Gait & Posture 57 (2017) 204–210

Contents lists available at ScienceDirect

Gait & Posture

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

Review

A systematic review of gait analysis methods based on inertial sensors and adaptive algorithms

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ARTICLE INFO

Keywords:
Gait kinematics
Artificial intelligence
Machine learning algorithms
Inertial measurement unit
Accelerometer

ABSTRACT

The conventional methods to assess human gait are either expensive or complex to be applied regularly in clinical practice. To reduce the cost and simplify the evaluation, inertial sensors and adaptive algorithms have been utilized, respectively. This paper aims to summarize studies that applied adaptive also called artificial intelligence (AI) algorithms to gait analysis based on inertial sensor data, verifying if they can support the clinical evaluation. Articles were identified through searches of the main databases, which were encompassed from 1968 to October 2016. We have identified 22 studies that met the inclusion criteria. The included papers were analyzed due to their data acquisition and processing methods with specific questionnaires. Concerning the data acquisition, the mean score is 6.1 ± 1.62, what implies that 13 of 22 papers failed to report relevant outcomes. The quality assessment of AI algorithms presents an above-average rating (8.2 ± 1.84). Therefore, AI algorithms seem to be able to support gait analysis based on inertial sensor data. Further research, however, is necessary to enhance and standardize the application in patients, since most of the studies used distinct methods to evaluate healthy subjects.

1. Introduction

Human gait corresponds to the physiological way of locomotion, which can be affected by several disorders [1]. Thus, gait analysis plays an important role in clinical practice, it provides information about subject's functional level and can be used for health monitoring to verify the efficiency of rehabilitation and to objectively evaluate surgeries' success [2]. The gold standard technologies for gait analysis are optoelectronic systems [3] that offer high accuracy in measuring kinematic features [4]. Unfortunately, such systems can only be used in large laboratories, as it is expensive and space consuming [5].

Regarding gait analysis, there are different nomenclatures for the classification of the events subdividing the gait cycle in distinct phases. Thus, we will start introducing the nomenclature used in this paper that is suggested by Perry and Burnfield [6]. As displayed in Fig. 1, one gait cycle can be divided into two phases, stance (ST) and swing (SW), which can be subdivided into five and three phases, respectively. Corresponding to the beginning of the ST phase, the initial contact (IC) describes the moment when one part of the foot, in physiologic gait the heel, touches the ground. The loading response (LR) starts with the IC and ends with the contralateral toe-off. Subsequently, the mid stance (MS) lasts until the heel-off of the reference leg. The MS is followed by the terminal stance (TS), which ends with the contralateral IC. The ST phase terminates with the pre-swing (PS), which ends with the toe-off of the reference leg. Considering the SW phase, the initial swing follows the PS and terminates when the ankle joint of the reference leg crosses the supporting leg. This phase is followed by the mid swing, which ends with the tibia of the reference leg being vertical to the ground. The gait cycle is concluded by the terminal swing, which ends with the initial contact of the reference leg.

There are several devices and methods to detect the aforementioned events [7]. Due to its practicality, wearable devices become more popular for providing people the possibility to measure bodily features constantly. Therefore, the request for such technology, which measures gait characteristics either for activity recognition or for gait event classification, has risen lately. The most cost-effective method uses either whole inertial measurement units (IMUs) consisting of gyroscopes, accelerometers, and magnetometers or parts of it to determine kinematic data [8]. The attempt of miniaturizing and mobilizing sensor technology [9] showed encouraging results [8]. These systems are used

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http://dx.doi.org/10.1016/j.gaitpost.2017.06.019
Received 1 February 2017; Received in revised form 20 June 2017; Accepted 22 June 2017

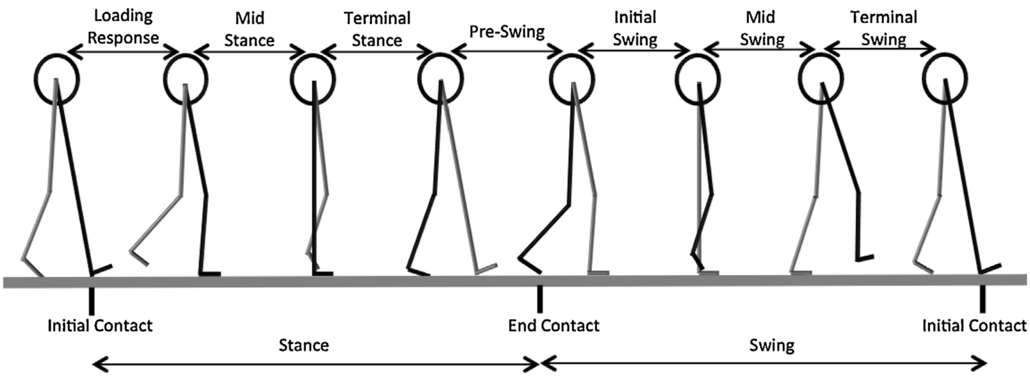

Fig. 1. Different nomenclatures for the gait phases is used in the literature. The terms of the RLAS are used in this review and displayed here.

to measure different kinds of kinematic gait data for diverse applications: functional electrical stimulation (FES) [9–11], gait initiation and termination [12], abnormal gait detection [13–18] and real-time applications [19–23].

