ON THE USE OF INERTIAL SENSORS TO DETERMINE TRUNK DISPLACEMENT DURING WALKING: A VALIDATION STUDY

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The aim of this study was to determine the accuracy trunk displacement extracted from an inertial motion capture system (IMC) compared to an optical motion capture system (OMC). Participants walked overground while trunk displacement data from IMC and OMC were simultaneously recorded. The resultant trunk speed from both systems during walking and brief standing periods were compared. No differences were found in trunk speed during walking between IMC and OMC. However, trunk speed was greater for the IMC during the transition periods when compared to the OMC ($p<0.05$). It is concluded that trunk kinematic parameters extracted from IMCs have fair accuracy when compared to a gold standard during walking, but accuracy is reduced and speed is overestimated when recording kinematics around stationary periods.

KEY WORDS: Kinematics, IMU, optical systems. Motion analysis, validity, accuracy, Xsens

INTRODUCTION: Inertial motion capture system (IMC) combine data acquisition from accelerometers, gyroscopes and magnetometers to extract segment motion patterns. IMCs have been considered a promising alternative to conduct motion analysis (Floor-Westerdijk et al., 2012; Karatsidis et al., 2017; Laudanski et al., 2011). This technology is highly attractive due to lower cost, simplified experimental setup and a vast array of possibilities to acquire data during real sports conditions. Despite the practical advantages, data acquired from inertial motion sensors (IMUs) may present accumulative distortions or drift, which can induce erroneous assumptions for segment and/or full body displacement in space (Damgrave and Lutters, 2009). Tracking the speed of an object or individual in space may be relevant in the sports, ergonomics and health research fields (Laudanski et al., 2011), thus optimized methods to acquire data can contribute to new applications if they are accurate (Floor-Westerdijk et al., 2012; Karatsidis et al., 2017). Therefore, the aim of this study was to determine the accuracy of trunk kinematics determined from an IMC in comparison to an optical motion capture system (OMC) in a walking task.

METHODS: Ten healthy individuals (nine male, one female, age 24±1 years, body mass 82.1±14.2 kg, and body height 180.2±13 cm) with no musculoskeletal disorders participated in this experiment. Participants were instructed to walk at self-selected speed through three different paths (1 x 1 m, 2 x 2 m and 2 x 3 m) marked on the floor of a motion analysis laboratory (Figure 1). Each participant was asked to perform three sequences of four laps in each path (12 laps in total for each path), with a standing period of 1 second in the initial position prior to the next lap. During the task, the participant's motion data were recorded using an inertial system based on IMUs (MVN Link, Xsens Technologies B.V., Enschede, The Netherlands). Simultaneously, data from retroreflexive markers placed bilaterally on the acromium and iliac crest, as well as on the manubrium of the sternum, xiphoid process and C7 vertebrae were recorded using an eight-camera OMC (Oqus 300-310, Qualisys, Göteborg, Sweden). The OMC was considered a gold standard method to determine translational distances for the purposes of this study.

From the IMC, trunk displacement data were extracted from sensors located at the levels of L3, L5, T8 and T12 vertebrae. Subsequently, the average across sensors represented the trunk segment displacement. For the OMC, the trunk center of mass displacement was calculated using a motion analysis software (Visual3D V6 Professional, C-Motion, Germantown, USA). The data from the anterior-posterior (AP), and medial-lateral (ML) and vertical directions (VERT) were used to calculate the resultant speed for both systems.

