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

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Abstract— **The quantitative assessment of the postural stability is allowed by means of the use of pressure or force plates which are able to record a CoP subject's trajectory during a quite standing. However, the pressure or force plates are commonly used in a clinical environment, due to their very complexity and expensiveness. So their applicability outside laboratories is extremely limited.**

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). Preliminary results showed a significant agreement between SF and ZP COP measurements, suggesting a clinical use of Sensoria for low cost home care based balance impairment assessments.

Keywords—posture; rehabilitation; e-textile; Sensoria; Zebris

I. INTRODUCTION

The center of gravity is defined as a projection of the center of mass in the horizontal plane of support, where the center of mass is considered that point in three-dimensional space that represents the center of gravity of the acting weight forces on each body part. The maintenance of upright posture implies two fundamental requirements: the first is to maintain the center of gravity within the support base, the second is to create a reference system to the body moving parts [1].

This capacity at rest during voluntary head, arm, and body movements, during transfers and wheelchair use (both indoors and outdoors) needs the coordination of several sensorial and motor mechanisms.

Particularly, the feed-forward predictive mechanisms are involved in the control [2] of the preparatory postural adjustments (goal-directed voluntary movements), in maintaining of balance. The degeneration in such mechanisms, as a consequence of a neuro-musculoskeletal disorder, result in several alteration in the balance control. Posturography provides information tended to address specific rehabilitation programs [3; 5]. The stabilometric platforms are the gold standard devices used to measure each instant the pressure exerted on the ground by the feet; the variations of the center of pressure (CoP) [6-8], which is the centroid of all the external forces acting on the plantar surface of the foot and its spatial and temporal variations (sway measures) are commonly used as a measure of the balance control.

Increased postural sway may be a cause of loss of balance in healthy humans in unstable conditions [9] as well as in patients with neurological disorders [10, 11].

The quantitative assessment of the postural stability is allowed by means of the use of pressure or force plates which are able to record a CoP subject's trajectory during a quite standing. The two dimensional plot of the antero-posterior and medio-lateral displacement of the COP are called Statokinesigramm, while medio-lateral displacement of the COP versus time or the antero-posterior displacement of the COP versus time are called stabilograms.

The analysis of COP signal can provide insight in the use of different strategies for maintaining balance. Starting from the stabilograms, several variables are commonly used in the quantification of body sway in the time and frequency domains, which can be used to discuss the frequency characteristics of several biomedical signals [12-17]. Among the several parameters proposed to quantify the postural control, parameters such as COP path length and area are the major measures of postural stability. However, the pressure or force plates are commonly used in a clinical environment, due to their very complexity and expensiveness. So their applicability outside laboratories is extremely limited. 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[9]. This considerations lead to the need to explore novel portable, inexpensive balance assessment systems which allow more easy and extensive home availability especially for older and chronic disable people [18-20].

The development of small, lightweight, low-cost and energy efficient textile-oriented systems offer the promise of home health care devices that integrate flawlessly into the wearer's everyday lifestyle with different functions and applications, particularly both in sport and rehabilitation fields.New wireless in-shoe textile system Sensoria [21], 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 a preliminary evaluation of static computed posturography in subjects with Parkinson's Disease (PD) 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.

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II. Materials and Methods

A. Study population

For this study 10 patients with PD have been enrolled through the assistance of neurologists and psychiatrists.

The inclusion criteria have been: (i) stage 2.5–3 according to the Hoehn and Yahr Scale, (ii) stable pharmacological treatment for the last 8 weeks (iii) Mini-Mental State Examination (MMSE)>25, (iv) Berg Balance Scale >35.

All patients have underwent a posturography test at 10.00 AM and during the medication ON.

This 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 organization permits 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.

Impairments of the postural control system induces changes of COP characteristics and parameters, therefore the investigation of such impairments is crucial to define effective rehabilitation protocols [22-25].

C. E-textile Sensoria socks

Sensoria fitness socks [21] 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.

The Sensoria Fitness Socks are embedded with 3 proprietary textile pressure sensors located in key positions under the foot (Figure 2). Each sock attaches magnetically to the Sensoria Fitness Anklet : 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.

When the Sensoria Fitness Socks, designed as textile circuit board, are connected with two companion anklet, which also include 3-axis accelerometer, they are able to collect the pressure. 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

We asked partecipants 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 20 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.

Figure 1. ZEBRIS PDM–Sx posturographic system.

Figure 2. On the left the 3 proprietary textile pressure sensors located in key positions under the foot. On the right the socks' magnetic contacts for the attachment of the anklet.

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®.

E. Center of Pressure Estimation

The quantitative evaluation of balance is associated with the evaluation of the displacement of the center of gravity (COG), which is the projection of a person’s center of mass onto the base of support and represents a meaningful outcome parameter[3].

