DEVELOPMENT OF A SENSOR MODULE AND DATA LOGGER CAPABLE OF MEASURING HIGH KINEMATIC PARAMETERS IN FOOTBALL

by

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LIST OF ABBREVIATIONS AND SYMBOLS

N.m	Newton meter
SI	International system of units
g	Gravitational acceleration equal to 9.81 m/s^2
m/s^2	Meter per second squared
m/h	Meter per hour
deg/s or °/s	Degree per second
Rad	Radian
rad/s	Radian per second
rad/s^2	Radian per second squared
Hz	Hertz
MHz	Mega Hertz
mV	Millivolt
V	Volt
FSO	Full Scale Output
BW	Bandwidth
F	Force
MEMs	Microelectromechanical Systems
RAM	Random Access Memory
ROM	Read-only Memory
EPROM	Electrically Programmable Read-only Memory
EEPROM	Electrically Erasable Programmable Read-only Memory
A/D or ADC	Analog-to-Digital Converter
I/O	Input/Output
IC	Integrated Circuit Chip
I^2C	Inter-integrated Circuit
SPI	Serial Peripheral Interface Protocol
HEX file	Intel Hexadecimal File
DOF	Degrees of Freedom
LED’s	Light Emitting Diodes
mA	Milliampere

RS-232	“Recommended Standard” for Computer Serial Port
TTL	Transistor-Transistor Logic
PCB	Printed Circuit Board
SMD	Surface Mount Devices
PC	Personal Computer
MB	Mega Byte
kbit/sec	Kilo byte per second
bit/sec (bps)	Bits per second
ASCII	American Standard Code for Information Interchange
PDF	Portable Document Format
GIF	Graphics Interchange Image Format
BMP	Bitmap Image Format
TIFF	Tagged Image File Image Format
HTML	Hypertext Markup Language
FAT	File Allocation Table
°C	Degree celsius
sin	Sine
psi	Pounds per square inch
ms	Millisecond
$kg.m^2$	Kilogram meter squared
$kg\ m^2/s$	Kilogram meter squared per second
cm	Centimeter
W	Watt
SD	Standard deviation
gr.	Gram
Min	Minute
Triaxial	Three axes
2-D	Two-dimensional
3-D	Three-dimensional
PDA	Personal Digital Assistant

ABSTRAK

PEMBANGUNAN MODUL PENGESANAN DAN DATA LOGGER YANG BERKEMAMPUAN MENGUKUR PARAMETER KINEMATIK TINGGI DALAM PERMAINAN BOLA SEPAK

PENGENALAN: Kefahaman mengenai kompleksiti pergerakan segmen dalam aktiviti sukan yang melibatkan putaran kinematik tinggi telah dikenalpasti amat berguna dalam meningkatkan prestasi. Sehingga kini hanya kaedah secara tidak langsung telah digunakan melalui 2 atau 3 dimensi videografi (Nunome, 2006). Walau bagaimanapun, tiada kaedah pengukuran secara langsung dilaporkan bagi mengukur putaran kinematik tinggi dalam tendangan “instep” dalam permainan bola sepak. **OBJEKTIF:** Kajian ini bertujuan, (1) untuk membangunkan satu modul pengesanan baru yang mampu mengukur linear tinggi dan putaran kinematik di dalam pergerakan betis dan paha semasa tendangan di padang, (2) untuk membangunkan perisian Data Logger bagi menyimpan data kinematik dalam kad memori dan perisian komputer yang berupaya untuk memproses data yang tersimpan, (3) untuk mengenalpasti kesahihan dan validasi alat pengesanan dan Data Logger dengan membandingkan nilai perolehan dengan mesin isokinetik standard (Biodex) pada ukuran 500º/s, 300º/s dan 210º/s, (4) untuk mengenalpasti kebolehaplikasian dan daya tahan-lasak peralatan tersebut semasa tendangan ”instep” di padang. **METODOLOGI:** Konfigurasi geomatrik alat pengesanan adalah berdasarkan kepada prinsip perbezaan pecutan (acceleration) pada paksi selari. Alat pengesanan mempunyai dua dwi-paksi (X-Y) dan tiga monopaksi (Z) accelerometer yang dipasang pada jarak 20 sm di atas papan litar bercetak (printed circuit board) yang paksinya selari antara satu sama lain, manakala Data Logger mempunyai hanya satu triaxial accelerometer. Konfigurasi ini mampu untuk merakam linear tinggi dan putaran pecutan pada betis and paha dalam tiga paksi serta dapat merakam magnitud dua dimensi halaju-sudut (angular velocity). Perisian Data Logger kawalan mikro telah ditulis dalam bahasa C, sementara perisian komputer hanya diprogramkan dengan Delphi dan FoxPro. Perisian komputer membolehkan parameter kinematik (linear, pecutan sudut (angular) dan halaju (velocity)) dan parameter kinetik (tekanan, tork, momentum dan kuasa) dikira selepas data direkod oleh Data Logger di padang. Untuk memastikan validasi dan kesahihan modul pengesanan Data Logger, ia telah diletakkan pada paras pergelangan tangan Biodex dan 5 orang subjek telah digunakan untuk menghasilkan 5 pergerakan extension/flexion di Biodex pada 500°/s, 300°/s dan 210°/s. Nilai perolehan serentak dari Data Logger dan Biodex telah direkod dan dibandingkan secara statistik menggunakan analisa regresi dan Cronbach Alpha. Di padang, aplikasi dan daya tahan-lasak alatan tersebut telah diuji dengan meletakkan modul pengesanan pada betis yang dominan dan Data Logger pula diletakkan pada pertengahan paha. Empat tendangan ”instep” telah dilakukan pada sudut 45° hingga 60°. Kemudian, data yang telah disimpan di Data Logger dimuat-turun ke dalam komputer untuk parameter kinetik kuasa, tork, momentum sudut dan kuasa sudut dikira. Semua keputusan telah dianalisa secara statistik menggunakan perisian SPSS dan dibentangkan dalam nilai purata dan selisihan piawai (±SD). **KEPUTUSAN:** Penilaian modul pengesanan dan Biodex pada 500°/s telah menunjukkan validasi dan kesahihan halaju-sudut (*r*