In addition to the simultaneous acquisition of information from different joints involved in the movement pattern, the system must be able to deal with the complexity of processing such data in short time. In this context, artificial intelligence (AI), also called adaptive, algorithms have been applied to evaluate gait data, which was acquired either based on optoelectronic systems or inertial sensors [2,24]. Such algorithms are able to adapt their decision-making process based on the input data, despite its variability. Most importantly, adaptive algorithms can simplify the walking evaluation.

Our overarching goal in this article is to summarize those studies that applied adaptive algorithms to gait analysis based on inertial sensors data, to verify whether these algorithms are able to support the evaluation of different kinematic gait parameters. Therefore, the accuracy in determining gait phases, spatiotemporal features and joint angles of former published studies is stated and compared. Furthermore, by systematically reviewing the literature, we intend to proof the following hypotheses: (i) IMU systems are able to acquire gait kinematic parameters such as walking phases, spatiotemporal features and joint angles; (ii) adaptive algorithms can accurately classify gait events; (iii) the classification performed by the AI algorithms is relevant to the clinical practice.

2. Methods

2.1. Study identification and selection

A systematic literature search was conducted to find related works to the research hypotheses posed here. The review process was divided into four phases as shown in Fig. 2. As this review is related to engineering and medicine, an automated search in the main databases available, namely, Web of Science, ScienceDirect, IEEE, PubMed/MEDLINE, SCOPUS, CINAHL and Cochrane Library was undertaken to identify relevant publications. The search terms used were defined as *(gait OR walking OR locomotion) AND (analysis OR evaluation OR assessment) AND (inertial sensor OR inertial measurement unit (IMU) OR accelerometer OR gyroscope OR smart phone) AND (artificial intelligence OR machine learning OR adaptive algorithm OR intelligent algorithm)*. Publications in English, German, Portuguese and Spanish were considered. The publication period investigated was from 1968 to October 2016. Studies evaluating kinematic gait parameters – joint angles, gait phases or spatiotemporal features – of healthy or impaired subjects were only included if they used artificial intelligence for processing data which was acquired using inertial measurement units, accelerometers or gyroscopes. In the second phase, titles and abstracts were screened and publications, which did not meet the aforementioned criteria, were excluded. In the third phase, the full texts of the remaining publications were assessed and those that were ineligible, for not covering the set criteria, were excluded. In the fourth phase, all remaining publications were evaluated and the references checked for further publications, which could be included in this review.

2.2. Type of studies

Journal papers comparing the results using inertial sensors and artificial intelligences to any kind of generally accepted measurement system are the basis of this review. Book chapters, review papers and conference proceedings were excluded. Furthermore, studies which did not use IMUs exclusively or which used algorithms that could not be considered adaptive were excluded.

2.3. Data extraction

Two independent researchers performed the data extraction and the results were compared afterwards. Disagreements were discussed and solved in light of strict observance of the set criteria. In exceptional cases they disagree, a third researcher was consulted. Considering the methodological quality, the two reviewers focused on the following topics: sample; description of the study; type of sensor; sensor placement on the body; generally accepted measurement system used.

2.4. Quality assessment

The quality assessment of the included studies was divided into two different topics. Using the Critical Appraisal Skills Program (CASP) for Diagnostic Test Studies [25], the quality of data acquisition of the studies was individually assessed. To assess the quality of the adaptive algorithm used, the questionnaire developed by Wen et al. [26] was adopted. Both questionnaires comprise ten questions and each question has only three optional answers: "Yes", "No" and "Partly", in case there was not enough information. These three answers are scored as follows: "Yes" = 1.0, "Partly" = 0.5, and "No" = 0.0. As this review combines the fields of medicine and engineering, both quality assessment tools are not used as exclusion criteria, but as possibilities to objectively compare the different publications considering the relevant aspects of the topics examined.

3. Results

This section was divided into three parts. The first subsection deals with the results gathered from the CASP and the second subsection provides information about the analysis and rating of the adaptive algorithms used. The third one summarizes the gait parameters evaluated in the different studies and provides information about the sensor placement, sensor type, and measurement accuracy. The literature search yielded 22 journal papers that met the inclusion criteria (Fig. 2).