Gait & Posture 63 (2018) 124–138

Contents lists available at ScienceDirect

Gait & Posture

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

Review

The use of wearable devices for walking and running gait analysis outside of the lab: A systematic review

Lauren C. Benson[a,*], Christian A. Clermont[a], Eva Bošnjak[a], Reed Ferber[a,b,c]

[a] Faculty of Kinesiology, University of Calgary, 2500 University Dr. NW, Calgary, AB, T2N 1N4, Canada
[b] Faculty of Nursing, University of Calgary, 2500 University Dr. NW, Calgary, AB, T2N 1N4, Canada
[c] Running Injury Clinic, 2500 University Dr. NW, Calgary, AB, T2N 1N4, Canada

ARTICLE INFO

Keywords:
Wearable devices
Gait
Walking
Running

ABSTRACT

Background: Quantitative gait analysis is essential for evaluating walking and running patterns for markers of pathology, injury, or other gait characteristics. It is expected that the portability, affordability, and applicability of wearable devices to many different populations will have contributed advancements in understanding the real-world gait patterns of walkers and runners. Therefore, the purpose of this systematic review was to identify how wearable devices are being used for gait analysis in out-of-lab settings.

Methods: A systematic search was conducted in the following scientific databases: PubMed, Medline, CINAHL, EMBASE, and SportDiscus. Each of the included articles was assessed using a custom quality assessment. Information was extracted from each included article regarding the participants, protocol, sensor(s), and analysis.

Results: A total of 61 articles were reviewed: 47 involved gait analysis during walking, 13 involved gait analysis during running, and one involved both walking and running. Most studies performed adequately on measures of reporting, and external and internal validity, but did not provide a sufficient description of power. Small, unobtrusive wearable devices have been used in retrospective studies, producing unique measures of gait quality. Walking, but not running, studies have begun to use wearable devices for gait analysis among large numbers of participants in their natural environment.

Conclusions: Despite the advantages provided by the portability and accessibility of wearable devices, more studies monitoring gait over long periods of time, among large numbers of participants, and in natural walking and running environments are needed to analyze real-world gait patterns, and would facilitate prospective, subject-specific, and subgroup investigations. The development of wearables-specific metrics for gait analysis provide insights regarding the quality of gait that cannot be determined using traditional components of in-lab gait analyses. However, guidelines for the usability of wearable devices and the validity of wearables-based measurements of gait quality need to be established.

1. Introduction

Quantitative gait analysis is an important clinical tool for both walking and running, and is commonly used to assist diagnosis and treatment of gait abnormalities, inform surgical procedures, and evaluate treatment effects [1–4]. Basic spatiotemporal gait parameters (e.g. step and stride length, step and stride time, cadence, speed) can be computed with minimal equipment, while more advanced measurement techniques can be used to determine kinematic (e.g. joint angles, angular velocity) and kinetic (e.g. ground reaction force, joint moments, joint power) variables [2]. However, the gold standard for these advanced techniques requires expensive 3D motion capture and force plate equipment, and trained personnel are needed to collect and analyze the data in what is typically a time-consuming process [3]. This not only limits the accessibility to these advanced gait analysis systems to select clinical and research facilities, but gait analyses conducted in this manner do not necessarily capture how an individual walks or runs in a real-world setting [5].

Wearable devices, on the other hand, are portable and affordable [6]. As a top worldwide fitness trend to improve health [7], wearable devices have become integrated into the daily lives of consumers [8], including healthy individuals [9], older adults [10], and those with chronic illnesses [11]. Evidently, wearable devices represent an opportunity to quantify the movement patterns of all types of individuals

* Corresponding author.
E-mail addresses: lauren.benson@ucalgary.ca (L.C. Benson), christian.clermont@ucalgary.ca (C.A. Clermont), eva.bosnjak@ucalgary.ca (E. Bošnjak), rferber@ucalgary.ca (R. Ferber).

https://doi.org/10.1016/j.gaitpost.2018.04.047
Received 13 October 2017; Received in revised form 20 March 2018; Accepted 28 April 2018
0966-6362/

in real-world settings. Sensors such as accelerometers, gyroscopes, and magnetometers [12], applied individually or in combination as an inertial measurement unit [13], have become a common alternative to the expensive and strictly lab-based methods of quantifying gait patterns, and recent systematic reviews have been published describing this trend [12,13]. Yet, these reviews often focus on a particular population (e.g. older adults [14], Parkinson's disease [15,16]), or walking [17] or running [18] exclusively. Since gait analysis methods are not exclusive to one population or type of gait, the use of wearable devices in one situation may be applicable in others. Therefore, a review that encompasses both walking and running as well as studies of multiple populations can provide a comprehensive summary of the state of wearables-based gait analysis. Additionally, even though wearable devices are well-suited for gait analyses in real-world settings, previously published studies often used wearable devices in gait labs or during contrived experiments. These analyses may not represent typical walking or running conditions since previous research using wearable devices for gait analysis have shown differences in walking [19] and running [20] patterns between treadmill and overground surfaces, as well as between clinical and daily-life overground walking conditions [21].

