

Paper:

# Human-Scale Motion Capture with an Accelerometer-Based Gaming Controller

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**Gaming controllers are attractive devices for research due to their onboard sensing capabilities and low cost. However, a proper quantitative analysis regarding their suitability for motion capture has yet to be fully reported. In this paper, a detailed analysis of the accelerometers of the Nintendo Wiimote is presented. The gravity-compensated acceleration data from the accelerometers of the Wiimote were plotted, compared and correlated with computed acceleration data derived from a six-camera motion capture system. The results show high correlation and low mean absolute error between the gravity-compensated data from the accelerometers of the controllers and computed acceleration from position data of the motion capture system. From the results obtained, it can be inferred that the Wiimote is well suited for motion capture applications where post-processing of data is practical.**

**Keywords:** motion capture, accelerometers, gaming controllers

## 1. Introduction

Video game controllers such as Nintendo's Wiimote have revolutionized how we interact with games by enabling intuitive motion sensing and interpretation rather than relying on keyboard, mouse, or button clicks. Recent developments in the field of Micro Electro Mechanical Systems (MEMS) have made it possible to develop high precision and high performance sensors for nominal cost [1]. The availability of these low-cost gaming controllers, and the wide range of tools available for open-source development, makes devices such as the Wiimote potential platforms for low-cost motion capture and gesture recognition. Although information on "hacking" the Wiimote is widely available [2], there have only been a few studies to directly report the performance of any specific gaming controllers, and fewer still that compare devices to high fidelity motion capture systems.

While we have explored the utility of just one gaming controller (the Wiimote) in this paper, the broader use of commercial gaming devices in domains beyond gaming is well documented. Applications reported in the litera-

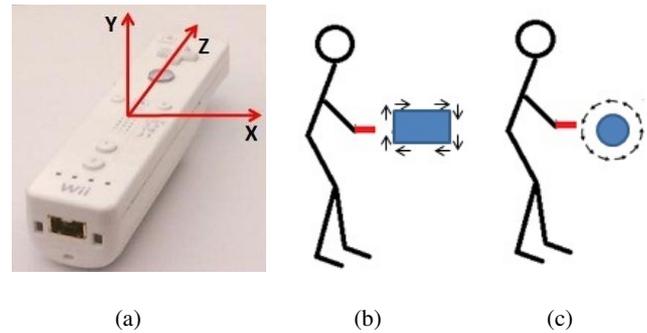
ture include rehabilitation (see [3], [4] for examples), collaborative music creation and navigation [5], and gesture recognition. The Wiimote in particular has been extensively used in studies involving extraction of patterns of motion from measured data [6–9], since, despite their low resolution and tendency to drift, these devices provide an inexpensive alternative for pattern or gesture recognition as precise and accurate movement data is not required. As a result, these devices can be used for efficient robot control as seen in [10]. Other groups have used the motion data from gaming devices more directly, either for teleoperation of a robotic device for human-robot interaction research [11], or for assessing rehabilitation outcomes by tracking wrist motion or patient balance [12–14]. Absent from many of these studies is explicit information on the performance capabilities of these gaming devices as motion sensors or as appropriate input devices when precision measurements are necessary.

Despite the lack of explicit reported data on the utility of gaming controllers for precise motion capture and other research applications, a number of groups have explored such uses of low-cost controllers and documented aspects of their performance. In one study, Ardito et al. compared low cost devices for interacting with virtual environments [15], but no sensor data was reported showing the reliability of the sensors on these devices and whether the controllers are suitable for high precision tracking devices. Attygalle et al. used the infrared cameras of two Wiimotes to track hand motion during physical therapy, later comparing the tracking results with those obtained from a 10-camera motion capture system (motion analysis) [16]. Although it was evident from their results that the performance of the Wiimote was reliable for motion capture, one of the main drawbacks of this system was that the Wiimote's infrared camera had to be pointed at the patient's arm at all times. Moreover, Attygalle et al. did not compute the correlations between the signals recorded from the Wiimote and the motion capture system. As a result, it is difficult to predict the dynamic performance of the Wiimote. In this paper, both the correlations between the Wiimote and the computed motion capture accelerations as well as the mean absolute error between the Wiimote and the computed motion capture accelerations are discussed, thereby giving a more holistic picture of the Wiimote's dynamic performance. More recently, there

