The Application of Inertial Sensors in Elite Sports Monitoring

Chapter · January 2006

DOI: 10.1007/978-0-387-45951-6_52

1 author:

Daniel Arthur James
Griffith University

The Application of Inertial Sensors in Elite Sports Monitoring

Daniel A. James

Abstract. The testing and monitoring of elite athletes in their natural training environment is a relatively new area of development that has been facilitated by advancements in microelectronics and other micro technologies. Whilst it is a logical progression to take laboratory equipment and miniaturize it for the training and competition environment, it introduces a number of considerations that need to be addressed. In this paper the use and application of inertial devices for elite and sub-elite sporting activities are discussed. The capacity of accelerometers and gyroscopes to measure human motion thousands of times per second in multiple axis and at multiple points on the body is well established. However interpretation of this data into well-known metrics suitable for use by sport scientists, coaches and athletes is something of a challenge. Traditional brute force techniques such as achieving dead reckoning position and velocity by multiple integration are generally regarded as an almost impossible task. However novel derivative measures of performance such as energy expenditure, pattern recognition of specific activities and characterisation of activities into specific phases of motion have achieved greater success interpreting sensor data.

1 Introduction

Athletic and clinical testing for performance analysis and enhancement has traditionally been performed in the laboratory where the required instrumentation is available and environmental conditions can be easily controlled. In this environment dynamic characteristics of athletes are assessed using treadmills, rowing and cycling machines and even flumes for swimmers. In general these machines allow for the monitoring of athletes using instrumentation that cannot be used in the training environment but instead requires the athlete to remain quasi static thus enabling a constant field of view for optical devices and relatively constant proximity for tethered electronic sensors, breath gas analysis etc. Today however by taking advantage of the advancements in microelectronics and other micro technologies it is possible to build instrumentation that is small enough to be unobtrusive for a number of sporting and clinical applications (James, Davey and Rice 2004). One such technology that has seen rapid development in recent years is in the area of inertial sensors. These sensors respond to minute changes in inertia in the linear and radial directions. These are known as accelerometers and rate gyroscopes respectively. This work will focus on the use of accelerometers, though in recent years rate gyroscopes are becoming more popular as they achieve mass-market penetration, thus increasing availability and decreasing cost and device size.

Accelerometers have in recent years shrunk dramatically in size as well as in cost (~$US20). This has been due chiefly to the adoption by industries such as the automobile industry where they are deployed in airbag systems to detect crashes. Micro electromechanical systems (MEMS) based accelerometers like the ADXLxxx series from Analog Devices (Weinberg, 1999) are today widely available at low cost. The use of accelerometers to measure activity levels for sporting (Montoye, Washburn, Smais and Ertl 1983), health and for gait analysis (Moe-Nilssen, Nene and Veltink 2004) is emerging as a popular method of biomechanical quantification of health and sporting activity and set to become more so with the availability of portable computing, storage and battery power available due to the development of consumer products like cell phones, portable music players etc.

2. Inertial Sensors

Accelerometers measure acceleration at the sensor itself and typically in one or more axis and are millimeters or smaller in size. In general a suspended mass is created in the design and has at least one degree of freedom. The suspended inertial mass is thus susceptible to displacement in at least one plane of movement. These displacements arise from changes in inertia and thus any acceleration in this direction. Construction of these devices vary but typically use a suspended silicon mass on the end of a silicon arm that has been acid etched away from the main body of silicon. The force on the silicon arm can be measured with piezoresistive elements embedded in the arm. In recent years multiple accelerometers have been packaged together orthogonally to offer multi-axis accelerometry.

Accelerometers measure the time derivative of velocity and velocity is the time derivative of position. Thus accelerometers can measure the dynamics of motion and potentially position as well. It is well understood though that the determination of position from acceleration alone is a difficult and complex task (Davey and James 2003).

