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Inertial data-based gait metrics correspondence to Tinetti Test and Berg Balance Scale assessments

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ABSTRACT

The analysis of selected gait metrics and their correspondence to human gait and balance abilities is presented in this paper. Accelerometric and gyroscopic data have been acquired from 42 older patients for the entire Berg Balance Scale examination along with expert assessments and additional gait segments of a ca. 1 min duration evaluated by means of the Tinetti Test. The inertial data is analyzed for gait and step detection and subjected to a detailed gait analysis using four metrics for both legs separately: pitch angle change, average duration of step swing and stance phase, and the average phase duration ratio. The analysis is performed offline. The results are compared to expert assessments using Spearman's rank correlation coefficient with $p < 0.001$. Three metrics are yielding high correlation up to 0.797 with outcomes delivered by both considered examinations. Moreover, statistically significant differences are obtained for three metrics produced by patients divided into low and medium fall risk groups (Mann–Whitney *U* test, $p < 0.007$). The values of the temporal metrics are higher and the angle changes are lower in the medium fall risk group. The proposed features enable the assessment of gait quality and may be of great importance while designing novel tools for quick preliminary fall risk prediction.

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1. Introduction

Telemedicine is becoming a meaningful part of health care. Rapid growth of technical resources results in the expansion of ambient assisted living (AAL) technologies [1–3], mostly designed for monitoring older people in the hospital or home environment. Beyond some obvious goals (automatic alerts [4], threat detection [5,6], communication tools [7,8], etc.), such systems might provide more comprehensive data (*e.g.* activity recognition [9,10] and distribution throughout the day [11,12]). The acquired information may lead into the knowledge-based patient-specific model, based on one's standard behavior or motion characteristics [13–15].

Clinical balance assessment tests are typical tools employed for gathering information on patient's physical condition and motion pathologies [16,17]. The tests are performed by a physical therapist or a physician and are based on numerical evaluation of certain activities (gait, changing position, turning, reaching, standing, etc.). For the purposes of further considerations we mention two such tests.

The Berg Balance Scale (BBS) [18] employs 14 tasks for the general balance assessment. Each task is rated by an expert in a 5-level scale (0–4), according to precise specification and guidelines [19]. The resulting total score classifies the patient into one of three groups reflecting one's balance abilities: *high fall risk – wheelchair bound* (0–20), *medium fall risk – walking with assistance* (21–40), or *low fall risk – independent* (41–56). The simplicity, universality, high inter-rater reliability and specificity (both over 95%) [16] of the BBS make the test very popular. Its drawbacks are identified, *i.e.*, in uncertainty between two close scores (an 8-point change is required to indicate a meaningful alteration in the subject's state) [20]. The Tinetti Test (TT) [21,22] consists of two parts: (1) the balance section with a maximum of 16 points to be scored, and (2) the gait section (Tinetti Gait Segment Examination, TGSE). TGSE takes 10 criteria into consideration: (1) walk initiation, (2) step length and (3) height for right foot and (4–5) left foot separately, (6) step symmetry and (7) continuity, (8) deviation from the path, (9) sway of the trunk, and (10) walk stance. For 8 tasks only one point can be given. The assessment of the 8th and 9th task is more complex (two points for each), which gives the maximum score of

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Table 1
Low (26 patients) and *medium* (18 patients) risk of fall patient group summary. Besides Berg Balance Scale (BBS) results, the groups feature statistically different distributions of Tinetti Gait Segment Examination (TGSE) and Activities of Daily Living (ADL) variables (Mann–Whitney *U*-test, $p < 0.05$). IQR – interquartile range.

	Low risk of fall ($BBS \geq 41$)						Medium risk of fall ($21 \leq BBS < 41$)					
	Mean	Std	Med	IQR	Min	Max	Mean	Std	Med	IQR	Min	Max
Weight (kg)	74.1	11.6	73.6	12.7	63	111	72.3	12.7	74.6	12.9	42	93
Height (cm)	157.9	7.0	158.5	7.0	141	169	158.0	8.3	158.0	10.0	139	172
ADL (pts)	5.4	1.0	6.0	1.3	3	6	5.9	0.5	6.0	0.0	4	6
Circumference (cm)												
Arm	26.1	3.7	26.0	3.5	18	36	26.4	3.6	26.5	3.0	16	32
Lower leg	33.4	1.8	33.0	3.0	30	36	32.8	3.1	33.0	3.0	26	40
Waist	91.8	10.4	88.0	8.5	79	125	91.1	11.4	92.5	13.0	63	105
Balance assessment												
BBS (pts)	35.0	4.9	36.5	5.0	23	40	48.2	4.0	48.0	4.0	41	56
TGSE (pts)	7.0	2.1	7.0	2.0	3	11	10.9	1.1	11.0	2.0	8	12

