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Short communication

Lifting style and participant's sex do not affect optimal inertial sensor location for ambulatory assessment of trunk inclination

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ABSTRACT

Trunk inclination (TI) is often used as a measure to quantify back loading in ergonomic workplace evaluation. The goal of the present study was to determine the effects of lifting style and participant's sex on the optimal inertial sensor (IS) location on the back of the trunk for the measurement of TI. Gold-standard TI, defined as the angle between the vertical and the line connecting the L5/S1 joint and the trunk center of mass, was measured using an optoelectronic system. Ten males and ten females performed experimental trials in which a box was lifted from floor level to a 75 cm elevated surface. In each trial the box was lifted using four different styles: symmetric and asymmetric free-style lifts, a stoop lift and a squat lift. Trials were repeated for 13 IS locations between 10% and 40% of the distance from the sacrum to the seventh cervical spinous process (C7). For each participant and each IS location, the root-mean-square error (RMSE) between the gold standard TI and the ISTI was determined. A three-way repeated measures ANOVA analysis revealed no significant effects of the participant's sex on the RMSEs, but the main effects of lifting style and sensor location and their interaction were significant. Despite this significant interaction, a sensor location between 20% and 27.5% of the distance from the sacrum to C7 yielded the smallest RMSEs across all lifting styles. In conclusion, regardless of participant's sex or lifting style, the optimal IS location for the measurement of TI is at about 25% of the distance from the sacrum to C7.

1. Introduction

Working with the trunk in a flexed posture has been identified as an important risk factor for the development of back pain (Hoogendoorn et al., 2000; Lötters et al., 2003). This is probably related to the inclination of the trunk (tilt with respect to the vertical). A large trunk inclination (TI) results in a large horizontal moment arm of the trunk center of mass (CoM) with respect to the low back. Because of the high mass of the trunk segment this leads to high spinal moments/forces (Hoozemans et al., 2008). Because of this, trunk inclination (TI) is often used as a measure to quantify back loading in ergonomic workplace evaluation (Kazmierczak et al., 2005; Taloni et al., 2004). Since the trunk is not a rigid segment, different definitions of TI have been used in the ergonomic literature, e.g., inclination of the line from the trochanter to the acromion (Seo et al., 1997). In the present study we defined the angle between the vertical and the line connecting the L5/S1 joint and the trunk CoM as the gold standard TI. This is motivated based on the direct relation of the so defined TI with the mechanical effect, as indicated above.

Inertial sensors (IS) are wearable sensors, consisting of 3D accelerometers, gyroscopes and magnetometers. When attached to the trunk, IS inclination can be estimated with high accuracy ($\sim 1^{\circ}$) during activities of daily living (Faber et al., 2009; Luinge and Veltink, 2005). Advantages of measuring TI with an IS instead of observational methods (Li and Buckle, 1999) are that it is less labor-intensive and that TI can be recorded continuously over long periods of time. A limitation of measuring TI with an IS is that, since the trunk is not a rigid segment, placement of the IS that is too high or too low on the back will result in either an over- or under-estimation of TI. A previous study showed that the optimal location for measuring TI is at about 25% of the distance from the midpoint between the posterior-superior iliac spines (MPSIS) to the 7th cervical spinous process (C7)(Faber et al., 2009). A limitation of this study is that only males participated and only one lifting style was used (stoop lifting). Since participant's sex affects spinal flexibility (Sullivan et al., 1994) and lifting style affects the distribution of spinal flexion over the spinal segments (Gill et al., 2007), the optimal IS location might be dependent on lifting style and participant's sex. Therefore, the

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present study investigated the effects of lifting style and participant's sex on the optimal IS location for the assessment of TI. The gold-standard TI, defined as the angle between the vertical and the line connecting the L5/S1 joint and the trunk CoM, was measured using an optoelectronic motion tracking system.

