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Effect of local magnetic field disturbances on inertial measurement units accuracy

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ABSTRACT

Inertial measurement units (IMUs), a practical motion analysis technology for field acquisition, have magnetometers to improve segment orientation estimation. However, sensitivity to magnetic disturbances can affect their accuracy. The objective of this study was to determine the joint angles accuracy of IMUs under different timing of magnetic disturbances of various durations and to evaluate a few correction methods. Kinematics from 12 individuals were obtained simultaneously with an Xsens system where an Optotrak cluster acting as the reference system was affixed to each IMU. A handling task was executed under normal laboratory conditions and imposed magnetic disturbances. Joint angle RMSE was used to conduct a three-way repeated measures analysis of variance in order to contrast the following disturbance factors: duration (0, 30, 60, 120 and 240 s), timing (during the disturbance, directly after it and a 30-second delay after it) and axis (X, Y and Z). The highest joint angle RMSE was observed on rotations about the Y longitudinal axis and during the longer disturbances. It stayed high directly after a disturbance, but returned close to baseline after a 30-second delay. When magnetic disturbances are experienced, waiting 30 s in a normal condition is recommended as a way to restore the IMUs' initial accuracy. The correction methods performed modestly or poorly in the reduction of joint angle RMSE.

1. Introduction

Inertial measurement units (IMUs) are a promising technology for motion analysis. In comparison to most optoelectronic or electromagnetic systems, the field of acquisition is not limited, and the technology is less costly, easily portable and rapidly set up. These advantages allow field deployment of applications that were previously restricted to laboratory settings. The first generations of IMUs were composed of accelerometers and gyroscopes. Orientation of a segment was estimated by integration of the angular velocities, and position was obtained by double integration of the translational acceleration. However, noise in the gyroscopes measurements signals created a random drift affecting accuracy up to 25° after 1 min (Roetenberg et al., 2005). Accelerometers can be used to estimate the tilt angle, but gravitational acceleration is invariant in the horizontal plane, which makes accelerometers unsuitable to correct heading drift. Newer generations of IMUs have added magnetometers to compensate heading drift and improve orientation estimation. The downside is that magnetometers are sensitive to the magnetic field disturbances often created by proximity to ferromagnetic objects.

Field investigations have to deal with a wide range of settings, and adaptations for motion analysis are often unrealistic or quite cumbersome, especially in workplaces. Hence, it becomes important to understand the impact of magnetic disturbances on IMUs accuracy. A few studies have reported IMUs errors due to different contexts of magnetic field disturbances. A heading error of up to 29° was reported on IMUs in a laboratory setting near the floor (de Vries et al., 2009). Lower limb kinematics measured in a laboratory, in comparison to outdoors, yielded lower repeatability on the transverse plane of each joint and the frontal plane of the ankle (Palermo et al., 2014). IMUs placed on different mobility aiding devices caused orientation errors of up to 35.3° depending on the type of device and the IMUs positions (Kendell and Lemaire, 2009). The RMSE between IMUs and an optoelectronic system could reach peaks of 50° near a large metal object, compared to 2.6° with no disturbance (Roetenberg et al., 2007).

Until gyroscopes measurements are substantially improved, IMUs will rely on magnetometers for orientation estimation. Several studies have shown that local magnetic disturbances can

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affect IMUs accuracy (de Vries et al., 2009; Kendell and Lemaire, 2009; Palermo et al., 2014; Roetenberg et al., 2007). Some correction methods or algorithms have been developed to compensate for such disturbances (Bergamini et al., 2014; Roetenberg et al., 2007). Most of the fusion algorithms such as the Kalman filter combine data from the accelerometers, gyroscopes and magnetometers to optimize the orientation estimation, while being robust to a certain extent of magnetic disturbances. However, the timing in relation to the magnetic disturbance remains unclear. Whether the error is only instantaneous when the IMUs are in proximity to the disturbance source, or whether a certain delay is needed for the fusion algorithm to restore the baseline accuracy, is debatable. In addition, the motion condition between static IMUs and dynamic IMUs during a magnetic disturbance is also unclear. Moreover, the impact of the disturbance duration on IMU accuracy has not been investigated.

Hence, the main objective of the study was to determine IMUs accuracy during imposed local magnetic disturbances. The specific objectives were to determine the effects of duration and timing of the magnetic disturbances on IMUs accuracy. The hypotheses are that longer magnetic disturbances will increase error and that a delay will be needed post-disturbance to restore baseline accuracy. The secondary objective of the study was to evaluate a few additional correction methods designed to reduce errors due to magnetic disturbances.