= 0.954, R^2= 0.910, p<0.0001; Cronbach Alpha = 0.973), dan pecutan sudut (r = 0.905, R^2= 0.819, p<0.0001; Cronbach Alpha = 0.960) yang amat baik jika dibandingkan dengan nilai yang diperolehi pada 300°/s dan 210°/s. Halaju-sudut maksimum yang telah direkodkan pada paksi X dan Z adalah 1921.3±166.4°/s dan 487.6±151.7°/s, berurutan dan Pecutan sudut pada betis di paksi X adalah 420.9±103.4 rad/s^2 dan paksi Z adalah 110.3±67.2 rad/s^2. Pecutan linear maksimum bahagian betis sebelum impak pada paksi; X (46.2±17.1 m/s^2), Y (163.6±47.9 m/s^2) dan Z (113.3±19.9 m/s^2). Pecutan paha linear sebelum impak pada paksi; X (90.2±18.4 m/s^2), Y (39.3±11.4 m/s^2) dan Z (103.2±18.6 m/s^2). Tork betis maksimum semasa impak pada paksi; X (80.1±24.5 N.m), dan Z (20.8±13.0 N.m). Magnitud betis sudut momentum ialah 6.49±1.38 kg.m^2/s dan kuasa semasa impak adalah 2884.7±1005.8 W. Daya betis sebelum impak pada tiga paksi adalah X (228.0±93.5 N), Y (312.3±75.1 N), dan Z (322.2±93.4 N). Daya paha sebelum impak pada paksi X, Y, Z adalah 958.2±241.2 N, 416.0±135.2 N dan 1095.5±249.0 N, berurutan. Berat badan didapati mempunyai kesan ketara ke atas parameter kinetik tendangan ”instep” bola sepak. **KESIMPULAN:** Sebagai kesimpulannya, rekabentuk modul pengesanan dan Data Logger yang telah diintegrasikan dengan perisian profesional mempunyai daya tahan-lasak dan dapat mengukur secara langsung putaran tinggi dan kinematik linear pada betis dan paha pada tendangan ”instep”. Perisian komputer yang telah dicipta juga berupaya untuk mengira parameter kinetik pada betis dan paha dan dapat mendedahkan maklumat baru mengenai sudut pecutan dalaman/luaran bahagian betis.

ABSTRACT

DEVELOPMENT OF A SENSOR MODULE AND DATA LOGGER CAPABLE OF MEASURING HIGH KINEMATIC PARAMETERS IN FOOTBALL

INTRODUCTION: Understanding the complexities of segmental movements in sporting activities involving high rotational kinematics is essential for performance enhancement. To date, the underlying mechanisms have been studied using indirect methods of 2 or 3-dimensional videography (Nunome, 2006). However, to the best of our knowledge, no direct method has been reported for measuring high rotational kinematics of the instep kick in football. **OBJECTIVES** of the present study are: (1) to develop a new sensor module capable of measuring high linear and rotational kinematics of the shank and thigh during an instep kick in the field, (2) to develop a Data Logger software for storing kinematic data in a memory card and a computer software for retrieving and processing the stored data, (3) to determine the reliability and validity of the sensor and Data Logger by comparing its output values with that of a standard isokinetic machine (Biodex) at 500 º/s, 300 º/s and 210 º/s, (4) to determine the applicability and robustness of the device during an instep kick in the field. **METHODS:** The geometric configuration of the sensor module was based on the principle of differentiations of parallel axis acceleration. Consequently, the sensor module had two dual axes (X-Y) and three mono-axial (Z) accelerometers placed 20 cm apart on a printed circuit board with similar axis parallel to each other while the Data Logger had one Triaxial accelerometer. This configuration enabled the capturing of the high linear and rotational acceleration of the shank and thigh in three axes as well as the magnitude of two-dimensional angular velocity. The Data Logger’s microcontroller software was written in C language while the computer software was programmed in Delphi and FoxPro. The computer software enabled kinematic parameters (linear, angular accelerations and velocity) and kinetic parameters (force, torque, momentum and power) to be derived from the data recorded by the Data Logger in the field. The validity and reliability of the sensor module of the Data Logger are verified by attaching the sensor module to the Biodex lever arm and recruited five (5) subjects to perform five extension / flexion movements on the Biodex at 500 °/s, 300 °/s and 210 °/s. The simultaneous output values from the Data Logger and Biodex were recorded and compared statistically using regression analysis and Cronbach's Alpha. In the field, the applicability and robustness of the device were tested by attaching the sensor module to the shank of the dominant leg and the Data Logger at the middle of the thigh. Four (4) instep kicks were performed at an approach angle of 45 ° to 60 °. The recorded data stored in the Data Logger was downloaded into the computer to compute the kinetic parameters of force, torque, angular momentum and angular power. The results were statistically analysed using SPSS and presented as mean±SD. **RESULTS:** Evaluation of the sensor module and Biodex at 500 °/s showed very good validity and reliability of angular velocity (r = 0.954, R^2= 0.910, $p<0.0001$; Cronbach's Alpha = 0.973) and angular acceleration (r = 0.905, R^2= 0.819, $p<0.0001$; Cronbach's Alpha = 0.960), respectively as compared to values obtained at 300 °/s and 210 °/s. The maximum angular velocity recorded in the X and Z-axes were 1921.3±166.4 º/s and 487.6±151.7 º/s respectively and the angular acceleration (rad/s^2) of the shank in the X and Z-axes were 420.9±103.4 and 110.3±67.2. Maximum shank linear acceleration (m/s^2) before impact in the X, Y, Z axes were 46.2±17.1, 163.6±47.9 and 113.3±19.9. Thigh linear acceleration before impact in the X, Y, Z axes were 90.2±18.4, 39.3±11.4 and 103.2±18.6 m/s^2. Maximum shank torque (X and Z axes) at impact were 80.1±24.5 N.m and 20.8±13.0 N.m. Magnitude of the shank angular momentum and power at impact in XYZ axes were 6.49±1.38 kg.m^2/s and 2884.7±1005.8 W. The shank forces before impact in the three axes were 228.0±93.5 N 312.3±75.1 N and 322.2±93.4 N. The thigh force before impact in X, Y, Z axes were 958.2±241.2, 416.2±135.2 and 1095.5±249.0 N. Body weight was found to have a marked effect on the kinetic parameters of the instep kick. **CONCLUSION:** These findings indicate that the sensor module and Data Logger integrated with designed professional software was robust and directly measured the high rotational and linear kinematics of the shank and thigh during the instep kick. In addition, the designed computer software was able to compute the kinetic parameters of the shank and thigh and revealed new information about the internal/external angular acceleration of the shank.