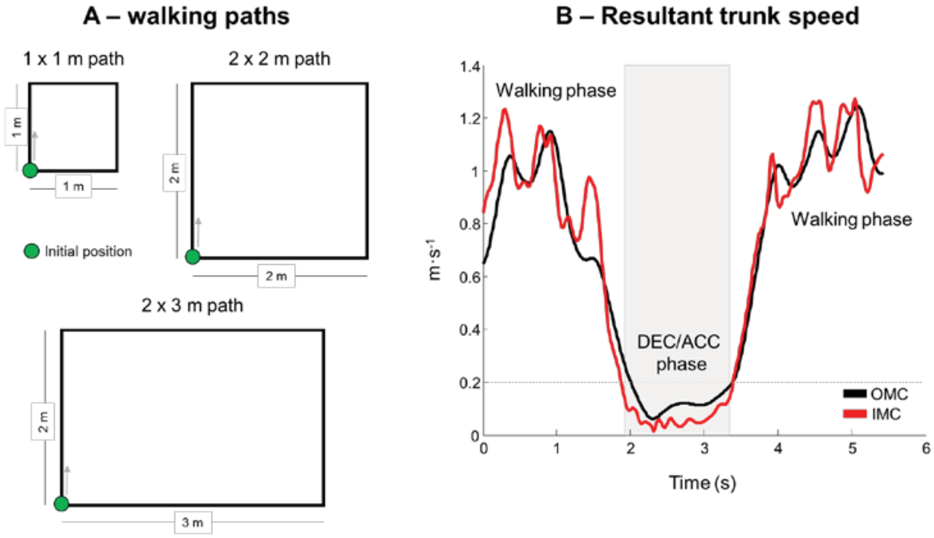

Figure 1 In A, illustrative representation of the walking paths marked on the floor of a motion capture laboratory. In B, illustrative curves from OMC and IMC during an illustrative trial.

The analysis of trunk resultant speed focused on two aspects: The first was related to the walking speed participants travelled, and the second was related to the speed measured while participants were decelerating, briefly stopping and moving again for the next lap (DEC/ACC period). The DEC/ACC period was defined when the resultant speed was below 0.2 $m \cdot s^{-1}$. For each participant, the resultant speed in each lap, as well as the resultant speed during each DEC/ACC period were averaged. Paired Student's t-tests were performed to compare the speed measured by the IMC and the OMC in the three different paths. The significance level was set at $p<0.05$. In addition, the root mean square error (RMSE) was computed between the resultant speed curves from the IMC and the OMC, and normalized by the average resultant speed from the IMC, for each walking and DEC/ACC trial.

RESULTS: Walking speed was 0.56±0.07 $m \cdot s^{-1}$, 0.82±0.06 $m \cdot s^{-1}$ and 0.95±0.07 $m \cdot s^{-1}$ for the 1 x 1, 2 x 2 and 2 x 3 paths, respectively. There was no difference in the total displacement measured in the AP direction regardless the path subject walked on (Table 1). On the other hand, there were greater distances in the ML direction measured using the IMC in comparison to the OMC for both 1 x 1 and 2 x 2 paths ($p<0.005$). In addition, there were greater distances in the VERT direction measured using the IMC in comparison to the OMC for both 2 x 2 and 2 x 3 paths ($p<0.05$).

Table 1 Total distance measured through the entire recordings (12 laps) using an inertial (IMC) and an optical motion capture system (OMC) in three different paths. * denotes significant difference in relation to the OMC (p<0.05).

		1 x 1 - total distance (m)			2 x 2 - total distance (m)			2 x 3 - total distance (m)		
		AP	**ML**	**VERT**	**AP**	**ML**	**VERT**	**AP**	**ML**	**VERT**
IMC	**Mean**	10.85	13.34*	0.45	30.83	33.39*	0.88*	51.20	35.96	1.14*
	SD	2.14	2.97	0.10	2.94	3.26	0.17	5.89	5.31	0.42
OMC	**Mean**	11.24	11.51	0.44	30.98	31.57	0.66	50.58	34.20	0.82
	SD	2.53	2.73	0.13	2.44	2.23	0.19	5.46	3.21	0.19

There were no differences in trunk speed measured by the IMC and the OMC during the walking recordings (Figure 2A, $p>0.05$). On the other hand, there was a greater speed measured during the DEC/ACC period (Figure 2B) for the IMC in comparison to the OMC for the 1 x 1 path ($p<0.001$), 2 x 2 path ($p<0.01$) and 2 x 3 path ($p<0.05$).

