A Smart Socks System for Running Gait Analysis

Peteris Eizentals[1], Alexei Katashev[1] and Alexander Oks[2]
[1]Institute of Biomedical Engineering and Nanotechnologies, Riga Technical University, Kalku 1, Riga, Latvia
[2]Institute of Design and Technology, Riga Technical University, Kalku 1, Riga, Latvia

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Abstract: Running gait analysis is an often used tool for running performance improvement and injury prevention due to an incorrect running style. The typical gait analysis methods are unavailable to amateur runners outside of special clinics due to their relatively high cost. Smart socks are a relatively cheap gait analysis method that can be used by amateur runners and professional athletes for running performance improvement. This paper presents a smart socks system for feet plantar pressure measurement during running, as well as methods for characterisation of the acquired plantar pressure measurement for running gait analysis. The validation of the smart socks with a Pedar insole system is described, and the measurement analysis methods are demonstrated by practical running tests. The validation tests demonstrated good temporal and pressure sensing characteristics of the system, while the simplicity of the developed gait analysis methods was demonstrated in the practical tests.

1 INTRODUCTION

Running is one of the most popular sport and recreational activities worldwide. Besides its beneficial effects on the health, it is also the cause of numerous injuries, and up to half of the runners report an injury annually (Fields et al., 2010). The most frequent running related injuries are medial tibial stress syndrome (incidence 13.6% – 20.0%, prevalence 9.5%), Achilles tendinopathy (incidence 9.1% – 10.9%, prevalence 6.2% – 9.5%), plantar fasciitis (incidence 4.5% – 10.0%, prevalence 5.2% – 17.5%), Patellar tendinopathy (incidence 5.5% – 22.7%, prevalence 12.5%), and ankle sprain (incidence 10.9% – 15.0%, prevalence 9.5%) (Lopes et al., 2012). Many of these injuries have high recurrence rates (Bramah et al., 2018) and therefore affect both daily life and training of the injured person. Running related injuries are especially frequent among amateur runners (De Araujo et al., 2015), who often lack the understanding of a correct running style. Although the connection between the running style and the rate of injuries is still debatable (Barton et al., 2016; Hamill & Gruber, 2017), running gait analysis for amateur runners could be beneficial for early detection of potentially harmful running style or gait pathologies (Vincent et al., 2014), as it is generally accepted that one of the main contributors to running related injuries is abnormal running kinematics (Barton et al., 2016). On top of that, running gait analysis is a valuable tool for performance improvement for professional runners and amateurs alike. Unfortunately, there are no simple and cheap tools for gait analysis that would be affordable for non-professionals. The typical gait analysis methods for feet plantar pressure analysis are pressure sensing mats and insoles and gait analysis by MEMS or 3D mapping (Taborri et al., 2016). All of these methods are rather expensive and unavailable for amateur runners outside of special clinics.

This paper describes running gait analysis by custom-designed smart socks system, DAid® Pressure Sock System (DPSS), and specially for this system designed gait analysis methods. The smart socks system was developed for solving some of the inherent limitations of the conventional gait analysis methods, as the socks are relatively cheap to produce, if compared to insoles or pressure mats, they don't interfere with the performed activity, and can be used with any type of shoes indoors and outdoors (Taborri et al., 2016). The feasibility of walking gait analysis by the DPSS has been demonstrated previously (Eizentals, Katashev & Oks, 2018a), but the performance of the system has not yet been verified with a certified commercial gait analysis system, and no tests had been done with running gait.

The system validation with the Pedar insole system as a reference demonstrated that the smart

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socks system has very good temporal characteristics, as the average differences for the calculated step and stride times between measurement by pedar and by DPSS were 1.75% and 1.34% respectively. Practical application of two dedicated running gait analysis methods for smart socks is demonstrated in this paper.

2 SYSTEM DESCRIPTION

The developed smart socks system described in this paper contains 6 pressure sensors on each sole, two on the heel, two under the arch and two under the metatarsals (see Fig. 1 and Fig. 2). Such sensor distribution enables monitoring of temporal walking and running gait characteristics, and comparing the features of plantar loading for normal (asymptomatic), flat (pes planus) foot as well as diagnosing supination and pronation conditions. Conductive pathways are designed to provide the connection between sensors and the data acquisition units. The data acquisition units are attached to the cuff of the sock by Velcro type tape and connected to the sock by snap fasteners.

