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A comparison of the accuracy of the smart sock system to force platform and optical system for measurement of temporal parameters of locomotion

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Abstract. The aim of the study was to present a new DAid®Pressure Sock System for feet locomotion monitoring and to verify it's temporal characteristics by data comparison with the same obtained by two other widely used methods as reference. Designed system is based on sensors which can be knitted directly in the garment or hosiery items. DAid®Pressure Sock System was created for sport and medical applications. Comparison of temporal characteristics of different types of locomotion, obtained using designed system and reference devises, showed good agreement between data.

1. Introduction

On-line monitoring of feet locomotion is important problem in both sport and medical applications, such as foot injury prevention and foot training, prediction of diabetic ulceration and sport coaching. It is evidently that such monitoring systems should be mobile, wireless and light in its weight, do not cause any discomfort.

Many research groups are working now on the development of effective feet locomotion control systems. For example, athletic plantar pressure analysis was used to improve sport achievements, providing a tool for soccer balance training and forefoot loading during running [1]

A variety of plantar pressure measurement and gate control systems are available now in the market or in the research laboratories. In general, there are two main types of devices: platform systems and in-shoe systems. Platform systems are usually embedded in a walkway. The typical commercial product is EMED-SF floor mounted capacitance transducer matrix platform (Novel USA, Inc.). It is frequently used in clinical studies of different foot pathologies and gait analysis [2]. However, this kind of systems can be used only in a laboratory / hospital, and only for barefoot measurements.

In-shoe systems, capable to record the plantar pressure distributions within a shoe, are much more flexible. Commercial products include F-scan measurement system (Tekscan, Inc.) and Novel pedar system (Novel USA, Inc.) that capture dynamic in-shoe temporal and spatial pressure distributions, further utilized for assessment of gait stability and gate event analysis [3]. However, both systems use electrical wires to connect in-shoe sensors and data acquisition system around the waist, which is inconvenient for long-term use. Alongside, these systems are not suitable for long-term outdoor measurements.

Other types of smart wireless insoles for gate and pressure control were proposed, as well [4, 5]. As a rule, these systems are equipped with Bluetooth®or similar data transmitting device, and with an energy source. Despite of wide variety of such systems, all of them have one common drawback these insoles form an additional elastic layer inside the shoe which thickness can be up to several millimeters. Such layer can distort the real data of plantar loading of the foot. In addition, these systems are comparatively expensive and inconvenient for daily use.

Abovementioned drawbacks can be overrun by using textile-based systems - such as socks with integrated sensors (Smart socks). This approach was used to develop sock based systems for temporal gate analysis in medical [6] and sport [7] applications, foot pressure control during snowboard training [8] and plantar pressure detection to prevent foot ulceration [9]. Unfortunately, most of already developed versions of Smart socks are handmade or utilize complicated manufacturing technology. A new sock-based feet locomotion monitoring system(DAid®Pressure Sock System) was proposed in [10]. Present paper is devoted to this system further development and verification, particular, in sport applications.

2. System Design

DAid®Pressure Sock System consists of sensor arrays distributed over the sole part of socks, connected by conductive lines and custom-designed connector with electronic devices that collect and transmit data from sensors to the data processing device (computer or smartphone) [10].

2.1. Pressure sensors

Embedded pressure sensors are originally designed piezo-resistive knitted structures, sensitive to the pressure load. They can be knitted by the commercial knitting machines as elements of design, thus being an integral part of the knitted garment or hosiery. The array of such sensors may be easily adapted to the wide range of necessary patterns, shapes and dimensions. Figure 1 shows typical dependence of the sensor electrical resistance R on the applied pressure P.