CHAPTER 1

INTRODUCTION

The study of human locomotion and the mechanisms underlying the acquisition and execution of skills has been a subject of intensive study in a variety of fields such as the health sciences, e.g. orthopaedic surgery, physiotherapy and sports science.

In order to define the characteristics of these skills, understand their execution and mechanical effectiveness as well as the factors that influence these skills, biomechanical techniques were used to gain a fundamental understanding and knowledge of these mechanisms essential for enhancing performance and learning of these skills (Lees and Nolan, 1998). In this regard, optical motion analysis systems such as photography, cinematography, videography, opto-electric and magnetic resonance imaging methods provided indirect methods for measuring these parameters. 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 had to be digitised before processing and analysis. Some of these systems had to be used in restricted controlled environments before measurements could be done. Despite these limitations, 2-dimensional videography as opposed to 3-dimensional videography has widely been used to study the instep kick in football in the past.

However, 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 and fabricating portable recording systems usable either in the field or for long-term 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; Aminian *et al.*, 2002; Salarian, 2004; Willemsen *et al.*, 1990) and in swimming (Ohgi *et al.*, 2002; Ohgi and Yasumura, 2000). This provided a viable alternative system to videography that was easily suitable for use both indoors and in the field.

Consequently, gyroscopes alone or in combination with accelerometers, electromagnetic sensors and digital compasses were employed for low range motion analysis as evidenced by previous published reports on gait analysis (Currie *et al.*, 1992; Evans *et al.*, 1991; Foerster and Fahrenberg, 2000), ambulatory movement monitoring (Aminian *et al.*, 1998; Aminian and Najafi, 2004; Aminian *et al.*, 2001), assessment of sit–stand–sit movement (Najafi *et al.*, 2002) and swimming stroke (Ohgi *et al.*, 2002).

To measure the high kinematic and kinetic parameters of an instep kick, 2-D and 3-D videography methods were used (Asai et al., 2002; Barfield et al., 2002; Dorge et al., 2002; Levanon and Dapena, 1998; Nunome et al., 2002; Nunome et al., 2006a; Nunome et al., 2006b; Rodano and Tavana, 1993; Van Deursen and Klous, 2001). The main reason(s) for a preference for the indirect method of 2-dimensional or 3-dimensional videography instead of a direct method using inertial devices might be related to the unavailability of direct methods to measure the high linear and angular kinematics. This could presumably be due to an interest in visualizing ‘whole body’ movements and hence the use of image-based techniques in most of these studies (Solberg, 2000)

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 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 (Chin-Woo, 2002; 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 the field of football for the measurement of high linear and rotational kinematics and in high impact sports.

The instep kick in football has been intensely investigated because it involves high linear and rotational kinematics that determines the ball’s velocity. Football is the most popular sport in the World and one of the main priority areas of sports in Malaysia. The instep kick of football determines the effectiveness of the transfer of the foot velocity to the ball as the shank goes through a high linear motion and an angular acceleration (Barfield, 2000; Lees and Nolan, 1998). It also generates the maximum force necessary for taking a shot at goal from a distance or when making a long pass (Luhtanen, 2005b).

A number of studies, using biomechanical techniques, have been used in an attempt to unravel the complexity of the instep kick (Asai *et al.*, 2002; Barfield *et al.*, 2002; Dorge *et al.*, 2002; Levanon and Dapena, 1998; Nunome *et al.*, 2002; Nunome *et al.*, 2006a; Nunome *et al.*, 2006b; Rodano and Tavana, 1993; Shan and Westerhoff, 2005; Van Deursen and Klous, 2001; Vaverka *et al.*, 2003). In the latest study, high-speed cameras were used to study the instep kick. It was then reported that due to the inadequacy of the sampling rate of the cameras coupled with the accompanying filtering techniques, values obtain for the instep kick in the past might not accurately replicate the observed kinematic parameters of the instep kick (Nunome *et al.*, 2006a; Nunome *et al.*, 2006b). This researcher therefore concluded that there was a need to find other ways for measuring the instep kick accurately so as to reflect the magnitude and nature of this kick.

Consequently, the present project was undertaken to design and fabricate 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 of the instep kick in football. Other attributes of this sensor module/Data Logger are that it should be cheap, portable and robust. Secondly, the integrated professional software should be capable of managing and computing kinetic parameters such as torque, angular momentum, power and force of the shank during an instep kick as well as the thigh force. The Data Logger should also be able to store data and be connectable to a computer for the transfer of recorded data and subsequent production of simple graphical and interpretable reports.

