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Short communication

A smart device inertial-sensing method for gait analysis

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ABSTRACT

The purpose of this study was to establish and cross-validate a method for analyzing gait patterns determined by the center of mass (COM) through inertial sensors embedded in smart devices. The method employed an extended Kalman filter in conjunction with a quaternion rotation matrix approach to transform accelerations from the object onto the global frame. Derived by double integration, peak-to-trough changes in vertical COM position captured by a motion capture system, inertial measurement unit, and smart device were compared in terms of averaged and individual steps. The inter-rater reliability and levels of agreement for systems were discerned through intraclass correlation coefficients (ICC) and Bland–Altman plots. ICCs corresponding to inter-rater reliability were good-to-excellent for position data (ICCs,.80–.95) and acceleration data (ICCs,.54–.81). Levels of agreements were moderate for position data (LOA, 3.1–19.3%) and poor for acceleration data (LOA, 6.8%–17.8%). The Bland–Altman plots, however, revealed a small systematic error, in which peak-to-trough changes in vertical COM position were underestimated by 2.2 mm; the Kalman filter's accuracy requires further investigation to minimize this oversight. More importantly, however, the study's preliminary results indicate that the smart device allows for reliable COM measurements, opening up a cost-effective, user-friendly, and popular solution for remotely monitoring movement. The long-term impact of the smart device method on patient rehabilitation and therapy cannot be underestimated: not only could healthcare expenditures be curbed (smart devices being more affordable than today's motion sensors), but a more refined grasp of individual functioning, activity, and participation within everyday life could be attained.

1. Introduction

For years, kinematic and kinetic analyses have been confined to clinical settings and conventional lab-based equipment, such as 3D motion capturing systems and force plates (Horvath et al., 2001; Sutherland, 2002). Although the brunt of current evidence suggests that clinical gait analysis noticeably enhances the diagnostic and treatment process, whether it equally impacts patient outcomes and social well-being remains equivocal (Wren et al., 2011). More specifically, it is cumbersome in that its data acquisition procedures are often time-consuming, its lab equipment is costly and requires trained personnel (Henriksen et al., 2004), and it cannot consistently account for a subject's daily functioning (Baker, 2006).

Wearable motion-sensing systems emerge as a preferable research option in many cases, as they are portable, more affordable than their laboratory counterparts, widespread, and relatively easy to operate (Steins et al., 2014). Contemporary gait analysis studies, in fact, draw upon wearable system applications founded on inertial measurement units (IMUs), because they can assess gait patterns and mobility levels with a reliability that cannot be gleaned solely through accelerometers (Giansanti et al., 2003; Kavanagh and Menz, 2008).

Advances in wearable systems render smart devices, such as the iPod Touch, available for remote computing purposes. Already containing an IMU attuned to the device's orientation, such smart technology possesses the potential to measure those physical parameters (e.g. linear acceleration, angular velocity) necessary for non-clinical measurements. Until now, studies have exclusively examined a smart device's tri-axial accelerometer's capacity (Lemoyne et al., 2010; LeMoyne et al., 2011) and feasibility (Chan et al., 2011; Nishiguchi et al., 2012; Yang et al., 2012) for gait analysis, indoor localization (Rui et al., 2013), and evaluation of motion data quality (Nymoen et al., 2012). A smart device's inertial