Instead, accelerometers are often used for short-term navigation and the detection of fine movement signatures and features (such as limb movement). Accelerometers can be used to determine orientation with respect to the earth's gravity as components of gravity are aligned orthogonal to the accelerometer axis. In the dynamic sports environment, complex physical parameters are measured and observed in relation to running and stride characteristics (Herren, Sparti, Aminian and Shultz 1999), and in the determination of gait (Williamson and Andrews 2001).

Researchers have also used accelerometers for determining physical activity and effort undertaken by subjects. These kinematic systems have been able to offer comparable results to expensive optical based systems (Mayagoitia, Nene and Veltink 2002). Rate gyroscopes, a close relative of the accelerometer, measure angular acceleration about a single axis and are also used to determine orientation in an angular co-ordinate system, although these suffer from not being able to determine angular position in the same way accelerometers have trouble with absolute position. Additionally many physical movements, such as lower limb movement in sprinting, exceed the maximum specifications in commercially available units that are sufficiently small and inexpensive for such applications.

2.1 Inertial navigation

If we consider a simple case of motion that is in a single direction (x) with constant acceleration (a_x) double integration with respect to time should enable displacement (s_x) to be calculated. Thus the equations for velocity (v_x) and displacement (s_x) become:-

$$\text{Velocity}_x \qquad v_x = \int a_x \,.\, dt = v_x + c_1 \tag{1}$$

$$\text{Displacement}_x \qquad s_x = \int (v_x + c_1).dt = s_x + c_1.t + c_2 \tag{2}$$

In each integration step additional constants (C_1, C_2) emerge. Thus for constant acceleration a sloped straight line offset appears after double integration. Clearly for a well-bounded problem these constants can be removed, but if there is any error in the boundaries the solution becomes increasingly unbounded. Additionally as the integration is usually numerical then the sampling considerations can contribute significantly. In practice this is much more complex as acceleration is non-linear.

Simple test applications involving displacements over just a few meters have resulted in positional errors of many meters after just a few seconds of double integration. In addition accelerometers are usually sampled discretely giving rise to errors from the sampling and digitization process. One technique is to apply known boundary elements to the data at regular intervals; because sporting movement is very often cyclic in nature a ‘zero’ point can then be applied at regular intervals. In applications such as running gait, motion in the vertical direction is, for flat terrain, self normalising. Wixted (Wixted, Thiel, James, Hahn, Gore and Pyne 2005) has shown that a simple low-pass filter can be used to extract variations in axial tilt to keep the coordinate system aligned orthogonal to the ground. Recent work (Channells, Purcell, Barrett and James 2005) shows that lower limb shank rotation can be calculated using two accelerometers. Gyroscopes, in general are unsuitable for this application due to the high rates of rotation of the limb during running. By monitoring the movement of individual limbs during the limb stride it may be possible to reconstruct the entire gait cycle. Applying anthropomorphic measures and measuring angles of takeoff for the flight phase potentially allow the displacement covered by the athlete between steps and the total distance traveled could be calculated.

2.2 Sampling Considerations

Accelerometer output is typically recorded digitally. Depending on the application, sample rate and resolution are important factors. Thus careful adherence to sampling theory is required to ensure that aliasing due to under sampling does not occur (Cutmore and James 1999). This is particularly relevant to studies based on human motion. Whilst the peak of human activity occurs below 20 Hz, sampling at much higher rates is required to capture the full detail of the motion, or if short term navigation is sought as there are significant higher order terms in the data that contain important information. Typically high rates such as 1000 Hz and 12-bit resolution preserves data quality for most applications. Of course sampling at these rates for multi-axial devices generates large data sets very quickly. Recent research (Lai, James, Hayes and Harvey 2003) suggests that in many cases the resolution can be reduced to 8 or 6 bits without loss of information, though preserving the high data rate is important. It is argued that error minismisation through shaping the measurement error in time and space, mindful of the noise characteristics of the device such as the noise floor of the sampling circuit and the bandwidth response of the devices themselves are more important than the number of bits used in sampling.

