Body Sensor Networks for Monitoring Rowing Technique

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Abstract

This paper presents a prototype for monitoring the kinematics of the femur and lower back (sacrum and thoraco-lumbar junction) during rowing. Data is collected from inertial sensors attached to the rower and a simple yet relatively accurate method for determining the rotation of the lower back and femur in the sagittal plane is presented. We also present results from an initial validation experiment using an optical tracking system which demonstrate that it is possible to monitor rowers using the proposed sensors and identify some common poor rowing techniques. Due to their small size, wireless capability and lightweight characteristics, the proposed Body Sensor Network (BSN) system has the potential to be used during ergometer sessions and whilst training on the water.

1. Introduction

The adoption of an efficient rowing stroke ensures that the maximum amount of energy expended by athletes contributes to the speed of the boat. Good rowing technique is not only vital for performance, but also helps prevent injury by removing undue stresses which may be placed on the body when poor rowing techniques are utilized [1].

To date, there has been several different approaches taken for objective rowing performance monitoring. Instrumented boats or rowing machines have been used, upon which sensors are placed to monitor force transmission so that the power output can be derived [2, 3].

Another approach measures the motion of the rowers' body, such as the flexion-extension angles of the hip and knee, and to this end a sensing leotard has been developed by Tesconi *et al* [4]. While this system demonstrates a non-intrusive method for rower monitoring, it has not been tested over multiple participants and requires an extensive testing phase, and might require personalized fitting.

It is also possible to monitor the motion of the rower using electromagnetic (EM) trackers, as demonstrated by Bull and McGregor [5]. In this paper they present methods for monitor lumbar spinal motion which could be used to discriminate between good and poor rowing techniques. While the work presented in [1] and [5] illustrates the necessity of lower back monitoring to help prevent injury through bad practice, major limitations exist in that it can not be used on-water due to the cumbersome monitoring environment.

In this paper, we present a system for monitoring the kinematics of rowers' using inertial sensors integrated with Body Sensor Network (BSN) nodes. Specifically, we focus on monitoring the rotation of the lower back (sacrum and thoraco-lumbar junction) and femur in the sagittal plane. A comparison of this system with a state-of-the-art motion capture system will be given followed by an example of how this system can be used to identify some common poor rowing techniques such as "slide-shooting" and "over-leaning".

In the following sections, a description of the BSN rowing platform is provided, including hardware description, system calibration and rotational calculations. A description of the experimental setup and validation results are also provided. We then illustrate the utility of our system by identifying two poor rowing techniques simulated by an experienced rower. Finally, we provide a discussion of our work giving conclusions and future directions.

2. BSN rowing platform

To enable unrestricted motion of the rower during training, the proposed system was developed with portability in mind. To this end, the BSN platform has been used as summarised in Section 2.1. To calculate rotation using a gyroscope, integration error, which leads to angular drift over time, is compensated for using a simple yet relatively accurate method, detailed in Section 2.2 and 2.3. This lightweight solution is suitable for on-node processing, creating possibilities for real-time feedback during training.

2.1. Hardware description

Three sensor nodes were developed based on the BSN node [6] developed at Imperial College, London, providing a flexible data collection platform and wireless communications to a base station. The BSN main board consists of a micro controller (TI MSP430F149), radio communications (Chipcon CC2420, an IEEE 802.15.4 compliant chipset), and 512KB flash memory (Atmel AT45DB041B). The BSN node uses the TinyOS operating system developed Berkeley, University of California [7]. A sensor board module providing channels for six analogue inputs, each connected to a corresponding 12 bit analogue-to-digital converter, allows for the simple integration of sensors with the BSN node.

The inertial sensors used in this system are Analog Devices 3-axis accelerometer, ADXL330 [8], and the InvenSense integrated dual-axis gyroscope, IDG 300 [9]. Both sensors have been integrated into a sensor board by SparkFun Electronics, the IMU 5 Degrees of Freedom, [10]. Prototype housing was developed for the BSN node and the sensors to allow for consistent sensor placement on the rower, Figure 1(a). Spirit levels at the base and top of the housing were included to calibrate the sensors, as shown in Figure 1(b).

Ground truth data for system validation was collected using the BTS Bioengineering BTS SMART-D system [11] by attaching passive infrared (IR) markers to the sensor nodes, as shown in Figure 1(c).

2.2. System calibration

To calibrate the system, 8 seconds of data is collected from the x-axis of the accelerometer at an angle of 90° and -90°, *i.e.*, at 1 g and -1 g, where g is acceleration due to gravity. This is achieved using the spirit level placed at the top and bottom of the node housing respectively as shown in Figure 1(b). 8 seconds of the gyroscope base-line was also collected, *i.e.*, when the sensors were not in motion.