To date, to the best of our knowledge, apart from the use of videography in measuring the instep kick, no measurement of the instep kick parameters have been reported using a direct method. Consequently, the objectives of the present study were to:

1. Design and fabricate a new sensor module and a Data Logger system capable of measuring high linear and rotational acceleration and velocity

2. Develop complementary software to manage and compute the kinematic and kinetic parameters measured by the sensor module and Data Logger accelerometers.

3. Validate the sensor module by comparing its output kinematic values with that of a standard isokinetic machine (Biodex)

4. Measure the kinematic and kinetic parameters of a football instep kick in the field to determine the applicability and robustness of the Data Logger system

CHAPTER 2

LITERATURE REVIEW

2.1 BIOMECHANICS AND HUMAN LOCOMOTION

2.1.1 Historical Perspective

The historical development of the application of biomechanics for the analysis of human locomotion attempted to answer fundamental questions about human body movement with technology. In 322-384 BC, Aristotle first described the complex motions of running and walking. Later, Hippocrates (370-460 BC) advocated that observations made about body locomotion should be on what the eye perceived. This notion however, was rejected by the Greek Philosophers (300-500 BC) who surmised that since the eye was incapable of capturing sequences of rapid limb movements, the use of the human eye for the analysis of human locomotion would be inaccurate and virtually impossible to capture (Andriacchi and Alexander, 2000).

Unfortunately, other experimental methods that were in use then could also not accurately replicate movements of the body. In 1992, Lorini *et al*. proposed logical reasoning approach for the analysis of body movements. Since then advances in the development of new tools for observation have enormously influenced the understanding of the processes involved in human locomotion. Later, Marey *et al*. (1997) and Muybridge (1979), using a series of cameras, took multiple pictures in rapid succession of both animals and humans in motion to establish quantified patterns of human movements. Wilhelm Braune and Otto Fisher (1988) reported on a study of body segmental movements using Newtonian mechanics aimed at improving the efficiency of troop movement (Braune and Fisher, 1988).

Subsequent years saw advancements in the application of biomechanics to the study of body motion that gave credence to the earlier classical work of Ebert in 1947 and Inman *et al*. in 1981, who laid the foundation for many current fundamental techniques for the study of human locomotion (Andriacchi and Alexander, 2000). In addition, recent advancements in instrumentation and computer technologies and the use of kinetic analysis have also provided new opportunities for the study of human locomotion (Mündermann *et al.*, 2006). Since then a number of methods for the measurement of human locomotion have evolved. These include:

i) Skin-based marker systems (Cappozzo *et al*., 1997; Sati *et al*., 1996; Reinschmidt *et al*., 1997; Holden *et al*., 1997)
ii) Point cluster techniques (Andriacchi *et al*., 1994)
iii) Invasive and radiation methods (Holden *et al*., 1997; Jonsson and Karrholm, 1994)
IV) The use of animal models (Borelli, A.G., 1989)

2.1.1.1 The Skin-based marker system

The primary limiting factor of these systems has been the inability to measure skeletal muscle movements at the sites of the markers on the skin.

The markers or fixtures on the skin's surface were supposed to replicate the underlying relative movement between two adjacent segments (e.g., knee joint) in order to define precisely the joint movement (Benedetti and Cappozzo, 1994). The flaw of this system was in its poor resolution of details of the joint movement (Cappozzo *et al.*, 1997; Holden *et al.*, 1997; Reinschmidt *et al.*, 1997; Sati *et al.*, 1996). Despite these flaws, however, the method was suitable for large motions such as flexion and extension with an acceptable error margin. A refinement of this method came with the introduction of the Point Cluster Technique.

2.1.1.2 Point cluster technique (PCT)

In 1996, Cappozzo *et al*. compared the results of a cluster of skin-based marker systems to that of external fixation. The technique utilized an overabundance of markers on each segment in order to minimize the effect of skin motion artefact. The effect of the skin motion artefact, in turn, was kept to a minimum by optimal weighting of the markers in accordance with their degree of deformation. Any error, therefore, that was induced by the segment deformation, associated with the skin marker movement relative to the underlying bone, was then corrected by applying transformation equations to the general deformation and modelling the deformation by an activity-dependent function. The deformation over a specified interval was then smoothened to the functional form (Andriacchi and Alexander, 2000). Unfortunately, these non-invasive methods still did not address the question of the activity of the underlying muscle. Consequently, invasive and radiation methods were introduced to capture the activity of the muscle movements.

2.1.1.3 Invasive and radiation methods

The invasive and radiation methods measure directly the muscle movements, but because of their invasive nature, they tended to impede the natural movements of the segment and hence did not reflect the natural patterns of the movement. Such methods include:

i) Stereoradiography (Jonsson and Karrholm, 1994)
ii) Single plane fluoroscopic techniques (Banks and Hodge, 1996; Stiehl *et al.*, 1995)
iii) Bone pins (Lafortune, 1991)
iv) External fixation devices (Holden *et al.*, 1997)

In all, the non-invasive, invasive and radiation methods did not provide clear information about the activity of the underlying muscles. This led to the introduction of animal models to help generate more information on muscle activity during movement.

2.1.1.4 Use of animal models

Information on intersegmental forces and moments of the body segments were determined by modelling the body as a system of rigid links and measuring the three-dimensional position of the limb segments and the external ground reaction force (Bresler and Frankel, 1983). To calculate and predict the muscle and joint contact forces, manipulation of the frequency characteristics and filtering considerations were done in experiments described by Winter *et al*.

(1974). These calculations now form the basis for the prediction of muscle and joint contact forces.