has been a number of studies indicating the use of inertial measurement units (IMUs), such as those found in gaming controllers, to track motions of different parts of the body [17–20]. In each of these papers, the authors compare certain body joint angles computed by the IMUs with those computed by optical motion capture systems; however, they do not conduct a detailed sensor analysis of the IMUs and do not compare the performance of each axis of the accelerometer with that of the motion capture system.

There are some reported comparisons of motion data derived from gaming controllers to high fidelity motion capture systems, including comparisons of the total acceleration of a triaxial accelerometer with the total acceleration computed using a motion capture system [21, 22]. However, a detailed performance analysis of each axis of the accelerometer was not reported. Comparisons of accelerations measured from multiple sensors during high frequency applications have been reported [22], with low frequency acceleration due to gravity removed via filtering from the recorded acceleration signal. These papers lack recommendations regarding an optimal dynamic range of the sensors in the IMUs, and reasons for their failure outside of this range. There have been a number of studies comparing the Wiimote with other controllers for gesture recognition. Natapov et al. compared the standard mouse with the Wiimote and Nintendo's Classic Controller in terms of tracking and pointing, though no quantitative performance results related to the Wiimote's onboard sensors were reported [23]. In another study, Gams et al. used two Wiimotes to map hand movements of a drummer to a robot playing a drum [1]. While the paper discussed the acceleration data acquired by the Wiimote devices, the authors did not compare these data with any other means of tracking motion data, therefore the accuracy of the sensors could not be judged. Finally, Xie et al. compared 24 dimensional data captured from eight Wiimote controllers to data captured by an eight camera motion capture system (Vicon) [24]. They carried out a Principal Component Analysis on the collected data and used a motion recognition algorithm, confirming that the Wiimote data compared well to the Vicon data. No details regarding the accuracy, resolution, sensitivity or reliability of the Wiimote sensors were reported.

In this paper, we analyze the accelerometers of the Wiimote, pictured in **Fig. 1**, in detail. Determining the suitability of the Wiimote as a low cost alternative for human-scale motion capture was the primary goal of this study. Our earlier experiments, where we compared the acceleration data from the accelerometers of the Wiimote to double differentiated position data from a high resolution linear encoder, have shown that acceleration data recorded from the Wiimote were highly correlated to the double differentiated position data from the linear encoder [25]. In this paper, in order to prove the viability of the Wiimote as a low cost alternative for motion capture, we compare the gravity-compensated acceleration data recorded from the Wiimote with the double differentiated position data recorded from a six camera motion capture system (hereafter referred to as mocap acceleration). We also discuss



**Fig. 1.** (a) Nintendo Wiimote shown relative to the motion capture system's left-handed coordinate system as referred to in our experimental analysis. Note that the  $y$ - and  $z$ -axes are interchanged from that of the controller's local coordinate system which is right-handed. The Wiimote was used to trace a box (b) and a circle (c) in all three planes in the presence of a six-camera motion capture system.

the dynamic range for which the Wiimote is best suited for high-fidelity tracking, thus pointing out the Wiimote's high-fidelity behavior within and its failure outside this range. Finally, we discuss the viability of the Wiimote for both motion analysis and as input devices for motion control especially in the fields of robotics, rehabilitation and other areas which require efficient and accurate gesture recognition. Therefore, this paper will guide researchers working in these areas to decide on a suitable device for their research, or provide guidance to those wishing to conduct similar experiments to validate the suitability of similar gaming controllers and sensors.

The paper is organized as follows: experimental methods are discussed in Section 2, followed by results and discussion in Section 3 and conclusions in Section 4.