Due to permanent balance correction movements of the human body, the direct measurement of the COG is not possible.

The center of pressure (COP) is usually alternatively used for COG estimation, since it fluctuates around the COG position with a higher magnitude and frequency as the COG [3].

At each time instant, the COP coordinates in the media-lateral (XCOP) and anterior-posterior (YCOP) direction has been calculated processing raw pressure Sensoria data.

Several parameters counting mean sway amplitude, peak-to-peak amplitude, sway path, sway velocity, root-mean-square (RMS) amplitude, can be obtained from the COP signals to compute alterations in stability.

From the COP signals, the following posturographic parameters were computed: the Sway Path (SP), calculated as the total length of the COP path:

$$SP = \sum_{n=1}^{N-1} [(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2]^{1/2}$$

Then is calculated the Mean Velocity (MV), which is the average speed that the COP moved, calculated by total distance traveled and diving by total time of test.

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

F. *Statistical Analysis*

Descriptive statistics of continuous variables are reported as mean ± SD.

In order to quantify the degree to which the posturographic variables are related, the results have been analyzed by means of the Pearson correlation and Passing Bablok Regression.

Passing and Bablok regression analysis is a statistical procedure that allows valuable estimation of analytical methods agreement and possible systematic bias between them [26]. It is robust, non-parametric, non-sensitive to distribution of errors and data outliers.

III. Results

The results of the posturographic tests are summarized on and the Pearson correlations between both systems for the sway path and the mean velocity are listed in Table I and in Figure 3.

Table I. statistical results

Descriptive Statistic		**Pearson correlation r (p-value)**
Sensoria Sway Path	884 ± 71	r= 0,96
Zebris Sway Path	868 ± 81	(***p<0.001)
Sensoria Mean Velocity	9 ± 1	r= 0,85
Zebris Mean Velocity	14 ± 2	(**p<0.01)

The COP in both ML and AP directions and the Statokinesigram traces, extracted from the Sensoria raw data, for a representative pathological subject are reported in Figure 4.

Then, the Passing Bablok regression analysis for the SP and MV indexes are summarized in figure 5, figure 6 and in Table II.

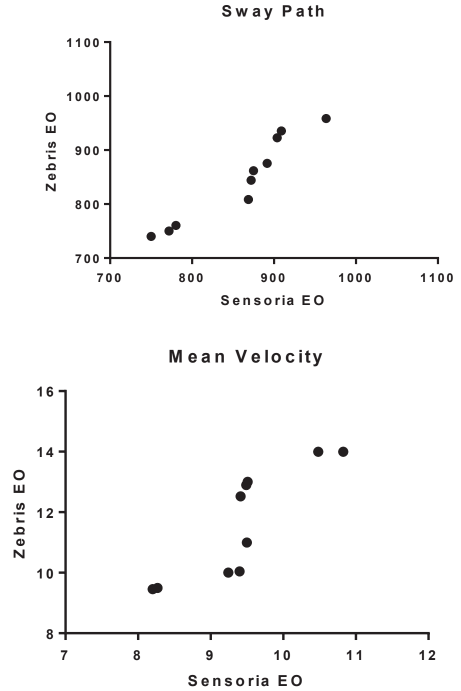

Figure 3. Pearson correlation of the sway path and mean velocity between Sensoria system and Zebris force platform system.

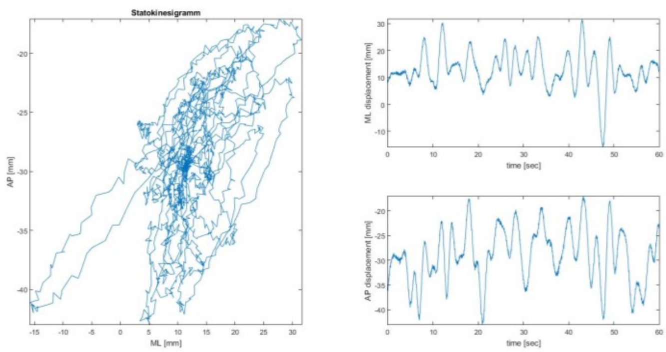

Figure 4. The Cop traces for one representative pathological subject. Particularly on the Left the Statokinesigramm, on top right the COP in ML direction and on bottom right the COP in AP direction. On the x-axis is reported the time (s) while on the y-axis the displacement (mm).