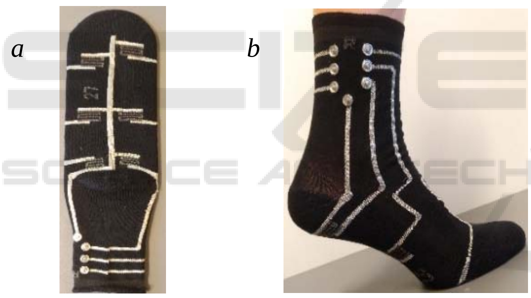

Figure 1: DAid Pressure Sock System, (a) sensors on the insole, and (b) connectors for the data acquisition unit.

The main advantage of this technology is the possibility to produce the DPSS socks using ordinary sock knitting machines, thus greatly decreasing the production cost. Moreover, the number and placement of the sensors can be easily modified according to the demands of a customer or applications.

The present version of the data acquisition unit collects the measurement simultaneously from all 6 pressure sensors and transmits them via Bluetooth to a remote data processing device, where the measurement is synchronized and saved to a file. The sampling frequency of data acquisition is up to 200Hz per channel, which is greater than 100Hz sampling speed which is the recommended in the literature for monitoring the change of feet plantar pressure during running (Mann et al., 2016). The sampling frequency can be adjusted to lower energy consumption, if prolonged monitoring is required, providing with more than 8h of continuous measurement. Additionally, the device allows changing the sensitivity range of the sensors and resetting the timer. The sensors are numbered according to Fig. 2: (1) front medial, (2) front lateral, (3) middle medial, (4) middle lateral, (5) heel medial, and (6) heel lateral.

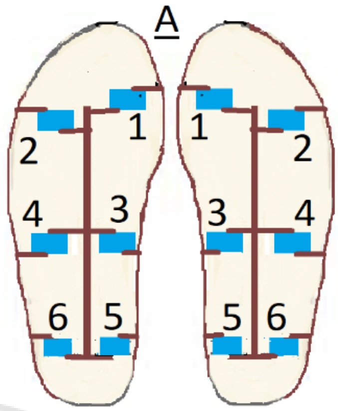

Figure 2: Sensor distribution and numbering on the Smart Socks system.

3 SYSTEM VALIDATION

To assess the performance of the DPSS, verification of the measurement was performed by the Pedar® system insoles (Novel GmbH, Munich), which is considered the golden standard for feet plantar pressure measurement for gait analysis (Tamura & Chen, 2018). Each Pedar insole contains 99 pressure sensors, and the measurement is sampled at 50Hz or 100Hz, and transmitted to the computer via Bluetooth connection. To analyze the performance of the Smart Socks system, 6 participants were requested to walk several times approx. 10m long distance in a normal gait, while the feet plantar pressure measurement was obtained simultaneously with both systems. A heel strike was performed before each walk for providing a sharp peak for signal synchronization. The Pedar measurement was obtained at the rate of 100Hz, which is the maximal sampling rate of the system, while the smart socks system sampling rate was approx. 200Hz.

For validation of the temporal accuracy of the DPSS, step and stride times were calculated and compared to those obtained by the Pedar system. The stride time is the time between two successive foot to ground contacts of the same foot, while the step time is the time from the first foot-to-ground contact of one

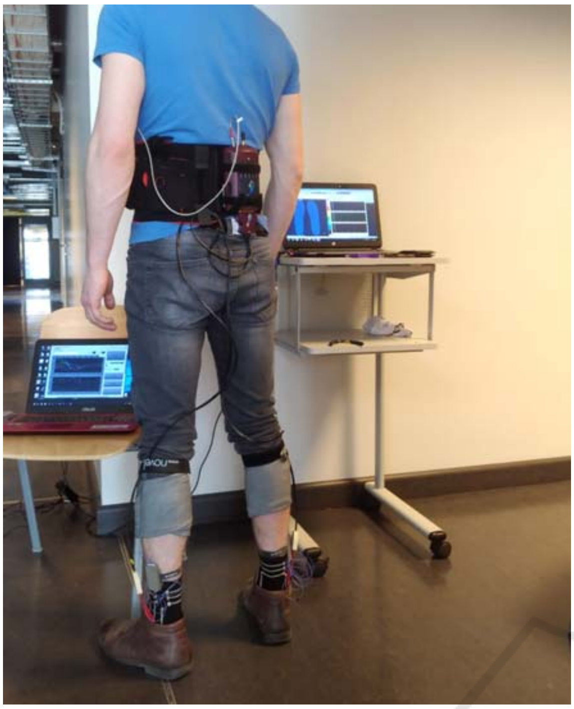

Figure 3: Test participant with the Pedar and the DPSS attached.