## 2. Methods

### 2.1. Experimental Protocol

The experiments served a twofold purpose of validating the use of the Wiimote for the range of human motions required during activities of daily living (ADL) and determining the suitability of each axis of the accelerometer for data collection during single and multi degree of freedom movements. Additionally, the repeatability of the performance of the Wiimote was also tested.

The experiments included the following tasks:

**Task Ia:** Tracing the edges of a block ( $11.5 \text{ cm} \times 7.5 \text{ cm} \times 7 \text{ cm}$ ) for 40 seconds (as shown in **Fig. 1(b)**).

**Task Ib:** Tracing the edges of a block ( $11.5 \text{ cm} \times 7.5 \text{ cm} \times 7 \text{ cm}$ ) 10 times.

**Task IIa:** Tracing the circumference of circles (12 cm in diameter) in all three planes for 40 seconds (as shown in **Fig. 1(c)**).

**Task IIb:** Tracing the circumference of these circles (12 cm in diameter) 10 times.

**Task III:** Performing pseudo-random movements with the Wiimote for 40 seconds.

The premise behind tracing the circumference of a block in all three planes was to individually test the fidelity of the data recorded by each axis of the accelerometer of the Wiimote. Tracing the circumference of the circle on the other hand would help in testing any two axes of the accelerometer at a given time, while performing pseudo-random motions with the Wiimote would help determining the suitability of the Wiimote to adapt to sudden changes in acceleration along a particular axis. The experiments which included 10 repetitions of tracing the block and the circle were used to determine the repeatability of the Wiimote to perform motion capture experiments. The dimensions of the objects were chosen such that the hand movements while tracing the objects would always remain within the camera work volume. All experiments were performed by the same subject.

## 2.2. Data Capture

Data capture during the experiments was done using the QuaRC blocks for the Wiimote and Optitrack motion capture system in Simulink, developed by MathWorks. QuaRC, developed by Quanser [a], is a real time software environment that can be used with Simulink for rapid controls prototyping and hardware-in-the-loop testing. The sampling rate for data collection was set at 100 Hz, the maximum available sampling rate for both the motion capture system and the Wiimote. This sampling rate was suitable to avoid aliasing since the maximum frequency of human motion is much less than 100 Hz [26, 27].

### 2.2.1. Nintendo Wiimote Controller

The Wiimote with the Motion Plus has a 3-axis linear accelerometer, an infrared digital camera and a two-axis gyro for pitch and roll along with a single-axis gyro for yaw. The controller communicates with the Wii console or a computer over a wireless Bluetooth interface (BCM2042 chip from Broadcom) [1]. The camera has a resolution of  $1024 \times 768$  [9] with more than 4 bits of dot size and a  $45^\circ$  horizontal field of view [2]. The accelerometer (Analog Devices ADXL 330 [b]) is of the capacitive type. The accelerometers on the Wiimote have a range of  $\pm 3$  g and a bandwidth from 0.5 Hz to 1600 Hz on the  $x$ - and the  $y$ -axes and a bandwidth from 0.5 Hz to 550 Hz on the  $z$ -axis [c]. The device has a sensitivity of 10% and 10 bits of precision on the  $x$ -axis as opposed to 9 on the  $y$  and the  $z$ . However, the different axes are all assumed to have a 10-bit range and the Least Significant Bit (LSB) is always set to zero for  $y$  and  $z$ .