Table II. Model Coefficients

	Value	Lower bound 95%	Upper bound 95%	Cumsum test for linearity
SP Intercept	144.51	-25.41	478	p>0.1
SP Slope	0.84	0.46	1.04	
MV Intercept	4.93	-1.10	7.10	p>0.1
MV Slope	0.34	0.20	1.00	

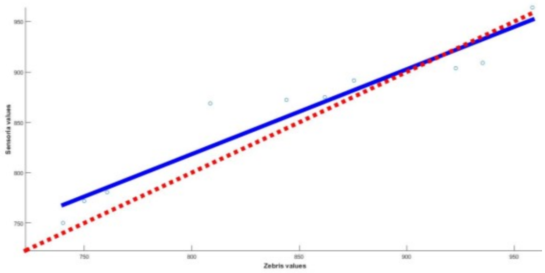

Figure 5. Passing and Bablok regression analyses of two methods for sway path index.

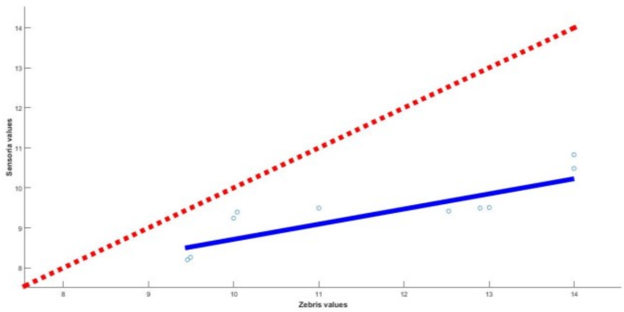

Figure 6. Passing and Bablok regression analyses of two methods for mean velocity index

Relatively to the sway path index, the regression line equation: $y = 144.51 + 0.84x$; 95% CI for intercept ranges from -25.41 to 478 and for slope ranges 0.46 to 1.04.

Relatively to the mean velocity index, the regression line equation: $y = 4.93 + 0.34x$; 95% CI for intercept ranges from -1.10 to 7.10 and for slope ranges 0.20 to 1.00.

The 95% CI for intercept and slope includes respectively the 0 value and 1 value, indicating a good agreement between the two methods. Cusum test for linearity indicates no significant deviation from linearity ($P > 0.10$).

IV. Discussion

Recently the development of small, easy to use E-textile fabrics with the electronics and interconnections woven into them, is gaining a high interest for the home health monitoring applications

In this preliminary study we aimed to evaluate if the use of the e-textile system Sensoria 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 about a use of Sensoria system as a clinical tool to evaluate balance impairments seems to be encouraging, showing a good accordance between the posturographic indexes measured with Sensoria socks and Zebris platform, in open eyes conditions on 10 pathological subjects.

Future studies will be focused on calculating other typical posturografic indexes derivable from Sensoria socks pressure signals, studying their reproducibility and extending this preliminary results also in different eye closed condition.

References

[1] A. B. C. (Anatomy, Biomechanics, Control) of Balance during Standing and Walking. Winter, David A. 1995 ISBN : 0-9699420-0-1.

[2] D.L. Sturnieks, R. St George, S.R. Lord Balance disorders in the elderly Neurophysiol Clin, 38 (6) (2008), pp. 467–47.

[3] D'Addio, G., Gallo, F., Iuppariello, L., Bifulco, P., Cesarelli, M., & Lanzillo, B. (2014, June). Comparison between clinical and instrumental assessing using Wii Fit system on balance control. In Medical Measurements and Applications (MeMeA), 2014 IEEE International Symposium on (pp. 1-5). IEEE.

[4] Iuppariello, L.; Bifulco, P.; D'Addio, G.; Lanzillo, B.; Lullo, F.; Gallo, F.; Romano, M.; Cesarelli, M., "The effects of the vibratory stimulation of the neck muscles for the evaluation of stepping performance in Parkinson's Disease," in Medical Measurements and Applications (MeMeA), 2015 IEEE International Symposium on , vol., no., pp.606-609, 7-9 May 2015.

[5] Cesarelli, M., Iuppariello, L., Romano, M., Bifulco, P., D'Addio, G. Bioengineering activities in proprioceptive and robotic rehabilitation at Salvatore Maugeri Foundation. (2015) 2015 AEIT International Annual Conference, AEIT 2015, art. no. 7415277, .

[6] P.A. Goldie, T.M. Bach, O.M. Evans Force platform measures for evaluating postural control: reliability and validity Arch Phys Med Rehabil, 70 (7) (1989), pp. 510–517.

[7] J. Middleton, P. Sinclair, R. Patton Accuracy of centre of pressure measurement using a piezoelectric force platform Clin Biomech (Bristol, Avon), 14 (5) (1999), pp. 357–360.

[8] H. Rogind, H. Simonsen, P. Era, H. Bliddal Comparison of Kistler 9861A force platform and Chattecx Balance System for measurement of postural sway: correlation and test-retest reliability Scand J Med Sci Sports, 13 (2) (2003), pp. 106–114.