foot to that of the other foot. The foot contact detection threshold for Pedar was set to 50kPa of the total pressure, where the total pressure was obtained by summing all sensor measurement. For the DPSS, the contact threshold was selected as 20% of the total pressure, and it was adjusted adaptively with a moving window algorithm. The adaptive adjustment was performed to account for possible sensor sensitivity change caused by feet sweating.

All calculated mean step and stride times are given in Table 1. As it can be seen, the temporal values obtained by the smart socks system are remarkably close to the ones obtained from the Pedar system, with the average difference of the mean values being 9.8ms (1.75% of the mean step time) and 14.9ms (1.34% of the mean stride time) for step and stride time respectively.

Direct comparison of pressure values between both systems is not possible, as calibration of textile pressure sensors is rather complicated due to the hysteresis and nonlinearity of the textile sensors, and is not performed for this application. As a result, the measured electrical resistance of the sensors was not converted to pressure units. Additionally, the size of the textile sensors is considerably larger than that of the Pedar insole sensors. To allow comparison of pressure change over time for both systems, the measurement was processed as follows. First, the

Table 1: Comparison of step and stride times obtained by the Pedar and DPSS.

Nr.	DPSS				Pedar			
	Step		Stride		Step		Stride	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
1	0.599	0.052	1.197	0.059	0.604	0.028	1.2	0.04
2	0.668	0.033	1.33	0.044	0.665	0.0275	1.327	0.043
3	0.541	0.075	1.07	0.109	0.569	0.075	1.105	0.021
4	0.525	0.048	1.042	0.033	0.523	0.2023	1.057	0.049
5	0.527	0.035	1.044	0.042	0.522	0.0211	1.038	0.026
6	0.527	0.111	1.054	0.106	0.538	0.0303	1.073	0.035

average pressure was calculated for Pedar system for six zones in the approximate position of each textile sensor (see Fig. 4, the chosen sensors on the Pedar insole are marked). These calculated values, as well as the values from the smart socks system, were normalized by using a sliding window normalization according to the equation:

$$u_i' = \frac{u_i - \min_{a \le i \le b} u_i}{\max_{a \le i \le b} u_i - \min_{a \le i \le b} u_i} \quad (1)$$

$$a = i - 0.5w \quad (2)$$

$$b = i + 0.5w \quad (3)$$

where u_i is the corresponding measurement and w is the normalization window size, which was selected to be 250 for Pedar ad 500 for DPSS. The width of the window was selected to include 3-5 steps at a normal walking speed.

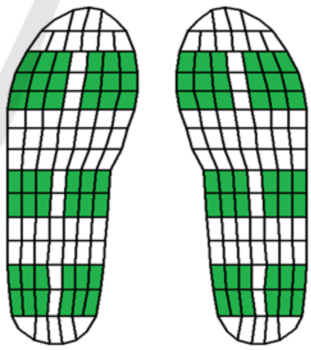

Figure 4: The sensors in the marked area were selected for plantar pressure measurement comparison with that of the Smart Socks System.

An example of the measurement from both systems after the normalization is provided in Fig 5. As can be seen, both measurements show a good similarity of the activation time and relative pressure change over the time. The middle sensors are not shown in the figure as they typically have low pressure values, and the values after normalization do not represent the real measurement.

