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A Novel Inertial Technique to Measure Very High Linear and Rotational Movements in Sports, Part I: The Hardware

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Abstract: In sports biomechanics, videography provided an indirect measurement method for measuring sport movements. However, these techniques are expensive, bulky and not portable. A novel inertial data logger designed to record the linear and rotational movements in three axes at 200 Hz and save the data on a memory card. A custom PC software was developed to measure the kinematics parameters (linear and angular accelerations and velocities) and compute the kinetic parameters (force, torque, angular momentum, impulse and angular power) of the attached limb during performance. The current system is applicable in sports that involve high linear and rotational kinematics and high impact contact. Evaluation of the sensor module at 500 °/sec showed very good validity and reliability of angular velocity ($r = 0.954$, $p<0.0001$; Cronbach's Alpha = 0.973) and angular acceleration ($r = 0.905$, $p<0.0001$; Cronbach's Alpha = 0.960), respectively as compared to values obtained at 300 and 210 °/sec. It is able to measure angular velocity up to ±100,000 °/sec and linear acceleration up to 2,452 m/sec^2. This is light, cheap, reliable, robust and accurate system to measure high kinematic and kinetic parameters in the field. This approach is in contrast to current high-tech videography systems that are expensive, bulky and cumbersome. This novel technique is suitable in Soccer, Rugby, American Football, Tennis, etc. to evaluate the player's performance in the field.

Key words: Inertial data logger, accelerometer, gyroscope-free system, movement, sport

INTRODUCTION

Biomechanical techniques providing knowledge of essential mechanisms for enhancing performance and learning of sports skills (Lees and Nolan, 1998). In this regard, optical motion analysis systems such as videography, photography, cinematography and opto-electric techniques provided indirect measurement methods for the motion analysis. These systems are however expensive, bulky and not portable. Their installation and calibration is time consuming and needs professional staff. In addition, their output data need digitization and smoothing before process and analysis. When using videography methods, application of some filtering techniques may significantly alter the displacement signal by cutting the high frequency components leading to an underestimation of the true displacement, velocity and acceleration patterns in the moment of impact (Kellis and Katis, 2007). Most of these systems require a restricted and controlled environments.

With the advent of inertial sensing technology and miniaturization in sensor technology coupled with the production of powerful microcontrollers, miniature sensors, high capacity memories and small batteries, the possibility for designing portable recording systems usable either in the field or for long-time ambulatory measurements became a reality. Consequently, these recording systems were used to monitor and measure a variety of physical activities involving low range motion analysis (Aminian *et al.*, 2001, 2002; Meamarbashi and Burhanuddin, 2006; Salarian *et al.*, 2004; Willemsen *et al.*, 1990) and in swimming (Ohgi *et al.*, 2002; Ohgi and Yasumura, 2000).

Accelerometers and gyroscopes operate on the principle of inertia. Accelerometers are sensors that measure the applied linear acceleration produced by the movement acting along their sensitive axis (Mathie *et al.*, 2004). Gyroscopes (angular rate sensors) alone or in combination with accelerometers, electromagnetic sensors and digital compasses were employed for low range motion analysis as evidenced by earlier published reports on monitoring physical activities (Bussmann *et al.*, 2000; Inoue *et al.*, 2003; McMillan *et al.*, 2005), gait analysis (Kavanagh *et al.*, 2006; Scapellato *et al.*, 2005; Willemsen *et al.*, 1990), clinical investigations related to fall risk in the elderly (Cho and Kamen, 1998; Najafi *et al.*, 2002), orthopaedic outcome (Jaecques *et al.*, 2003) and some sport performances (Davey *et al.*, 2005; Ohgi *et al.*, 2002). However, this combination is not able to measure high angular kinematics in most of sports especially in the field.

