New Posturographic Assessment by means of Novel E-textile and Wireless Socks Device in Normal Subjects

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Abstract—Commercially available, laboratory pressure systems are recognized as an outstanding tool for assessing balance, due to their ability to accurately measure center of pressure (COP) which gives the point location of the ground reaction force. However, high costs, non-portability, custom setup and training required for its operation often hinder a widespread use, usually just limited to clinical settings. New e-textile and wireless wearable sensor technologies enable to extend the posturography in new low-cost and home assessment contexts. Twenty posturographic tests has been performed on normal subjects at the same time both by pressure signals derived by Sensoria fitness (SF) e-textile socks and by a gold standard stabilometric Zebris platform (ZP). Results showed a significant strong correlation between SF and ZP COP measurements, suggesting a clinical use of Sensoria for low cost home care based balance impairment assessments.

I. INTRODUCTION

Balance is defined as the ability of human body to maintain center of gravity within the base of support to prevent falling [1]. Maintenance of balance requires coordination between sensorineural and musculoskeletal systems and the adequate posture control is considered as a fundamental motor skill during lifespan [2].

Postural sway has been commonly assessed on validated force platforms that can be regarded as gold standards [3-5]. Center of pressure (COP) is the location of the ground reaction force that can be recorded through force plates. Defined as the centroid of all the external forces acting on the planar surface of the foot, the COP has further been used to identify balance control, foot function, and treatment efficacy. Increased postural sway may be a cause of loss of balance in healthy humans in unstable conditions [6] as well as in patients with neurological disorders [7]. Muscle weakness may make it harder to stand, or patients can have tremors and other neurological issues that impair the ability to balance and stand safely. To quantify the central nervous system adaptive mechanisms involved in the control of posture and balance, is used the Posturographic technique.

The gold standard for static posturography is currently the use of a pressure or force plates. Force plates provide information about the medio-lateral and anterior posterior displacements of COP signal. COP can be used to study the effect of sensorineural and muscular systems in control of balance. Analysis of COP signal can provide insight in the use of different strategies for maintaining balance. Output parameters such as COP path length and area are direct measures of postural stability.

Despite its advantages, force plate technology is seldom used outside laboratories and research environments because of its expensive instrumentation and operational complexity. Also, the process of operation is time consuming and requires a trained technician for its use and interpretation of results. These factors limit its availability and use by clinicians and therapists[8]. Moreover, although these systems are easy to use in a clinical environment, they are stationary and are not suitable for long-term outdoor measurements.

Above considerations highlights the need to investigate novel portable, inexpensive balance assessment systems allowing more easy and widespread home availability especially for older and chronic disable people [9, 10]. Recently, wearable and textile-oriented systems are gaining a rapidly growing interest, mainly because of their low-cost, versatility and comfort with different functions and applications, particularly both in sport and rehabilitation fields.

New wireless in-shoe textile system Sensoria [11], originally designed as fitness and sport monitoring device, have recently been commercially available. Worn just like normal athletic socks, the Sensoria Fitness Socks appear as one of the first example of a truly wearable devices potentially part of each consumer’s daily workflow.

Aim of the paper has been the evaluation of static computed posturography in normal subjects by means of pressure signals derived by a pair of Sensoria socks, comparing their agreement’s degree with results at the same time performed by a gold standard clinical stabilometric Zebris force platform.

II. MATERIALS AND METHODS

A. Study population

Twenty posturographic tests has been performed on healthy males (age: 22 ± 5 years, height: 180 ± 8 cm, weight: 75 ± 5) volunteers participating in this study. No participant reported a major back or lower limb pathology, use of medication, or a history of neurologic disease that may influence standing balance. The study has been carried out in accordance with Good Clinical Practice, the Declaration of Helsinki, and the moral, ethical and scientific principles that justify medical research, and all participants provided informed consent.
B. Posturographic clinical gold standard device

The posturographic test was performed with the stabilometric platform of the latest generation ZEBRIS PDM–Sx (Figure 1), equipped with 1920 capacitive sensors of new generation arranged in a matrix of 34 x 41 cm (55 x 40 cm) with a sampling frequency of 120 Hz.

This arrangement allows analysis of changes in the distribution of vertical force in the forefoot and hind-foot of both feet; in addition, center of pressure data (COP) were analyzed in anterior-posterior (AP), medio-lateral (ML) directions. The COP trajectory reflects the body sway during standing and the ability of the nervous and musculoskeletal systems to integrate information from multiple sensory systems, including the visual, the somatosensory, and the vestibular system to maintain balance.