### 2.2.2. Optitrack Motion Capture System

Natural Point's Optitrack motion capture system (model number V100R2 [d]), shown in Fig. 2, can be used



**Fig. 2.** The Wiimote in an acrylic case covered with paper and reflective markers lying in the work volume of Natural Point's Optitrack motion capture system. The data from the Wiimote are acquired through Bluetooth.

to capture full body motion of an object with reflective markers. Each camera has a resolution of  $640 \times 480$  pixels, corresponding to submillimeter accuracy for position measurement in the work volume, and is capable of being used at frame rates of 25, 50 and 100 FPS. Additionally, the cameras are equipped with 26 LEDs and have a 10 ms latency period with  $38^\circ$ ,  $46^\circ$ , and  $58^\circ$  lens FOV. The six cameras were connected individually to two USB hubs (three to each hub) which were further connected to the computer through the computer's USB 2.0 port. The reflective markers used for this experiment were of  $5/8$ " diameter, semi-soft and spherical with a  $8/32$ " threaded hole. There were four markers placed on the Wiimote, two on the top face (one next to button "A" and one next to the "Home" button), one on the side and one next to the IR camera. There were none placed underneath (on the face which has the button "B") to avoid marker occlusion. It should also be noted that the global coordinate system for the camera system was left handed.

The motion capture system is equipped with its own software (Tracking Tools), which provides modules for accurate camera calibration, rigid body identification and tracking. The data recorded from the motion capture system provide the spatio-temporal location of each marker as well as the center of mass of the rigid body as a whole in the global or camera reference frame. For accurate data collection with reliable sampling, the QuaRC block for the Optitrack motion capture system was used within Simulink. Following the camera calibration process, the experiments were carried out and the motion data collected.

## 2.3. Post Processing

The raw position and acceleration signals recorded from the motion capture system and the Wiimote had to be further processed before they could be used for any analysis.

### 2.3.1. Filtering

The Wii mote's ADXL 330 accelerometer chip produces uniform white Gaussian noise at all frequencies. Therefore, in post processing, the sampled data from the accelerometers of the controllers were filtered with a 6th order Butterworth filter with a cutoff frequency of 4 Hz. A Butterworth filter was chosen because of its maximally flat pass band. The filter order was chosen to ensure that the filter gain was 1 for the entire pass band and for a sharp transition band. The data were filtered both in the forward and the backward directions to compensate for phase lag. After filtering, a gravity compensation technique was used to remove the component of gravity from each axis of the recorded acceleration data.

The position data from the motion capture system were filtered in a similar manner to remove the high frequency noise present in the data. Furthermore, the position data from the camera system were filtered after each step of differentiation.

### 2.3.2. Gravity Compensation

The accelerometers of the Wii mote are sensitive to the direction of gravity. As a result, accurate comparison of the acceleration data recorded from the Wii mote with the mocap acceleration is not possible without an accurate gravity compensation technique. The acceleration data recorded from the accelerometer of the Wii mote at any given time instant can be given by:

$$a_{wii mote} = a_{actual} + a_{gravity} \quad . . . . . (1)$$

where  $a_{wii mote}$  is the recorded acceleration reading along a particular axis,  $a_{actual}$  is the actual linear acceleration along that axis and  $a_{gravity}$  is the component of acceleration due to gravity along that axis. The mocap acceleration can be treated as an accurate estimate of  $a_{actual}$ , requiring only computation of  $a_{gravity}$  at each sample period.

The data recorded from the motion capture system contained the six degree of freedom (DOF) spatio-temporal information of the center of mass of the Wii mote in the global reference frame with a right handed coordinate system, while the acceleration data from the local reference frame of the Wii mote was recorded with respect to a left handed coordinate system. To compensate for gravity, the acceleration vector of the center of mass of the Wii mote in the local reference frame of the Wii mote was first converted to the left handed coordinate system and then premultiplied by a rotation matrix comprising of the sines and cosines of the Euler angles between the two reference frames (namely the global or camera frame and the local reference frame of the Wii mote). This operation was followed by subtraction of acceleration due to gravity from the  $y$ -axis of the transformed Wii mote acceleration data. The rotation matrix was designed assuming a  $yxz$  sequence of Euler rotations and is denoted by  $\mathbf{R}$ .

Then, transform the vector of accelerations according to  $V = \mathbf{R}U$ , where  $U$  is the vector of accelerations of the center of mass of the Wii mote in its local reference frame

and  $V$  is the same vector after being transformed to the global reference frame.