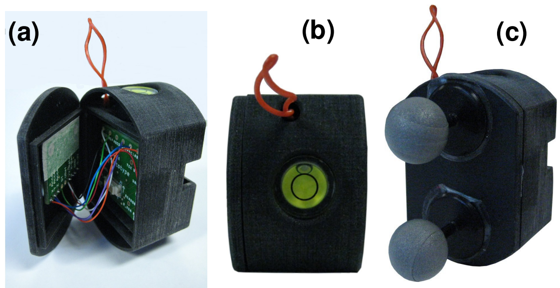

Figure 1. BSN rowing node prototype, (a) open housing showing the sensor board and BSN node, (b) top view of the housing showing a calibration spirit level, (c) front view of the housing with passive infrared markers for collecting ground truth data.

2.3. Calculating rotation from inertial sensors

Inertial sensors, such as accelerometers and gyroscopes, have been used extensively for body monitoring systems to determine angle [12, 13, 14]. One of the major problems of using these types of sensors is compensating for drift. This can be done by through the use of other sensors, such as magnetometers [14], to provide additional information. A system for measuring knee angle in two dimensions by Williamson and Andrews [12] used *auto-resetting* and *auto-nulling* algorithms to compensate for the drift of the gyroscope. Low accelerometer variance was used to assume the gyroscope was stationary. Kalman filters have also been used to compensate for drift [13]. These systems all work in either two or three dimensions. For monitoring rowers, we shall only be looking at the rotational angles in the sagittal plane, *i.e.,* in one dimension. This greatly reduces the complexity of the algorithms necessary to compensate for drift.

In order to determine rotation using this system, we rely on the detection of pauses during the stroke, *i.e.*, times when angular velocity is zero. The following algorithm compensates for the gyroscope integration drift by using accelerometer data during these pauses to estimate the angle and correct for error. Examples of the raw gyroscope and accelerometer data can be seen in Figure 2(a).

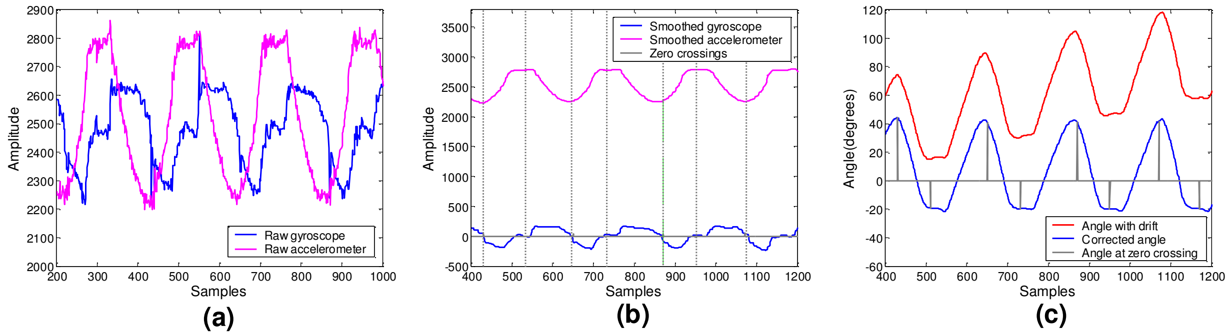

Figure 2. (a) Raw gyroscope and accelerometer data, (b) smoothed accelerometer data and gyroscope data offset by the gyroscope baseline. Gyroscope zero-crossings have been indicated, (c) an example of the angular drift and the use of angles derived from the accelerometers to correct for the drift.

To find the angle, $\theta(t)$, at time t, the angular velocity, $\omega(t)$, was measured with the gyroscope where

$$\omega(t) = \frac{d\theta}{dt} \tag{1}$$

$$\omega'(t) = \omega(t) + \varepsilon(t) \tag{2}$$

and $\varepsilon(t)$ is the noise at time t. The angle can be estimated from the gyroscope data by integration:

$$\theta'(t) = \int \omega'(t)dt = \int \omega(t) + \varepsilon(t)dt \tag{3}$$

$$\theta'(t) = \theta(t) + \int \varepsilon(t)dt \tag{4}$$

Over time, the drift, $\int \varepsilon(t)dt$, will build up. Based on the assumptions that in rowing, when there is no translational motion, $\theta(t)$ should be close to the angle derived from the accelerometer, it is possible to use accelerometer data to correct for the drift of $\theta'(t)$. By assuming that the drift is linear over a short time period:

$$\int \varepsilon(t)dt = \theta'(t) - \theta(t) = \alpha t \tag{5}$$

As such, the correction for drift when $\omega'(t_0) = 0$ is as follows:

$$\alpha = \frac{\theta_{acc}(t_0) - \theta_{gyro}(t_0)}{t_0} \tag{6}$$

where θ_{acc} and θ_{gyro} are the angles derived from the accelerometer and gyroscope respectively.

