Journal of Biomechanics 42 (2009) 1578–1581

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short Communication

# IMU: Inertial sensing of vertical CoM movement

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ARTICLE INFO

*Article history:*
Accepted 21 March 2009

*Keywords:*
Accelerometer
Quaternions
Centre of mass
Inertial measurement unit

ABSTRACT

The purpose of this study was to use a quaternion rotation matrix in combination with an integration approach to transform translatory accelerations of the centre of mass (CoM) from an inertial measurement unit (IMU) during walking, from the object system onto the global frame. Second, this paper utilises double integration to determine the relative change in position of the CoM from the vertical acceleration data. Five participants were tested in which an IMU, consisting of accelerometers, gyroscopes and magnetometers was attached on the lower spine estimated centre of mass. Participants were asked to walk three times through a calibrated volume at their self-selected walking speed. Synchronized data were collected by an IMU and an optical motion capture system (OMCS); both measured at 100 Hz. Accelerations of the IMU were transposed onto the global frame using a quaternion rotation matrix. Translatory acceleration, speed and relative change in position from the IMU were compared with the derived data from the OMCS. Peak acceleration in vertical axis showed no significant difference ($p \geqslant 0.05$). Difference between peak and trough speed showed significant difference ($p < 0.05$) but relative peak-trough position between the IMU and OMCS did not show any significant difference ($p \geqslant 0.05$). These results indicate that quaternions, in combination with Simpsons rule integration, can be used in transforming translatory acceleration from the object frame to the global frame and therefore obtain relative change in position, thus offering a solution for using accelerometers in accurate global frame kinematic gait analyses.



## 1. Introduction

Optical motion capture systems (OCMS) are used for kinematic analyses of an object in a three-dimensional calibrated volume and seen as the gold standard (Wong et al., 2007). These systems are relatively expensive, time consuming and not easily applicable outside laboratory conditions (Mayagoitia et al., 2002). Accelerometers offer an alternative way to obtain kinematic data in a variety of environments (Refshauge et al., 1995; Schneck, 2000). However certain methodological problems need to be addressed (Kavanagh and Menz, 2008). During circular movements, such as in human gait, the 3D axes rotate.

Commercially available systems combining accelerometers, gyroscopes and magnetometers into an algorithm, known as inertial measurement units (IMU), can transpose translatory acceleration from the object system to the global system using a rotation matrix (Luinge, 2002; Roetenberg, 2006).

Conventional rotation matrices use Euler angle matrices to perform their rotations, but show singularities when using certain sequences of rotations (Pfau et al., 2006).

Quaternions are geometrical operators which represent rotations by using complex numbers forming an algebra (Gravelle, 2006).

This study investigated a lower spine point estimate of centre of mass (CoM), as a simple reference that indicates global gait quality (Meichtry et al., 2007). IMU over the lower spine has an increased risk of showing singularities using Euler angles, therefore quaternions have been chosen as rotation matrix operators (Moe-Nilssen and Helbostad, 2004). Quaternions allow fast computation and simple expressions to be developed for complex rotations and rotating reference frames (Spring, 1986; Hanson, 2006).

This study will investigate the application of an IMU and quaternion-based rotation matrix compared to an OMCS to measure the estimated CoM translatory acceleration during human walking. It also examines double integration of translatory acceleration to obtain relative change in position.

## 2. Materials and methods

Five subjects (age: 23.4±3.8 years, weight: 80.5±14.3 kg and height: 181±5.4 cm) participated. The IMU (MTx, Xsens, Netherlands) was fixed with adhesive tape, in an angle of ±90° (due to sensor design), over the fourth lumbar vertebra. A reflective marker was placed on the middle of the IMU to measure the

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doi:10.1016/j.jbiomech.2009.03.049

displacement with the OMCS (Proflex, Qualisys, Sweden). Both systems were synchronized and measured at 100 Hz.

Baseline gravitational measurements were recorded before the subjects walked three times through the calibrated measurement volume at their self-selected walking speed (SSWS).

Global axes are defined as in $x$ being forward, $y$ being lateral and $z$ being vertical (Cavagna et al., 2000).

Position data from the OMCS was smoothed using a five points window Savitzky–Golay smoothing filter (Savitzky and Golay, 1964). Acceleration was symmetrically derived from position in the global frame (Malmivuo and Plonsey, 1995).

IMU data were analysed using LabVIEW 8.5.1 to transpose the accelerations from the object onto the global system using a matrix multiplication (2.1).

$$a_{(gs)}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = a_{(os)}\begin{bmatrix} x \\ y \\ z \end{bmatrix} \cdot R_{(q)}\begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad (2.1)$$

where $a_{(gs)}$ is the translatory acceleration in the global system, $a_{(os)}$ is the translatory acceleration in the object system displayed as a $3\times1$ matrix and $R_{(q)}$ is the quaternion rotation matrix with $q_0$ as real value and $q_1$, $q_2$ and $q_3$ as complex numbers combined in a $4\times4$ matrix. Rotation matrix $R_{(q)}$ is displayed in Eq. (2.2).

$$R_{(q)} = \begin{bmatrix} (q_0^2+q_1^2-q_2^2-q_3^2) & (2q_1q_2-2q_0q_3) & (2q_1q_3+2q_0q_2) & 0 \\ (2q_1q_2+2q_0q_3) & (q_0^2-q_1^2+q_2^2-q_3^2) & (2q_2q_3-2q_0q_1) & 0 \\ (2q_1q_3-2q_0q_2) & (2q_2q_3+2q_0q_1) & (q_0^2-q_1^2-q_2^2+q_3^2) & 0 \\ 0 & 0 & 0 & (q_0^2+q_1^2+q_2^2+q_3^2) \end{bmatrix} \quad (2.2)$$

A 4th order Butterworth low-pass filter (cut-off frequency, 25 Hz) was applied to the transposed acceleration. An average of the gravitational forces during rest was set to $-1$ G ($-9.82\pm0.02\,\mathrm{ms^{-2}}$) and subtracted from $z$-axis translatory acceleration to compare with the data from the OMCS.

