

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 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—accelerometry; accelerations; inertial measurement; validation; movement analysis; camera systems; error; accuracy

I. 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 sophisticated 3D camera 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. 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 (r) 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.

II. METHODS

A. Experiment

A healthy young adult sat at a table with the hand hanging relaxed at the side of the 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. Ten trials of this movement task were recorded.

B. Instrumentation

Two precision-machined wooden boxes were attached via Velcro straps to the upper arm and forearm (Fig. 1). Xsens (XSSENS, Xsens Technologies B. V., Enschede, Netherlands) and Kionix (Kionix Inc., Ithaca, New York, USA) inertial measurement units were secured inside each box and a cluster of three reflective markers was attached to rods protruding from each box (Fig. 1). A Vicon set up consisting of 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. All data was sampled at 100 Hz and a pulse signal captured by one of the Vicon analog channels was used to synchronize the Xsens data with the other two measurement systems.

C. 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. 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:

$$\mathbf{X}_{\text{Upper Arm}} = (\mathbf{C}_{12} - \mathbf{C}_{11}) / \|\mathbf{C}_{12} - \mathbf{C}_{11}\| \quad (1)$$

$$\mathbf{V}_{\text{Upper Arm}} = (\mathbf{C}_{12} - \mathbf{C}_{11}) \times (\mathbf{C}_{13} - \mathbf{C}_{11}) \quad (2)$$

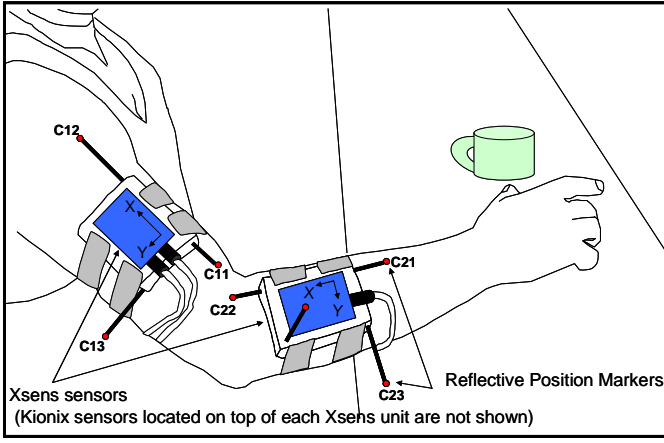


Figure 1. Experimental set up showing marker clusters and accelerometers.

$$Y_{\text{Upper Arm}} = V_{\text{Upper Arm}} / \|V_{\text{Upper Arm}}\| \quad (3)$$

$$Z_{\text{Upper Arm}} = X \times Y \quad (4)$$

$$X_{\text{Forearm}} = (C_{22} - C_{21}) / \|C_{22} - C_{21}\| \quad (5)$$

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

$$Y_{\text{Forearm}} = V_{\text{Forearm}} / \|V_{\text{Forearm}}\| \quad (7)$$

$$Z_{\text{Forearm}} = X \times Y \quad (8)$$

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.

D. Statistical Analysis

All signals were compared using Pearson's correlation coefficient (r) and RMS error (ϵ). Mean values for r and ϵ across all trials are reported.

III. RESULTS

In general, the linear acceleration trajectories closely approximated each other, with slightly more noise on the Kionix and Xsens acceleration trajectories. Fig. 2 shows linear accelerations for the upper arm for all three measurement systems, while Fig. 3 displays the same for the forearm. A small offset was observed for the linear acceleration along the Kionix Z axis of the forearm (Fig. 2, bottom).

Tables 1 & 2 show Pearson's correlation coefficients and RMS errors between the acceleration trajectories of the three different measurement systems. For the upper arm high correlation coefficients ($0.947 < r < 0.998$) were obtained for all comparisons. The RMS errors ranged from 0.22 to 0.42 m/s^2 . Similarly, comparison between systems on the forearm resulted

in high values for r . However, for the Z axis of the forearm the RMS errors were 0.76 and 0.70 when comparing Kionix with Vicon and Kionix with Xsens, respectively - much greater than for any other signal comparison.

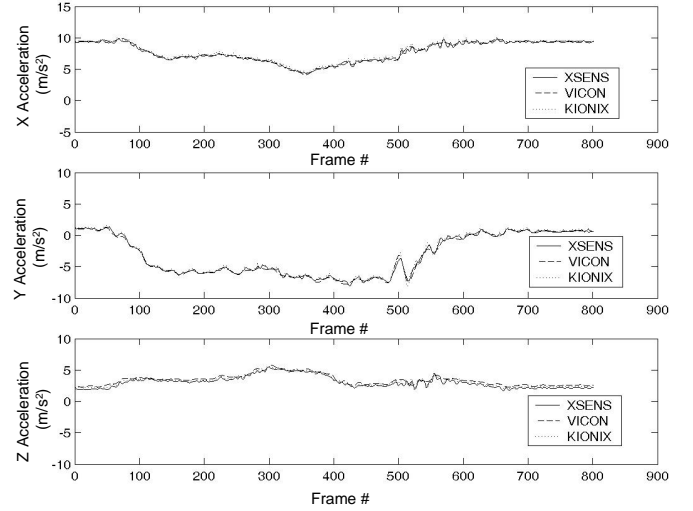


Figure 2. Example trial data illustrating the acceleration trajectories obtained from the three measurement systems on the upper arm.