To find the angle from the accelerometer, the projection of gravity acceleration onto the node coordinate system is measured, which varies with the angle of the sensor with respect to the Earth's frame of reference. The stages of this algorithm have been illustrated in Figure 2.

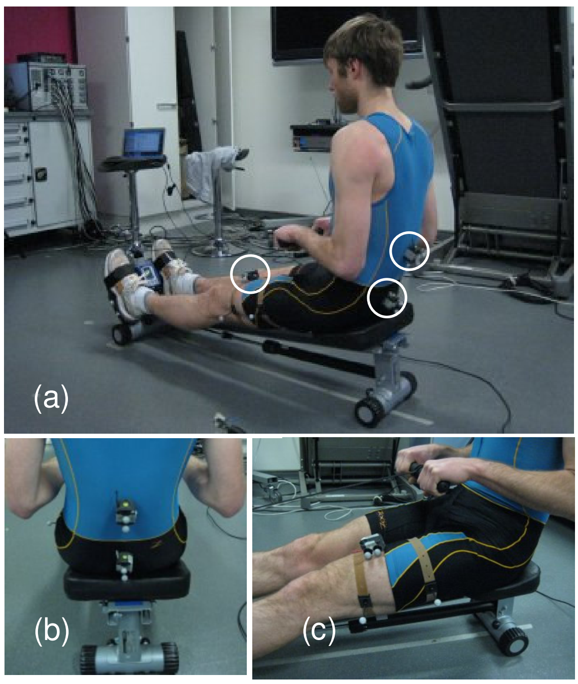

Figure 3. Experimental setup, (a) a rower with sensor nodes attached to the (b) sacrum and thoraco-lumbar junction and (c) the femur.

3. Experimental method

To validate the proposed system, 5 novice rowers were invited to take part. Each rower was asked to row on the York Inspiration Rower with sensor nodes attached to the sacrum, thoraco-lumbar junction, and femur, as shown in Figure 3. Before rowing, a demonstration of basic rowing technique was given to each rower before they began and a period of time was given to warm-up. For evaluation, the first part of experiment was performed to determine the accuracy of the system measuring the rotation in the lower back and femur.

The second part of the testing is performed to establish the potential for this system to be used for monitoring the technique of a rower by providing examples of two poor rowing techniques, slide-shooting and over-leaning, comparing these to a good technique. Data was collected from the sensor nodes at a sampling rate of 50 Hz and transmitted wirelessly to a base station. In this study, all data was post-processed after the experiment.

As previously described in Section 2.1, IR markers were attached to each sensor node to gather ground truth data using the BTS system. It was found that the IR markers placed on the femur node were severely occluded by the rower's body. To over come this, the IR markers were placed on the side of the leg as shown in Figure 3(c). Because the reference IR markers were not placed on the sensor node itself, a significant shift in angle can be observed. This shift can be measured accurately using the BTS system when the markers on the node are not occluded to compensate for the shift. For each set of rowing data, the algorithm, described in Section 2.3., was applied to the data over a period of ten rowing strokes to find the rotation at each sensor node. Figure 4(a) shows an example of the resulting rotational data with the corresponding BTS ground truth data.