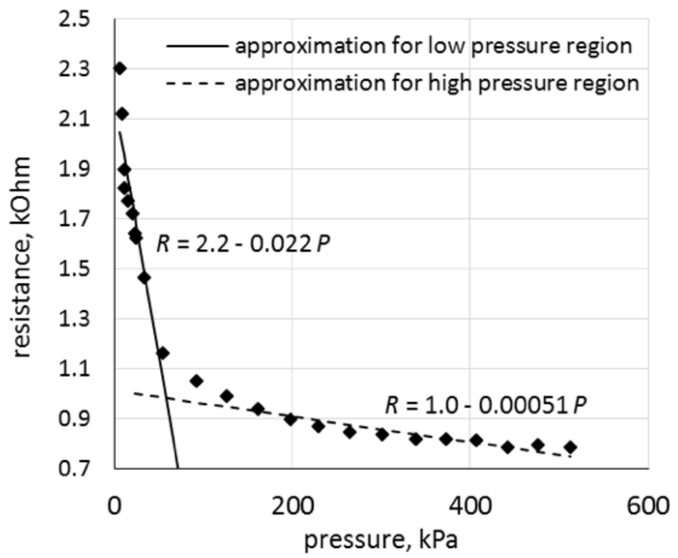

Figure 1. Example of sensor characteristic (sensing field 7 cm^2) [10].

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2.2. Sensor sock
The array of pressure sensors was knitted in the sole part of socks together with electro - conductive lines (Figure 2). In the present version of DAid®Pressure Sock System, each sock has five knitted sensors, placed in accord with the figure 2. Knitted conductive lines connect sensors with the contact buttons mounted on the upper part of socks.

Figure 2. DAid®Pressure Sock System [10].

2.3. Sensing circuit, data acquisition, processing and presentation
Developed version of acquisition system gives possibility to collect data from 6 pressure sensors and transmit them via Bluetooth module to tablet computer or another compatible electronic gadget. Figure 3 shows functional diagram of the acquisition and transition modules. All sensors RXi were connected with one common point. A reference resistance R0 provided output voltage, that corresponded to the plantar load from "unloaded" with sportsman's foot raised up to the "full load", when sportsman stand on one foot. Data acquisition and transmission to remote electronic gadget was provided custom made electronic device capable to capture differential voltage signal over 6 channels.

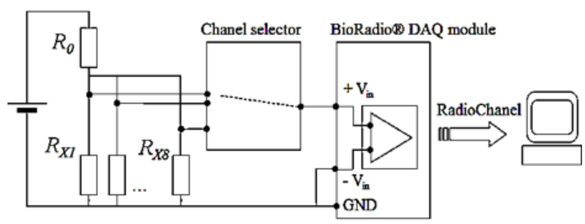

Figure 3. 6-channel data acquisition and transmitting device [10].

Data processing and presentation software was developed under LabView®environment. The software gives possibility to make time, frequency and correlation analysis as well as visualize received data. The software application for tablet computer is shown in figure 4.

3. Methods
Validity and operation of the DAid®Pressure Sock System was checked by tests made for different walking/running patterns. Validation was made by comparison temporal data of locomotion obtained by designed system with measurement results from two commercially available reference devices used in laboratory conditions. The first one was the force platform

