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Accuracy of angular displacements and velocities from inertial-based inclinometers

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ABSTRACT

The objective of this study was to evaluate the accuracy of various sensor fusion algorithms for measuring upper arm elevation relative to gravity (i.e., angular displacement and velocity summary measures) across different motion speeds. Thirteen participants completed a cyclic, short duration, arm-intensive work task that involved transfering wooden dowels at three work rates (slow, medium, fast). Angular displacement and velocity measurements of upper arm elevation were simultaneously measured using an inertial measurement unit (IMU) and an optical motion capture (OMC) system. Results indicated that IMU-based inclinometer solutions can reduce root-mean-square errors in comparison to accelerometer-based inclination estimates by as much as 87%, depending on the work rate and sensor fusion approach applied. The findings suggest that IMU-based inclinometers can substantially improve inclinometer accuracy in comparison to traditional accelerometer-based inclinometers. Ergonomists may use the non-proprietary sensor fusion algorithms provided here to more accurately estimate upper arm elevation.

1. Introduction

Measuring human motion with accuracy is critical for many applications in occupational ergonomics, such as estimating exposure to non-neutral working postures (Douphrate et al., 2012) and evaluating workplace designs (Fethke et al., 2011). Human motion is most accurately quantified using laboratory-based electromagnetic or optical motion capture systems (OMC). However, high equipment costs and constrained recording areas generally prevent such systems from use in field-based occupational research (Cuesta-Vargas et al., 2010; Sabatini, 2006).

Dual-axis and tri-axial piezoresistive accelerometers are commonly used as inclinometers in field-based applications to estimate posture and movements of the trunk and upper arm with respect to the gravity vector (Amasay et al., 2009; Bernmark and Wiktorin, 2002; Douphrate et al., 2012; Fethke et al., 2016; Wahlström et al., 2010). Accelerometer-based inclinometers, however, are (i) less accurate as motion speeds increase and (ii) cannot accurately capture rotation about the gravity vector (Amasay et al., 2009; Bernmark and Wiktorin, 2002; Korshøj et al., 2014). In theory, inertial measurement units (IMUs) overcome the limitations inherent to accelerometer-based measurement through the addition of gyroscopes, magnetometers, and sensor fusion algorithms (e.g., Kalman filter, complementary filter, or particle filter) to estimate body segment orientation in three-dimensional space (Madgwick et al., 2011; Roetenberg et al., 2005; Sun et al., 2013; Valenti et al., 2015; Yadav and Bleakley, 2014; Yun et al., 2008).

Previous research suggests that IMU-based motion capture can be highly accurate in controlled, laboratory settings (Bergamini et al., 2014; Faber et al., 2013; Kim and Nussbaum, 2013; Plamondon et al., 2007; Robert-Lachaine et al., 2016). However, local magnetic field disturbances can lead to joint angular displacement measurement errors of 180° (Bachmann et al., 2004). Strategies such as magnetic field rejection (Ligorio and Sabatini, 2016; Sabatini, 2006; Sun et al., 2013), zero velocity updating (Schiefer et al., 2014), and kinematic modeling (El-Gohary and McNames, 2012, 2015; Miezal et al., 2016) have been implemented with sensor fusion algorithms to improve IMU-based motion capture accuracy. Such approaches, however, can only

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compensate for magnetic field disturbances over short measurement durations (i.e., minutes) (El-Gohary and McNames, 2015; Ligorio and Sabatini, 2016). Consequently, and despite considerable research concerning IMU-based motion capture and continued improvements to IMU hardware, systems capable of recording full three-dimensional motion for longer time periods (i.e., hours) in unconstrained environments have been largely elusive. Given the current limitations of IMU-based motion capture systems, sensor fusion algorithms that focus on inclination estimates (i.e., IMU-based inclinometers) rather than spatial orientation have instead been used to improve the accuracy of trunk inclination and upper arm elevation measurements with promising results (Lee et al., 2012; Ligorio and Sabatini, 2015; Schall et al., 2015, 2016).

