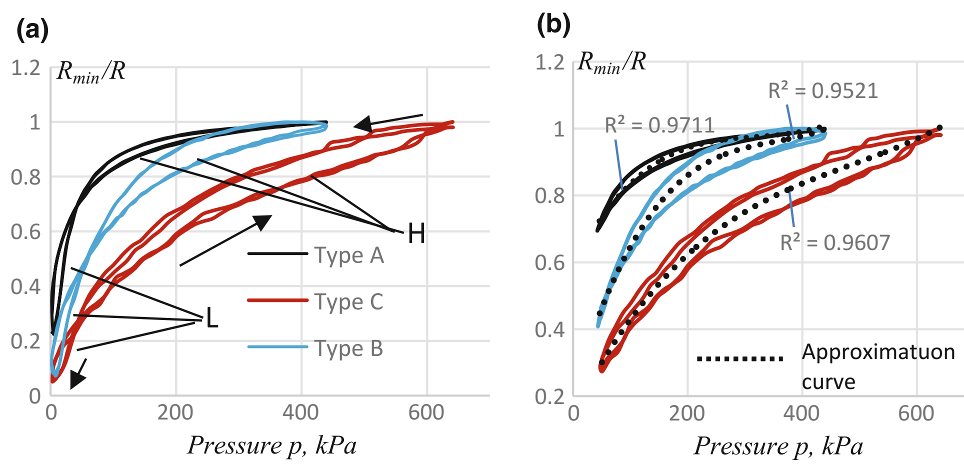


Fig. 1 Knitted pressure sensors

Fig. 2 Dependences $R_{\min}/R(p)$



commercially available knitting machines. Five sensors of each type were tested by using complex of Zwick/Roell Z2.5 and Agelent 34970A devices. This complex has provided circling loading of sensors and simultaneous monitoring of their electrical resistance. Loading range was from 2 to 50 N; loading rate—25 N/s. Each test consisted of five loading-unloading cycles.

Effective squares of pressure platforms were 1.142 m^2 for A and B types and 0.782 m^2 for C sensor type. Thus, provided loading pressure was up to 440 kPa for A and B types and up to 640 kPa for C type. As the result, dependences of electrical resistance R from applied pressure p were obtained.

2.2 Test Results and Analysis

Obtained characteristics $R(p)$ had the same main features as were described in [3]: high decrement of resistance in low pressure zone ($p < 50$ kPa) and low decrement for $p > 50$ kPa.

It is known [5], that region of maximal plantar pressures during human gate and running corresponds to $p > 200$ kPa, i.e. to high pressure zone. So, to increase the sensitivity of measurement in this zone, it was assumed to use inverted dependences $1/R(p)$ instead of direct data $R(p)$ in further analysis. Examples of normalized inverted characteristics $R_{\min}/R(p)$ for all the sensor types are shown in Fig. 2a for both fourth and fifth loading cycles. It can be seen, that dependences $1/R(p)$ of all sensor types represent hysteresis loops, which consist of two subloops ("low" and "high" pressure subloops, marked as L and H, correspondently. Arrows show loading and unloading branches of the loops.) It can be also seen, that sensors demonstrate quite good repeatability under cyclic loading. Exclusion of several first "warming" loading cycles from data analysis provides essential increase of data repeatability. To achieve the best approximation possible for $p > 100$ kPa data only H subloops were used (see Fig. 2b). Analysis showed that these subloops can be approximated by third order polynomial functions with $R^2_{A,B,C}$-squared values not lower than $R^2_{A,B,C} < 0.95$. Obtained approximation

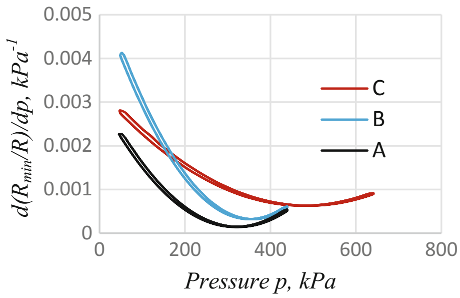


Fig. 3 Relative sensitivity of knitted pressure sensors

functions were used to compare sensors sensitivity to pressure variations and to estimate possible measurement errors. Figure 3 shows relative sensitivity graphs $d(R_{min}/R)/dp$ of studied sensors. It can be seen, that in the high pressures range the best sensitivity to pressure variation has type C. On the contrary, in lower pressures range type B is more sensitive. The lowest sensitivity in all range of pressures has type A.

Estimation of measurement errors due to assumed approximation of hysteresis loops showed, that the highest relative error corresponds to the middle parts of the loops for all type of sensors. Value of maximal error varies from ±25% for type A to ±15% for type C. To improve accuracy of measurements special hysteresis loop models and algorithms of hysteresis compensation can be used [6].

3 Monitoring of Shoe Cushioning Properties

3.1 Test Protocol

Three male volunteers had participated in three walk test trial series: first trial—walking without shoes ("bare" walking—only smart socks had been put on the feet) and second shoed trials—walking in shoes with different midsole stiffness (hard and soft). These trials will be referred further as "B"-bare, "H"-hard and "S"-soft. Midsole stiffness differs for each volunteer, because they used their own shoes, comfortable for them. So, midsole stiffness of shoes used for S trial by volunteer 1 can be harder or equal to the same of H trial of second volunteer, and so on. Each trial had included 6 repeated series of walking with the length of 40–46 strides each. All trials were made with the same walking speed, which was monitored by using metronome device.