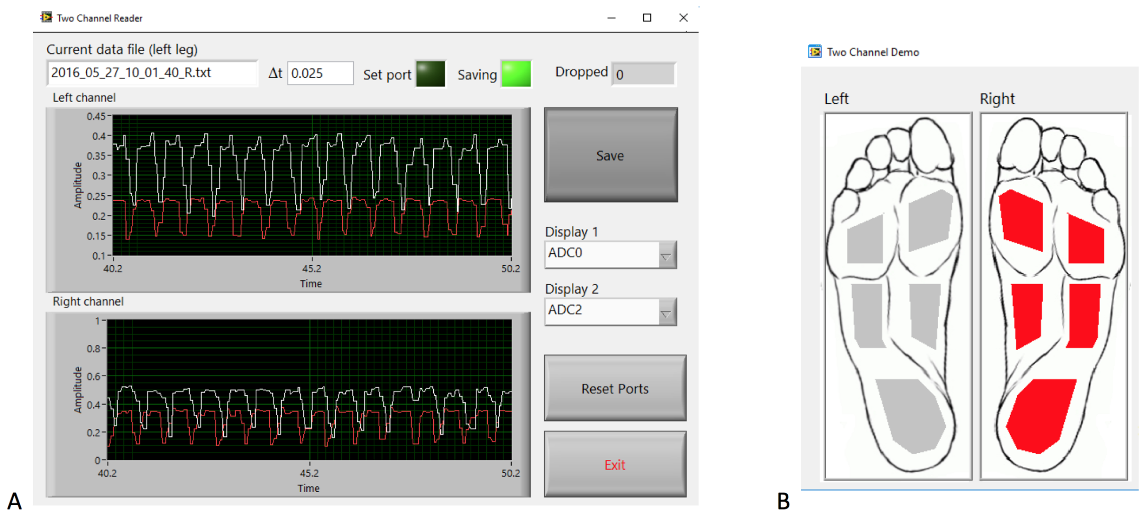

Figure 4. User interface of gate data acquisition software. A - DAQ mode, B - demo mode.

(BTS P-6000, Italy), sampling at 1000 Hz. The sensitive area of force plates was 60 x 40 cm, minimum height - 5.7 cm. Runners performed one successful running step over the force plates at one time. Other method was optical system (OptoJump Next, Microgate, Italy). The OptoJump Next system consists of 2 bars which can be placed on a treadmill. Each of these contains 32 LEDs (light-emitting diodes), positioned 0.3 cm from the bottom of the bar at 3.12 cm intervals. The LEDs on the transmitting bar communicate continuously with those on the receiving bar resistance then one used for the sensors

Three types of locomotion were analyzed: walking (only with the optical system, figure 5A), race walking (figure 5B) and running (only with the optical system, figure 5C). Ground contact time was defined as the time from when the foot contacts the ground to when the foot toes off the ground (measured with force platforms). Step time was defined as the time from when one foot contacts the ground to when the other foot contacts the ground (measured with optical system). Participants performed repeated steps over the force plates and continuous activity on motorized treadmill while measuring with the optical system. Both systems have previously been shown to accurately determine these variables.

Descriptive statistics were calculated and Student's t-test was performed to compare data.

All data were processed and calculated using RStudio [11]. "Ggplot2" package to plot graphics was used [12].

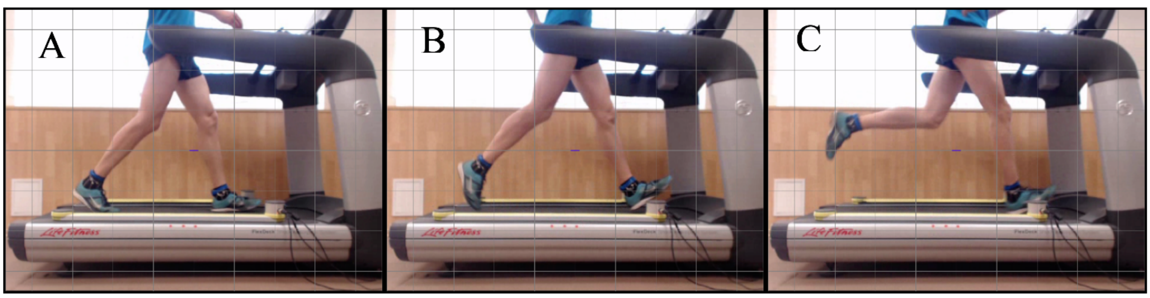

Figure 5. Three different types of locomotion. A - walking, B - race walking, C - running.

4. Results and Discussion

The Bland-Altman plot was used to determine agreement between methods. The mean difference between step times was 0.0027s in walking (n=167, figure 3A), -0.0024s in race walking (n=252, figure 3B) and -0.0013s in running (n=275, figure 3C). Graphical representation of difference between Smart Socks and OptoJump is shown in figure 6.