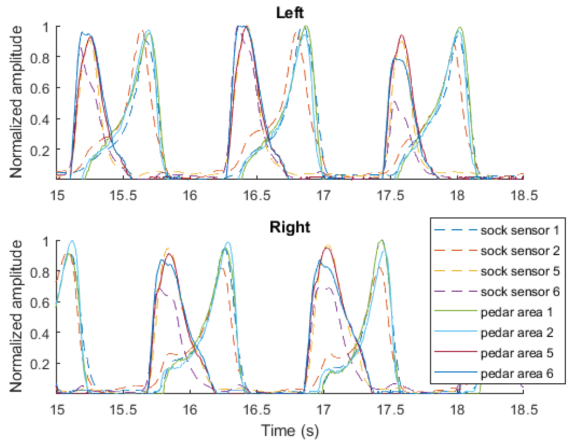

Figure 5: Example of normalized measurement for both systems, the sensor numbers for the DPSS sensors are according to Fig. 2 while the Pedar areas for each textile sensor are given in the Fig. 4.

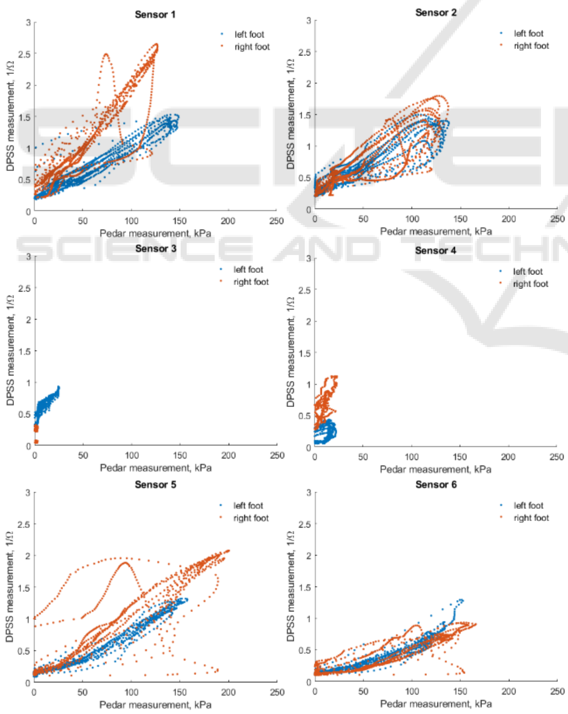

Figure 6: An example of a measurement comparison of several consecutive steps for Pedar and smart socks systems. A linear relationship can be observed between measurement of both systems.

An example of the raw measurement value comparison for both systems is provided in Fig. 6. A linear relationship between the measurement obtained by DPSS and that of the Pedar system can be observed for all sensors except those under the arch of the foot, which are not activated due to the relatively low pressure in the area under the arch of the foot. This signifies that a calibration of the smart socks system could be performed by obtaining the calibration coefficients from these measurements.

The results obtained from simultaneous measurements with both the Pedar and the Smart Socks system confirmed that the developed system has good temporal accuracy. The step and stride times calculated from the measurement of the smart socks system were reasonably close to those obtained from the measurement of the Pedar system. Moreover, the measured pressure change over time was in a good agreement between both systems, as shown in Fig. 5. It can be concluded from these results that the smart socks system is a reliable tool for gait temporal parameter measurement, and the system calibration for absolute measurements is possible.

4 RUNNING GAIT ANALYSIS

Two experiments were performed for testing the feasibility of the developed smart socks system and the dedicated methods for running gait analysis. For the first experiment, two amateur runners performed a test run on a treadmill, starting with a 2min warm-up at 5kmh, proceeded with 8-10min run at 10kmh, and finishing with 1min cooldown at 5kmh. For the second experiment, one amateur runner performed a 30min run at 10kmh followed by a 2min cooldown. The plantar pressure measurement was performed with the smart socks system. The obtained measurement from both experiments was analyzed by gait analysis methods developed exclusively for the smart socks system – *Force Vector* and *Pressure Wave* methods.