The gravity corrected acceleration in the global frame was de-drifted by subtracting the estimate of the DC component determined by using a Hanning window of three points (Karié et al., 2003). Afterwards the signal was integrated to velocity ($\mathrm{ms^{-1}}$) according to Simpson's rule (Bishop, 2007) as described in Eq. (2.3), with the initial and final conditions assumed to be zero. By repeating this step, relative position (cm) was calculated. De-drift value was calculated by 3rd order polynomial applied to the relative position. Differences between peak and trough were taken to calculate relative change in velocity and position. Error in velocity and relative position was calculated as the difference between the OMCS and IMU at $t_n$. Random error of acceleration, velocity and position is calculated as twice the standard deviation.

$$y_i = \frac{1}{6}\sum_{j=o}^{i}(x_{j-1}+4x_j+x_{j+1})\Delta t \quad (2.3)$$

Peak amplitudes of the $z$-axis were extracted from both data sets and imported into SPSS 14. Data sets were compared using a paired sample $t$-test and an intra-class correlation (ICC) test 3,1 according to McGraw and Wong (1996) and standard deviation were calculated.

Relative peak and trough difference of velocity and position of the CoM in the vertical axes were calculated for both systems and compared using a paired sample $t$-test. A ICC 3,1 was repeated for peaks and troughs for speed and position. Adequate test-retest reliability was defined as an ICC$\geqslant$0.75 (Sim and Wright, 2000).

Error described as the relative differences in speed and position of OMCS subtracted from IMU error was calculated for peaks and troughs data.

## 3. Results

Table 1 shows the average difference and standard deviation over three walks for five healthy subjects in the $z$-axis. Error between both systems of a random participant is plotted in Fig. 1

The data between IMU and OMCS acceleration shows good agreement. $Z$-axis amplitudes from IMU and OMCS were not significantly different ($p\geqslant0.05$). In addition ICC $=0.952$ and random error $0.176\,\mathrm{ms^{-2}}$ demonstrated strong agreement between systems.

A paired sample $t$-test between the relative change in speed (peak to trough) in the OMCS and IMU showed a significant difference ($p<0.05$). A two-way mixed ICC showed a significant relationship between IMU and OMCS (ICC $=0.888$ and $p<0.01$) with a random error of $0.05\,\mathrm{ms^{-1}}$. Error between OMCS and IMU is visible in Table 2.

A paired sample $t$-test between the relative position (peak to trough) in the OMCS and IMU showed no significant difference ($p\geqslant0.05$). A two-way mixed ICC showed a highly significant correlation (ICC $=0.782$ and $p<0.01$) and a random error of 0.12 cm.

## 4. Discussion

We found that the mathematical transformation using quaternions in combination with double integration applied to IMU data resulted in accurate speed and relative position in the global $z$-axis during SSWS for short measurements. To the authors knowledge this technique provides more accurate CoM displacement data than previously obtained using Euler angles and step-by-step analysis method described in previous publications (Pfau et al., 2005, 2006). For this method, the IMU used in this research was sufficiently accurate for a very short period of time (~10 s) and required a stationary period before the measurements to correct for the expected drift of the gyroscopes. There is a need however to look into long-term effects of drift.

Translatory acceleration in the global axes showed a high correlation between IMU and OMCS data with no significant difference in peak acceleration. The OMCS is the gold standard for measuring position (Ehara et al., 1995, 1997). Deriving position to speed and acceleration causing increasing errors resulting in higher peak accelerations due to artefacts multiplied by the differentiation process.

There was a significant difference in $z$-axis speed between the IMU and OMCS, However peak and trough difference was highly correlated demonstrating good agreement between systems. Due to the typical double peaks in the speed data, $\Delta v$ becomes less accurate to calculate as the peaks vary during locomotion. Error in speed compared between the average error and OMCS was apparent to be less than $-2.5\%$.

Deriving position from the IMU requires two steps of integration. The error increases during this process. After subtracting the

**Table 1**
Mean and standard deviation peak-to-trough data collected from IMU and OMCS over three walks for each subject.

| Subject | Acceleration | | Velocity | | Position | |
|---|---|---|---|---|---|---|
| | $\Delta a_{IMU}$ ($\mathrm{ms^{-2}}$) | $\Delta a_{OMCS}$ ($\mathrm{ms^{-2}}$) | $\Delta v_{IMU}$ ($\mathrm{ms^{-1}}$) | $\Delta v_{OMCS}$ ($\mathrm{ms^{-1}}$) | $\Delta p_{IMU}$ (cm) | $\Delta p_{OMCS}$ (cm) |
| 1 | 2.16±0.30 | 2.36±0.26 | 0.40±0.06 | 0.44±0.06 | 4.11±0.40 | 4.22±0.44 |
| 2 | 2.65±0.26 | 2.70±0.20 | 0.57±0.05 | 0.57±0.04 | 5.08±0.29 | 4.99±0.40 |
| 3 | 1.75±0.17 | 1.92±0.18 | 0.36±0.01 | 0.36±0.01 | 3.34±0.27 | 3.34±0.07 |
| 4 | 1.58±0.09 | 1.83±0.10 | 0.31±0.05 | 0.35±0.04 | 3.24±0.38 | 3.33±0.36 |
| 5 | 2.38±0.08 | 2.64±0.09 | 0.45±0.01 | 0.47±0.05 | 4.42±0.13 | 4.43±0.48 |