Since then biomechanics and concepts borrowed from physics have been used in a number of fields including medicine (e.g., gait analysis), sports science, engineering and mechanics to unravel the complexities of how movement is controlled and regulated by the motor cortex

2.1.2 Control of Human Body Movement

The motor system of the human body coordinates the actions of muscles, bones and joints using sensory information and centrally determined objectives. The “motor programme” sends a set of structured commands to the muscles of the body with the appropriate timing to initiate the sequence of movements. Coordination of this highly complex biomechanical system involves the cerebral motor cortex, cerebellum, basal ganglia, spinal cord, peripheral nerves and sensory receptors.

The motor system utilises two pathways. Namely:

i) An indirect activation pathway that forms tracts extending from the brain stem to the spinal cord mediating postural reflexes. This pathway carries signals from the primary motor cortex, premotor cortex and supplementary areas of the brain. The output from these areas relay on a pool of interneurons in the brain stem then to the spinal cord before sending axons to the ventral horn cells to activate the muscles.

ii) A direct activation pathway that enables the transfer of information without intervening synapses. It is fast and mediates fine controlled voluntary movements. It has two control circuits that fine-tune the direct activation pathway at the supratentorial level. It is mostly involved with conscious control of voluntary activity and skilled movements.

Hence, both the indirect and direct pathways serve as the final pathways for the activities of the primary motor cortex, premotor, supplementary and other areas of the brain, which modulate and integrate motor activity of the cerebral motor cortex (Figure 2-1).

The cerebral motor cortex perceives, interprets and integrates all the various sensations and plans the execution of the many complex motor activities, including highly skilled manipulative movements (Trew and Everett, 1981). Further, it sends parallel information to the cerebellum and the basal ganglia that are involved with higher order cognitive aspects of motor control, such as the planning of motor strategies (Shumway-Cook and Woollacott, 2001). The output fibres of the cerebellum and basal ganglia synapse on the brain stem and are concerned with primary learned automatic behaviour and the maintenance of posture for voluntary activity. This pathway constitutes the indirect pathway or the extrapyramidal tracts for involuntary activities.

In contrast to the indirect pathway, the fibres of the direct descending pathway (corticospinal tracts) terminate on interneuron pools of both the brain stem and the ventral horn cells of the spinal cord to organize the voluntary muscle activity.

Initiation of body movement is by either intrinsic information or information from the somatic sensory system with auditory and visual inputs. The information programmed in the primary motor cortices, which also receives input from the supplementary areas connected to other areas of the cortex and basal ganglia, initiate the initial planning of the involuntary or voluntary muscle activity. The output of the premotor cortex feeds into the motor cortex that in turn, employs a parallel circuit to transmit the information to both the cerebellum and the basal ganglia.

The cerebellum coordinates the sequence of movements of the relevant muscle movements and corrects any errors of muscle function during active movement using feedback information fed to it from the sensory receptor, the muscle spindle. The basal ganglia, on the other hand, is responsible for higher order cognitive aspects of motor control such as the planning of motor strategies (Shumway-Cook and Woollacott, 2001).

Information from the output of the cerebellum and basal ganglia is fed into the brain stem that is concerned with primarily learnt automatic behaviour and the maintenance of posture for voluntary activity. Fibres originating from the brain stem initiate spinal reflexes to effect the movement. At the same time, parallel output of the cerebellum and basal ganglia sends a feedsback to the thalamus, a relay centre, to eventually relay in the motor cortex for the relevant correlation between the intended and planned movements. Activation of the programmed voluntary movement is mediated through the direct pathway by fibres that terminate on neurons in the brain stem and spinal cord.

The spinal cord receives and processes somatosensory information (from muscles, joints, and skin) before initiating the relevant reflexes for voluntary movement and the maintenance of posture. Recent reports (Smith, 2005) have indicated that people are capable of learning to adapt their motor performance as well as optimise the rate at which this adaptation takes place.