In recent years, studies have explored the use of wearable technology to analyze out-of-lab walking and running gait patterns. It is expected that the portability, affordability, and applicability of wearable devices to many different populations will have contributed advancements in understanding the real-world gait patterns of walkers and runners. However, considering the many different protocols, devices, and environments featured in these investigations, it is important to summarize the existing literature and assess the quality of this body of work. Therefore, the purpose of this article was to provide a systematic review of studies that have utilized wearable devices for gait analysis in out-of-lab settings. Specifically, the review's aims were to identify the goals and outcomes of the studies, participants, gait analysis environment, wearable device characteristics, and the features extracted from the wearable device signals. Considering the differences between the capabilities of wearable devices and traditional gait analysis systems, the following findings were anticipated: (i) gait analyses would be performed during long walking and running bouts within a single session (e.g. all waking hours or a complete training run) and/or during the course of many sessions (e.g. a full week or an entire training program), which would facilitate prospective studies and the development of subject-specific models of gait patterns; (ii) studies would include large numbers of participants, which would facilitate the identification of subgroups of walking and running patterns; (iii) gait analyses would be performed in the participants' actual walking or running environment, and not just a controlled out-of-lab setting; (iv) wearable devices would be small, easy to use and unobtrusive, while containing the necessary hardware components for the desired gait analysis; (v) the features extracted from the wearable device signals would provide information regarding the quality – not just quantity – of gait, using variables unique to the wearable device gait analysis process.

2. Methods

2.1. Eligibility criteria

The focus of this review was on journal articles or conference proceedings published in English since the year 2001 that described the use of wearable devices to assess gait quality during walking or running outside of a laboratory setting. Book chapters and review papers were excluded. Studies were excluded if their sole purpose was the determination of step counts or level of physical activity, classification or recognition of types of physical activity, biometric identification, quantification of pedestrian navigation, the testing of new techniques or systems related to wearable devices, or the use of wearables for any purpose other than gait analysis. Additionally, if the study protocol involved the use of robotic orthoses, exoskeletons, virtual reality environments, gait analysis during a clinical test (e.g. Timed Up and Go) or other prescribed mental or motor task (e.g. dual task or scripted task that mimics daily life), or gait analysis while walking or running on a treadmill or constrained (less than 200 m) walkway, then that portion of the study was not considered for this review.

2.2. Search strategy and study selection

The review process was completed in four steps. First, potentially relevant records were identified through a systematic search for published papers in the following scientific databases: PubMed, Medline, CINAHL, EMBASE, and SportDiscus. The search terms used were *(wearable* OR inertial sensor* OR inertial measurement unit* OR gyroscope* OR magnetometer* OR acceleromet* OR cell phone OR smart phone*) AND (gait OR run* OR walk* OR jog* OR kinematic* OR biomechanic* OR acceleration* OR center of mass OR centre of mass OR center of gravity OR centre of gravity OR cadence OR step length OR step width OR step time OR stride length OR stride time OR stance phase OR swing phase OR stance time OR swing time OR single support OR double support OR ground contact OR gait speed OR walking speed OR running speed OR heel strike OR heel-strike OR toe off OR joint adj4 angle OR hip adj4 angle OR knee adj4 angle OR ankle adj4 angle)*, where '*' indicates that the search term can have any ending, and 'adj4' searches for both terms within four words of each other. The search of the databases was completed on May 24, 2017. In the second phase, the title and abstract of all records identified through database searching were screened for relevance. If the record appeared relevant or if relevance was not immediately clear, the full text of the article was retrieved. All records deemed irrelevant based on title and abstract screening were excluded. Third, the full text records were read, and eligibility was determined using the eligibility criteria defined above. In the fourth stage, relevant information was extracted from the records that were included, and the quality of each record was assessed. Additionally, the references of all included studies were checked for additional publications that could be included in this review. At all stages of the study selection process, decisions regarding inclusion or exclusion were made by two authors (LB and EB), with a third author (CC) serving as the tie-breaker.

2.3. Data extraction

Information was extracted from each included article regarding the participants, protocol, sensor(s), and analysis. Participant information included number and type of participants, age, and sex. Information about the type, brand/model, size, weight, sampling frequency, range, and location on the body of each wearable sensor was also recorded. The study protocol included information about the environment (i.e. indoor or outdoor, type of surface, or location), as well as the speed and distance or time the gait analysis was conducted. If participants ambulated at a comfortable speed but were required to maintain that speed, the speed was labeled "self-selected." If participants were able to walk at their own pace without restriction, the speed was labeled "not controlled." Analysis information included a record of all variables computed from each wearable sensor signal.

2.4. Quality assessment

The quality of each of the included articles was assessed using a custom quality assessment worksheet (Table 1). This worksheet was adapted from the methods of quality assessment outlined by Campos et al. [22] and Downs and Black [23]. Each article was evaluated by two authors (LB and CC) on 13 questions that considered the reporting, external validity, internal validity and power of the study. Each question had three possible answers: "Yes", "No", or "Unable to determine." Any discrepancies in scoring between authors were discussed until an agreement was reached. As this review represents a qualitative