It is necessary to mention if highest range (±1200 °/sec) triaxial angular rate sensor (gyroscope) available in the market (MEMSENSE, 2007; Xsens, 2007) incorporated with triaxial accelerometer (>±100 gravity) still this configuration could not be able to measure high angular velocity of high sport movements (>2000 °/sec) due to low measurement range and its low bandwidth of gyroscopes. It therefore becomes necessary to design a sensor module with a configuration that can measure directly the high linear and rotational kinematics as an alternative to videography.

In the realm of mechanics an inertial system without using gyroscope is called Gyroscope-Free system. A gyroscope-free inertial system is a system that only uses accelerometer measurements to compute the linear displacement and angular rotation of a moving rigid body. To achieve this, the accelerometers need to be strategically distributed on the rigid body (Tan and Park, 2002).

The complete state of acceleration of a rigid body is specified by its linear acceleration and angular velocity. The acceleration of any point (P) of the body is:

$$a_p = a_O + \acute{\omega} \times (P-O) + \omega \times (\omega \times (P-O))$$

where, a_O is the acceleration of a point O on the body and ω and $\acute{\omega}$ are the body angular velocity and acceleration and P−O is the relative position of P with respect to O.

In the rigid body, angular acceleration and centripetal acceleration are always perpendicular and total acceleration vector of any point calculating by Eq. 1.

$$a_{total} = \sqrt{(a_t)^2 + (a_c)^2} = \sqrt{r^2\omega^4 + r^2\alpha^2} \quad (1)$$

In theory, a Gyroscope-Free configuration using only accelerometers provides this possibility. Theoretically, a minimum of six accelerometers are required for a complete description of a rigid body motion in a cube shaped configuration (Tan and Park, 2002; Nevalainen, 2008; Park *et al.*, 2005). However, the number of accelerometers needed for the measurement of any particular kinematic parameter is determined by the configuration of the accelerometers, location, orientation and the computational method for the accelerometer output. It would seem therefore that accelerometers could be used in many sports for the measurement of high linear and rotational kinematics and also in high impact sports.

In this method, traditional analytical methods are replaced with an innovative method to process two triaxial accelerometers and one axis (Z) accelerometer parallel to the rigid body. Different with previous methods that used cube-shape configuration with six uniaxial accelerometers and placement of accelerometers are strategic, this method mounted accelerometers in planar board only. Planar configuration giving highest accuracy in electronic placement of accelerometers and significant reduce the orientation errors.

Earlier researchers applied mathematical procedures to solve the accelerometers output by solving the matrix but in this method exploited some geometrical procedures. In this design tried to miniaturize the electronic parts, reduce the product cost to be more applicable in movement analysis applications in the filed of medicine and sports biomechanics where the current systems are cumbersome and not appropriate for measurements out of laboratory.

Consequently, the present project was undertaken to design and manufacturing a sensor module and a data logger integrated with professional software using only accelerometers in a special configuration and orientation that is capable of directly measuring the high linear, angular acceleration and angular velocity in three axes. This system was then applied to compare the left and right legs kinematics and kinetics of instep kick in soccer.

MATERIALS AND METHODS

Equipment and software: Accelerometers (Freescale Semiconductor, Arizona, USA) were used in the design of the current data logger and sensor module. In the data logger, a built-in triaxial accelerometer consisting of a dual-axis (X-Y) and mono-axial (Z) accelerometers were implemented. In the sensor module, two dual-axis (X-Y) and three mono-axis (Z) accelerometers were used (Fig. 2). A block diagram and schematic diagram of the data logger and sensor module shown in Fig. 1.

The sensor module (weight = 80 g, dimensions = 23×2.3×4 cm) and data logger system (weight = 70 g, dimensions = 6×5.7×2.5 cm) shown in Fig. 2 designed based on the differentiation of parallel axes acceleration and geometric configuration of the accelerometers using the principle of rigid body dynamics. This sensor module is capable of measuring high rotational acceleration in three axes as well as magnitude of two-dimensional angular velocity (X-Z) without using a gyroscope in the following way.

