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A wearable smartphone-enabled camera-based system for gait assessment

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ABSTRACT

Quantitative assessment of gait parameters provides valuable diagnostic and prognostic information. However, most gait analysis systems are bulky, expensive, and designed to be used indoors or in laboratory settings. Recently, wearable systems have attracted considerable attention due to their lower cost and portability. In this paper, we present a simple wearable smartphone-enabled camera-based system (SmartGait) for measurement of spatiotemporal gait parameters. We assess the concurrent validity of SmartGait as compared to a commercially available pressure-sensing walkway (GaitRite®). Fifteen healthy young adults (25.8 ± 2.6 years) were instructed to walk at slow, preferred, and fast speed. The measures of step length (SL), step width (SW), step time (ST), gait speed, double support time (DS) and their variability were assessed for agreement between the two systems; absolute error and intra-class correlation coefficients (ICC) were determined. Measured gait parameters had modest to excellent agreements (ICCs between 0.731 and 0.982). Overall, SmartGait provides many advantages and is a strong alternative wearable system for laboratory and community-based gait assessment.

1. Introduction

Assessment of spatiotemporal gait patterns provides essential information regarding functional ability, stability, fall risk, selection of therapeutic intervention, assessment of patient progress, and mortality [1–6]. In fact, gait speed has been described as a 'vital sign' due to the important information it provides regarding current and predicted health status [2]. New gait assessment technologies are continually emerging, but currently available devices and systems have a number of limitations. The most accurate systems that provide a full set of gait measures are laboratory-based system which are usually expensive, and require trained personnel. For example, the Optotrak Certus (NDI, Canada) has accuracy of up to 0.1 mm and resolution of 0.01 mm [7], but the system is expensive and requires training. These systems by their nature lack field assessment capability, thus cannot provide a window into typical gait behavior when a person is completing everyday tasks including adaptations to multiple obstacles, such as stairs, ramps, curbs, and gravel [8]. In order to understand gait behavior in challenging environments, such obstacles have been replicated in the lab. While a dozen or so steps are typically captured and quantified in these replicated environments, hundreds of steps are recommended to reliably assess step width and gait speed variability [9,10].

Wearable devices based on inertial sensors can be adapted for field assessment (e.g. Physilog, GaitUp, Switzerland). Such systems extrapolate the gait measurement from the inertial sensors. Wearable devices provide a limited set of gait measures, most commonly number of steps, speed, step length (SL), and/or step time (ST) [11–14]. In addition, measurement of SL using inertial sensors requires assessment of displacement, which cannot be measured directly with inertial sensors. The acceleration signal must be integrated twice to determine displacement, but the result is confounded by the unknown constants that result from integration. These inertial-based devices require steady-state gait (i.e., excluding initiation and termination steps) and cannot

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measure step width (SW) and its variability, which are key parameters in assessing stability and fall risk [1,3,15,16]. Portable video recording enables a more accurate assessment technique. For example, iWalker is a system that utilizes a pair of cameras mounted on the rollator frame to capture step width [17]. This system, however, is limited to the people who use rollators and cannot be adopted for wider population. In this paper, we describe a new wearable device based on video recording from a smartphone camera mounted on the waist of an ambulatory user that provides the assessment of the measures of other wearable devices, but also SW and SW variability. After outlining the hardware and software modules of our system (SmartGait), we determine its concurrent validity with a pressure-sensing walkway (GaitRite, CIR Systems, New Jersey, USA) [16,18,19]. GaitRite was chosen as a comparison device due to its validity [18,20] and widespread use as a clinical and research tool.

2. Materials and methods

2.1. Hardware

SmartGait hardware consists of a smartphone (Apple, iPhone 5s), a custom-designed waist belt with a holster, a detachable 90-degree wide-angle lens (Mondizen Inc., Hilo), and two colored circular foot markers (attached on the foot dorsum and centered over the proximal phalanges) (Fig. 1).

SmartGait utilizes the embedded camera of the smartphone to enable real-time assessment of gait parameters with 60 Hz sampling rate. To capture foot markers on shoes while the smartphone is in a vertical position, the viewing angle of the camera is converted from front-facing to floor-facing by using a 90-degree lens. The smartphone with the lens affixed is placed in the holster case and attached to the front of a belt. The belt has a reinforced front region to support the weight of the smartphone (iPhone5s weight is 112 g) and a 5 cm adjustable rod between the holster and the belt to reduce camera obstruction by the thighs and clothes while walking. The smartphone angle can be adjusted on the rod to optimize video capture of the feet markers. The circular foot markers can be any color that is highly visible and can be distinguished from the surroundings (e.g., bright green markers, $d = 4.6$ cm).