2.3 Sensor artifact

The mechanical coupling of inertial sensors to the region of interest requires a number of considerations. Firstly within the musculoskeletal system it is usually the dynamics of joint and bone segments that are of primary interest. However, it is rarely possible to mount these sensors directly to these segments. Instead sensors are mounted directly onto the skin surface and the tissue beneath it necessarily separates itself from the bone of interest in usually non-linear coupling that is susceptible to stretching and distortion generated during movement. Secondly subject comfort and the neutrality of the sensor is important; if the subject is uncomfortable in any way the performance characteristics of their movement may be subtly different. Finally, attachment of the acceleration sensors also has the potential to affect the very dynamics of what is to be measured by the addition of additional mass and surface area on the site of interest. For example, introducing added mass creates drag in monitoring swimmers, and skin based artifact when monitoring leg or shank movement.

Fortunately accelerometers today weigh only a few grams and can be packaged simply using epoxy or similar compounds. The advent of body hugging clothing and suits in many sports allows for the incorporation of sufficiently small sensors and accompanying instrumentation relatively easily using sewn pouches for example.

3. Applications

A number of sporting activities have been investigated using accelerometers. Central to these investigations has been the development of a modular sensor system that can be customized for the intended sport. This system (James et al. 2004) was initially applied to both rowing and swimming, before being trialed in a number of other sports and a commercial prototype produced (Fig.1.(a)). In each case the system was packaged separately and allowed additional modules to be added as required to facilitate data storage, RF communications in near real-time and post event IR data download and sealing for aquatic applications.

Rowing was trialed initially because of a number of advantages. Firstly rowing is predominantly a 1-D activity thus it was hoped that inertial navigation might be possible. Secondly the monitoring equipment could be mounted to the scull rather than the athlete simplifying packaging constraints. Thirdly, and almost most importantly, rowing is a technical sport and already uses a number of technologies in the training environment, thus there was little cultural change required by athletes and coaches to adopt a newer technology. Very quickly it was noticed that there was a lot of high frequency accelerations, perhaps due to mechanical artifacts such as oarlock movement and the seat movement. Data from the accelerometers proved useful in identifying stroke phase characteristics such as the catch, drive and recovery phases, something which is difficult to do even with a video system. From these basic measures such as stroke rates and counts could easily be extracted and combined together with GPS and other data such as heart rate to analyse performance and further develop race strategy.

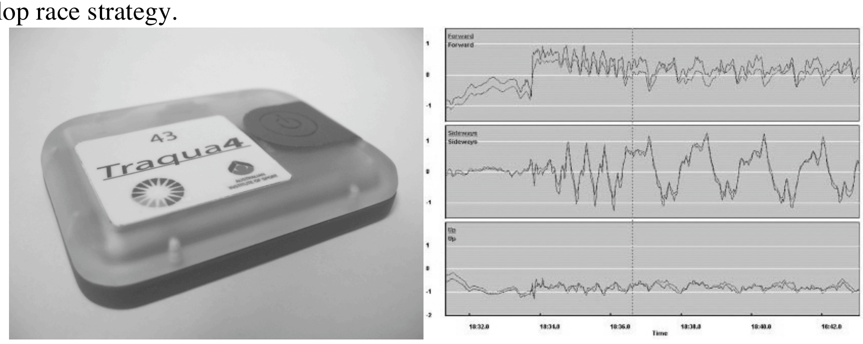

Fig. 1.(a) Prototype Accelerometer Platform **(b)** Acceleration outputs for swimming analysis

The system was then encased in water proofing material and applied to trunk movement in swimming. Visually examining tri-axial traces enabled the identification of stroke type, stroke counts, lap times and tumble turns (Fig. 1.(b)). A model of body roll dynamics was constructed allowing the development of automated algorithms to extract performance characteristics and stroke identification routines (Davey, and James 2003). These produced data that exceeded hand timed and counted data and was comparable with underwater video and touch pad equipped pools.

