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Review

Quantified self and human movement: A review on the clinical impact of wearable sensing and feedback for gait analysis and intervention

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ABSTRACT

The proliferation of miniaturized electronics has fueled a shift toward wearable sensors and feedback devices for the mass population. Quantified self and other similar movements involving wearable systems have gained recent interest. However, it is unclear what the clinical impact of these enabling technologies is on human gait. The purpose of this review is to assess clinical applications of wearable sensing and feedback for human gait and to identify areas of future research. Four electronic databases were searched to find articles employing wearable sensing or feedback for movements of the foot, ankle, shank, thigh, hip, pelvis, and trunk during gait. We retrieved 76 articles that met the inclusion criteria and identified four common clinical applications: (1) identifying movement disorders, (2) assessing surgical outcomes, (3) improving walking stability, and (4) reducing joint loading. Characteristics of knee and trunk motion were the most frequent gait parameters for both wearable sensing and wearable feedback. Most articles performed testing on healthy subjects, and the most prevalent patient populations were osteoarthritis, vestibular loss, Parkinson's disease, and post-stroke hemiplegia. The most widely used wearable sensors were inertial measurement units (accelerometer and gyroscope packaged together) and goniometers. Haptic (touch) and auditory were the most common feedback sensations. This review highlights the current state of the literature and demonstrates substantial potential clinical benefits of wearable sensing and feedback. Future research should focus on wearable sensing and feedback in patient populations, in natural human environments outside the laboratory such as at home or work, and on continuous, long-term monitoring and intervention.

1. Introduction

The miniaturization of sensing, feedback, and computational devices has opened a new frontier for gait analysis and intervention. Wearable systems are portable and can enable individuals with a variety of movement disorders to benefit from analysis and intervention techniques that have previously been confined to research laboratories and medical clinics. Consumer demand for wearable computational devices such as smart phones has driven down the cost of sensing and actuation components, while simultaneously pushing technological development to enable long-term (hours and days) of continuous use. Thus, there is increasing potential for wearable sensing and feedback systems to provide significant clinical benefits to the broader population.

Increasingly, individuals are joining societal movements such as quantified self [1], life log [2], and Sousveillance [3] and amassing large amounts of personal information through automated wearable systems. In addition, as the distribution of commercial wearable systems, such as Nike + Fuelband, FitBit, Jawbone UP and Google Glass, spreads, societies are moving toward a point where the tracking and feedback of daily information related to walking, working, eating, and sleeping is standard. One aspect of this technological transformation which holds particular interest is that of wearable systems for clinical gait assessment and intervention.

Wearable sensing has long been suggested as a means of measuring human movements [4]. Recent technological advances

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have produced sensors that are smaller, lighter, and more robust than previous versions and are often combined with portable computation devices, such as smartphones, for a variety of applications [5]. The small size and light weight of accelerometers, gyroscopes, and magnetometers make these a convenient and practical choice for mobile measurements, and the combined packaging of accelerometers and gyroscopes in an inertial measurement unit [6] or accelerometers, gyroscopes, and magnetometers in a magnetometer-accelerometer-rate-gyro [7] have further facilitated the ease-of-use. These advances have enabled new opportunities, not previously possible, to utilize technology for human movement analysis and intervention. Simple systems involving a single accelerometer or a foot switch have been used to detect various spatiotemporal parameters such as step count, stride length, cadence, and walking speed [8–11], while more complex systems have been created with arrays of accelerometers, gyroscopes, and magnetometers worn across the body to measure joint and segment kinematics [6,12–14].

While wearable sensing enables gait assessment, wearable feedback facilitates gait intervention. Wearable haptic (touch) feedback has been used to facilitate gait changes in foot progression angle [15], tibia angle [16], and medio-lateral trunk tilt [16–18]. Wearable haptic feedback has also been used to alter knee loading patterns during gait by alerting users of center of pressure values [19] or knee loading measurements [20]. Wearable auditory feedback has been used to improve balance through modifying trunk displacement [21].

Although more and more people are incorporating wearable systems into their daily lives, the clinical applications providing societal benefits of these systems are unclear. We undertook this review to determine the clinical applications of wearable sensing and feedback for human gait assessment and intervention. Analysis of these applications could suggest future research in which wearable systems could benefit society by enhancing mobility, and treating and preventing neuromusculoskeletal disease.