2.2. Image processing application software in smartphone

A custom software application (Xcode 5.0.2, Apple) has been developed with the target platform of iOS8 (Apple). The software algorithm has three phases: (1) the image-processing phase (Fig. 2a, left column), (2) the on-board gait assessment phase (Fig. 2a, middle column); and (3) the off-board optional post-processing gait analysis phase (Fig. 2a, right column).

The image-processing phase begins with raw image capture in RGB (Red, Green, Blue) format (Fig. 2b) of the feet and markers. This is converted to HSV (Hue, Saturation, Value) format for increasing the color of foot marker contrast with respect to the environment, resulting in a threshold image (Fig. 2c and d). In the final step, minimum circle contours are drawn over foot markers in order to identify the Cartesian coordinates of the right and left foot in pixel units (Fig. 2e).

2.3. On-board gait analysis

On-board assessment provides measurement of SL, SW, ST, and speed and begins with a standing calibration: the smartphone is mounted on the belt, and the participant stands still with the feet together. The angular position of the smartphone is adjusted such that both foot markers are visible and aligned on a reference line on the smartphone screen (Fig. 2b). The calibration factor (pixels to cm) is determined for the standing position. Note that the calibration factor will change as the distance between the camera and the foot changes during the gait; this is included in the off-board processing (termed dynamic calibration of unit distance). On-board processing, however, relies on this single standing

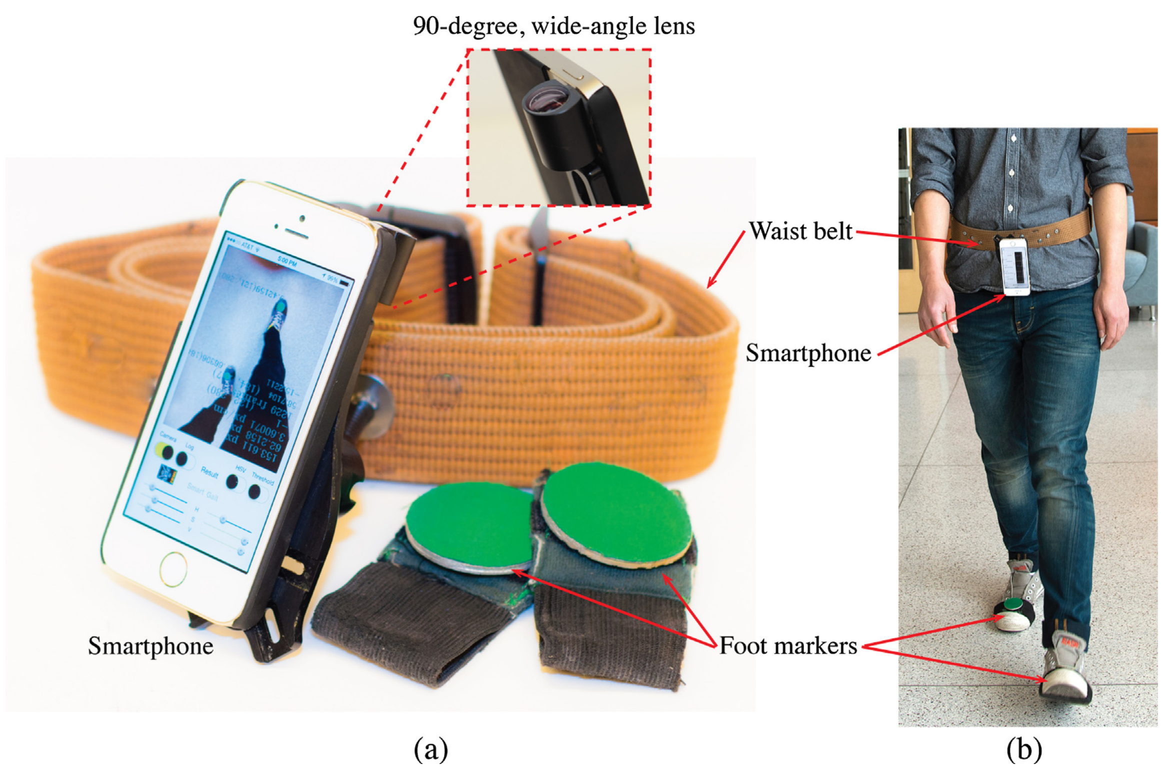

Fig. 1. Photograph of: (a) SmartGait system and its various hardware components and (b) a participant wearing the SmartGait.