### 2.4. Analysis

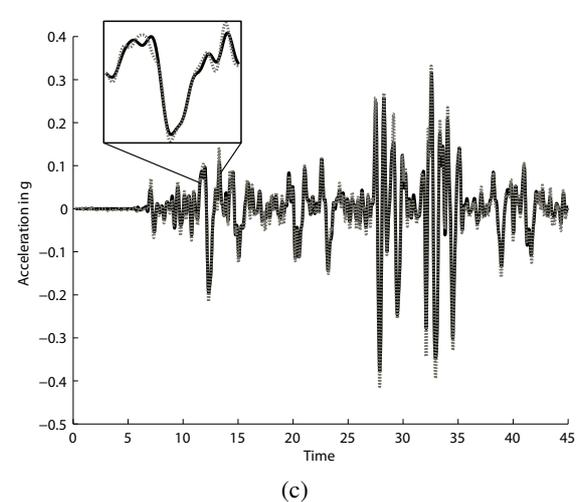
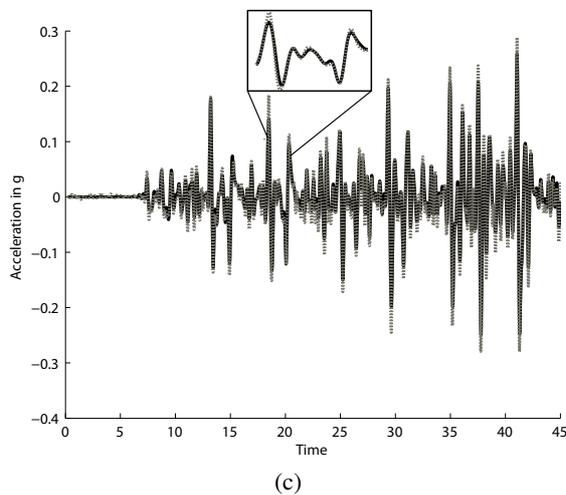
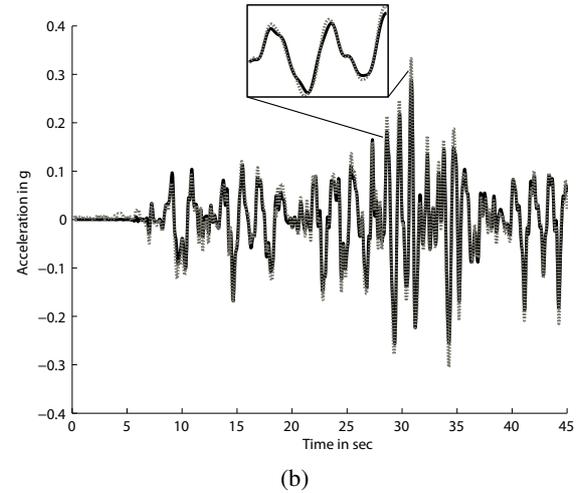
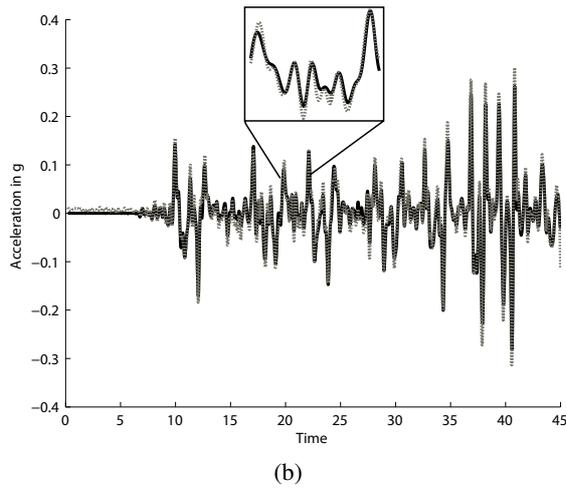
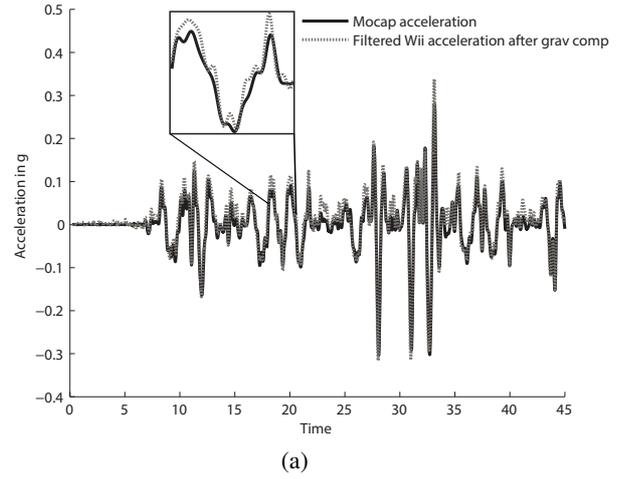
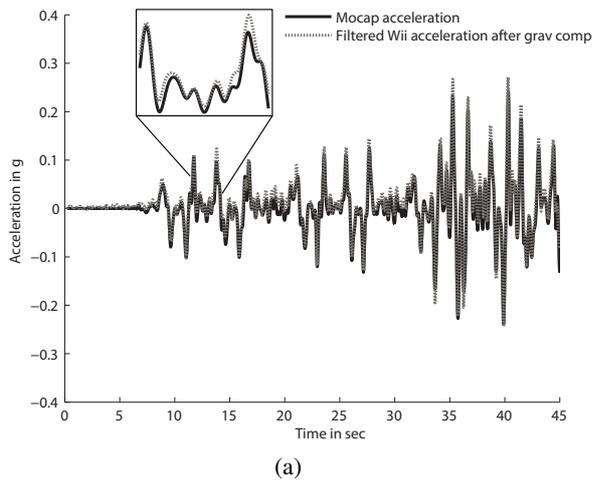
As a part of the analysis, the correlation coefficients and the mean error between the mocap acceleration and the gravity compensated acceleration signals from the Wii mote were computed.