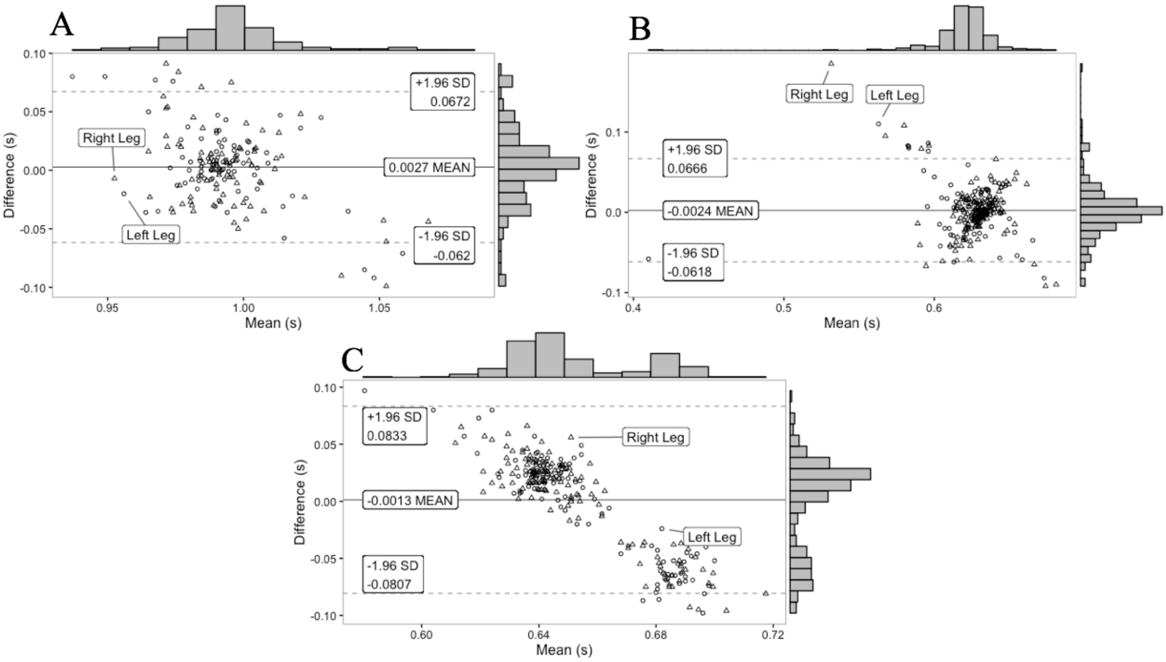

Figure 6. The level of agreement plots (Bland-Altman) showing 95% limits of agreement (dashed lines) between methods. Solid black line represents the mean bias between methods. A - walking, B - race walking, C - running.

Coefficient of variation (CV) during walking was higher within values measured by Smart socks (3.1%) compared to Optojump - 1.9%. While race walking CV was higher within values measured by Smart socks (6.0%) compared to Optojump - 4.4%. During running CV was also higher by Smart socks (7.2%) compared to Optojump (1.4%), see table 1. It could be partly explained by artifacts. As the mean difference was close to zero, it shows that none of two methods measured significantly ($p>0.05$) higher or lower step time values in any of three types of locomotion.

Mean difference between ground contact times in race walking (n=89) was -0.017s. The difference was statistically significant ($p<0.01$). The mean ground contact times were 0.281s (Smart Socks) and 0.298s measured with force plates. The time of mean difference makes 5-6% of the contact phase time.

So designed DAid®Pressure Sock System an both reference devices showed practically equal step times during three types of locomotion.

5. Conclusion and future work

Proposed textile based DAid®Pressure Sock System gives adequate temporal data for different types of feet locomotion. It is lightweight and mobile, do not disturb walkers and runners during execution of exercises. So, potentially it can be used as a practical tool for sport applications. Anyway, more data needed for deeper analysis. Also, durability tests of the system are planned.

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Table 1. Descriptive statistics of collected data with DAid®Pressure Sock System and OptoJump.

	Walking		Race walking		Running	
	Opto	Sock	Opto	Sock	Opto	Sock
Mean	0.995	0.992	0.627	0.62	0.654	0.655
Median	0.993	0.99	0.631	0.629	0.655	0.634
Mode	0.991	0.991	0.631	0.631	0.661	0.625
SE	0.001	0.002	0.002	0.003	0.001	0.004
SD	0.019	0.031	0.027	0.037	0.009	0.047
CV (%)	1.9	3.1	4.4	6.0	1.4	7.2

Acknowledgments
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