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Short communication

Optimal inertial sensor location for ambulatory measurement of trunk inclination

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ABSTRACT

Trunk inclination (TI) is used often to quantify back loading in ergonomic workplace evaluation. The aim of the present study was to determine whether TI can be obtained using a single inertial sensor (IS) on the back, and to determine the optimal IS location on the back for the estimation of TI. Gold standard TI, the angle between the vertical and the line connecting the L5/S1 joint and the trunk centre of mass, was measured using an optoelectronic system. Ten subjects performed experimental trials, each consisting of a symmetric and an asymmetric lifting task, and of a left–right lateral flexion movement. Trials were repeated and, in between trials, the IS was shifted in small steps from a location on the thorax towards a location on the sacrum. Optimal IS location was defined as the IS location with minimum root-mean-square (RMS) error between the gold standard TI and the IS TI. Averaged over subjects, the optimal IS location for symmetric and asymmetric lifting was at about 25% of the distance from the midpoint between the posterior superior iliac spines (MPSIS) to the C7 spinous process. The RMS error at this location, averaged over subjects, was $4.6 \pm 2.9^{\circ}$. For the left–right lateral flexion task, the optimal IS location was at about 30% of the MPSIS to C7 distance. Because in most activities of daily living, pure lateral flexion does not occur often, it is recommended place the IS at 25% of the distance from the MPSIS to C7.

1. Introduction

Flexed trunk postures constitute an important risk factor for the development of back pain (Hoogendoorn et al., 2000; Lötters et al., 2003). Therefore, in ergonomic workplace evaluation, trunk inclination (TI) is used often to characterize back loading (Taloni et al., 2004). TI is usually measured with observational methods (Li and Buckle, 1999). Alternatively, TI could be estimated using an inertial sensor (IS) consisting of accelerometers, gyroscopes and magnetometers (Roetenberg et al., 2005), which would be less labour-intensive and more accurate (Luinge and Veltink, 2005). Another advantage of using an IS is that TI can be measured continuously in static and dynamic conditions. However, because the trunk is not a rigid segment, too high or too low placement of the IS on the back will result in either an over- or underestimation of TI.

The aim of the present study was to determine whether TI can be estimated sufficiently accurate using a single IS, and to determine the optimal IS location on the back for the determination of TI. Because the effect of TI on back loading is directly related to the moment arm of the trunk centre of mass (COM) relative to the low back, the inclination of the line through the L5/S1 joint and the trunk centre of mass (COM) was used as a gold standard reference of TI.

2. Methods

2.1. Subjects and procedure

After signing the informed consent, 10 healthy male subjects (age: 30.0 ± 5.5 years; mass: 76.4 ± 4.5 kg, height: 181.6 ± 6.8 cm) participated in the experiment, which was approved by the local ethics committee. Because optimal IS location for estimating TI may depend on the asymmetry of a task, subjects performed 3 tasks varying in asymmetry: (1) symmetric lifting, (2) asymmetric lifting and (3) left–right lateral trunk flexion. In the lifting tasks, an 8.5 kg crate was moved from ground level to a 75 cm high table and back to ground level. In the symmetric lifting task, 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 (Fig. 1). An asymmetry of 45° was chosen because higher asymmetry does not occur often in practice (Dempsey, 2003). Subjects were instructed to stand in an upright posture for 5 s at the start of each trial (looking at a target at eye height on the wall about 2 m in front of them). To achieve a large TI and minimize variations in maximal TI over trials, subjects were asked to keep their legs as straight as possible.

2.2. Gold standard trunk inclination

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 (trunk COM). Segments were followed over time by relating them to marker

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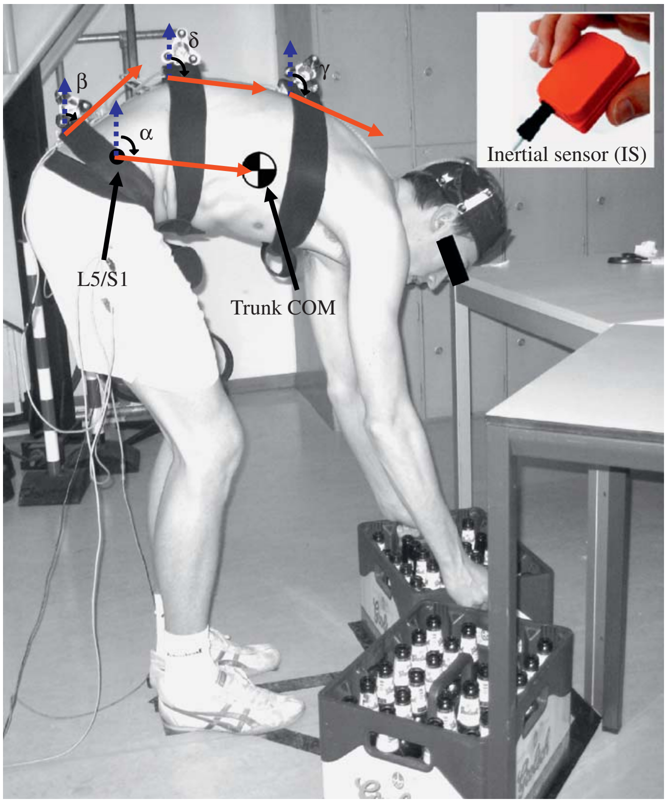