Two dual axis (X-Y) and two mono-axial (Z) accelerometers were mounted on a Printed Circuit Board (PCB), 20 cm apart with similar axis parallel to each other. This arrangement allowed for the measuring of rotational and linear acceleration that is independent of the axis of rotation and eliminates the effect of gravity on the computation of rotational kinematics. The analog output of parallel axes (e.g., X_1 and X_2, etc.) simultaneously sampled by two fast 16-Bit A/D converters.

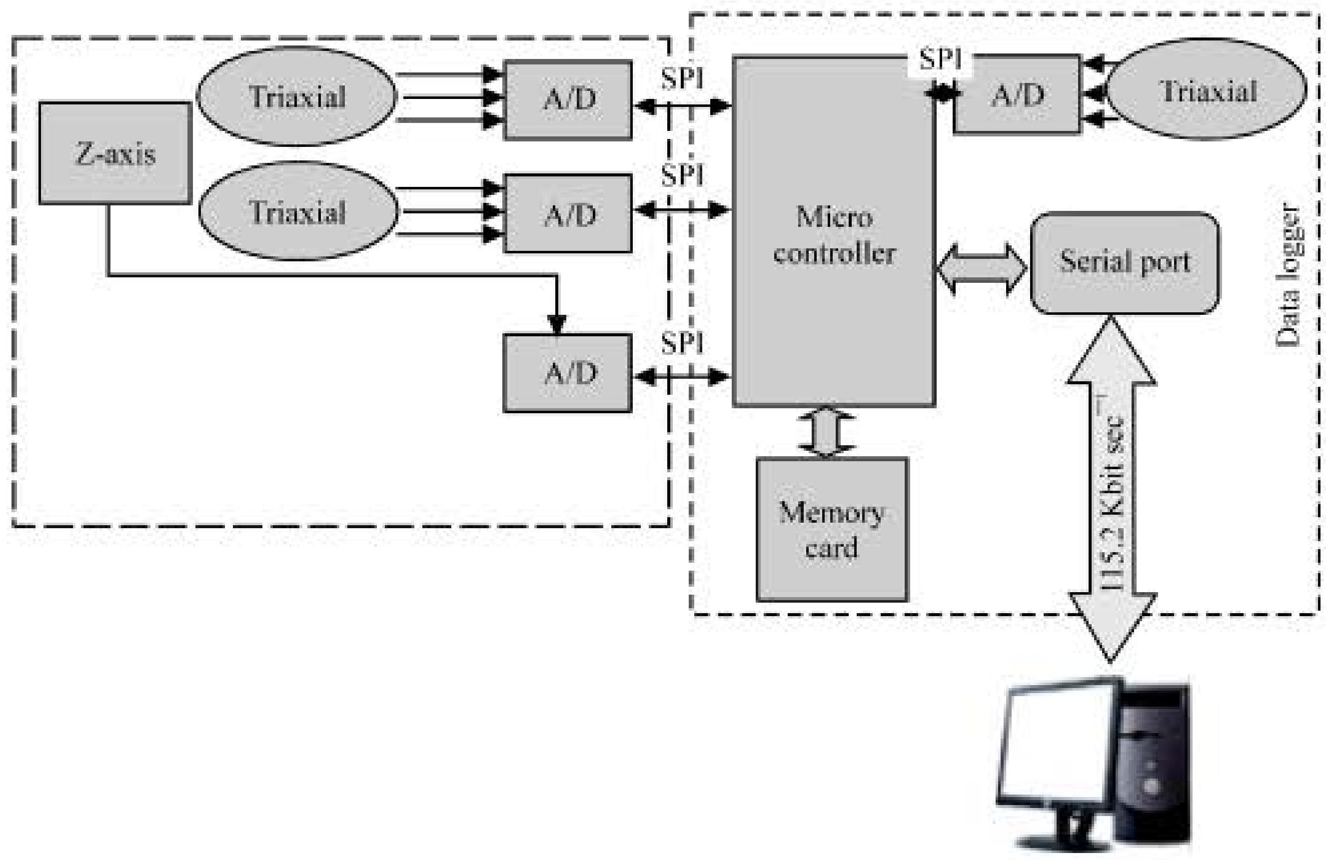

Fig. 1: A block diagram showing the sensor module and data logger connections

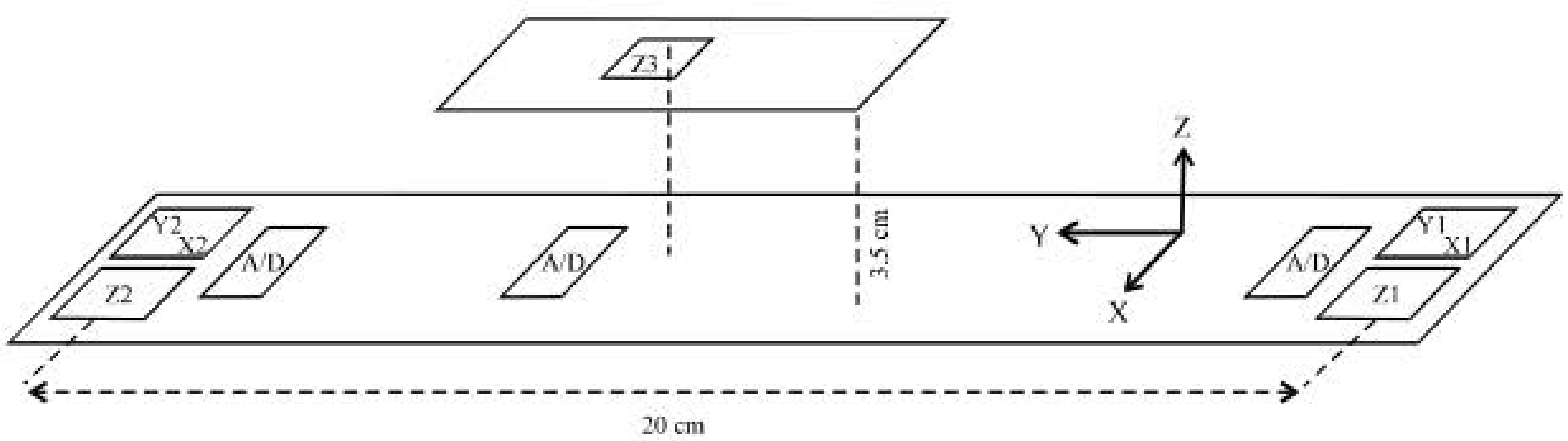

Fig. 2: Configuration of the sensor module

In order to measure the shank rotation (internal/external rotation) during an instep kick, a third Z-axis accelerometer (Z_3) was mounted on a small PCB inside the aluminium case. This PCB was placed parallel and co-central with the main PCB sensor module board 3.5 cm apart. The analog output of each accelerometer axis simultaneously digitised by 16-bit A/Ds. The sensor module was enclosed in an aluminium case and connected to the data logger by external cable. The data logger had an ultra-high speed microcontroller, a 32 MB Multimedia Card (MMC), a built-in triaxial accelerometer (±40 gravity) and a 16-bit A/D converter. The accelerometers output (10 axes) were saved on memory card at 200 Hz.

Measurement of kinematics parameters and calculation of kinetic parameters: The linear acceleration values from each set of triaxial accelerometer and the parallel Z-axis accelerometer are recorded and linear and rotational kinematic and kinetic parameters derived with the designed software. In this way, the effect of gravity and linear acceleration of each parallel axes would be the same. Another feature of this design is that even though the rotational kinematics is dependent on the distance between the two parallel accelerometers yet it is insensitive to the axis of rotation.

