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A learning system for automatic Berg Balance Scale score estimation

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ABSTRACT

The objective of this work is the development of a learning system for the automatic assessment of balance abilities in elderly people. The system is based on estimating the Berg Balance Scale (BBS) score from the stream of sensor data gathered by a Wii Balance Board. The scientific challenge tackled by our investigation is to assess the feasibility of exploiting the richness of the temporal signals gathered by the balance board for inferring the complete BBS score based on data from a single BBS exercise.

The relation between the data collected by the balance board and the BBS score is inferred by neural networks for temporal data, modeled in particular as Echo State Networks within the Reservoir Computing (RC) paradigm, as a result of a comprehensive comparison among different learning models. The proposed system results to be able to estimate the complete BBS score directly from temporal data on exercise #10 of the BBS test, with ≈10 s of duration. Experimental results on real-world data show an absolute error below 4 BBS score points (i.e. below the 7% of the whole BBS range), resulting in a favorable trade-off between predictive performance and user's required time with respect to previous works in literature. Results achieved by RC models compare well also with respect to different related learning models.

Overall, the proposed system puts forward as an effective tool for an accurate automated assessment of balance abilities in the elderly and it is characterized by being unobtrusive, easy to use and suitable for autonomous usage.

1. Introduction

All European countries are experiencing aging of their populations, with a decrease in the number of people of working age per retiree. By 2050, an estimated 35% of the European population will be over the age of 60, compared to 20% in 2005. Health trends among older people are mixed: severe disability is declining in some countries but increasing in others, while mild disabilities and chronic diseases are generally increasing. The aging process is characterized by a constant decline of body functions and is frequently associated to a series of impairments involving reduction in mobility and cognitive decline (Tinetti et al., 1995): these aspects work synergistically increasing the risk of falls. These, and related injuries, represent one of the major causes of morbidity/mortality (Bradley and Harrison, 2007) and decline of elderlies' quality of life (Cumming et al., 2000; Tinetti, 2003). Commonly, falls are considered the result of multifactorial elements working synergistically together, such as vision problems, lower limb weakness, altered mobility and somatosensory function alterations (Kulmala et al., 2009; Whipple et al., 1987; Tinetti et al., 1988). Prevention of falls should be one of the first defense lines to support an active aging. Accordingly, the balance assessment of elderly is assuming great relevance in clinical practice, with the development of several screening tools and tests that are used to assess stability or its deterioration: these include both simple clinical measures and also sophisticated technologies (Browne and O'Hare, 2001). One of the common and easiest functional tests frequently used in medical practice is the Berg Balance Scale (BBS) test. Initially, this was proposed for balance assessment in elderly population but it has been frequently used in subjects with stroke (Blum and Korner-Bitensky, 2008), Parkinson's disease (Qutubuddin et al., 2005), brain injury (Juneja et al., 1998), and multiple sclerosis (Cattaneo et al.,

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2006). The test is composed by 14 items, in the following also referred to as *exercises*, with a score ranging from 0 to 4 points. The maximum BBS score is 56 and the test duration time is ≈15–20 min. A score of 45 is indicated as a threshold for subjects at high risk of fall (Riddle and Stratford, 1999); each reduction of 1 point in BBS score is correlated to an increased risk of 6%–8% to fall (Shumway-Cook et al., 1997).

Recently, within the aims of the DOREMI European project,[1] a technological platform to support and motivate elderly people to perform physical activity has been developed, targeted at a reduction in sedentariness, cognitive decline and malnutrition, at the same time promoting an improvement in the quality of life and social inclusion. The general architecture of DOREMI is described in Bacciu et al. (2015), whereas an analysis of the platform reliability under the influence of human factors in the real setting is provided in Palumbo et al. (2017). The DOREMI project is focused on the development of a systemic solution for healthy aging able to prolong the functional capacities of the elderly. Through an integrated control of psychologically related socio-physical disabilities, vital signs combined with nutritional behavior, physical activity and social interaction, it should be possible to counteract cognitive and physical decline. This hardware and software-based platform is able to monitor users' physical activity levels, integrating this information with nutritional parameters. One of the main innovative objectives of the DOREMI platform consists in the development of an automated system for balance assessment. In the proposed approach, the balance assessment system is an easy-to-use, cost-effective and unobtrusive solution for early pre-frail risk detection and frailty prevention. This system, being part of elderly daily activities, could support the remote identification of potential negative evolution of the physical health status, thus favoring the development of user-specific treatments. This innovative DOREMI solution leverages the Wii Balance Board, a low-cost, portable and widely available force platform, able to evaluate the user weight distribution at the four corners of its surface, developed by Nintendo for the Wii gaming console. This device has been compared to laboratory-grade force platforms (Clark et al., 2010; Leach et al., 2014) and its accuracy proved to be acceptable for the employment in numerous scientific studies involving balance assessment (Clark et al., 2010; Young et al., 2011) and gait or balance rehabilitation (Gil-Gómez et al., 2011; Shih et al., 2010; Deutsch et al., 2008). In Deutsch et al. (2008), the Wii Balance Board device accuracy was tested against a laboratory grade device on the measurement of COP (Center of Pressure) path length. The authors have shown that the Wii Balance Board exhibits excellent test–retest reliability for COP path length, also proving concurrent validity with laboratory-grade force platforms. In Leach et al. (2014), the authors compared the Wii Balance Board against a gold-standard force plate produced by AMTI on the simultaneous measurement of COP displacement, also implementing an improved device calibration algorithm. The relation between COP related features (e.g., mean location, root-mean-square displacement and mean frequency) and the evaluation of the balance stability in elderly patients has been investigated in Maki et al. (1994), which presents a comparative study on stability-related measures using regression methods on data collected from a force platform with the aim of estimating the probability of patients' fall. However, it is worth to note that the whole temporal signal generated by a force platform, such as the Wii Balance Board, potentially contains richer information than the above mentioned static parameters, thereby allowing to envisage approaches that try to directly and automatically exploit such richness of signal dynamics.