Alterations of the postural control system are reflected in changes of COP characteristics and parameters, which is therefore a key variable for monitoring the postural control system [12-15].

C. E-textile Sensoria socks

Sensoria fitness socks [10] are a product by Sensoria Inc. Redmond WA United States originally designed for fitness and sport application and aimed to help subjects become better runners and prevent common injuries allowing to identify and assess harmful running styles.

Sensoria smart socks are infused with comfortable and washable textile pressure sensors (Figure 2). They detect real-time heel or toe foot striking. Each smart sock is infused with three proprietary textile sensors under the plantar area located in the following positions under the foot: I) fifth metatarsal bone (MTB5), close to the little toe, II) first metatarsal bone (MTB1), close to the big toe and III) Heel, to detect main foot pressure sites.

The conductive fibers relay data collected by the sensors to the ankle. The sock has been designed to function as a textile circuit board. Each sock features magnetic contact points below the cuff to easily connect a companion anklet able to activate the textile sensors and containing a 3-Axis accelerometer. The anklet, weighing less than 28 g, is slightly adjustable, being made with flexible electronic circuit board to fit different ankle sizes. When connected to the sock, the anklet wirelessly transmits continuously through Bluetooth Smart all 3 textile pressure sensors and 3-axis accelerometer signals at 32 Hz sampling rate.

D. Test protocol

Participants have been asked to remove their shoes, to wear both the Sensoria socks and stand upright on the Zebris force plate. Before each trial, feet position was kept consistent by a wooden template with a divergent angle of 30 degrees and with a 12 cm distance between the heels. Subjects have been asked to remain as still as possible in a relaxed posture (Figure 3) putting arms to their sides in a comfortable position and distributing their body weight evenly on both feet while breathing normally. Finally, the participants were instructed to look straight ahead at an “X” on the opposite wall located 2 meters away at eye level. If the patient usually wore glasses, they continued to do so during this procedure.

Subjects underwent to 2 trials, each consisting of 60 seconds, with at least 120 s of rest between trials. A 60-second assessment was chosen to mimic constituent periods of standing during typical activities of daily living (e.g., waiting for a bus or elevator). To avoid inconsistencies in the data at transitions, we informed the participants of the data collection start time 5 seconds before the actual start time. Data have been simultaneously collected (hand synchronization) using the Sensoria system and the Zebris measurement system and automatically stopped on both system after 60 s. At the test end Zebris system automatically calculate the main posturographic indexes.

The two raw pressure data array of each Sensoria socks were wirelessly transmitted by a Bluetooth connection on a pc laptop workstation instrumented with the Sensoria Developer Kit for Windows. Both arrays were off-line post processed by a customized Matlab software developed by the authors and resampled at 100 Hz to synchronize data of both socks on the same time scale.
E. Center of Pressure estimation

For a quantitative evaluation of the ability of a participant to maintain balance, the displacement of the center of gravity (COG) is a meaningful parameter [12]. The COG is the projection of a person’s center of mass onto the base of support [12]. If the COG is placed outside the supporting area of a resting person’s feet, the person will fall without further intervention [13]. Due to permanent balance correction movements of the human body, the direct measurement of the COG is not possible.

Since for static conditions, the center of pressure (COP) varies around the COG position with a higher magnitude and frequency as the COG [14], COP is usually alternatively used for COG estimation. At each time instant, the COP coordinates in the media-lateral (X_{COP}) and anterior-posterior (Y_{COP}) direction has been calculated processing raw pressure Sensoria data according the following equations:

\[
X_{COP} = \frac{\sum_{i=1}^{n} X_i P_i}{\sum_{i=1}^{n} P_i}, \quad Y_{COP} = \frac{\sum_{i=1}^{n} Y_i P_i}{\sum_{i=1}^{n} P_i}
\]

where \( n \) denotes the total number of sensors, \( i \) denotes a certain sensor, \( X, Y \) are the sensor coordinate inside the whole foot shape area and \( P \) the pressure value.

Based on the COP, the Sensoria Sway path (SSP) parameter has been calculated. The SSP is the accumulated distance of the COP in a specified time interval. For \( N \) sampling points, the sway path is calculated as:

\[
SSP = \sum_{i=2}^{N} \sqrt{(X_{COPi-1} - X_{COPi})^2 + (Y_{COPi-1} - Y_{COPi})^2}
\]

The same sway path index, as automatically calculated by the Zebris system (ZSP), has been used as the gold standard value.