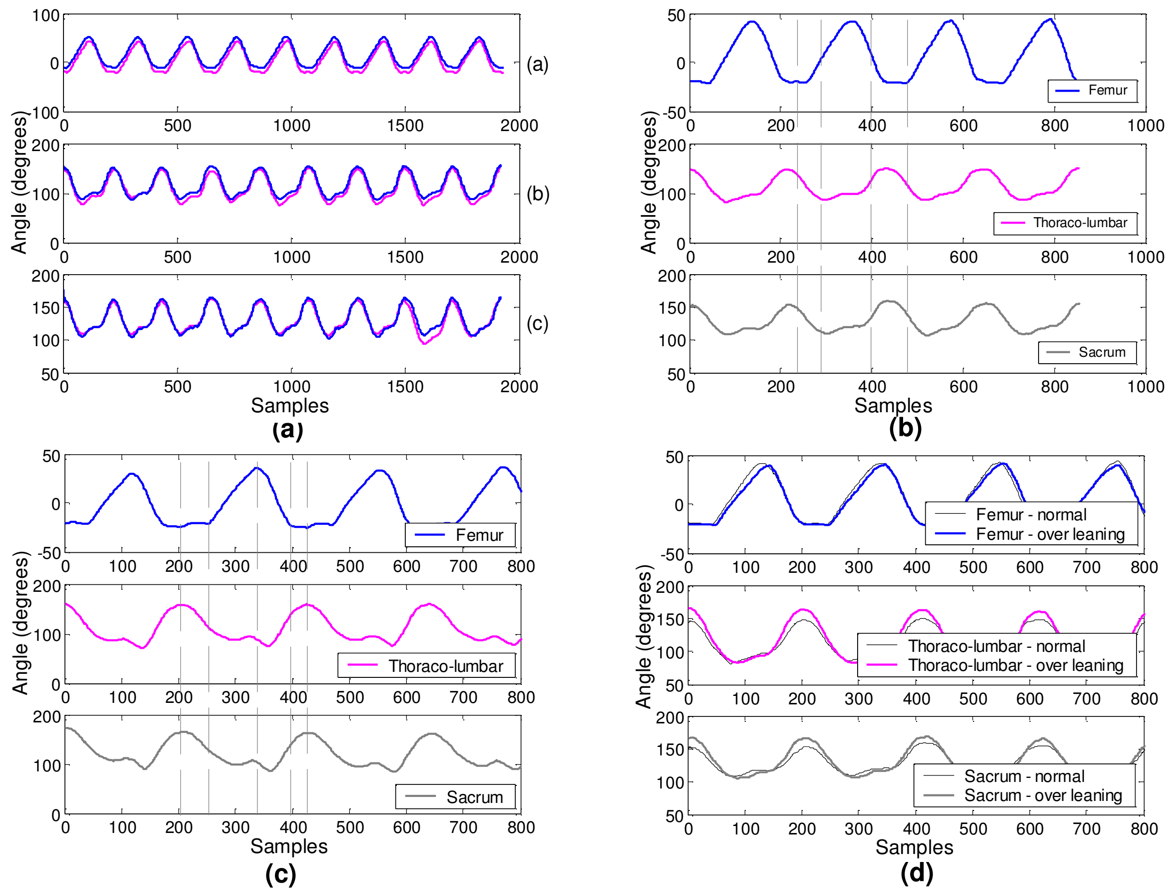

Figure 4. (a) An example of the rotation of the femur, thoraco-lumbar junction and sacrum. BTS ground truth data is shown in cyan with the measured rotation shown in magenta, (b) demonstrates data from a good technique, while (c) and (d) demonstrate the poor techniques slide-shooting and over-leaning respectively.

Table 1. Mean error and standard deviation between the measured angles using the BSN nodes and BTS.

	Femur (f)		Thoraco-lumbar (tl)		Sacrum (s)	
	μ_f	σ_f	μ_{tl}	σ_{tl}	μ_s	σ_s
Rower 1	2.0499	2.3438	2.9813	1.9688	3.1556	4.4564
Rower 2	2.8440	2.7758	1.9684	1.7681	2.7883	3.2935
Rower 3	2.8555	3.1416	5.3273	2.7080	6.2296	2.8469
Rower 4	3.5803	2.8253	5.3212	2.5814	4.4331	3.4561
Rower 5	6.8629	5.7397	4.2921	1.8995	3.8005	4.2798
Average:	**3.63852**	**3.36524**	**3.97806**	**2.18516**	**4.08142**	**3.66654**

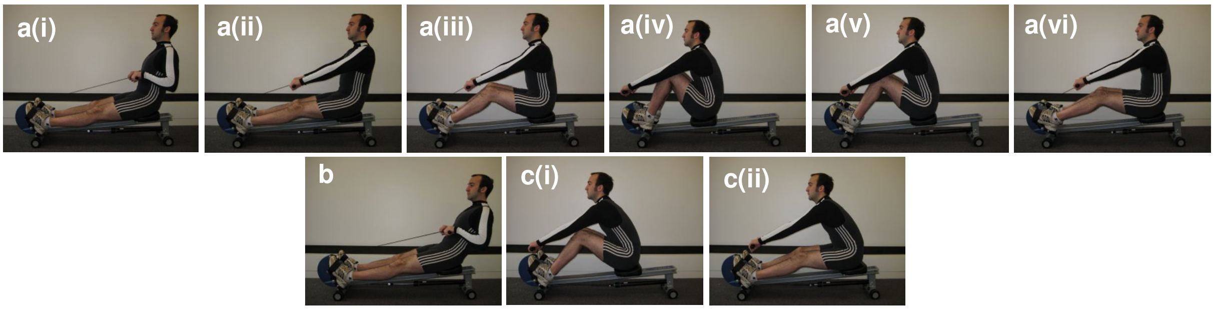

Figure 5. a(i) – a(vi) Rowing sequence from the finish position to the drive position and back, (b) an example of over-leaning; the rower should be in a similar posture to a(i), c(i) and (ii) an example of slide-shooting; the rower should be in similar posture to a(v) and a(vi).