2. Methods

2.1. Participants

The experimental protocol was approved by institutional review boards of the Harvard School of Public Health and the Liberty Mutual Research Institute for Safety. After signing an informed consent, 10 males (age: 38 ± 18 years; mass: 78 ± 9 kg, height: 181 ± 11 cm), and 10 females (age: 29 ± 13 years; mass: 62 ± 11 kg, height: 167 ± 8 cm) participated in the experiment.

2.2. Experimental trials

Each participant performed experimental trials, repeated for a range of IS locations (see Section 2.3). In each of these trials, an 8.5 kg crate was lifted from ground level to a 75 cm elevated surface using four lifting styles: (1) a symmetric free-style lift, (2) a stoop lift (straight legs), (3) a squat lift (crate between the knees, straight and upright trunk, see Fig. 1) and (4) an asymmetric free-style lift. In the first three lifting styles, the crate was moved in the sagittal plane, whereas in the asymmetrical lifting task it was moved in a plane oriented 45° to the right of the sagittal plane. The order in which the four lifting styles were performed was randomized over participants. At the start of each trial, participants were instructed to stand in an upright posture for 5 s (looking at a target at eye level on the wall about 4 m in front of them).

2.3. Trunk inclination measurement

Gold-standard trunk inclination: The gold-standard TI was defined as the angle between the vertical and the line between the L5/S1 joint and the combined CoM of the abdomen, thorax and head/neck segments (trunk CoM). The 3D motions of the pelvis and the trunk segments were measured at 50 Hz using optoelectronic marker clusters (Northern Digital Inc., Waterloo, ON, Canada). Anatomical coordinate systems were constructed and related to the marker clusters by digitizing pre-defined anatomical landmarks in an upright posture, using a probe with 4 markers.

For the pelvis, the left and right anterior-superior iliac spines (ASIS), the MPSIS and the opmhalion were digitized and used to estimate the L5/S1 joint position based on the anatomical data published by Reynolds et al. (1982). The horizontal segmentation planes for the trunk segments were the planes through the omphalion (bottom of abdomen), xiphoid (between abdomen and thorax) and C7 (between thorax and head/neck) (de Leva, 1996). The head/neck cranial endpoint was the head vertex.

For the abdomen and thorax, the longitudinal CoM positions were determined based on these segment endpoints (de Leva, 1996). The anterior–posterior CoM position for each of the two segments was determined using an extra virtual point on the posterior side of the trunk at a height approximately halfway the segment endpoints (Plagenhoef et al., 1983). The head CoM position was defined as the midpoint between the left and right tragion (de Leva, 1996). Mass of each segment was estimated based on the segment endpoints (segment lengths) plus segment circumference (de Leva, 1996; Zatsiorsky, 2002). All but one of these above anatomical parameters were based on sex-specific data from the literature. No female data for the anterior–posterior positions of the abdomen and thorax were available and, therefore, male percentages were also used for the females in the current study.

For the pelvis segment the marker cluster was attached to the sacrum right below the MPSIS, for the thorax segment to the back at 75% of the distance from the MPSIS to C7, and for the head/neck segment to the side of the head. No separate marker cluster was used to measure the motion of the abdomen segment because it would be in the way of the IS that was repositioned between trials (see below). Instead, anatomical landmarks connected to the thorax cluster (xiphiod) and the pelvis cluster (omphalion and MPSIS) were used to reconstruct the movement of the abdomen segment.

Inertial sensor trunk inclination: IS inclination relative to the reference posture was used as our target measure, i.e. IS based TI (ISTI). ISTI was measured at 50 Hz using an MT*x* inertial sensor (Xsens Technologies, Netherlands) which was placed on the back in between the sacrum and thorax marker clusters (Fig. 1). To prevent IS shift during the data collection, the IS was secured with a neoprene strap and the IS surface that touched the skin was covered with a layer of anti-slip neoprene. Experimental trials were repeated for each participant and in every trial the movable IS was placed at another location on the line between the MPSIS and C7. Based on a previously-reported optimal IS location of 25% of the distance from the MPSIS to C7 (Faber et al., 2009), movable sensor locations were chosen to range from 10% to 40% with increments of 2.5%, resulting in a total of 13 locations. The order in which the trials were executed for the different locations was randomized over participants.