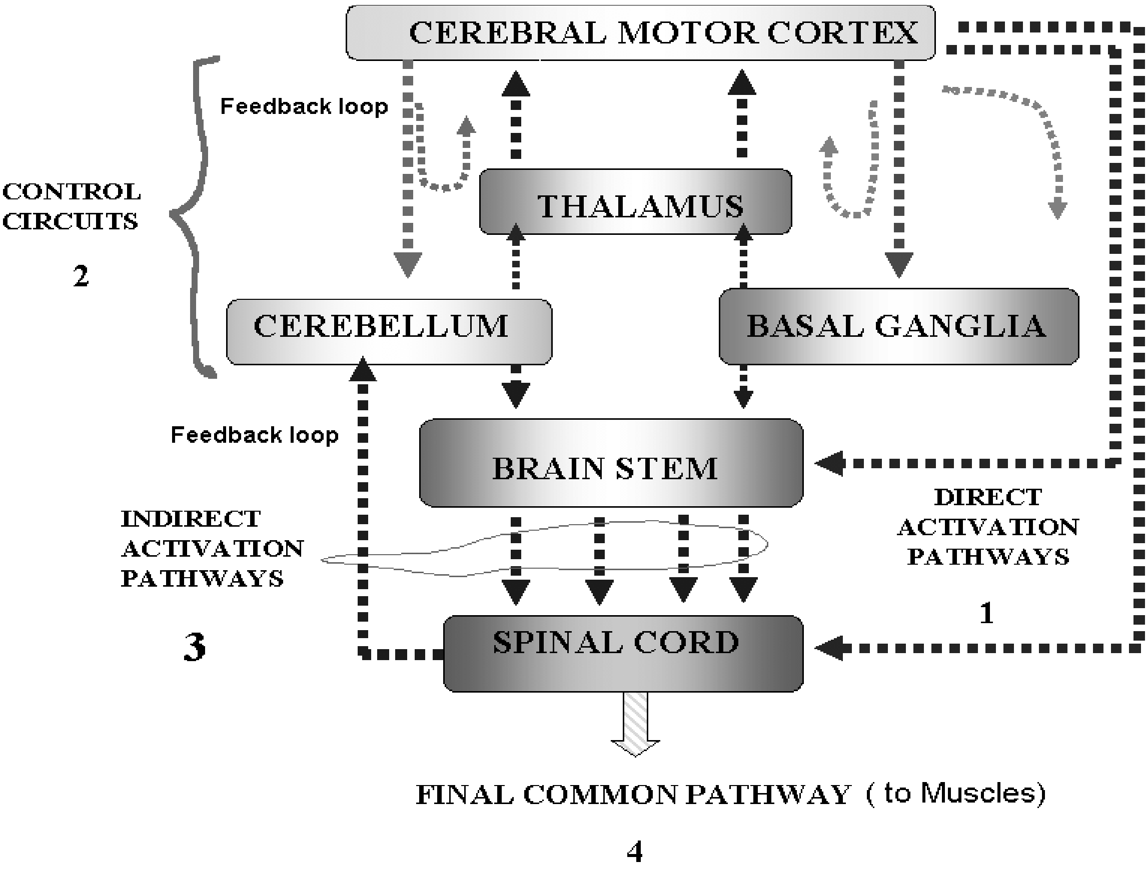


Figure 2-1: Schematic diagram of motor control of voluntary and involuntary movements

Over the years, the complex processes of body movements have fascinated researchers. In order to understand the mechanisms involved, physical concepts and principles of mechanics have been used to explain the underlying mechanisms.

2.2 PHYSICAL CONCEPTS AND PRINCIPLES OF MECHANICS

2.2.1 Linear Motion and its Derivatives

Linear motion, sometimes referred to as translatory or rectilinear motion, is characterized by the movement of a body in a straight line through the same distance in the same direction (Dyson, 1986). The movements can occur at different velocities and acceleration.

2.2.1.1 Linear velocity

Linear velocity is the rate of change in body position with respect to time. It is a vector quantity with magnitude and direction. It measure in meters/second (m/s) (Bronner, 2004; Redfern, 2001). Even though velocity and speed are synonymous, yet in mechanics there is a distinction between velocity and speed. An example of this is in track and field where the term ‘speed’ is more appropriate than ‘velocity’. This is because a runner may move at a speed of 24 m/h but the direction of motion has to be taken into consideration in order to state his velocity. The rate of change in velocity with time is termed ‘acceleration’.

2.2.1.2 Linear acceleration

Linear acceleration is a vector quantity defined as "the rate at which an object changes its velocity". Velocity divided by time is used in calculating acceleration. The SI unit of acceleration is meter per second squared (m/s^2). It can also be in terms of gravity (g), where g value at sea level at latitude of 45 degrees is 9.80616 m/s^2. Further, the position of an object can also be determined from the curves of velocity as a function of time (Figure 2-2).

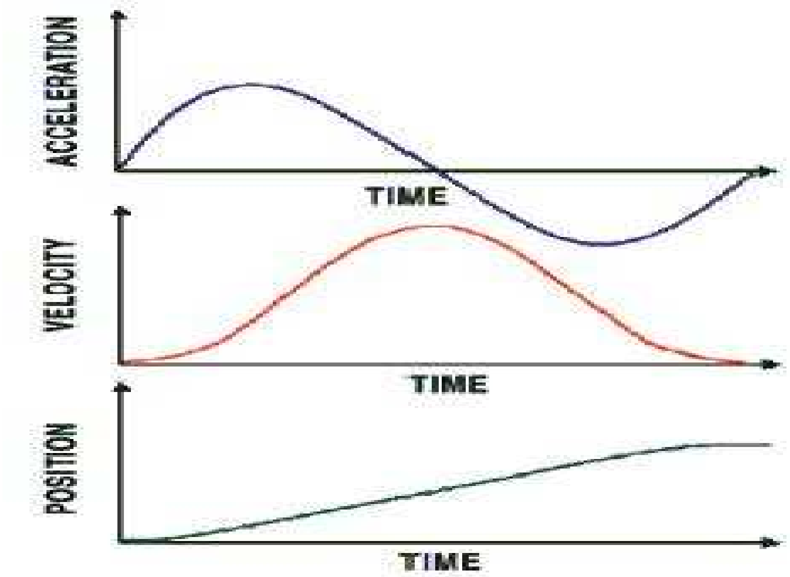


Figure 2-2: Graphs depicting how the position of a body can be determined from acceleration and velocity curves as a function of time (Mohammad, 2006).

Another form of motion and other derivatives of motion that the body undergoes is rotational or angular motion.

2.2.2 Rotational (angular) Motion and its Derivatives

In the determination of angular or rotational motion, consideration of linear motion is important since angular motion can be translated into linear motion. Rotational motion is common in human and animal locomotion (Dyson, 1986) and has derivatives of angular velocity and angular acceleration.

2.2.2.1 Angular velocity

Angular velocity is the rate of change in angular displacement with respect to time. It is a vector quantity and is reported in degrees/second (º/s or deg/s) or radians/second (rad/s). Formulated as: $\omega = \theta t$

Where ω = angular velocity, θ = angle, t = time

2.2.2.2 Angular acceleration

Angular or rotational acceleration is a quantitative expression of the change in angular velocity that a spinning object undergoes per unit time. It is a vector quantity with magnitude and direction. The magnitude of the angular acceleration vector is directly proportional to the rate of change of the angular velocity. It is measured in radians per second squared (rad/s^2 or $rad \cdot s^{-2}$) or in degrees per second squared (deg/s^2 or $deg.s^{-2}$) (Dyson, 1986). Expressed as:

$\alpha = \omega / t$

Where α *= angular acceleration,* ω = angular velocity, t = time

These fundamental concepts are important in understanding of the analysis of human locomotion by a number of sensors.

