Computerized Medical Imaging and Graphics 46 (2015) 169–177

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

journal homepage: www.elsevier.com/locate/compmedimag

Accelerometric signals in automatic balance assessment

Pawel Badura*

Faculty of Biomedical Engineering, Silesian University of Technology, Roosevelta 40, 41-800 Zabrze, Poland

ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 24 April 2015
Accepted 19 May 2015

Keywords:
Ambient assisted living
Computer-aided diagnosis
Balance assessment
Feature extraction

ABSTRACT

The paper presents the automatic computer-aided balance assessment system for supporting and monitoring the diagnosis and rehabilitation process of patients with limited mobility or disabled in home environment. The system has adopted seven Berg Balance Scale activities. The assessment approach is based on the accelerometric signals acquired by the inertial sensors worn by the patient. Several specific, mostly medium frequency features of signals are introduced and discussed. The reduction of the feature vector has been performed using the multilevel Fisher's linear discriminant. The classification employs the multilayer perceptron artificial neural network. The direct assessment effectiveness ranges from 75% to 94% for various activities.

1. Introduction

The clinical balance assessment has been an object of study in the past years [1]. Various disorders and diseases (Parkinson's disease, multiple sclerosis, neurological and musculoskeletal diseases [2,3]) are accompanied by balance problems. Due to the aging of contemporary societies, the safety and well-being of the elderly emerges as one of the major concerns in health care; this general consideration easily covers balance assessment and therapy. The postural perturbations and balance disorders control is critical for the selection of the proper treatment and rehabilitation [4]. The assessment requires dedicated procedures and standards to provide reliable inference and enable detection of possible threats. It has been discovered and proven, that specific activity-based testing of certain tasks (transfer, turning, reaching, standing, gait) meets this requirement very well [5].

Several clinical tests for balance assessment have been proposed in the past 50 years. A comprehensive review throughout this area might be found in [6]. Lets mention just few propositions from the last 30 years. In the Tinetti Balance and Gait Test [7] a clinician rates a total of 24 postural balance and gait tasks, which enable reliable fall prediction. The Activities-Specific Balance Confidence Scale (ABC) test [8,9] collects knowledge via a 16-item questionnaire on the subject's confidence while attempting different daily activities. The quick one-task tests ("timed up and go" – TUG [10], functional reach [11] and some earlier propositions) provide fast results, yet yield neither comprehensive nor sufficient information about the balance problem. On the other hand, advanced or multi-input ideas (Physiological Profile Approach – PPA [12], Balance Evaluation Systems Test – BESTest [13]) show satisfactory fall prediction sensitivity and inter-rater reliability, yet are difficult to perform due to a long duration (ca. 30 min) and equipment requirements.

Among these approaches, the Berg Balance Scale (BBS) test [14–16] is recognized as a reasonable tool for balance evaluation. The easy to use test consists of 14 various tasks, each one rated between 0 and 4 according to precisely defined criteria. The total score classifies a subject into one of three groups, referring to the physical abilities and fall risk. The test takes ca. 10–15 min with the individual task duration ranging between 5 and 120 s. The BBS is valued for its high inter-rater reliability and specificity indicators (both over 95% [6]). However, some recent studies have shown its relatively poor sensitivity in fall prediction, as well as frequent uncertainty between two close scores: the BBS requires an 8 point change to be considered a clinically relevant difference [17,18]. Nonetheless, the Berg test remains popular and is willingly used in balance evaluation.

To the best of our knowledge, there are only isolated, preliminary reports on the attempts to automatize the BBS scoring. An application for mobile device has been proposed in [19], using the ACHILE acquisition system [20]. It consists of a set of different sensors (accelerometer, gyroscope, force, temperature, and humidity sensors, bending variable resistor) placed in a sole. Each BBS task has been implemented in a form of a serious game with the inference output based on acquired signals. The application has been tested with nine male students, yet neither profound numerical results, nor the application-to-expert reference have been reported. Rare commercial (mobile) applications offer user-friendly

* Tel.: +48 322777466.
E-mail address: pawel.badura@polsl.pl

http://dx.doi.org/10.1016/j.compmedimag.2015.05.007
0895-6111/

interfaces for the test supervision, yet the scoring is not automated and still relies on the operator's assessment [21,22]. Since inertial sensors are kept more common due to their presence in easily accessible mobile devices, the reliable automatic assessment tools may become a basic and valuable instrument in the elderly care, also in home environment. This, however, requires a comprehensive study on inertial signals features, repeatability, inter-device, inter-subject or even inter-clothe invariance, using the simplest and less expensive or disturbing devices. This paper stands for the primary investigation on the accelerometric signals usefulness in such a task.

In our previous works, we focused on the development of an ambient assisted living (AAL) system for activity monitoring of the elderly in home environment [23,24]. The overall aim of the current research is to ensure well-being of the elderly people who are living (possibly alone) in their homes. Although the patient might be assigned to a higher risk group for falls or fainting, she/he can still live a normal life. The remote AAL supervision should not disturb the patient, and the equipment is supposed to be as simple and cheap as possible. Minor goals include direct incident detection, short-term threat prediction and long-term subject's condition monitoring, able to indicate more or less noticeable decreases in health. Furthermore, we would like to create some sort of a subject-specific model on the basis of one's standard behavior, *e.g.* overall and detailed motion characteristics, activity time distribution, etc. To do so, a remotely accessible computer-aided diagnosis (CAD) [25] AAL system has been proposed [24], employing mobile data acquisition devices with inertial sensors at the lowest level of the architecture. Preliminary study on signal personalization in feature domain has been reported in [26]. Having the entire system prepared and running, as well as some assessment standards as defined above, we can attempt to use the available data to monitor and evaluate the patient's balance abilities.