A comparative study of kinematic measurement of the sensor module: The validity and reliability of the angular velocity and angular acceleration of sensor module had verified in controlled condition. It had been tested by comparing with Biodex isokinetic machine (Model 2.15). Biodex afforded a chance to compare angular velocity and angular acceleration in controlled conditions. The sensor module was fixed to the lever arm of the Biodex. Five male healthy volunteers with ages ranging from 25-35 years were selected for this part of the study. The information form and methodology had previously approved by the university ethical committee. Subjects were requested to exercise on a cycle ergometer at 25-50 W for 3-5 min and then followed by leg stretches for 2-3 min.

Subjects were asked to sit on the Biodex chair after which the attachments of the dynamometer were readjusted accordingly. The knee was positioned 5 cm away from the lever arm axis. A calf pad was placed 5 cm proximal to the lateral malleolus and secured with a padded shin strap. Subjects were stabilized with thigh and shoulder straps (Taylor *et al*., 1991). The range of motion of the lever was adjusted between 0-90°. The subjects were made to perform three series of five repetitions of extension and flexion of the knee at three angular velocities: 500, 300 and 210 °/sec. Three minute rest was given between each test to minimize muscle fatigue.

Statistical analysis: After processing the raw data, the results transferred into an SPSS format for statistical analysis. The level of significance was set at $p<0.05$. Results are reported as Mean±SD. SPSS software (SPSS, Chicago, Illinois) was used for the statistical analyses (version 12.0).

Simple regression was used for the validity test and Cronbach's coefficient alpha was used as a measure of internal consistency for the reliability test of the kinematic parameters.

RESULTS

Comparison of the measured angular velocity between biodex and sensor module accelerometers: Comparison of the recorded magnitude of angular velocity measured by the sensor module accelerometers (Gyroscope-Free system) and Biodex for five subjects at 500, 300 and 210 °/sec is shown in Table 1. The angular velocity values of the Biodex as compared to that of data logger sensor module were statistically analysed. Using a simple regression and reliability test (Cronbach's Alpha), a very good relationship and reliability between the Biodex and the data logger angular velocity values of the lever arm movement at 500 and 300 °/sec were found. The r, R^2 and Cronbach's Alpha were lower at 210 °/sec when compared to that at 500 °/sec.

An example of tracings of the magnitude of angular velocity during five extension/flexion of a subject's shank recorded by the Biodex and data logger at a preset level of 500 °/sec is shown in Fig. 3.

Comparison of the angular acceleration measured by the biodex and sensor module accelerometers: Computed angular acceleration (rad/sec^2) values of the Biodex compared to that of the data logger sensor module for five subjects were statistically analysed. Using a simple regression and Cronbach's Alpha, there was a very good relationship and reliability between the Biodex and the data logger angular acceleration values of the lever arm movement at 500, 300 and 210 °/sec (Table 2). The r, R^2 and Cronbach's Alpha were higher at 500 °/sec compared to 210 °/sec.

A sample recording of the angular acceleration at 500 °/sec obtained from the Biodex and data logger sensor module during five extension/flexion of the shank is shown in Fig. 4.

Table 1: Comparison of the angular velocity at 500, 300 and 210 °/sec between Biodex and data logger sensor module accelerometers

Velocity (°/s)	r	R^2	a±SE	b±SE	95% CI of b*	Cronbach alpha
500	0.954	0.910	48.219±4.470	0.869±0.012	0.846-0.892	0.973
300	0.910	0.829	-26.579±2.569	1.088±0.011	1.067-1.110	0.946
210	0.664	0.441	13.972±3.806	0.932±0.022	0.889-0.976	0.768