2.3 A SENSOR AND ITS CHARACTERISTICS

A sensor is a device that converts different physical modalities into electrical signals. It acts as an interface between the physical world and the world of electrical devices (Putnam, 1996). It has the following characteristics:

2.3.1 Sensitivity

The sensitivity of a sensor is a relationship between the physical signal input and the electrical signal output. It is a ratio of a small change in electrical signal to a change in a physical signal. Consequently, it is expressed as the derivative of the transfer function with respect to the physical signal (e.g., an accelerometer is said to have a "high sensitivity" if a small change in acceleration causes a large change in voltage).

2.3.2 Resolution

A sensor’s resolution is the minimum detectable signal fluctuation. Fluctuations are temporal phenomena. There is a relationship between the time scale for the fluctuation and the minimum detectable amplitude. Hence, in defining resolution, there should be consideration of some information about the nature of the measurement. Many sensors have a limitation due to the white noise (Putnam, 1996).

2.3.3 Span or Dynamic Range of a Sensor

The span or dynamic range of a sensor is the input physical signal converted into electrical signal. Signals outside of this range can cause an unacceptably large inaccuracy. The supplier usually specifies the dynamic range.

2.3.4 Accuracy

The accuracy of a sensor is the largest expected error between the actual and the ideal output signals. It is a fraction of the full-scale output.

2.3.5 Hysteresis

A sensor has hysteresis when its output value does not return to the same value after cycling the input stimulus up or down. The width of the expected error in terms of the measured quantity is the hysteresis of the sensor.

2.3.6 Nonlinearity

Nonlinearity is the maximum deviation from a linear transfer function over a specified dynamic range. The most common measure compares the actual transfer function with the `best straight line' that lies midway between the two parallel lines encompassing the entire transfer function over the specified dynamic range of the device.

2.3.7 Bandwidth

All sensors have finite response times to any instantaneous change in physical signal. In addition, these sensors have decay times that represent the time between a step change in physical signal and the time the sensor output takes to decay to its original value. The reciprocal of these times correspond to the upper and lower cut-off frequencies, respectively. The bandwidth (BW) of a sensor, therefore, is the range between these two frequencies. A higher bandwidth provides more samples/second (Figure 2-3).

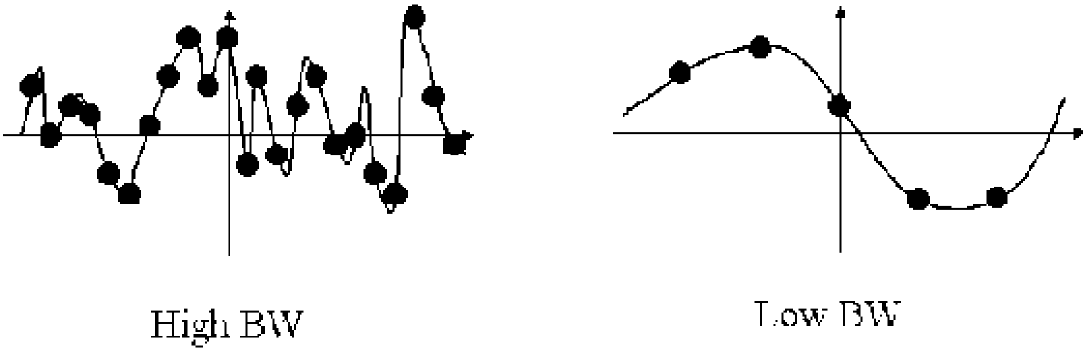


Figure 2-3: Curves shows analog signal sampling rate in high and low bandwidth (BW)

2.3.8 Noise

All sensors have some output noises that are superimposed on the real output signal. In some cases, the noise of the sensor is less than the noise originating from the components of the electronic circuitry. In other sensors the noise tends to limit the performance of the system.

2.4 DATA LOGGER COMPONENTS AND INERTIAL SENSORS

2.4.1 Accelerometers

Accelerometers are instruments that measure the applied acceleration acting along their sensitive axis (Mathie *et al.*, 2004). The basic physical principle of an accelerometer is comparable to a simple mass spring system (Figure 2-4). Applying Newton's law to such a system implies that if a mass (*m)* is undergoing acceleration (*a)* then there must be force (*F)* acting on it. This is expressed as *F=ma* (Mathie *et al.*, 2004; Putnam, 1996).

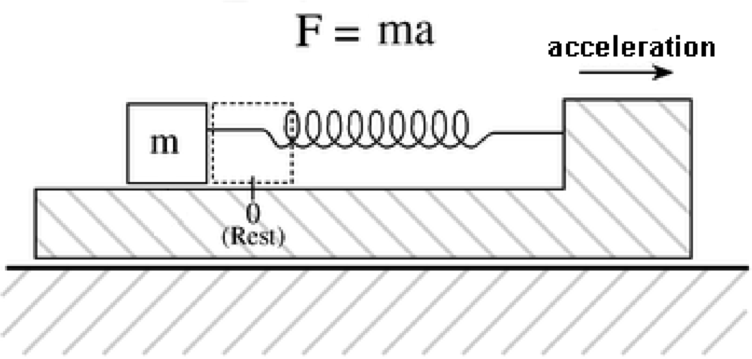


Figure 2-4: Basic physical principle of an accelerometer

When the accelerometer is in motion, the measured acceleration is the vector sum of the gravitational and the projected acceleration onto its sensitive axis. Thus, accelerometers measure the sum of the acceleration due to the movement and the effect of gravity acting along its sensitive axis (Mathie *et al.*, 2004; Tsung-Lin Chen 2005) (Figure 2-5).