To determine the accuracy of this system, the mean average error and standard deviation of the angles between those calculated using the system presented and the BTS were calculated for each of the three sensors, as shown in Table 1.

3.1. Examples of poor rowing technique

To demonstrate the potential for using the BSN sensor nodes for identifying poor rowing technique, data was collected from an experienced oarsman. Two different poor rowing techniques were simulated; slide-shooting and over-leaning. For a good rowing technique, the rower moves in cycles between the *finish* position and the *drive* position [15], as illustrated in Figure 5. The drive position is given in Figure 5 a(iv).

With a good rowing technique, a movement of the seat from the start of the drive position has corresponding leg and handles motion. During slide-shooting the legs push back but if the trunk is not braced there is less power transferred from the legs to the handles, [15]. This results in the back leaning forwards and no arm movement as the legs push backwards, as shown in Figure 5 c(i) and c(ii). Over-leaning occurs when the rower leans back too far in the finish position [15]. When returning to the drive position from the finish position the stroke is less efficient, and does not justify the benefits of a longer rowing stroke, Figure 5(b). Examples of good rowing technique, slide-shooting, and over-leaning can be seen in Figure 4 (b), (c), and (d) respectively.

4. Results and discussion

4.1. System accuracy

It can be seen in Table 1 that for the rotations in the lower back, an average error of 2.0° and 2.9° can be achieved for thoraco-lumbar junction and sacrum rotations respectively for Rower 2. The average error over-all rotation is 4.0° and 4.1° for the thoraco-lumbar junction and sacrum respectively. In both cases it can be seen that the standard deviation is low, demonstrating the consistency of the error through out the sample. The error in the rotation of the femur can be as little as 2.0° with an average over-all error of 3.6°.

4.2. Examining rowing technique

An example of the data collected from the lower back and femur using the sensor nodes for a good rowing technique can be seen in Figure 4(b). The finish position is characterized by a peak in angle of the thoraco-lumbar junction and sacrum and a trough in angle of the femur. As the rower moves into the drive position the lower back angle can be seen to reduce as the rower leans forwards until the legs start to bend bringing the rower forwards to the drive position. From here the rotation in the back increases as the rower leans backward and the femur rotation decreases as the legs straighten out. It can be seen that the rotation of the sacrum and thoraco-lumbar junction is very similar indicating the trunk is braced and rotation is occurring from the hips and not a bend in the back.

Figure 4(c) and 4(d) show examples of lower back and femur rotation using the sensor nodes for poor techniques, slide-shooting, and over-leaning respectively. Slide-shooting can be characterized by the decrease in lower back angle as the legs are straightening out. This shows the back is leaning forwards indicating the trunk is not braced and power is not being transferred from the legs to the handles. Over-leaning is more subtle, as shown in Figure 4(d), where the angle that the rower leans back by is greater. While there are many more poor rowing techniques, these examples demonstrate the sensor nodes ability to collect data from which technique can be monitored.

Although the accuracy of the rotation is not as fine a resolution as systems such as the BTS or many EM tracking systems it can provide a good estimate of the rower's posture from which from differing techniques can distinguished and characterized. Another advantage of using these sensor nodes is the system is not custom made for an individual person and can be fitted to any rower. Due to the wireless nature of the system, it also has the potential to be used during on-water training, monitoring not only individual rowers, but the whole crew. Extensive testing or the system is still required on experienced rowers and in on-water scenarios.

5. Conclusion

In this paper we have described a Body Sensor Network for monitoring the rotations in the lower back and femur. Sensor nodes including accelerometers and gyroscopes were used to measure the posture of rowers with the aim of distinguishing good rowing technique from poor. A simple algorithm has been presented to measure the rotation of the sensor nodes in the sagittal plane. We have achieved an average accuracy of 4.0°, 4.1°, and 3.6° for the thoraco-lumbar junction, sacrum, and femur respectively. Finally, it has been demonstrated how data collected with this system can indicate bad rowing posture and technique.

6. References

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