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# Comparison of linear accelerations from three measurement systems during "reach & grasp"

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**Abstract**

Given the increased use of accelerometers in movement analysis, validation of such inertial sensors against conventional 3D camera systems and performance comparisons of different sensors have become important topics in biomechanics. This paper evaluates and compares linear acceleration trajectories obtained from two different 3D accelerometers and derived from Vicon position data for an upper limb "reach & grasp" task. Overall, good correspondence between the three measurement systems was obtained. Sources of error are discussed.


*Keywords:* Accelerometers; Xsens; Kionix; Vicon; Signal comparison; Sensors

## 1. Introduction

Accelerometry has long been employed in the analysis of human movements [1]. The use of accelerometers has become increasingly popular over the last decade, offering an inexpensive alternative to optical motion capture systems that allows for the unsupervised monitoring of human motion outside the research laboratory. Areas of application range from movement classification [2], assessment of balance impairments [3] and fall risk [4], to the control of functional electrical stimulation (FES) devices [5].

Despite their increased use in human movement analysis, only a few studies have been concerned with the accuracy of 3D position and orientation data derived from inertial sensor output as compared to position and orientation obtained from 3D camera systems [6,7]. Furthermore, surprisingly little attention has been given to the comparison of accelerations measured directly using accelerometers with accelerations obtained via double differentiation of position data from 3D camera systems.

Rapid technological advancements in the development of micro-fabricated inertial sensors have taken place, resulting in a large number of commercially available products including, most recently, single chip 3D accelerometers. As these products become more readily available, it is important to gain an improved understanding of their characteristics with respect to conventional movement analysis tools, so that the best tool, or combination of tools, can be chosen for a given problem.

It is the objective of this paper to compare the accelerations obtained from two commercially available inertial sensors, namely Xsens and Kionix, with accelerations derived from Vicon position data. The Pearson's correlation coefficient and RMS error were computed for the upper limb acceleration trajectories of a healthy young adult performing a "reach & grasp" task. Possible sources of error are discussed.

## 2. Methods

### 2.1. Experiment

A healthy young adult, who had given informed consent, sat at a table with the hand hanging relaxed at the side of the

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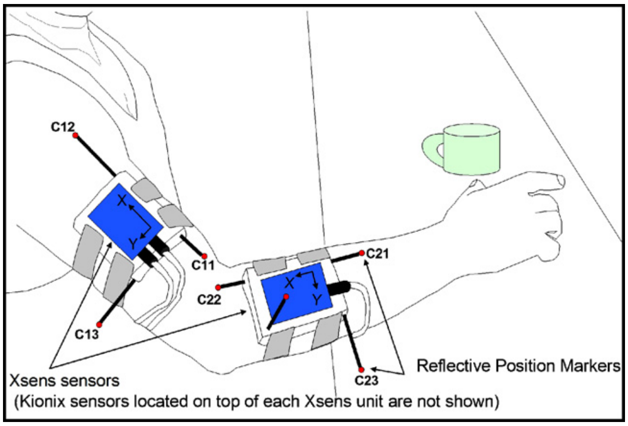


Fig. 1. Experimental set-up showing marker clusters and accelerometers.

body. A glass was placed on the table in front of the subject such that it could be reached comfortably without moving the torso. The subject was instructed to reach forward, grasp the glass, briefly move it up towards the mouth, place it back on the table, and retract the arm back to the starting position. This movement task was chosen as it is representative of a variety of activities of daily living with regard to movement frequency and amplitude. Ten trials of this movement task were recorded.

### 2.2. Instrumentation

Two precision-machined wooden boxes, each with a cluster of three reflective markers attached to protruding rods, were attached via Velcro straps to the upper arm and forearm (Fig. 1). Xsens (XSENS, Xsens Technologies B.V., Enschede, The Netherlands) and Kionix (Kionix Inc., Ithaca, New York, USA) inertial measurement units were then secured inside each box such that their sensor coordinate frames were aligned. Both inertial measurement systems provide an appropriate full-scale range (±2 g) and sampling frequency (quoted standard: 250 and 500 Hz for Xsens and Kionix, respectively) for "reach & grasp" tasks. A Vicon set-up (Vicon Motion Systems, Los Angles, USA) consisting of 10 cameras and analog input channels was used to record position data for the reflective markers and the Kionix accelerations, respectively. Xsens data was collected by a separate computer. A pulse signal, captured by one of the Vicon analog channels, was used to synchronize the Xsens data with the other two measurement systems. In this study all kinematic data were sampled at 100 Hz, an adequate sampling frequency for movements with frequency content below 30 Hz.

### 2.3. Data processing

All data processing was done within MATLAB® (MathWorks, Inc., Natick, MA, USA). Vicon position data for the markers were low-pass filtered with a 4th order Butterworth filter using a cutoff frequency of 6 Hz. The cutoff frequency was determined through frequency domain analysis, which showed that more than 98% of the signal power is below 6 Hz. Furthermore, similar values are used in other upper limb movement studies [8]. Local marker coordinate systems for the wooden boxes on the upper arm and forearm were defined such that each was aligned with its respective Xsens and Kionix coordinate systems:

$$X_{\text{upper arm}} = \frac{C_{12} - C_{11}}{||C_{12} - C_{11}||} \tag{1}$$

$$V_{\text{upper arm}} = (C_{12} - C_{11}) \times (C_{13} - C_{11}) \tag{2}$$

$$Z_{\text{upper arm}} = \frac{V_{\text{upper arm}}}{||V_{\text{upper arm}}||} \tag{3}$$

$$Y_{\text{upper arm}} = Z_{\text{upper arm}} \times X_{\text{upper arm}} \tag{4}$$

$$X_{\text{forearm}} = \frac{C_{22} - C_{21}}{||C_{22} - C_{21}||} \tag{5}$$

$$V_{\text{forearm}} = (C_{22} - C_{21}) \times (C_{23} - C_{21}) \tag{6}$$

$$Z_{\text{forearm}} = \frac{V_{\text{forearm}}}{||V_{\text{forearm}}||} \tag{7}$$

$$Y_{\text{forearm}} = Z_{\text{forearm}} \times X_{\text{forearm}} \tag{8}$$

Rotation matrices were calculated between the Vicon global coordinate system and the two marker clusters' local coordinate systems. Position data for each cluster origin (marker $C_{11}$ and $C_{21}$ for upper arm and forearm, respectively) were then double differentiated in global coordinates and gravity was added to the vertical acceleration component. Finally, the calculated linear accelerations of each marker cluster's origin were rotated from global to local coordinates. Linear accelerations obtained from Xsens and Kionix accelerometers were directly compared with those calculated for the marker clusters, taking into account the small offsets between coordinate frame origins.

### 2.4. Statistical analysis

All signals were compared using Pearson's correlation coefficient ($r$) and RMS error ($\varepsilon$). Mean values for $r$ and $\varepsilon$ across all trials are reported. To investigate the effects of alignment and calibration errors, a least squares linear regression was performed for each pair of signals. The resulting regression equation ($y = mx + c$) was then applied in order to adjust for any gain and zero offset (i.e. bias). RMS error was then determined a second time for the signals after removal of systematic errors (Pearson's correlation coefficient was not recomputed since it is invariant to linear transformations).

## 3. Results

In general, the linear acceleration trajectories closely approximated each other, with slightly more noise on the