## 3. Results and Discussion

Before comparing the acceleration data acquired from the Wii mote to the mocap acceleration recorded from the camera system, the resolution of the Wii mote's accelerometers were determined to be 1.05%, 2.13% and 1.98% of gravity for the  $x$ -,  $y$ - and  $z$ -axes. The differing resolutions across the axes may be due to different levels of precision on the internal variables used to report the sensor data. It can also be due to the analog filter bandwidth at  $x_{OUT}$ ,  $y_{OUT}$  and  $z_{OUT}$ , which are the acceleration values along the  $x$ -,  $y$ - and  $z$ -axes from the accelerometer chip. The working details of the Wii mote's accelerometer chip along with the functional block diagram can be found in [28].

**Figures 3–5** show the gravity compensated acceleration data of the Wii mote and the mocap acceleration in the  $x$ ,  $y$  and  $z$ -directions for the three tasks listed earlier. **Table 1** shows the correlation coefficients and the mean errors between the gravity compensated and uncompensated accelerations from the Wii mote and the mocap accelerations in the  $x$ -,  $y$ - and  $z$ -directions for the experiments without repetitions. **Table 2** shows the correlation coefficients and the mean errors between the gravity compensated and the uncompensated accelerations from the Wii mote and the mocap accelerations in the  $x$ -,  $y$ - and  $z$ -directions for the experiments where the repeatability of the Wii mote was tested. In each figure, the data sets represented by thick black continuous lines indicate the mocap accelerations and thick grey dotted lines indicate the gravity compensated accelerations of the Wii mote. It should be noted that the black mocap acceleration is not clearly visible under the thick grey dotted line indicating a very high correlation and very low mean absolute error between the gravity compensated Wii mote acceleration and the mocap acceleration. The high correlation coefficient and low mean absolute error suggest that the sensors in the Wii mote are well-suited to operate as motion tracking devices to capture human motion.

