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Short communication

The validity of assessing temporal events, sub-phases and trunk kinematics of the sit-to-walk movement in older adults using a single inertial sensor

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ABSTRACT

The aim of this study was to develop a method to identify temporal events, sub-phases and trunk kinematics of the sit-to-walk (STW) using a single inertial sensor (IS) worn at the lower back and to determine the validity of this method. Twenty-seven healthy older adults performed a STW movement, which started from sitting in a chair and included walking 3 m.

Participants' movements were recorded with the IS, a reference measurement system consisting of an optical motion capture system (3 markers on the IS and one on each foot) and on–off switches located in the seat of the chair.

Using the data from the IS and the reference measurement systems, the following signals and variables were calculated and compared: 3D IS motion (accelerations, velocities, displacements and angles), temporal events (start of trunk movement, seat-off, end of trunk flexion phase, end of trunk rising phase and gait initiation) and trunk kinematics (flexion range, maximum flexion velocity, maximum forward velocity and forward velocity during seat-off and at first heel-strike and maximum vertical velocity and vertical velocity at first heel-strike).

For most variables acceptable differences (RMSE < 10%) were found between IS and reference measurement systems, except for sideways displacements and non-sagittal plane rotations. Furthermore, good results were found for temporal event detection, with ICC values for all variables being 0.988 or higher. With exception of the vertical velocity at heel-strike agreement for trunk kinematics was high, with ICC values being 0.867 or higher.

1. Introduction

Researchers and clinicians usually assess physical functioning of older people through self-report. To assess the ability to perform daily activities in a more objective way, standardized clinical physical performance tests have been developed. A number of these tests are widely used, such as the Timed Up and Go (Podsiadlo and Richardson, 1991) and the Short Physical Performance Battery (Guralnik et al., 1994). These tests include one of the most demanding daily activities: rising from a chair, which is of key importance for independent functioning. Conventionally, manually recorded time events are used as outcome measures.

More recently, camera-based systems and force plates have been added to explore the kinematics of rising from a chair. Kinematic variables have been found that contribute to identifying people at risk of losing independent functioning (Bernardi et al., 2004; Buckley et al., 2008; Chen and Chou, 2013; Kerr and Kerr, 2001). However these measurement systems are bound to a lab environment and are only to a limited extent used for routine clinical assessment. For routine clinical use, an easy to handle, efficient and unobtrusive measurement system is more suitable.

Inertial sensors (IS) may offer a potential for use in research and clinical practice. A single IS, worn on the lower back, has successfully been used for analyzing sub-phases and trunk kinematics during chair rise (Giansanti and Maccioni, 2006; Millor et al., 2013; Schwenk et al., 2012; Van Lummel et al., 2012; Van Lummel et al., 2013; Weiss et al., 2011, 2010) and have been validated against other instrumentation for the sit-to-stand task (Boonstra et al., 2006; Janssen et al., 2008; Zijlstra et al., 2012). But

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the validity of using an IS during the biomechanically challenging sit-to-walk (STW) task, which is common in daily life, has not yet been investigated (Kouta and Shinkoda, 2008). Therefore, the aim of this study was to develop and validate a method to identify relevant temporal events, sub-phases and trunk kinematics of the STW using a single IS.

2. Methods

2.1. Participants

Twenty-seven healthy older adults participated in this study (13 female; mean age: 74.7 ± 8.5 years; mean weight: 76.8 ± 13.2 kg; mean height: 172.2 ± 8.2 cm), which had been approved by the ethics committee of the faculty of human movement sciences (ECB 2014-3M). Prior to testing, all participants provided written informed consent.

2.2. Movement task

STW started from sitting in a chair without armrests and a seat height of 44.5 cm and included walking 3 m. STW initiated after a countdown from 5 to 1 followed by a verbal go command. At the end of the STW, participants were asked to stand still. Two tests were performed in which the first one served as a practice trial.

2.3. Instrumentation

Participants wore a single IS (DynaPort® Hybrid, McRoberts) which was inserted in an elastic belt at the level of the fourth lumbar spinous process (Rispens et al., 2014; Zijlstra et al., 2012). The DynaPort included 3 accelerometers and 3 gyroscopes with a sample rate of 100 samples/s.

Motion data were captured with an optical motion capture system (Optotrak Certus®, Northern Digital Inc.) at 200 samples/s and were resampled to 100 samples/s. Two single markers were attached to the heels of the shoes. Furthermore, a cluster of markers was mounted on a metal plate which was attached to the DynaPort. The marker cluster was related to the DynaPort by digitizing specified positions of the DynaPort using a probe with six markers.

The custom-made chair contained a plate on top of the seat, with four on/off switches between plate and seat. DynaPort, Optotrak and switch data were electronically synchronized.

2.4. STW assessment

Before data processing, Optotrak (displacements) and DynaPort (accelerations and angular velocities) were filtered with a bi-directional second-order low-pass Butterworth filter at 15 Hz cut-off frequency. For DynaPort 3D velocities, displacements and angles were calculated. For Optotrak, 3D accelerations, velocities and angles were calculated (Fig. 1). After each differentiation and integration step, the signals were filtered using a filter as described above.