[9] AS. Aruin, WR. Forrest, ML. Latash (1998) Anticipatory postural adjustments in conditions of postural instability. Electroencephalogr Clin Neurophysiol 109:350–359.

[10] FB. Horak, SM. Henry, A. Shummway-Cook (1997) Postural disturbations: new insights for treatment of balance disorders. Phys Ther 77:517–533.

[11] Iuppariello, L., Bifulco, P., Romano, M., Cesarelli, M., D'Addio, G. Submovements composition and quality assessment of reaching movements in subjects with Parkinson's Disease (2015) 2015 IEEE International Symposium on Medical Measurements and Applications, MeMeA 2015 - Proceedings, art. no. 7145222, pp. 329-334.

[12] Romano, M., Cesarelli, M., Iuppariello, L., Faiella, G., Bifulco, P., D'Addio, G. Frequency domain and symbolic dynamics analysis for the study of cardiac pathologies (2013) 2013 E-Health and Bioengineering Conference, EHB 2013, art. no. 6707269, .

[13] Romano, M., Faiella, G., Clemente, F., Iuppariello, L., Bifulco, P., Cesarelli, M. Analysis of foetal heart rate variability components by means of empirical mode decomposition (2016) IFMBE Proceedings, 57, pp. 71-74.

[14] Romano, M., Iuppariello, L., Ponsiglione, A.M., Improta, G., Bifulco, P., Cesarelli, M. Frequency and Time Domain Analysis of Foetal Heart Rate Variability with Traditional Indexes: A Critical Survey (2016)

Computational and Mathematical Methods in Medicine, 2016, art. no. 9585431, .

[15] D'Addio, G., Cesarelli, M., Bifulco, P., Iuppariello, L., Faiella, G., Lapi, D., Colantuoni, A. Effects of wavelets analysis on power spectral distributions in laser doppler flowmetry time series (2014) IFMBE Proceedings, 41, pp. 647-650.

[16] Mastantuono, T., Lapi, D., Battiloro, L., Cesarelli, M., D'Addio, G., Iuppariello, L., Colantuoni, A. Microvascular blood flow regulation impairments in hypertensive obese people (2014) 2014 8th Conference of the European Study Group on Cardiovascular Oscillations, ESGCO 2014, art. no. 6847584, pp. 191-192.

[17] Mastantuono, T., Muscariello, E., Novellino, T., Lapi, D., Cesarelli, M., D'Addio, G., Iuppariello, L., Colantuoni, A. Changes in frequency components of blood flow oscillations in hyperglycemic obese people (2014) 2014 8th Conference of the European Study Group on Cardiovascular Oscillations, ESGCO 2014, art. no. 6847581, pp. 185-186.

[18] H.L.P. Hurkmans, J.B.J. Bussmann, E. Benda, J.A.N. Verhaar, H.J. Stam Techniques for measuring weight bearing during standing and walking Clin Biomech, 18 (2003), pp. 576–589.

[19] P. Arpaia, P. Cimmino, E. De Matteis, G. D'Addio “A low-cost force sensor-based posturographic plate for home care telerehabilitation exergaming” Measurement (2014) vol 51 (1), pp. 400-410.

[20] Arpaia, P., Cimmino, P., De Matteis, E., D'Addio, G. “A balance board device for home care telerehabilitation exergaming” (2012) 20th IMEKO World Congress 2012, 2, pp. 1459-1462.

[21] Sensoria (®) is a registered trademark of Sensoria Inc Redmond, Washington, United States http://www.sensoriafitness.com

[22] R. J. Schilling, E. M. Bollt, G. D. Fulk, J. D. Skufca, and C. J. Robinson, “A quiet standing index for testing the postural sway of healthy and diabetic adults across a range of ages,” Biomedical Engineering, IEEE, vol. 56, no. 2, pp. 292–302, 2009.

[23] Y.-C. Pai and J. Patton, “Center of mass velocity-position predictions for balance control,” Journal of biomechanics, vol. 30, no. 4, pp. 347–354, 1997.

[24] T. E. Prieto, J. B. Myklebust, and B. M. Myklebust, “Characterization and modeling of postural steadiness in the elderly: a review,” IEEE Transactions on Rehabilitation Engineering, vol. 1, no. 1, pp. 26–34, 1993

[25] L. Rocchi, L. Chiari, A. Cappello, FB. Horak., “Identification of distinct characteristics of postural sway in Parkinson's disease: a feature selection procedure based on principal component analysis”, Neurosci Lett 2006, 394(2):140–145.

[26] PW Strike, Statistical Methods in Laboratory Medicine, ISBN:0750613459.