F. Statistical analysis

The mean value between the two trials has been considered for all posturographic test.

In order to quantify the degree to which the two SSP and ZSP variables are related, the results were first studied by a two-tailed Pearson correlation analysis between SSP and ZSP measurement of each posturographic tests.

Besides, since the standard linear regression assumes a cause-effect model where all the uncertainty is in the dependent variables and the dependent variables values are perfectly known, while in this case both SSP and ZSP variables have to be considered as subject to error, the linear regression fitting has been performed using a method known as Deming, or Model II, regression [16]. SSP and ZSP have been considered of different uncertainties and to assess the uncertainty of each method, the duplicate measurements of the two trials has been used, calculating the standard deviation of the error using the equation below:

\[
SD_{\text{error}} = \sqrt{\frac{\sum d_i^2}{N}}
\]

where each \( d_i \) is the difference between two measurements of the same subject and \( N \) is the number of measurements.

All statistical analysis has been performed by GraphPad Prism version 6.00 for Windows, GraphPad Software, La Jolla California USA, www.graphpad.com. A 95% confidential interval has been chosen for all tests.

III. RESULTS AND DISCUSSION

Conclusions

Results, as shown in Table I and Figure 4, allow to point out the following three findings.

First, SSP exhibited values generally about four times lower than those achieved by ZSP. This could be mainly explained by two reasons: the more limited spatial sampling of plantar pressures due to only three sock’s sensors than the widest array of sensors of the platform; and the lower time sampling frequency of Sensoria than that of the Zebris.

Second, SSP values showed an extremely significant (p<0.001) moderate-to-strong positive correlation (r=0.7) with ZSP measures, clearly indicating that pressure signals derived from Sensoria are anyhow able to follow COP movements with an acceptable agreement’s degree in comparison to an high precision clinical gold standard force platform system.

Third, visual data inspection suggest a quite linear relationship between SSP and ZSP values, which can be well described by a slope Deming linear regression best fitting value of 3.9. Since most of the points lie very close to the regression line, except few outliers anyhow inside the 95% prediction band, such relationship suggest the possibility to obtain from Sensoria a sufficiently approximate estimation of COP movement suitable for a clinical evaluation.
TABLE I. STATISTICAL RESULTS

<table>
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<tr>
<th>Descriptive Statistic</th>
<th>Sensoria Sway Path</th>
<th>Zebris Sway Path</th>
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<tr>
<td>12 ± 2 cm (mean ± sd)</td>
<td>54 ± 9 cm (mean ± sd)</td>
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<tr>
<th>Pearson correlation analysis</th>
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<tr>
<td>r</td>
<td>0.699</td>
<td></td>
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<tr>
<td>95% confidence interval</td>
<td>0.371 to 0.872</td>
<td></td>
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<tr>
<td>R squared</td>
<td>0.488</td>
<td></td>
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<tr>
<td>P value</td>
<td>0.0006***</td>
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<tr>
<th>Deming Regression Best-fit values</th>
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<tr>
<td>Slope</td>
<td>3.870 ± 0.934</td>
<td></td>
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<tr>
<td>Y-intercept when X=0.0</td>
<td>7.738 ± 11.47</td>
<td></td>
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<tr>
<td>Equation</td>
<td>Y = 3.870*X + 7.738</td>
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IV. CONCLUSIONS

In this study we aimed to evaluate if the use of the Sensoria system could be considered a valid method for assessing static COP path length, comparing results with a gold standard clinical stabilometric Zebris force platform.

Preliminary results showed promising performance about a use of Sensoria system as a clinical tool to evaluate balance impairments, showing good correlations between the SSP and the ZSP in open eyes conditions on healthy subjects.

Future studies need to be addressed to assess further improvement in the algorithms, calculating other typical posturographic indexes derivable from Sensoria socks pressure signals, studying their reproducibility and extending this preliminary results also in different eye closed condition.

Moreover it should be investigated the sensibility of this new posturographic assessment by mean of novel e-textile and wireless socks device to discriminate normal from pathological results in order to verify if the low-cost Sensoria system could be considered as a valid support to the traditional clinical practice, especially for home based assessments.

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REFERENCES