Fig. 1. Picture of an experimental trial illustrating the way the trunk inclination (TI) was determined with the gold standard method (α, angle of the line between the L5/S1 joint and the trunk COM and the vertical (dashed arrows)), and with fixed ISs on sacrum (β) and T9 (γ) and a movable IS (δ) in between the fixed ones. In this experimental trial, the movable sensor was optimally located for the estimation of the gold standard IT. In the right upper corner, an IS is shown. During each experimental trial subjects performed a symmetric lift (lifting the crate in front of them), an asymmetric lift at 45° to the right of them and a left–right lateral flexion of the trunk.

clusters of 3 infrared light emitting diodes, which were used for movement registration with an optoelectronic system (Optotrak, NDI). These clusters were attached to the sacrum (pelvis segment), to the back at the level of T9 (abdomen+thorax segment) and to the side of the head (head segment). Before the experimental trials, anatomical landmarks were related to the marker clusters using a probe with 6 markers. Mass and position of COM of each segment were estimated using the anatomical landmarks, segment circumferences and anthropometric data from literature (Plagenhoef et al., 1983; Zatsiorsky, 2002). The L5/S1 joint position was estimated based on Reynolds et al. (1982).

2.3. Inertial sensor trunk inclination

For estimation of TI, MTx sensors (Xsens Technologies, Netherlands) were used. One IS was placed beneath the sacrum marker cluster and another beneath the T9 marker cluster (fixed sensors). A third movable IS (+ marker cluster) was placed on the back in between these two ISs. To prevent shifting of the ISs during the experimental trials, they were fixed using neoprene straps (Fig. 1). Furthermore, the movable IS was covered with anti-slip neoprene, while the other ISs were fixed with double-sided tape. Experimental trials were repeated and, in between trials, the movable IS was shifted from the T9 IS towards the sacrum IS, on average, in 12 steps. On average, step size was 2.3% of the distance from the midpoint between the posterior superior iliac spines (MPSIS) to the 7th cervical spinous process (C7). Orientation of the ISs in global axes (Z-axis upwards; X-axis towards 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 each IS with respect to its orientation during the upright reference posture was calculated by post-multiplying the orientation matrix during the experimental trial (R_{exp}) by the inverse of the orientation matrix during the reference measurement at the start of each trial (R_{start}):

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

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

$$\mathrm{TI} = \mathrm{a\,cos}(R_c(3,3))$$

Optotrak and IS data were synchronously recorded at a sample rate of 50 Hz.

2.4. Statistical analysis

IS location was expressed as percentage of the distance from the MPSIS to C7, measured during the upright posture at the start of each trial. For each subject, the error of the IS-based TI with respect to the gold standard TI, for each task and IS location, was calculated over the total movement time (RMS error) and at the instant of peak TI (absolute error at peak TI). Optimal IS location, for both error types, was defined as the IS location with minimum error. The effect of task (symmetric lifting; asymmetric lifting; left–right lateral flexion) and error type (RMS error; absolute error at peak TI) on the optimal IS location was tested with a 3×2 repeated measures ANOVA.

3. Results

Fig. 2 shows an example of TIs measured during an experimental trial. Fig. 3 shows the errors between gold standard TI and IS TI, as a function of IS location. Individual optimal IS locations showed very small errors (generally below 3°). Because optimal IS location differed between subjects, the average curves show larger minimum errors. Averaged over subjects and lifting tasks, the RMS error and absolute error at peak TI were $4.6 \pm 2.9°$ and $5.6 \pm 4.0°$, respectively. No effect of error type ($p = 0.549$) on optimal IS location was found. The effect of task was significant ($p < 0.001$), while no interaction with error type occurred ($p = 0.670$). After averaging over the optimal IS locations based on RMS error and on absolute error at peak TI, no difference in optimal IS location was found between the symmetric and asymmetric lifting tasks ($23.3 \pm 4.1\%$ versus $22.7 \pm 3.5\%$, respectively; $p = 0.166$), but optimal IS location for left–right lateral flexion was significantly higher ($30.7 \pm 3.8\%$) than for both the lifting tasks ($p < 0.001$).

4. Discussion

Our results show that the optimal location of an IS on the back for measuring TI during symmetric and asymmetric lifting tasks is at approximately 25% of the distance from the MPSIS to C7 (between the L1 and L2 spinous processes). For left–right lateral flexion a higher optimal location was found (30%). This is probably because the range of motion is more uniformly distributed over the thoraco-lumbar spine for lateral flexion than for flexion-extension with the latter predominantly taking place in the lumbar region (White and Panjabi, 1990). Substantial lateral flexion was found in the asymmetric lifting task (averaged over subjects, $20 \pm 5°$), but this did not increase the optimal IS location relative to the symmetric lifting task. Pure lateral bending appears rather uncommon and lateral flexion will usually be accompanied by flexion as in the asymmetric lifting task. Therefore, it appears reasonable to recommend placing an IS at 25% of the distance from the MPSIS to C7.

To our knowledge, only one other study (Seo et al., 1997) investigated the effect of sensor (inclinometer) location on the back on estimated TI. However, only 3 locations were investigated and TI was defined as the inclination of the line connecting the trochanter and the acromion, which is not obviously related to mechanical back loading.

It should be mentioned that, in the present study, high correlations between the IS and gold standard TI were found not only for the optimal IS location, but also for higher IS locations