The *Force Vector* is a graphical gait characterization method that is comparable to the center of pressure method typically used for gait analysis (Eizentals et al., 2018b). For each measurement, a point is calculated, which is derived from the measured pressure values of all sensors, and the positions of each sensor on the sock as a unit vector. All points calculated for any step together make a line or trajectory, which describes the respective step. The Y-axis of the graph represents the foot in posterior (Y < 0) and anterior (Y > 0) directions while X-axis represents the medial (X < 0) and lateral (X > 0) directions (see Fig. 7). The Force Vector values were calculated according to the following equations 4 and 5:

$$V_x = \sum_{i=1}^{n=6} k_i u_i' \cos \varphi_i \quad (4)$$

$$V_y = \sum_{i=1}^{n=6} k_i u_i' \sin \varphi_i \quad (5)$$

where u' is the normalized measurement value for each sensor obtained from equation (1), $k = [1, 1, \cos\alpha, \cos\alpha, 1, 1]$ is a weight coefficient assigned to each sensor and $\varphi = [75°, 105°, 0°, 180°, 285°, 255°]$ is the assigned angle of each sensor. The sensor order is according to that presented in Fig. 2.

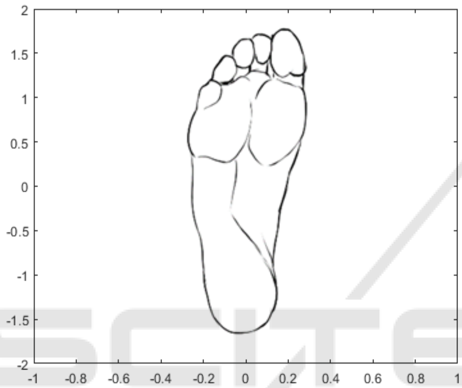

Figure 7: The approximate position of a foot on the Force Vector axis (not to scale).

The *Pressure Wave* diagram is a graphical gait representation method that attempts to visualize all sensor values for the whole step duration at each moment of the step. To achieve this, an image is created, where each sensor measurement during a step is displayed as a color bar, the color intensity representing the normalized value of the sensor (0 – 1), and on Y-axis normalized time of the step (0 – 100%) (see Fig 8). Sensors in the image are distributed in following order (from left to right): left lateral metatarsal, left lateral tarsus, left lateral heel, left medial heel, left medial tarsus, left medial metatarsal, right medial metatarsal, right medial tarsus, right medial heel, right lateral heel, right lateral tarsus, and right lateral metatarsal. Such distribution allows analyzing the sensor activity during the whole step in a comprehensible way, giving information about which parts of the foot were in contact with the ground at which moment of the step and what was the relative pressure.

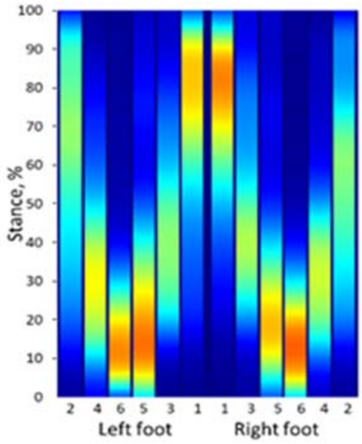

Figure 8: Example of a Pressure Wave diagram. The sensor measurement during the stance phase is represented as a color-bar plot with the colors representing the sensor measurement amplitude at each moment. The sensor numbering is according to that given in Fig. 2.

An example of the *Force Vector* lines for several steps acquired in the first running measurement is given in Fig. 9 and 10. Several conclusions can be drawn from this result. First, both amateur runners are rearfoot runners, as the vector line goes through the lower part of the graph. The cooldown phase measurement also shows less variation between the steps as the *force vector* lines in Fig. 9c and Fig. 10c are noticeably closer to each other compared to those in Fig. 9a and Fig. 10a. The trajectory of *force vector* lines in the cooldown phase is resemble the trajectory of running phase more than that of the warmup phase. The conclusion about rearfoot running style is also supported by the image obtained from the *Pressure Wave* diagram (see Fig. 11 and 12). According to these images, for both participants, the initial contact during this experiment was on the heel, as both heel sensors (sensors 5 and 6) activated slightly before the middle sensors.

In the second experiment, a participant was requested to run for 30min at 10kmh to analyze both the performance of the socks in a prolonged monitoring, and possible effect of fatigue on the running style. The results of this measurement indicate that the style of running for the participant gradually changed from rearfoot running to midfoot running. The Force Vector diagram shows that the center of pressure value during each step shifted from both heel (X < 0) and toe (X > 0) directions to the center (see Fig. 13).