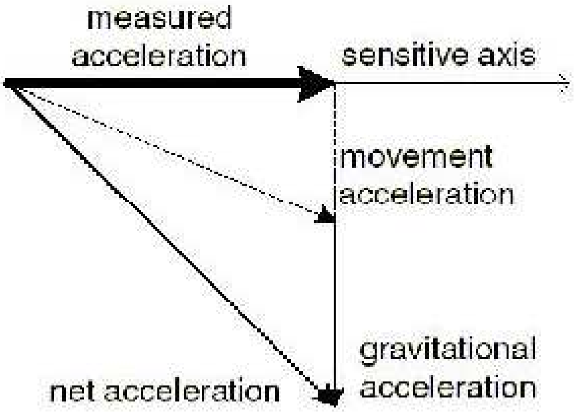


Figure 2-5: Measure of acceleration due to movement and gravity

The accelerometer measurement unit is “g” equal to gravity force and the applied acceleration unit is m/s^2 (meter per second squared).

2.4.1.1 Microelectromechanical accelerometer systems (MEMs)

Microelectromechanical systems (MEMs) are integrated systems that combine electrical and mechanical components. MEMs devices contain three-dimensional mechanical structures. These “micromachined” mechanical structures have dimensions which are measured in micrometers (Bachmann, 2000) and are thus different from semiconductor or microelectronic production. The advent of MEMs has made it possible to fabricate inertial sensors that are small, cheap and have many applications.

2.4.1.2 Accelerometer output error and sensitivity

A number of error sources influences an accelerometers output to deviate from its correct value. In the case of a MEMS accelerometer, the error sources include scale factor, bias, and noise. Consequently, in utilizing a MEMs accelerometer (Figure 2-6) all these errors have to be identified and calibrated either on-line or off-line as accurately as possible to reduce the error measured during movements (Chin-Woo, 2002).

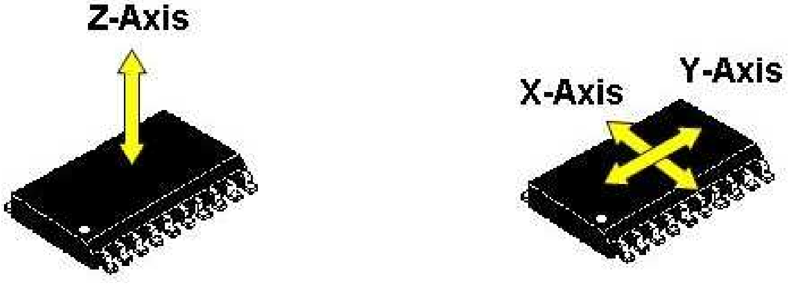


Figure 2-6: Axes X-Y Z of MEMs accelerometers

2.4.2 Gyroscopes

Gyroscopes operate on the principle of a vibrating mass that is undergoing an additional vibration caused by a “Coriolis effect” (Luinge, 2002). A “Coriolis effect“ is an inertial force that is related to the motion of the object (Luinge, 2002).

The benefits of gyroscopes include (Bronner, 2004):

i) Direct measurement of rotational motion unaffected by gravity

ii) Its small size

Its disadvantages include (Bronner, 2004):

i) An increasing error of several degrees per second caused by the gyroscope offset and noise.

ii) Small orientation errors that can result in larger integration errors in the calculation of angular displacement or position from angular velocity over time.

Consequently, gyroscopes are not used regularly in the measurement of human motion due to their inaccuracy over periods greater than one second, their limitation of range of measurement and low sampling rate (Bandwidth) (Bronner, 2004).

2.4.3 Operational Amplifier

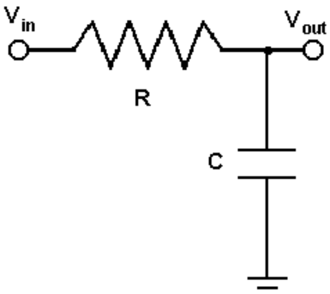
An operational amplifier (Op-Amps) is an electronic device that is used for signal processing and amplification. It is essentially a two input one output device (Putnam, 1996).

2.4.4 Filter

Many sensors have output signals with other different signal components superimposed on the real signal. The unwanted signals/noise is filtered out with an analog circuitry called ‘filters’ prior to the digitisation of the real signal. As an example, if 60 Hz interference distorts the output of low output sensors, a signal conditioning circuitry (filter) filters out the “noise” before the actual signal is amplified and digitised. Two types of filters frequently used in this regard are namely: i) Low-pass filter and ii) High-pass filter

2.4.4.1 Low-pass filter

A simple low-pass filter uses a resistor and a capacitor in a voltage divider configuration (Figure 2-7). At high input frequencies, the `resistance' of the capacitor decreases correspondingly resulting in an output voltage. This effectively filters out the high frequencies (noise) while `passing' the low frequencies.

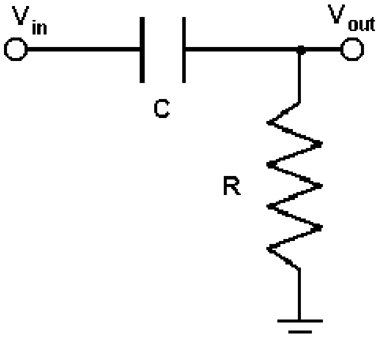


V_{in} = Input voltage
R = Resistor
C = Capacitor
V_{out} = Output voltage

Figure 2-7: Circuit diagram of a low-pass filter

2.4.4.2 High-pass filter

In a high-pass filter, the roles of the resistor and capacitor are reversed. The function of the circuit is analogous to that of the low-pass filter (Putnam, 1996) (Figure 2-8).



V_{in} = Input voltage
R = Resistor
C = Capacitor
V_{out} = Output voltage

Figure 2-8: Circuit diagram of a high-pass filter

2.4.5 Analog to Digital Converters

Analog to Digital converters (ADC or A/D) are used to translate an analog voltage input into a digital output. Multichannel A/D converters have a multiplexer for measuring several signals with a single output channel (Figure 2-9).

Multiplexing is a common technique used for measuring several signals with a single output channel. The multichannel A/D converter samples one