2. Methods

2.1. Subjects

Prior to participation in the study, 12 healthy participants (9 men, 3 women, 26.3 ± 4.4 years, height 171.4 ± 6.8 cm and weight 74.4 ± 18.3 kg) completed a consent form approved by the Université de Sherbrooke Ethics Committee. Inclusion criteria were good physical capacity according to the Physical Activity Readiness Questionnaire (PAR-Q) and no self-reported musculoskeletal disorders during the last year. Age over 60 was the exclusion criterion.

2.2. Instrumentation

Whole-body kinematics were recorded at 30 Hz simultaneously with an 8-camera Optotrak system (Northern Digital Inc., Ontario, Canada) and a full-body Xsens system (MVN, Xsens Technologies, Enschede, Netherlands). The systems were synchronized using MVN Studio 3.5 with a trigger signal coming from the Optotrak system. The Xsens system is composed of 17 IMUs strapped over the hands, forearms, upper arms, scapulae, head, sternum, pelvis, thighs, shanks and feet (Fig. 1). When possible, sensors were placed over the bones and not the muscles to reduce soft tissue artifact (Leardini et al., 2005). A four-LED Optotrak cluster was rigidly affixed to the top of every IMU with Velcro and tie-wrap (Fig. 1). Optotrak wires were securely attached around the waist to ensure freedom of movement and reduce load on the limbs. The Xsens IMUs were connected to each other and to two Xbus attached at the waist, which transferred the data wirelessly.

2.3. Experimental protocol

Anthropometrics including height, shoe sole height, arm span, shoulder width, foot length, ankle height, knee height, hip height and hip width were gathered for every subject. These measurements were input into the MVN model of Xsens to estimate segment lengths with regression equations (Roetenberg et al., 2009). Afterwards, anatomical landmarks following the International Society of Biomechanics (ISB) recommendations (Wu et al., 2002, 2005) were identified with a probe from the Optotrak system during a standing static neutral position. To establish a relationship between sensor and segment orientation, the IMUs system was calibrated with a T-pose for the MVN model. This single posture consisted of standing straight with arms abducted to 90°, elbows extended, palms facing the ground and legs straight with feet pointing forward. The subjects were passively placed in the desired position by the operator and were asked to maintain the position for a few seconds to improve the accuracy of the calibration (Robert-Lachaine et al., 2017b).

Each subject performed a trial of three repetitions of simple, short, functional movements involving each joint successively. Manual material handling tasks were performed on a rectangular aluminum platform (size 130 × 190 × 18 cm). Four stations were set up, one at each corner of the platform; the first station was 106 cm in height and the second station, opposite it, was 14 cm. These two stations were mirrored by the third and fourth stations at the other end of the platform. An empty box (size 34 × 26 × 33 cm, mass 0.5 kg) was moved from the first station to the second and then returned to the first station. A pace was imposed, with sounds indicating when to pick up and deposit the box. At the other end of the platform, a metal box (size 34 × 33 × 21 cm, mass 3.1 kg) was moved from the third to the fourth station. In addition, a metal drawer filled with ferromagnetic objects to deviate the magnetic field was placed between the third and fourth stations, in front of the subject. One side of the platform was thus a normal laboratory condition and the other side was an imposed magnetic disturbance condition. The subjects were asked to keep pace, but no instructions were given with regards to handling technique. An indication of the range of motion for each joint during the tasks was previously described (Robert-Lachaine et al., 2017a).

2.3.1. Dynamic trial

A dynamic trial was performed to measure the effects of timing, duration and axis of the magnetic disturbances, and to evaluate the correction methods. The dynamic trial was composed of intervals alternating between lifting an empty box on the normal laboratory side and lifting a metal box on the imposed magnetic disturbance side (Fig. 2). The subjects performed lift intervals alternating between the two sides of the platform as follows:

- 1 min normal side (16 lifts)
- 30 s disturbance side (8 lifts)
- 1 min normal side (16 lifts)
- 1 min disturbance side (16 lifts)
- 1 min normal side (16 lifts)
- 2 min disturbance side (32 lifts)
- 1 min normal side (16 lifts)
- 4 min disturbance side (64 lifts)
- 1 min normal side (16 lifts)

2.3.2. Static trial

A static trial was conducted to determine IMUs accuracy while the subject remained static near the magnetic disturbance and to evaluate the correction methods under this condition. A large metal chair was placed close to the metal drawer. The subject started by lifting the empty box for one minute on the normal side. Then, the subject sat on the chair while staying close to the drawer and remained static for four minutes (Fig. 3). Finally, the subject repeated the 16 lifts during 1 min on the normal side.

2.4. Biomechanical model

Two segmental biomechanical models were used with the two