12 points. The total score indicates the patient's susceptibility to falls by classification to one of three groups of certain risk levels. The Tinetti scale with several modifications [23] is a recognized and commonly used tool. The examination of gait may provide an insight into the risk of falls [24,25]. Gait disorders are the cause of 10–20% of all accidents involving older people [26]. Motion quality deteriorates with age and can be evaluated using metrics extracted from each step or longer periods of walking [27]. There are already scales and tests to assess the gait [21,28], but they require the presence of a trained, self-reliant expert and provide neither precise temporal analysis of walking phases nor stride length. The first attempts to make the gait evaluation objective and accessible involved simple tools like markers attached to the patient's heels [29] drawing the path on the floor. Recent papers present a video- [30] or controller-based assessment [31]. However, the introduction of wearable sensors, such as accelerometers or gyroscopes, allows complex automatic or semi-automatic quantitative and qualitative gait feature extraction. It also becomes possible in daily life due to the small dimensions of these sensors [32–34].

In our previous study, an AAL system has been designed for the remote monitoring of older people in a home environment [35]. The general aim of the system covers the computer-aided diagnosis paradigms: the employment of information systems for supporting the physician's knowledge and observations in diagnosis, care, rehabilitation planning, possible immediate interventions in case of threats, etc. The system involves inertial sensors attached to certain body parts [35]. The analysis of accelerometric data has been used for step detection, acceleration trajectory-based feature extraction [36], activity recognition [37], and automatic balance assessment using selected BBS activities [38] and the entire examination [39]. Finding movement features related to the patient's condition could be used in this kind of AAL system to provide the therapists with data on daily trends and tendencies in the patient's fitness, and as a result help in the process of making therapeutic decisions. As such data are gathered remotely, the sudden change in feature values may also be useful as an alarm trigger.

The main goal of this study is to propose new inertial data-based gait features and to investigate a correlation between them and the expert gait and balance assessment scoring. For this purpose, we describe a data acquisition scheme along with the processing technique. Our main contribution is (1) a gait analysis method including the pitch-based gait metrics extraction, (2) a study on correspondences between gait metrics and results of BBS and TGSE. A new approach for gait cycle phases calculation is proposed and referred to the others, previously described in literature. A comprehensive statistical analysis is performed using BBS and TGSE expert assessments for a group of 42 older patients featuring various balance levels. Correlations found between automated analysis and human assessment encourage to involve the inertial measurements and processing tools in diagnosis and monitoring of the patients. The obtained patient-specific thresholds and features may be of great importance while implementing classifiers and designing novel tools for quick preliminary fall risk prediction.

2. Materials and methods

2.1. Subjects

During the experiments, the data were acquired from 42 patients (33 female and 9 male, mean age 77.5 ± 6.4 std) under the care of the John Paul II Geriatric Hospital in Katowice, Poland [40]. The inclusion criterion was the ability to walk a short distance without help. In all cases, the Katz Index of Independence in Activities of Daily Living (ADL) was higher than two, which means that none of the patients showed severe functional impairment [41].

Each patient performed the BBS exercises as well as a gait segment of a ca. 1 min duration, assessed by an expert using TGSE instructions [22]. Based on the BBS results, the patients have been divided into two groups, featuring low ($BBS \geq 41$, 26 patients) and medium ($21 \leq BBS < 41$, 18 patients) fall risk (Table 1). Distributions of TGSE and ADL results were significantly different between the groups (Mann–Whitney *U*-test, $p < 0.05$), which is understandable as these variables describe some aspects of patient's physical independence as well as BBS. Distributions of anthropometric data values were not significantly different between the groups at $p < 0.05$.

No patient had a confirmed drug addiction. Seven reported a past bone fracture (4 in low fall risk, 3 in medium fall risk group). Even though during daily activities seven patients in the medium fall risk group used walking sticks and one patient used a crutch, no kind of any walking aid was employed during the test.

The study received approval from the Bioethics Committee of the Jerzy Kukuczka Academy of Physical Education in Katowice, Poland.

2.2. Signal aquisition

The designed AAL system employs a mobile data acquisition device, which collects data from 5 inertial sensors located at selected body parts (Fig. 1a). Sensor units, including accelerometers and gyroscopes, are attached to closely adjacent garments (belt and suspenders) not to harm patient's skin nor disrupt his/her movements. Each sensor produces accelerometric and gyroscopic signals at a sampling frequency $f_s = 100$ Hz. The preprocessed data are passed through the home endpoint to the telecare center signal processing unit. The detailed AAL system description can be found in [35].

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