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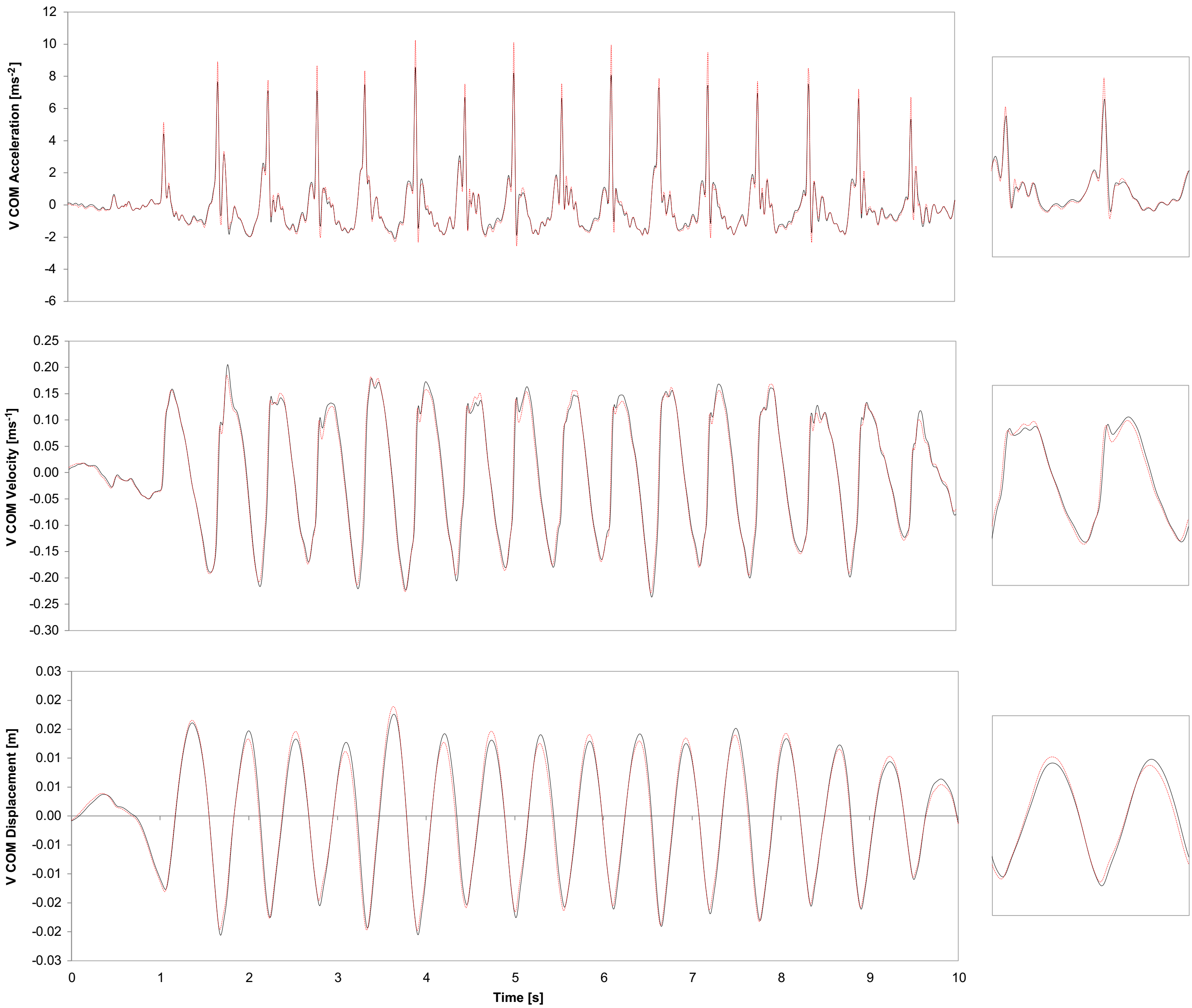

Fig. 1. A standard COM plot of the vertical acceleration, velocity, and displacement pattern during a 10 m walking trial. The gait pattern slightly changes when transposed from the object onto the global frame; black line represents the object frame and the red dotted line represents the transposed data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

sensing capabilities, however, have not been explored, despite their potential to track gait characteristics with the reliability and accuracy defining the gold standard 3D motion capture system (Wong et al., 2007) or conventional inertial sensor (Esser et al., 2009).

Addressing such critical gaps, this study aims to: (1) propose a method relying on a smart device's inertial sensors that reliably measures the body's COM trajectories in the global frame, and (2) assess this method's validity against that of a 3D motion capture system and conventional IMU for averaged and individual step data.

2. Materials and methods

Overground walking was studied in ten subjects: age 25.6 ± 3.5years, height 1.73 ± .17 m, and mass 73.0 ± 17.1 kg. For four times at self-selected speeds, all subjects walked over a 10 m straight walkway arranged in a gait laboratory.

Linear accelerations of the lower trunk were measured by two inertial measurement units: one Xsens 3-DOF inertial sensor (MTx, Xsens Technologies, Netherlands) with a measurement range of ±2 g, and one inertial sensor-embedded smart device (iPod Touch 4th generation, iOS operating system version 6.0.1, Apple, UK) with a measurement range of ±2 *g* and 16 bit data output. Like the iPhone 4 and 5, the iPod Touch contains an LIS331DLH tri-axial accelerometer and L3G4200D tri-axial gyroscope manufactured by STMicroelectronics. The Xsens inertial sensor was attached to the iPod with double-sided adhesive tape and secured on the dorsal side of the subject's lower trunk at the level of the third lumbar vertebrae—a positioning considered reliable for gait analysis (Henriksen et al., 2004) because closely reflecting actual COM accelerations during walking (Moe-Nilssen, 1998). Global axes were defined as follows: positive *X* values denoted anterior acceleration; positive *Y* values, right acceleration; and positive *Z* values, upward acceleration.

A retro-reflective marker was additionally positioned over the middle of the Xsens sensor to measure trunk displacement with an optical motion capture system (Oqus 300, Qualisys, Sweden). A total of six cameras were employed to obtain a high resolution of the calibrated volume. Xsens and Qualisys data were both measured at 100 Hz, whereas the iPod was consistently sampled at around 100 Hz (±2 Hz).

2.1. Data processing

Accelerometers generally measure some degree of gravitational acceleration, depending on the sensor's degree of deviation from the global horizontal. Any misalignment contaminates linear acceleration data (Kavanagh and Menz, 2008) and was therefore preemptively corrected.