3.2 Materials and Methods

Plantar loading forces were measured during walking trials by using DAid™ Pressure Sock System with sensor placement on the sole as follows [3]: toe part—under first and fifth metatarsal; midfoot—inside under foot arc and symmetrically outside; heel part—in the middle of the heel. Shoes cushioning was tested by measurement of midsole's heel parts stiffness. Measurements were made using Zwick Z 100 device.

To study the possibility of midsole cushioning estimation by using smart socks, two approaches of data processing and analysis were used. The first one—Peak Value analysis (PVA) was based on defining and comparison of the relative average $\overline{a_k}$ of peak values of pressure forces for B, H and S trials. The second one—Loading Rate Analysis (LRA)—on comparison of average loading rate of each sensor or sensor group for B, H and S trials. Calculations for AP and LRA were made using the following formulas:

For PVA:

$$(\overline{A_k})_{B,H,S} = \left(\frac{1}{n}\sum_{i=1}^{n} A_{ik}\right)_{B,H,S} \tag{1}$$

$$(\overline{A_{sum}})_{B,H,S} = \left(\frac{1}{5}\sum_{i=1}^{5} A_k\right)_{B,H,S} \tag{2}$$

$$(\overline{a_k})_{B,H,S} = \frac{(\overline{A_k})_{B,H,S}}{(\overline{A_{sum}})_{B}}, \tag{3}$$

where k = 1…5—sensor number, n—number of strides in a trial, A_{ik}—peak value of pressure force.

For LRA:

$$(u'_{ik})_{B,H,S} = \left(\frac{u_{ik} - \min_{a \le i \le b} u_{ik}}{\max_{a \le i \le b} u_{ik} - \min_{a \le i \le b} u_{ik}}\right)_{B,H,S} \tag{4}$$

$$a = i - 0.5w \tag{5}$$

$$b = i + 0.5w \tag{6}$$

$$(v_{ik}^{max})_{B,H,S} = \left(\max\left(\frac{du'_{ik}}{dt}\right)\right)_{B,H,S} \tag{7}$$

and then using Eqs. (1)–(3), replacing there A_{ik} with v_{ik}^{max}.

In Eqs. (4)–(6) u_{ik} is inverted signal of i-th stride from k-th sensor, w is the normalization window size.

3.3 Results and Analysis

Data of measurements of shoe midsoles stiffness are presented in Table 1. Further, for convenience, results from H trial of volunteer with number n will be marked as nH, from

Table 1 Shoes midsole average stiffness, kN/m

Trial/Volunteer	1	2	3
H	110	300	170
S	71	100	110

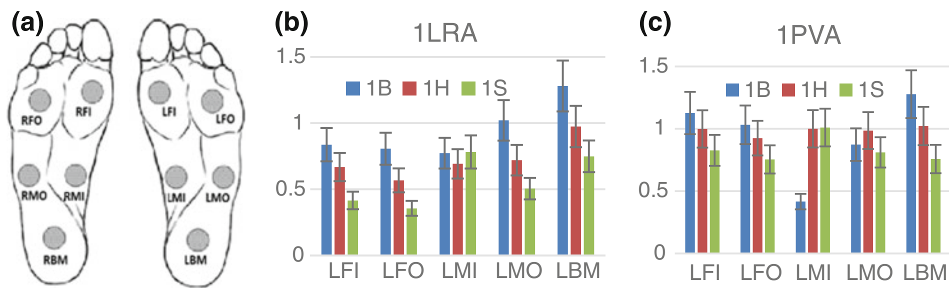


Fig. 4 Sensor placement schema (**a**) and loading histograms for volunteer 1, left foot (**b**, **c**)

his S trial—as *n*S, etc. Also following abbreviations for sensors are used: L, R—left and right foot; F, M, B—front, middle, back; I, M, O—inside, middle, outside. So, for example, LFI is the mark of frontal inside sensor of the left foot (Fig. 4a) Using PVA and LRA, histograms of $(\overline{a_k})_{B,H,S}$ and $\overline{(v_k^{max})_{B,H,S}}$ values were built for each sensor separately and, also, by zones (toe, midfoot and heel). Examples of such histograms built for separate sensors are shown in Fig. 4b, c.

It can be seen, that tested system "fills" even local changes of lower foot cushioning: essential difference in force amplitude peak values and sole loading rates performs between B, H and S trials. One can also see, that PVA and LRA give similar results for toe and heel parts of foot (see LFI, LFO and LBM sensors). For midfoot part results are different. It is explained by specificity of sensors placement and features of midfoot loading. So, to recognize local cushioning ability of shoes the results from both PVA and LRA must be compared. Grouping of sensors gives the possibility to test quality of midsoles cushioning by specific zones.

4 Conclusions

New types of knitted pressure sensors are designed and tested. It is shown that highest sensitivity has "curved line" type sensor. Maximal amplitude measurement error with third order polynomial approximation of sensor characteristic is not exceeding 15%. Possibility to use DAid™ Pressure Sock System for testing shoe midsole cushioning quality is shown. Methods of data processing for cushioning quality estimation and comparison are proposed.

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Conflict of Interest The authors declare that there is no any conflict of interest.

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