In this paper we propose a novel system for automatic assessment of balance abilities in elderly, able to estimate the overall BBS score of a user based on the stream of input signals gathered from the Wii Balance Board during the execution of only 1 BBS exercise out of 14. The major scientific goal of this work is to assess the feasibility of accurately estimating the overall BBS score by exploiting the temporal series from pressure sensors gathered during a single exercise execution by the user, and to provide an experimental validation of the proposed system on real-world data.

Such a scientific challenge requires to address the fundamental questions of whether such temporal series contain enough information to be correlated with the full BBS score and whether a machine learning model can efficiently exploit such an information to automatically estimate the score. Keeping in mind these objectives, we resort to the class of Recurrent Neural Networks (RNNs) (Kolen and Kremer, 2001), which is widely recognized as particularly appropriate for processing and extracting relevant dynamic knowledge from noisy temporal data. In particular, as a result of an extensive and comprehensive comparison among different learning models, we take into consideration the Reservoir Computing (RC) paradigm (Lukoševičius and Jaeger, 2009; Verstraeten et al., 2007) and specifically the Echo State Network (ESN) model (Jaeger and Haas, 2004; Jaeger, 2001), which represents a state-of-the-art approach in the context of efficient learning in temporal domains (Gallicchio et al., 2017). Moreover, in our analysis, we investigate specific approaches aiming at tailoring the proposed system to the learning task at hand and to its challenges. On the side of the learning model design and settings, this includes taking into consideration the possible left–right symmetry during the execution of the balance exercise, as well as the integration of the temporal input pressure signals with static clinical data of the subjects. Besides, another relevant aspect of analysis concerns the careful selection of the physical exercise to be performed, in order to account for both safety of exercise execution, under a clinical perspective, and richness of the gathered signals, on the information processing side. The proposed approach is experimentally validated on real-world data collected through a measurement campaign on 21 volunteer users, also through a performance comparison with alternative learning models in the field of machine learning and neurocomputing.

Overall, the system described in this paper represents an automatic solution for the assessment of balance abilities in elderly people, which is unobtrusive, safe, easy-to-use (even without the supervision by clinicians), and requires the execution of only 1 of the 14 BBS exercises, thereby allowing to practically save time for monitoring the balance stability. To the best of our knowledge, the approach proposed in this paper represents the first attempt to estimate the BBS score of a subject from temporal data collected by using a non-intrusive external (unworn) device during the execution of a single balance exercise of very short duration (≈10 s). Alternative recent literature approaches are based on more intrusive solutions in the sense that they require the use of wearable devices and the execution by the user of a wider set of exercises for the BBS score estimation. Moreover, they did not explore machine learning models tailored to the direct treatment of the temporal dimension of the gathered signals, such as RNN. In particular, among the contributes for the automatic (unobtrusive and objective) BBS score estimation, the pioneering work described in Simila et al. (2014) proposes a k nearest neighbor (k-NN) approach to estimate the BBS score of a subject by using data collected from a tri-axial accelerometer placed on the lower back, during the consecutive execution of various items of the BBS test. In Badura and Pietka (2016) it is proposed an automatic system in which the BBS score of a subject is estimated by summing up the output of 14 Multi Layer Perceptrons, each of which is individually and specifically trained on data pertaining to one of the different BBS exercises. The system described in Badura and Pietka (2016) uses feature-based data from 5 inertial body-fixed sensors (3-axial accelerometers and angular velocity) and requires the subject to execute the complete BBS test (i.e., all the 14 balance exercises), thereby resulting in a comprehensive but more intrusive and time-consuming approach.

This paper consistently extends the preliminary work presented in Gallicchio et al. (2016), (i) by introducing a complete description of the *system* including the hardware, the modules for data collection and the pre-processing; (ii) by considering a larger set of BBS exercises individually used for system assessment, (iii) by making publicly available a

[1] EU FP7 DOREMI project (contract no. 611650), http://www.doremi-fp7.eu/.