It is evident from **Table 1** that the correlation coefficients are highest when the subject traced the block, followed closely by the circle and the pseudo-random motion tasks. The marginally better correlation coefficient for the block experiment can be attributed to the fact that the Wii mote's sensors are better suited for motions with low frequencies and higher amplitudes [25]. The circle and the pseudo-random motion experiments requiring motions with higher frequencies and lower amplitudes result in a lower correlation coefficient as compared to the

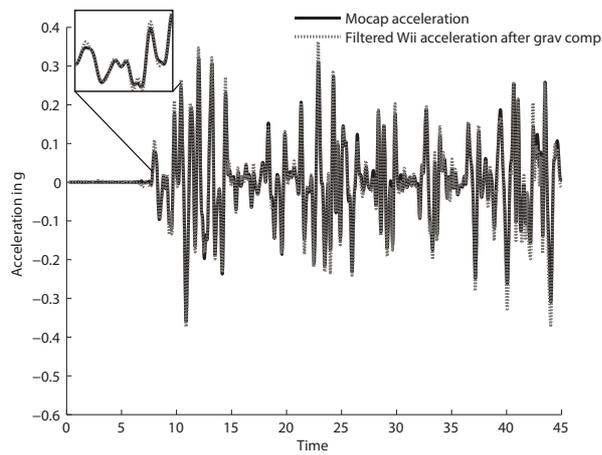


**Fig. 3.** Box tracing experiments showing high correlation and low mean absolute error between the Wiimote's gravity compensated acceleration and the mocap acceleration in the a) x-, b) y- and c) z-directions.

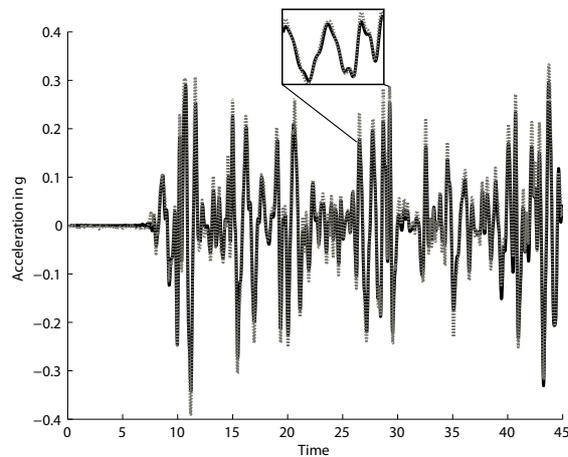
**Fig. 4.** Circle tracing experiments showing high correlation and low mean absolute error between the Wiimote's gravity compensated acceleration and the mocap acceleration in the a) x-, b) y- and c) z-directions.

block experiments. The reason for the better results of the Wiimote at low frequencies and higher amplitudes may be because of the high stiffness of the spring mass system of the accelerometers. Consequently, the deflection of the spring may not be sufficient to cause a deflection in the

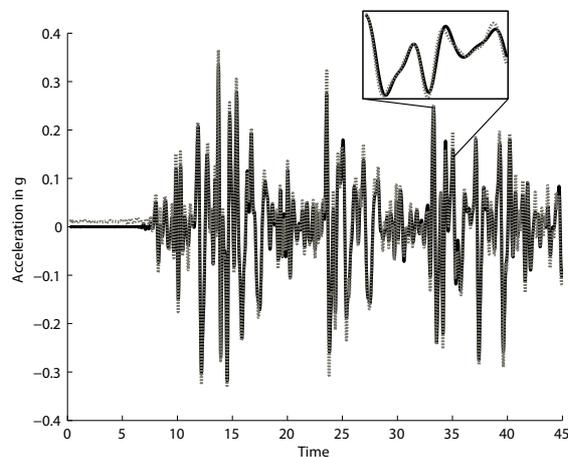
capacitive plate to which the spring is attached, resulting in an insignificant voltage change. At higher frequencies and amplitudes, the Wiimote exhibits low noise in the sensor data [25]. When used for slow and low amplitude ap-