2. Methods

2.1. Literature search strategy

A literature search was performed for articles published through March 6, 2013 using the following databases: Medline (1950-), Science Citation Index Expanded (SCI-EXPANDED) (1900-), Cumulative Index to Nursing and Allied Health Literature (CINAHL) (1981-), and Cochrane Central Register for Controlled Trials (COCHRANE) (1966-). The search focused on retrieving articles that included the following elements: wearable AND gait AND (sensing OR feedback) (see Table 1 for specific search terms). The search was limited to articles published in English and excluded dissertations, theses, conference proceedings, and conference abstracts.

2.2. Inclusion and exclusion criteria

Two reviewers (PBS and WJ) independently reviewed all titles and abstracts of articles retrieved from the databases search. Inclusion/exclusion disagreements were resolved by consensus. The full text was then retrieved and further reviewed for all articles that could not be excluded based on the title and abstract alone.

Articles were included which involved a system with wearable sensing or wearable feedback used to either assess or train human gait. Wearable, or body-worn, was defined as being supported off the ground by the body. Wearable examples could include: an accelerometer strapped to the shoe, headphones worn in the ears, a visual display held in the hand, a vibration motor taped to the body, or a gyroscope in a backpack worn on the back. Wearable sensing and feedback were required to report values of at least one of the following: (1) segment kinematics of the foot, shank, thigh, pelvis, or trunk; (2) joint kinematics of the ankle, knee, or hip; (3) joint moments of the ankle, knee, or hip; or (4) joint forces in the ankle, knee, or hip. Because other articles have reviewed wearable systems for measuring spatiotemporal parameters [8], for physical activity identification [22], and for electromyographic (EMG) measurements [23], we included articles focused on spatiotemporal parameters, physical activity identification, and wearable EMG only when they also targeted at least one of the required gait parameters listed in the previous sentence. Wearable feedback studies were required to alert the user to modify at least one of the gait parameters listed above through one of the five senses: sight, hearing, touch, smell, or taste.

Table 1
Specific search terms used in the systematic literature review. In general the search focused on retrieving articles which involved elements of: wearable AND gait AND (sensing OR feedback). * Indicates wildcard for the rest of the term.

General	Specific search terms
Wearable	portab* OR weara* OR attach* OR strap* OR tape*
	AND
Gait	gait OR walk* OR jog OR run OR runn* OR ambulat* OR locomot*
	AND
Sensing OR feedback	sensin* OR acceler* OR gyro* OR magnatom* OR imu OR feedb* OR biofeedb* OR real-time* OR haptic* OR vibra* OR vibro* OR visual* OR touch* OR audito* OR train* OR retrain* OR altered* OR modific*

Articles were excluded for movement activities other than gait. Articles were excluded that did not involve living human subjects, such as animal studies or human cadaver experiments, as were articles that did not involve primary research. Studies that initiated involuntary gait modifications, such as wearable robotic rehabilitation or powered exoskeletons, were also excluded as this has been the subject of previous review [24]. Bibliographies of articles from the databases search passing the inclusion/exclusion criteria were searched recursively for other potentially eligible articles.

2.3. Data extraction

Two reviewers (PBS and WJ) carefully read and extracted the following data from each included study: study design (sensing, feedback, or both); subject type (e.g. healthy, osteoarthritis, or Parkinson's disease); walking surface (e.g. overground or treadmill); gait parameters (segment orientations, joint kinematics, joint moments, and joint forces); sensor type (e.g. accelerometer or potentiometer); feedback sensation type (e.g. touch or vision).

3. Results

In total, 1344 articles were retrieved from the literature search (Fig. 1). A critical examination of the titles and abstracts using the pre-determined inclusion and exclusion criteria produced 116 remaining articles, and the full text review ultimately yielded 76 articles that satisfied all the inclusion criteria. The publication dates of included articles spanned from 1969 to 2013, and 70% of the articles were published in the last 10 years.

The majority of articles involved testing on healthy subjects alone (Table 2). For articles involving patient populations, osteoarthritis was the most common, followed by vestibular loss, Parkinson's disease, and hemiplegia. Sixty-four articles involved studies with only wearable sensing, 3 articles involved only wearable feedback, and 9 articles involved both wearable sensing and wearable feedback. Studies with only wearable feedback used grounded cameras and marker-based motion capture for sensing [16,19,20]. In most studies, gait trials were performed overground (58 articles). In 8 articles, gait trials were performed on a treadmill, and in 7 articles, trials were performed both overground and on a treadmill. Two studies did not report where gait trials were performed, and one study performed gait trials on a mini-trampoline.

3.1. Sensing for human gait

The most common wearable sensor for measuring gait was the inertial measurement unit (Table 3). An inertial measurement unit, or IMU, is comprised