*95% confidence Interval of the b

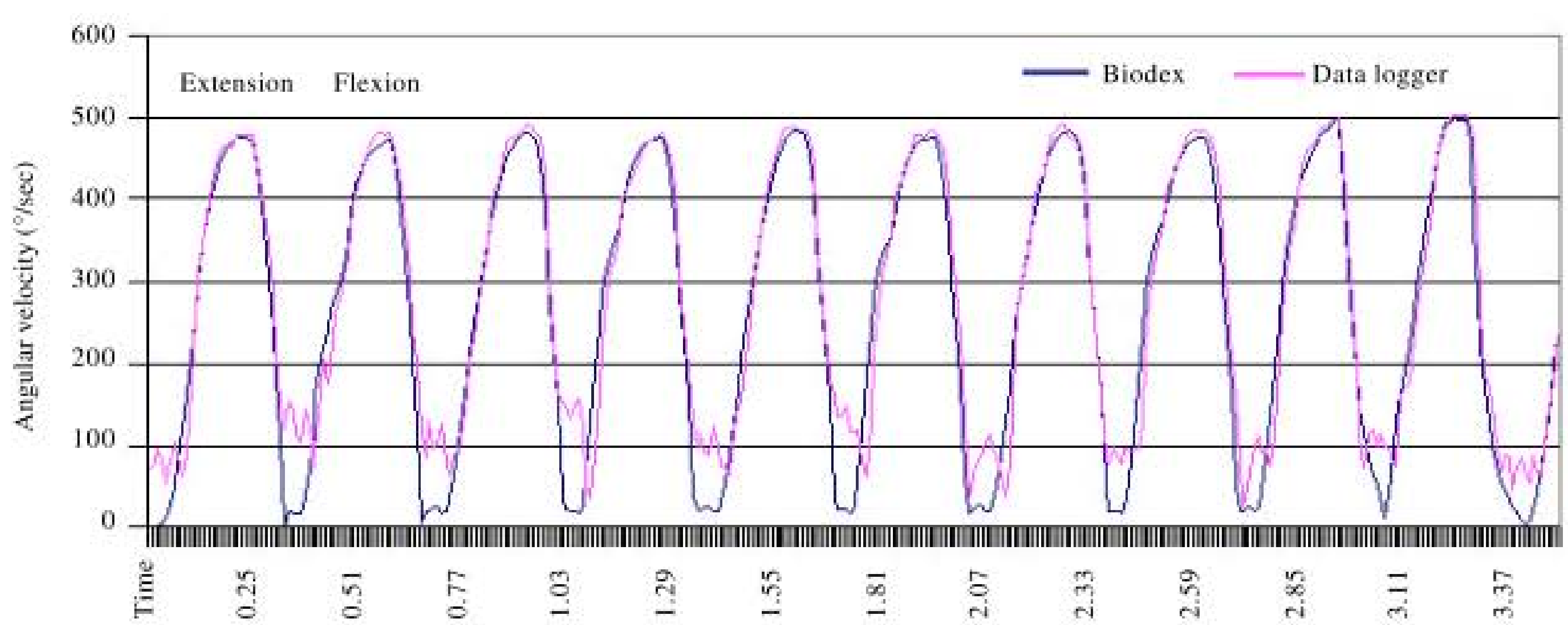

Fig. 3: A graphical comparison between the magnitude of angular velocity at 500 °/sec measured by the Biodex and accelerometers of the sensor module during five extension/flexion of a subject shank