(a)



(b)



(c)

**Fig. 5.** Pseudo random motion experiments showing high correlation and low mean absolute error between the Wiimote's gravity compensated acceleration and the mocap acceleration in the a)  $x$ -, b)  $y$  and c)  $z$ -directions.

plications, adequate noise filtering is required. The high correlations and low mean absolute errors of the gravity compensated acceleration data with the mocap acceleration data in **Table 2** suggest that the Wiimote can be used

**Table 1.** Correlations and mean absolute errors between Wiimote and mocap accelerations for the experiments without repetitions.

Axis	Box		Circle		Pseudo Random	
	Corr	MAE (g)	Corr	MAE (g)	Corr	MAE (g)
$x_{comp}$	0.97	0.0113	0.97	0.0141	0.99	0.0143
$x_{uncomp}$	0.77	0.0441	0.75	0.0387	0.53	0.0792
$y_{comp}$	0.98	0.011	0.98	0.0121	0.98	0.0158
$y_{uncomp}$	0.79	0.0335	0.88	0.0259	0.79	0.0411
$z_{comp}$	0.98	0.01	0.99	0.0102	0.98	0.0151
$z_{uncomp}$	0.97	0.117	0.99	0.011	0.97	0.0194

**Table 2.** Correlations and mean absolute errors between Wiimote and mocap accelerations for the experiments with repetitions.

Axis	Box		Circle	
	Corr	MAE (g)	Corr	MAE (g)
$x_{comp}$	0.97	0.0066	0.97	0.0065
$x_{uncomp}$	0.85	0.0161	0.71	0.0186
$y_{comp}$	0.96	0.0083	0.97	0.0091
$y_{uncomp}$	0.77	0.0241	0.8	0.0217
$z_{comp}$	0.97	0.0069	0.97	0.0068
$z_{uncomp}$	0.97	0.0072	0.97	0.0072

reliably for extended periods of data capture.

It should also be noted that the gravity compensation was carried out using a coordinate transform method discussed earlier. Several gravity compensation techniques have been presented in the literature for cases where both accelerometers and gyros are available as in the Wiimote [29–31]. Since the goal of this paper was to validate the Wiimote as a viable replacement for expensive motion capture systems, a coordinate transformation based technique to compensate for gravity was used based on the motion capture data. Had the gravity compensation been carried out using just the sensors on the Wiimote (namely the accelerometers and the gyros as in [29–31]) the results would have been the same.

The advantages of using the Wiimote for motion capture are numerous. Firstly, the Wiimote does not require tracking markers. As a result, the problems associated with occluded markers, markers falling off or relative marker movement are absent. Mechanical motion capture systems address the issues of marker occlusion [32]; however, these systems are bulky and interfere with human movement. Secondly with the Wiimote, motion cap-

ture experiments can be performed anywhere, they do not have to be limited to the confines of the area with the camera system. Thirdly, motion capture systems require a lot of time to setup and calibrate. Great care has to be taken to ensure that the cameras are not disturbed from their positions post calibration, failing that the data recorded will be erroneous. For the Wiimote no such requirements have to be met. Lastly, motion capture systems are much more expensive compared to gaming controllers like the Wiimote.

#### 4. Conclusions

The use of low cost gaming controllers is attracting attention in research domains where human-scale motions and wearable sensor technology are of interests. This paper has presented a detailed comparison of dynamic sensor data of the Wiimote and computed acceleration data from a six camera motion capture system. The results show that the Wiimote's performance is highly reliable and repeatable. For optimal performance as motion capture devices, the acceleration data from the controllers needs to be filtered and gravity-compensated in post processing, as the data from the accelerometers of the controllers are noisy and sensitive to the direction of gravity.

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- [d] "Optitrack motion capture system." <http://www.naturalpoint.com/optitrack>



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