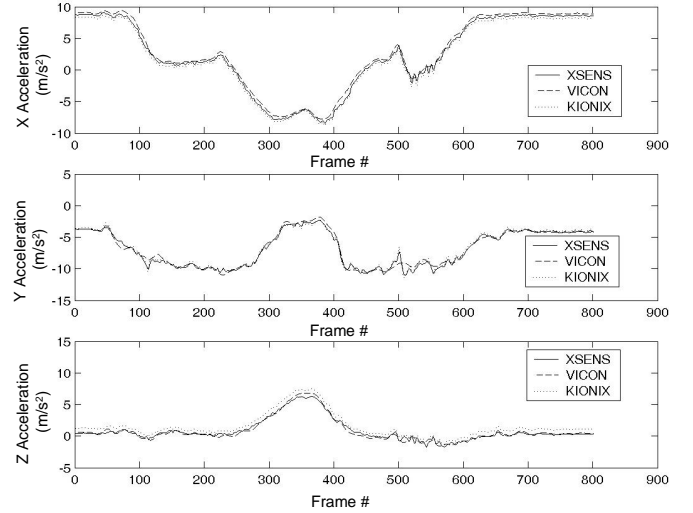


Figure 3. Example trial data illustrating the acceleration trajectories obtained from the three measurement systems on the forearm.

TABLE I. COMPARISON BETWEEN MEASUREMENT SYSTEMS LOCATED ON THE UPPER ARM VIA PEARSON'S CORRELATION AND RMS ERROR

	Upper Arm		
	X	Y	Z
XSENS-VICON	$r = 0.988$ $\epsilon = 0.23$	$r = 0.997$ $\epsilon = 0.25$	$r = 0.947$ $\epsilon = 0.42$
KIONIX-VICON	$r = 0.984$ $\epsilon = 0.27$	$r = 0.996$ $\epsilon = 0.34$	$r = 0.947$ $\epsilon = 0.27$
KIONIX-XSENS	$r = 0.995$ $\epsilon = 0.24$	$r = 0.998$ $\epsilon = 0.22$	$r = 0.987$ $\epsilon = 0.25$

TABLE II. COMPARISON BETWEEN MEASUREMENT SYSTEMS LOCATED ON THE FOREARM VIA PEARSON'S CORRELATION AND RMS ERROR

	Forearm		
	X	Y	Z
XSENS-VICON	$r = 0.999$ $\epsilon = 0.43$	$r = 0.991$ $\epsilon = 0.37$	$r = 0.988$ $\epsilon = 0.27$
KIONIX-VICON	$r = 0.999$ $\epsilon = 0.78$	$r = 0.989$ $\epsilon = 0.41$	$r = 0.993$ $\epsilon = 0.76$
KIONIX-XSENS	$r = 1.0$ $\epsilon = 0.40$	$r = 0.997$ $\epsilon = 0.23$	$r = 0.996$ $\epsilon = 0.70$

IV. DISCUSSION

Overall the Xsens, Kionix and Vicon measurement systems performed similarly. Good correspondence was obtained between all three systems, despite the challenges associated with sensor alignment and signal noise.

The fact that Vicon showed less noise on the acceleration signals is probably due to the low-pass filtering of the marker position data while Xsens and Kionix signals were compared without any further processing. This was done to show the difference between "actual" accelerometer output and typical Vicon data processed using widely accepted procedures. If Vicon systems are used to simulate accelerometers at different locations on the body, then a representative measure of noise should be added to the Vicon data. This is crucial for applications where researchers use 3D camera data to find the "ideal" position for an accelerometer for reliably detecting gait events and/or activity [8].

Despite the use of precision-machined wooden boxes a slight offset was obtained for the forearm Z axis of the Kionix device. Misalignment of axes inside the accelerometer might be a possible source of error, although the Kionix accelerometer shows low cross axis sensitivity, suggesting internal misalignment is minimal. In general, care with reference frame alignment needs to be taken when comparing systems: errors due to misalignment between Vicon and accelerometer coordinate frames can be magnified as a result of the sensitivity of accelerometers to the gravity vector.

We believe that the offset of the Z axis was responsible for the increased RMS error obtained when comparing the Kionix device with the other two measurement systems. Moreover, since Z accelerations were smaller than X and Y accelerations, alignment errors would show a proportionally greater effect for that axis. In general, such systematic errors can be easily taken care of post data collection with customized MATLAB[®] code. Fig. 4 shows an example where the systematic error on the Z axis has been removed using a least squares fit approach.

We conclude that accelerometer units such as Xsens and Kionix are a satisfactory substitute for Vicon cameras when recording segmental linear accelerations. Their application has the advantage to enable researchers to perform tests outside the gait laboratory. Future studies may investigate different filtering techniques and/or the introduction of artificial noise to accelerations calculated from camera data where the requirement is to simulate accelerometers [8, 9].

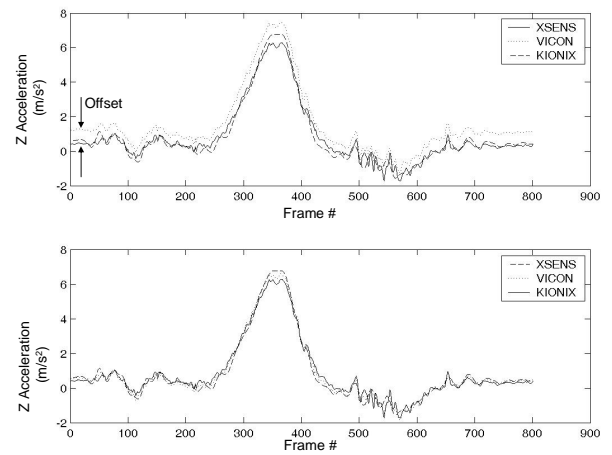


Figure 4. Linear Z acceleration of the forearm before (top) and after (bottom) removal of a constant offset using a least squares fit.

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