Few studies that have evaluated IMU-based inclinometers, however, have also reported the accuracy of (i) accelerometer-derived angular displacement measurements, (ii) angular velocity measurements, or (iii) posture and movement summary measures used for health-based decision making in the context of occupational ergonomics. Thus, the ability of IMU-based inclinometers to improve measurement accuracy relative to established accelerometer-based approaches remains unclear. Previous work compared accelerometer and IMU-based inclinometers to an electrogoniometer used to measure trunk motion (Schall et al., 2015) and to a biomechanical-based optical motion capture system (Schall et al., 2016). The results indicated (i) errors in the IMU measurements relative to the reference devices on the order of 5–9° depending on motion plane and body segment and (ii) marginal differences between accelerometer-based and IMU-based inclination measurements. However, error sources not reflective of sensor accuracy, such as measurement system misalignment (Mecheri et al., 2016) were not fully managed. Furthermore, the similarities in measurement accuracy between accelerometer and IMU-based inclinometers due to motion speed were not evaluated.

Acknowledging that field-based IMU measurement of full three-dimensional motion may not be achievable in many industrial environments due to magnetic field disturbances, we explored the potential benefits of intermediary solutions (IMU-based inclinometers) that forgo the use of magnetometer data and instead rely on accelerometer and gyroscope data. The specific objective of this laboratory study was to evaluate the effects of motion speed and upper arm elevation calculation method (i.e., no sensor fusion and a variety of sensor fusion approaches) on the error in measures of upper arm posture and movement. In particular, we aimed to isolate the error associated with the sensor (i.e., technological error) (Robert-Lachaine et al., 2016). To mimic methods commonly reported in field studies, a single IMU secured to the upper arm was used and upper arm elevation was calculated with respect to the gravity vector. We hypothesized that sensor fusion would improve measurement accuracy, particularly as motion speed increased.

2. Methods

2.1. Participants

Thirteen participants (11 male, mean age = 27.2 ± 6.6 years, right-hand dominant) were recruited from the University of Iowa community. All participants were screened for any self-reported cases of: (i) physician-diagnosed musculoskeletal disorder in the past six months, (ii) pain during the previous two weeks prior to enrollment, and (iii) medical history of orthopedic surgery in the upper extremity (shoulder, elbow, wrist, hand). Each participant provided written informed consent. The University of Iowa Institutional Review Board approved all study procedures.

2.2. Task

Each participant completed six trials of a simulated work task that involved transferring wooden dowels (2 cm diameter x 8 cm length) from a waist-high container in front of the participant to a shoulder-height container located 45° diagonally from the participant (Fig. 1). Each transfer required the participant to (i) grasp the dowel, (ii) transfer the dowel to the unloading container, and (iii) return their hand to the material feed container. Each participant completed two trials at the given material transfer rate: slow (15 cycles/min), medium (30 cycles/min), and fast (45 cycles/min). The transfer rate was controlled using a metronome and experimental conditions were randomized to control for potential order effects. Each participant was given time to acclimate to the assigned motion speed before each trial was captured. In preliminary tests, it was difficult for the participants to maintain the fastest transfer rate (45 cycles/min) for longer than 1 min due to fatigue. Consequently, each trial was 1 min in duration and was followed by a rest period of 5 min.

2.3. Instrumentation

An IMU (series SXT, Nexgen Ergonomics, Inc., Pointe Claire, Quebec, CA) was secured to the lateral aspect of the dominant upper arm midway between the acromion and the lateral epicondyle (Fig. 2). The IMU was mounted to the upper arm with the x-axis oriented along the longitudinal axis (with positive x directed distally), the y-axis oriented along the anterior-posterior axis (with positive y directed anteriorly), and the z-axis oriented along the mediolateral axis (with positive z directed laterally). Raw accelerometer, gyroscope, and spatial orientation measurements (quaternions from an embedded Kalman filter) were captured from the IMU at 128 Hz.

Spatial orientation was also simultaneously recorded using a six-camera OMC system (Optitrack Flex 13, NaturalPoint, Inc., Corvallis, OR, USA) that tracked a cluster of four reflective markers mounted to the surface of the IMU with double-sided tape (Fig. 2). This was used in contrast to a biomechanical-based marker set to control for soft-tissue artifacts in order to isolate sensor error. The OMC measurements were recorded at 120 Hz. Initialization and calibration of the IMU and OMC instrumentation systems was performed using manufacturer-specified procedures. No additional (biomechanical) calibration procedures were performed as our goal was to compare the orientation of the IMU to the orientation of the marker cluster affixed to the IMU (i.e., sensor error was isolated).

Fig. 1. Placement of the waist-height container holding the wooden dowels and the shoulder-height container.