Uni-axial accelerometers have been used successfully for measuring walking gait and energy expenditure, however the correlation is less clear for running and other physical activities such as in the various football codes. Energy expenditure can be calculated with greater accuracy using tri-axial accelerometers (Wixted et al. 2005). By extracting and examining body tilt other activity types can also be recognized as distinct signatures. Thus by determining activity type and intensity an estimate of energy expenditure can be determined, based on historical and laboratory based calibration. Furthermore by doing correlation studies with in-sole pressure sensors and high speed video it has been found that trunk mounted accelerometers alone can reliably determine gait cycle characteristics such as heel down and toe off as well.

Implements used in sports have also been instrumented (James, Gibson and Uroda 2005; Ohgi, Baba and Sakaguchi 2005) showing that key characteristics of swing can be measured and extracted, and that they and correlate well with athlete skill. Recently the device has been applied to winter sports to detect and quantise aerial activity time and type in ski and snowboard events.

4. Discussion

A purely technology based approach using accelerometers for sporting applications has yielded little success, whereas informed signal processing of the data through the use of sport specific knowledge and involvement of sport scientists has allowed the extraction key features in the data which can then be interpreted in a useful manner. Critical to the success of this work has been to ensure that the development of the technology has been in partnership with key stakeholders including athletes, coaches and sport scientists. Keeping the technology development and interpretation firmly grounded on providing useful outputs that benefit athletes has been critical to enhancing sporting activity.

References

Channells, J., Purcell, B., Barrett R. and James, D.(2005), Determination of rotational kinematics of the lower leg during sprint running using accelerometers, SPIE Bio MEMS and Nanotechnology, December, Brisbane Australia

Cutmore, T.R.H., and James, D.A. (1999). Identifying and reducing noise in psychophysiological recordings. Int J Psychophys., 32, 129-150.

Davey, N. and James, D.A. (2003). Signal analysis of accelerometry data using gravity based modelling, Proceedings of SPIE Vol. 5274, SPIE, Bellingham, WA, 362-70.

Herren, R., Sparti, A., Aminian, K., and Schutz, Y. (1999). The prediction of speed and incline in outdoor running in humans using accelerometry. Med Sci Sports Exerc, 31, 1053-1059.

James, D., Gibson, T. and Uroda, W.(2005), Dynamics of a swing: A study of classical Japanese swordsmanship using accelerometers, *The Impact of Technology on Sport*, Subic. A., Ujihashi, S. ASTA, 355-60

James, D.A, Davey, N. and Rice, T.(2004), An Accelerometer Based Sensor Platform for Insitu Elite Athlete Performance Analysis, IEEE, Sensors, Vienna

Lai, A., James, D.A., Hayes, J.P. and Harvey, E.C. (2003). Application of triaxial accelerometers in rowing kinematics measurement, Proceedings of SPIE 5274, (SPIE, Bellingham, WA) 531-42

Mayagoitia, R., Nene, A. and Veltink, P. (2002). Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems, Journal of Biomechanics 35, 537-542.

Moe-Nilssen, R., and Helbostad, J. L.,(2004), Estimation of gait cycle characteristics by trunk accelerometry, J Biomech, 37(1), 121-126

Montoye, H., Washburn, R., Smais, S., Ertl, A., Webster, J.G., and Nagle, F.J., (1983), Estimation of energy expenditure by a portable accelerometer, Med. Sci. Sports Exerc., 15, 403 (1983)

Ohgi, Y., Baba, T. and Sakaguchi, I., (2005) measurement of Deceleration of Golfers Sway and uncock timing in driver swing motion, *The Impact of Technology on Sport*, Subic. A., Ujihashi, S. ASTA, 349-54

Weinberg, H. (1999). Dual Axis, Low g, Fully Integrated Accelerometers, Analogue Dialogue 33, Analogue Devices (publisher).

Williamson, R. and Andrews, B. J. (2001). Detecting absolute human knee angle and angular velocity using accelerometers and rate gyroscopes. Med Biol Eng Comput, 39, 294-302.

Wixted, A., Thiel, D., James, D., Hahn, A., Gore, C. and Pyne, D. (2005), Signal Processing for Estimating Energy Expenditure of Elite Athletes using Triaxial Accelerometers, IEEE Sensors 2005, Irvine, USA