Orientation of the IS in global axes (Z-axis upwards; X-axis toward the magnetic north; Y-axis perpendicular to the X- and Z-axes) was calculated using Kalman filtering (Luinge, 2005). The change in orientation (R_c) of the IS with respect to its orientation during the upright reference posture was calculated by post-multiplying the orientation matrix (with column vectors) during the experimental trial (R_{exp}) by the inverse of the orientation matrix during the upright reference posture at the start of each trial (R_{ref}) according to Zatsiorski (1998):

$$R_c = R_{exp}\mathrm{inv}(R_{ref})$$

Subsequently, for each IS, ISTI was calculated by taking the arccosine of the third diagonal element of R_c:

$$ISTI = \mathrm{acos}\,(R_c(3,3))$$

2.4. Statistical analysis

ISTI measurement performance was quantified by the RMSE between the gold-standard TI and the ISTI. A three-way ANOVA was applied to test the effect of the participant's sex (between-subjects factor) and the effect of sensor location and lifting style (within-subjects factors) on this RMSE. Because of a significant interaction between sensor location and lifting style (see results), additional post-hoc tests were carried out to further investigate the effect of IS location for each lifting style separately (males and females together; $n=20$). First, the sensor location with minimum average RMSE was determined (optimal sensor location). Subsequently, paired t-tests were used to test whether the average RMSE at this location was significantly different from the average RMSE at the other locations.

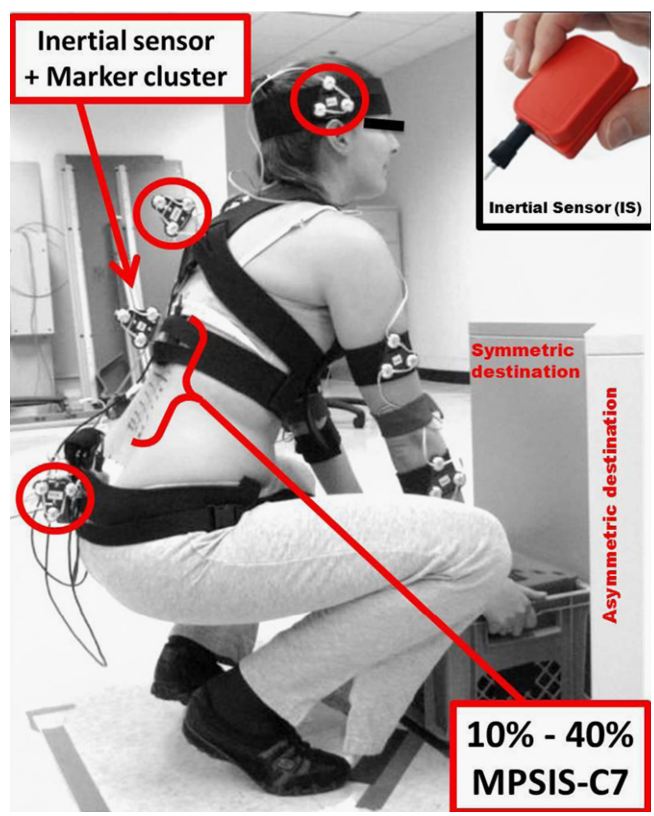

Fig. 1. Subject during one of the four lifts (squat lift) which were performed in every experimental trial. Experimental trials were repeated for 13 different inertial sensor (IS) locations ranging from 10% to 40% of the distance from the midpoint between the posterior–superior iliac spines (MPSIS) to the 7th cervical spinous process (C7). In this case the IS was placed at one of the highest locations. Marker clusters used to calculate the gold-standard trunk inclination are indicated with the red circles. The marker-cluster data of the arms were not used in the present study. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)