2.4.1. Optotrak

At each time instant, an arbitrary technical coordinate system (CS) was constructed based on the position of the markers on the DynaPort. Subsequently, this CS was aligned with the global CS and expressed relative to the sitting posture by post-multiplying the orientation matrix at each time-sample by the inverse of the orientation matrix during the sitting posture (Faber et al., 2013). Euler angles were calculated based on the aligned orientation matrix using the following Euler angle decomposition order: flexion (leftward axis), lateral (forward axis) and axial (upward axis). Linear velocities and linear accelerations were calculated by differentiating and double differentiating the displacements averaged over markers.

2.4.2. DynaPort

DynaPort orientations were defined for the sitting and standing postures based on the gravity vector measured by the accelerometers (Moe-Nilssen, 1998). The heading of the DynaPort was assumed to be zero at these instances.

Next, the orientation matrix was rotated over time for each time-sample by integrating the angular velocities. Due to integration drift, the calculated integrated DynaPort orientation matrix at the standing posture was slightly different from the orientation matrix determined based on the accelerations. Using this orientation error, the orientation matrix time series were corrected. To get a smooth curve, the error correction was distributed over the whole movement period (rotating around the helical axis of the error matrix with the identity matrix), assuming that error grows linearly with time.

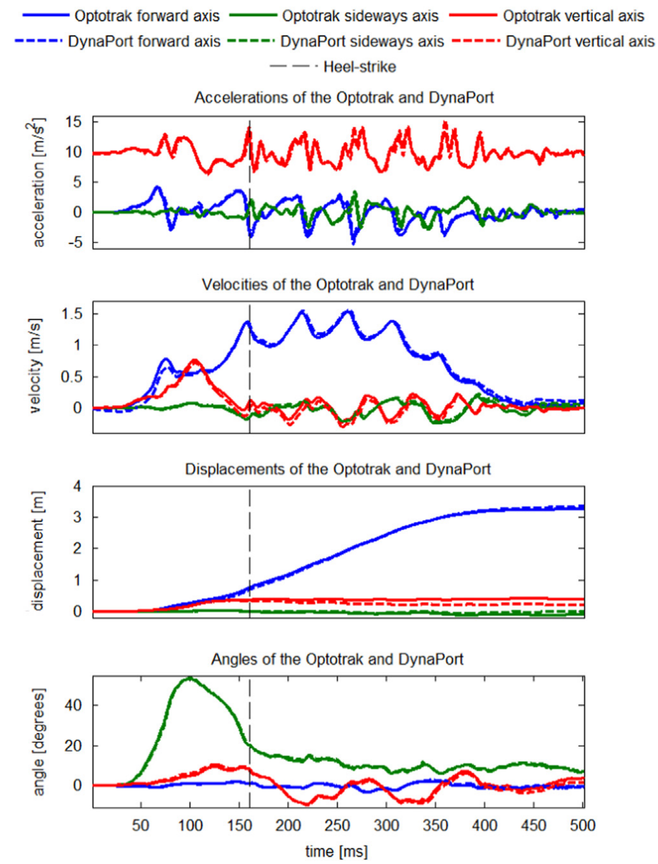

Fig. 1. Example of the 3D accelerations (first pane), velocities (second pane), displacement (third pane) and angles (fourth pane) calculated with the Optotrak and the DynaPort.

Based on the corrected orientation matrix, a new orientation matrix was calculated, describing DynaPort orientation relative to the global axis system, with gravity upward and overall displacement in the horizontal plane defined as forward. Euler angles were calculated, identical to those for the Optotrak described above.

DynaPort accelerations were rotated to the global CS using the DynaPort orientation calculated above. Next, the offset on the accelerations caused by gravity was removed. To obtain velocities, the accelerations were integrated over time. These velocities are subject to integration drift, causing the velocities to be non-zero at the ending posture. To correct for this, the error was linearly distributed over time and subtracted from the velocities between sitting and standing postures. To obtain displacements, the velocities were integrated over time.

Because the DynaPort was not perfectly aligned with the trunk segment and subjects did not sit perfectly straight on the chair, the forward axis of the DynaPort was not pointing perfectly forward in the starting posture. This resulted in a non-straight trajectory. To correct for this, trajectories, velocities and accelerations were rotated around the vertical such that there was no sideways displacement between the sitting and standing posture.

2.4.3. Event detection

Based on accelerations, velocities, trajectories and angles, the following events were defined: start of trunk movement, seat-off, end of trunk flexion phase, end of trunk rising phase and gait initiation. For both Optotrak and DynaPort, start of trunk movement was defined as the start of flexion rotation after the sitting period (Van Lummel et al., 2013) (Fig. 2, pane 1). Using the on–off switches, seat-off was defined as the first instant when all switches were off (Kralj et al., 1990) (Fig. 2, pane 2). Using the DynaPort, seat-off was defined as the minimum vertical acceleration within 0.1 s of first 25% of the vertical trajectory range (Fig. 2, pane 3). For both Optotrak and DynaPort end of trunk flexion phase was defined as the instant when the derivative of the flexion rotation was 0 (Fig. 2, pane 4) and end of trunk rising phase was defined as the downward peak vertical velocity after the upward vertical velocity reached zero (Fig. 2, pane 5). Using the Optotrak, gait initiation was defined as first heel-strike: the instant when the derivative of the vertical trajectory of the marker on the stepping leg reached 0 after a local minimum (Fig. 2, pane 6). Using the DynaPort, gait initiation was defined using high frequency components of sensor signals. Raw