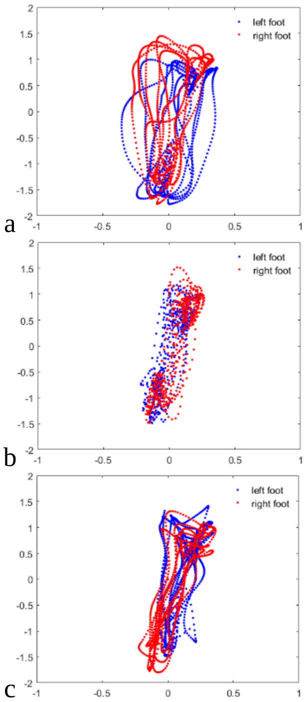

Figure 9: Example of the calculated Force Vector result for few steps of participant #1, (a) warmup, (b) running and (c) cooldown.

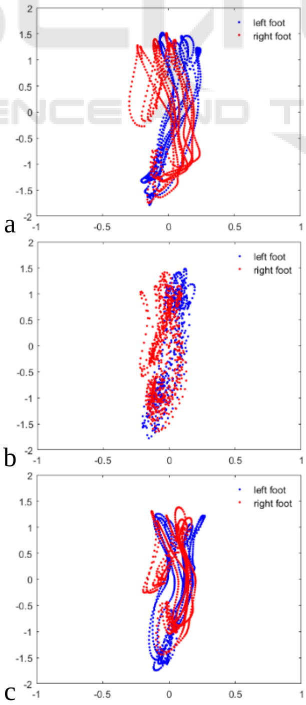

Figure 10: Example of the calculated Force Vector result for few steps of participant #2, (a) warmup, (b) running and (c) cooldown.

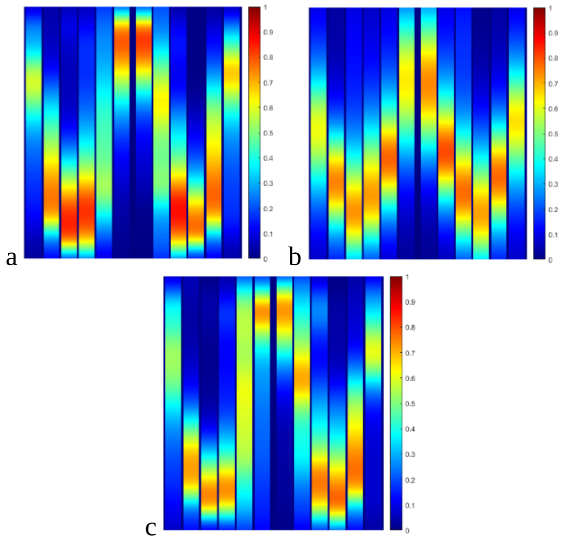

Figure 11: Pressure Wave result for participant #1, (a) warmup, (b) running and (c) cooldown.

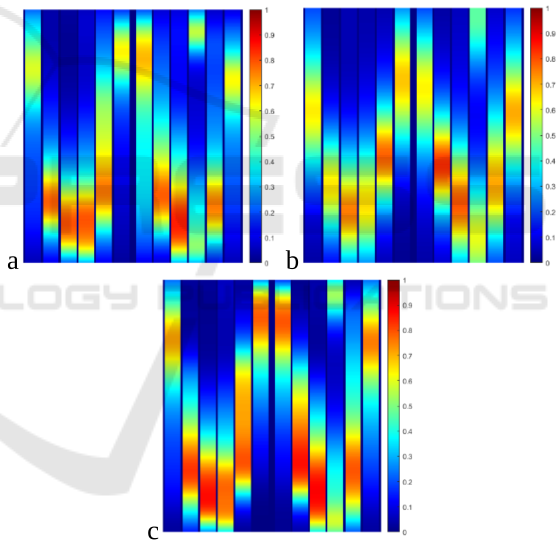

Figure 12: Pressure Wave result for participant #2, (a) warmup, (b) running and (c) cooldown.

The same result can be observed in the Pressure Wave diagram (Fig. 14), where initially each sensor reached its peak value at a noticeably different time, but with time the overlap gradually increased. At the 20min mark the calculated center of pressure is mostly at the center of the feet, implying the midfoot running style, which differs from the initial rearfoot running. This could signify that the person might have naturally found the running pattern with the least energy consumption.