The ultimate goal of this study is to develop an automatic system of accelerometric signal analysis that supports the balance assessment. Such a solution plugged into the AAL system designed to monitor the patient in home environment is supposed to substantially aid the balance evaluation according to well known standards without a need to visit the hospital. The system is supposed to serve as a long-term objective tool able to evaluate specific activities periodically performed in home environment and remotely supervised by the physiotherapist. Therefore, seven activities from the BBS able to be performed at home have been chosen under the physician's and physiotherapist's supervision. A set of specific signal features have been proposed as premises for the automatic inference system. Most of them are extracted from the medium and high frequency range and thus reflect the directional motion characteristics of the patient. The feature space dimensionality reduction and classifier training and testing have been performed to indicate features most relevant for certain activities and motion patterns.

The paper is organized as follows. After the introduction, all aspects of the methodology are presented in details in Section 2: the sensors description and arrangement, the input data, selected activity types under consideration, feature definition, extraction, and selection techniques, and the expert system specification. Section 3 introduces and summarizes the experimental results. Section 4 concludes the paper.

2. Materials and methods

2.1. System description

The overall scheme of the proposed assessment system is presented in Fig. 1. All experiments described in this paper have been supervised by physicians and physiotherapists. Each activity is

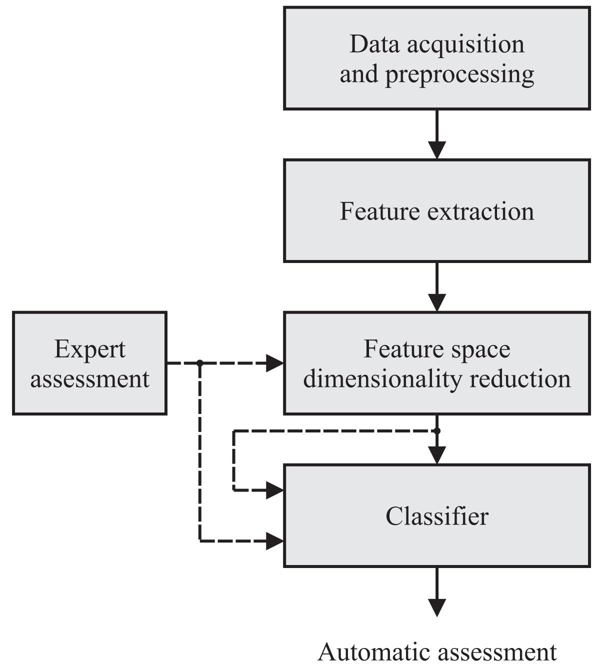

Fig. 1. The automatic balance assessment scheme. Dashed lines indicate training paths.

monitored by five inertial sensors (MPU6050 modules), measuring the acceleration and angular velocity in three directions (Fig. 2).

With sampling frequency f_s set to 100 Hz, each sensor produces two 3-element samples in time t: (1) acceleration $a(t) = \left[a_x(t), a_y(t), a_z(t)\right]^T$ normalized with respect to the gravitational acceleration g and (2) angular velocity $\omega(t) = \left[\omega_x(t), \omega_y(t), \omega_z(t)\right]^T$ in radians per second.

The raw acceleration data from inertial sensors are preprocessed according to procedures described in [26]. This includes *e.g.* the gyroscope data-based virtual sensor rotation to the default position, applied to predict and remove the gravitational acceleration influence on each of the sensor axis using complementary filter [27,28].

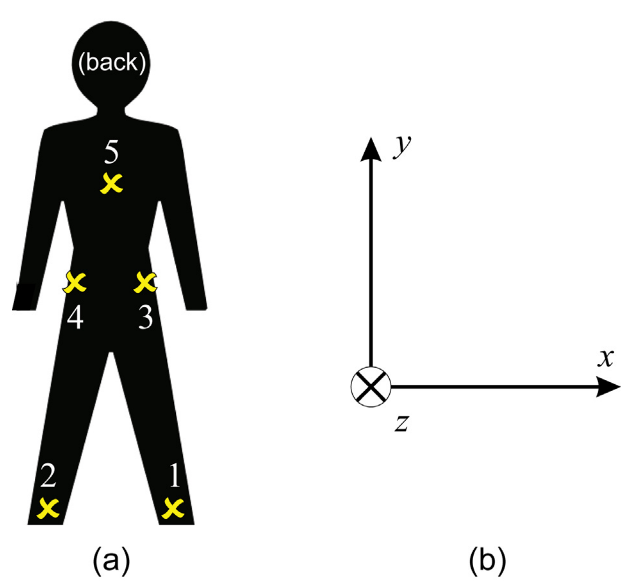

Fig. 2. Inertial sensor locations (a) and coordinate system orientation (b) during experiments.