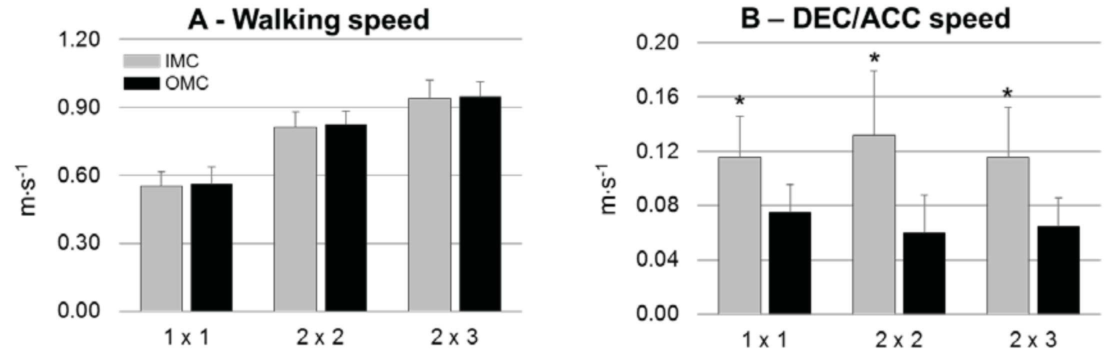

Figure 2 Mean(SD) distance recorded during walking (A) and while decelerating, stopping and accelerating again (DEC/ACC, B) from a motion capture system based on IMUs (IMC, *grey bars*) and an optical motion tracking system (OMC, *black bars*). * denotes significant difference in relation to the OMC ($p<0.05$).

The RMSE from walking speed was 19.7±7.9% across all paths (Figure 3). On the other hand, RMSE from DEC/ACC periods were consistently greater (51.1±14.7% across all paths) when qualitatively compared to the walking RMSE.

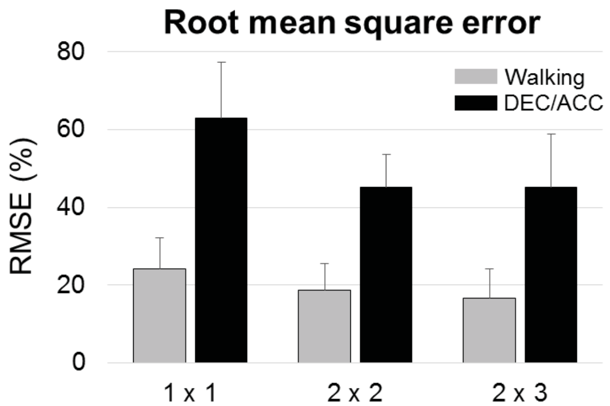

Figure 3 Relative root mean square error (RMSE) calculated between resultant speed extracted from an inertial and an optical motion capture system during walking (*gray bars*) and while decelerating, stopping and accelerating again (DEC/ACC*, black bars*).

DISCUSSION: The aim of this study was to determine whether an IMC could retrieve accurate estimations of trunk kinematics in a pre-established path compared to a gold standard system. The results suggested that the system based on inertial sensors can retrieve similar distances in the AP direction, and similar resultant speed in comparison to a gold standard during walking. However, there was a larger measurement error in between system during the DEC/ACC period, causing overestimation of speed computed from the inertial system when compared to the gold standard.

The validity of motion capture systems based on inertial sensors has been investigated with fair estimates for center of mass (Floor-Westerdijk et al., 2012), lower limb kinematics in the sagittal plane (Zhang et al., 2013) and extraction of ground reaction forces during walking (Karatsidis et al., 2017). Despite these promising results, other studies have suggested that inaccuracies in kinematic parameters extracted from inertial sensors are related to the type of motion recorded (Damgrave and Lutters, 2009). Cuevas-Vargas et al. (2010) suggested in a systematic review that inertial sensors have high accuracy for repeated movements, and that this accuracy is site specific. Segment acceleration/deceleration might compromise the accuracy of the estimation, therefore it is expected that longer lasting movement (e.g. standing still) and fast movements (e.g. jumping) would decrease the precision of IMCs (Damgrave and Lutters, 2009). This phenomenon could be caused by extracting segment positions from accelerations. Our results corroborate this previous work, as there were greater difference in the resultant trunk speed measured during the acceleration/deceleration around the brief standing pause in comparison to the walking period.

Measuring accuracy has been a crucial step to validate the use of inertial sensors to investigate human biomechanics Laudanski et al., (2011) found RMSE between 5% and 7.5% for walking speed computed using inertial sensors located in the shank and foot, but their comparison was between a pre-established treadmill speed and the inertial sensor's speed. In this study, we found RMSE of ~17% across all paths for the speed measured during walking, but substantially greater RMSE for the speed measured during the DEC/ACC periods (~51%). However, direct comparison between studies need caution, as the methods for comparing speed were different. The greater RMSE during DEC/ACC periods may suggest that the process of converting sensor data into displacement is less accurate when the segment acceleration varies substantially. This information is relevant for system developers to further enhance the extraction of kinematic data from inertial sensors.

CONCLUSION: In summary, the trunk speed measured using inertial sensors is not significantly different from a gold standard optical motion capture system during walking. On the other hand, trunk speed measured during the segment deceleration/acceleration showed poorer accuracy, and subsequent overestimation, when using inertial sensors.

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