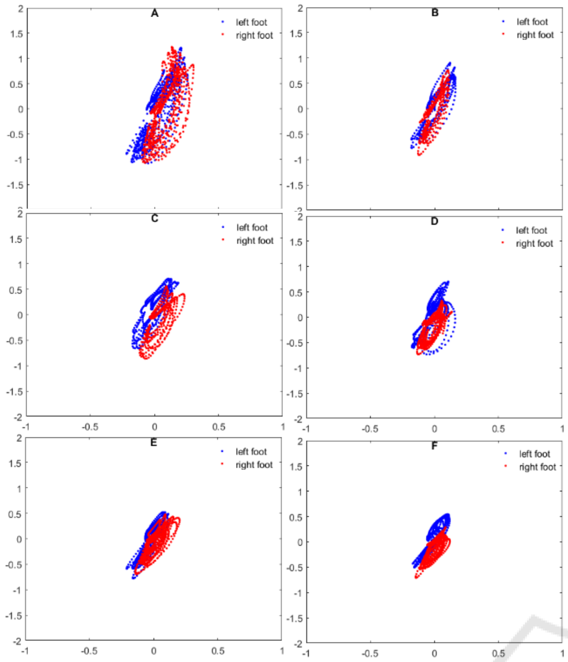

Figure 13: The calculated Force Vector diagrams for the 30min running measured at (a) 5min, (b) 10min, (c) 15min, (d) 20min, (e) 25min and (f) 30min.

No significant change in the sensitivity of the textile sensors during the 30min run was observed, however, no strong conclusions could be drawn as the participant didn't sweat too much. It is expected that wet from the sweat would affect the sensitivity of the textile sensors.

5 CONCLUSIONS

Feet plantar pressure measurement and running gait analysis with a smart socks system has been demonstrated in this paper. The measurement accuracy of the developed system was evaluated by comparing it to the measurement obtained by the Pedar measurement system. The mean differences between step and stride times obtained by both systems were 9.8ms and 14.9ms.

Two gait analysis methods were demonstrated in practice for short (10min) and medium (30min) long runs. The demonstrated methods were developed for analysing the plantar pressure measurement obtained by the SPSS and enable simple running gait characterization. It was demonstrated how these methods can be applied to evaluation of the plantar pressure variation during running.

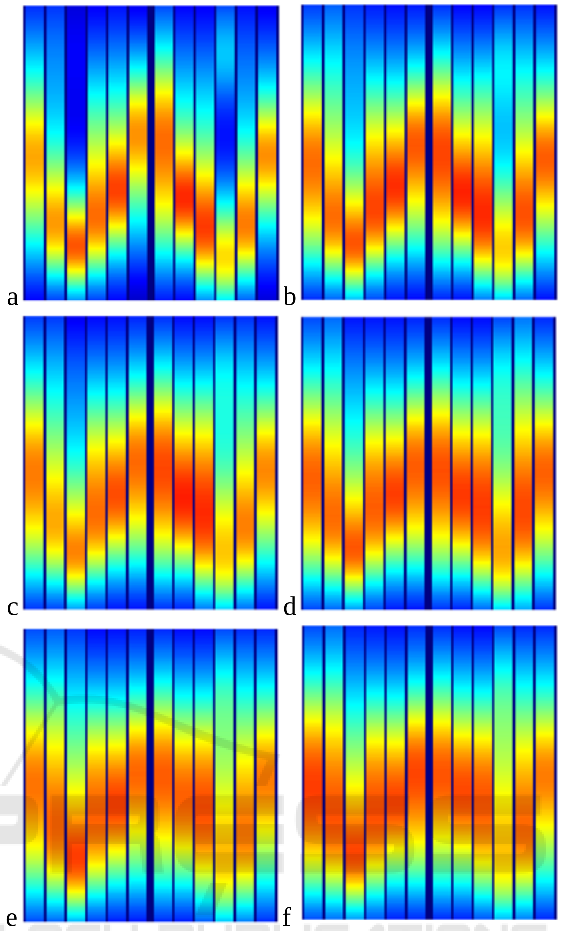

Figure 14: Pressure Wave diagrams for the 30min running measured at (a) 5min, (b) 10min, (c) 15min, (d) 20min, (e) 25min and (f) 30min.

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