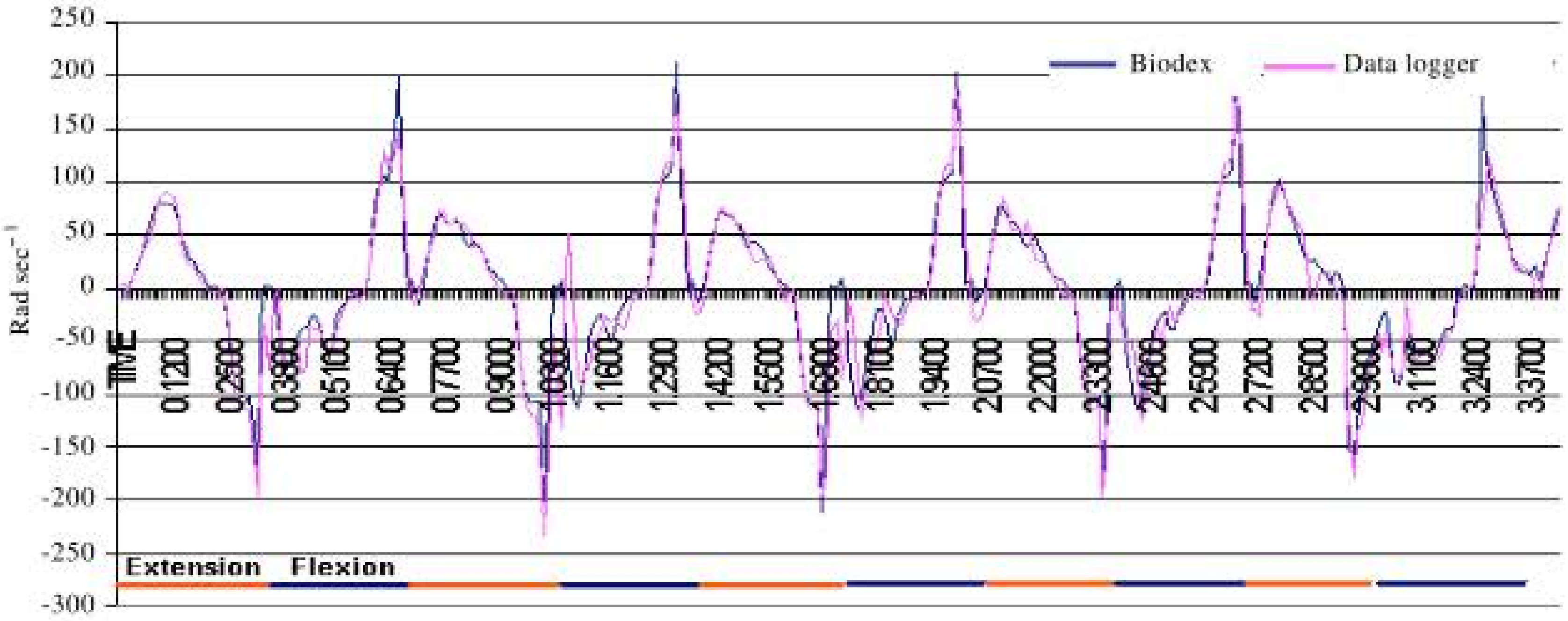

Fig. 4: Tracings of angular acceleration (rad/sec^2) obtained with the Biodex and data logger sensor module during five extension/flexion of the shank at 500 °/sec

Table 2: Comparison of the angular acceleration at 500, 300 and 210 °/sec of biodex and data logger sensor module accelerometers

Velocity (°/s)	r	R^2	a±SE	b±SE	95% CI of b*	Cronbach alpha
500	0.905	0.819	1.698±0.626	0.843±0.009	0.825-0.862	0.960
300	0.927	0.859	2.148±0.337	0.828±0.007	0.813-0.842	0.959
210	0.877	0.770	1.767±0.286	0.757±0.009	0.739-0.774	0.935

*95% confidence Interval of the b

DISCUSSION

The study of multiple segments is the great advantage of vidography. However, these techniques are considering indirect measurement methods. In this research, a novel direct measurement method applied to measure the sport performance in the field. It is light, small, portable, cheap, fast, robust, flexible and adaptable to many sports. It can measure angular velocity up to ±100,000 °/sec and linear acceleration up to 2,452 m/sec^2 in Z and 981 m/sec^2 in X and Y axes. However, for the multi-segment study, the instrument can be attached to each segment and use in a sensor network. This novel technique is also suitable in many of other sports or in the low range movements (e.g., gait, dance, etc.) using low range accelerometers. Using lower accelerometer range for low range motion analysis will increase the precision of the system. This method is valuable to improve the skill and identify the neuromuscular problems through training and retests. This method provided a rapid evaluation in the field for the coaches to understand the player's skill level and correct the techniques.

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