Physical and neurophysiological factors influencing dynamic balance

By

Khaled Jebril Abuzayan

A thesis submitted in partial
fulfilment of the requirements of
Liverpool John Moores University for
the degree of Doctorate of Philosophy

April, 2010

Abstract

Abstract

Static and dynamic balance are essential in daily and sports life. Many factors have been identified as influencing static balance control, two of which are carrying additional weight and localized muscle fatigue but their influence on dynamic balance in sport activities has not been fully established. Therefore, the aim of this thesis was to investigate the characteristics of dynamic balance in sport related activities, with specific reference to the influence of body mass changes and muscular fatigue.

Study one: The objectives of study one (methodological study, n = 5) were to apply the extrapolated Centre of Mass (XCoM) method and other relevant variables (centre of pressure, CoP; Centre of Mass, CoM; shear forces, F_h; kinetic energy, KE; momentum, P; and angular impulse, AI) to investigate sport related activities such as hopping and jumping. Many studies have represented the CoP data without mentioning its accuracy so several experiments were done to establish the agreement between the CoP and the projected CoM in a static condition. It was found that there was an inaccuracy with the average difference about 4mm. This meant that the angular impulse could not be reliably calculated. Its horizontal component, representing the Friction Torque (Q), could be reliably computed for dynamic balance. The implementation of the XCoM method was found to be practical for evaluating both static and dynamic balance. The general findings were that the CoP, the CoM, the XCoM, F_h, and Q were more informative than the other variables (e.g. KE, P, and AI) during static and dynamic balance. The XCoM method was found to be applicable to dynamic balance as well as static balance.

Study 2: The objectives of study two (baseline study, n = 20) were to implement Matlab procedures for quantifying selected static and dynamic balance variables, establish baseline data of selected variables which characterize static and dynamic balance activities in a population of healthy young adult males, and to examine any trial effects on these variables. The results indicated that the implementation of Matlab procedures for quantifying selected static and dynamic balance variables was practical and enabled baseline data to be established for selected variables. There was no significant trial effect. Recommendations were made for suitable tests to be used in later studies. Specifically it was found that one foot-tiptoes tests either in static or dynamic balance are too challenging for most participants in normal circumstances. A one foot-flat eyes open test was considered to be representative and challenging for static balance, while adding further vertical jump and landing tests (two feet flat and one foot flat vertical jump) to the horizontal jumping and hopping for dynamic balance was considered to be more representative of sports situations. The main differences between horizontal and vertical jumping were in anterior-posterior direction.

Study 3: The objectives of study three (differentiation study, n = 20) were to establish the influence of physical (external added weight) and neurophysiological (fatigue) factors on static and dynamic balance in sport related activities. This was typified statically by the Romberg test (one foot flat, eyes open) and dynamically by jumping and hopping in both horizontal and vertical directions. Statically, added weight increased body's inertia and therefore decreased body sway in anterior-posterior direction though not significantly. Dynamically, added weight significantly increased body sway in both mideo-lateral and anterior-posterior directions, indicating instability, and the use of the counter rotating segments mechanism to maintain balance was demonstrated. Fatigue on the other hand significantly increased body sway during static balance as a neurophysiological adaptation primarily to the inverted pendulum mechanism. Dynamically, fatigue significantly increased body sway in both mideo-lateral and anterior-posterior directions again indicating instability but with a greater use of counter rotating segments mechanism. Differential adaptations for each of the two balance mechanisms (inverted pendulum and counter rotating segments) were found between one foot flat and two feet flat dynamic conditions, as participants relied more heavily on the first in the one foot flat conditions and relied more on the second in the two feet flat conditions.

Conclusion: Results from this thesis are expected to aid towards advancing the understanding of balance in sport related activities, and can provide a solid foundation for future work in this area. In particular, a method was established to assess static and dynamic balance, baseline data for these associations was provided, and differential adaptations to physical or neurophysiological constraints were found. Valuable associations between specific variables and the first two mechanisms of balance were demonstrated.

Acknowledgments

Acknowledgment

First of all, I am thankful to God the most Merciful for giving me the patience, perseverance and courage to finish this work.

To complete the work that is required to study and write a thesis of this kind is not possible on my own. Also, this study could not have been brought to fruition without the support of a number of people, to whom I owe a debt of gratitude.

I wish to express my especial thanks and appreciation to my supervisor, Professor. Adrian Lees, Professor of Biomechanics and Deputy Director of the Research Institute for Sport and Exercise Sciences at Liverpool John Moores University. Indeed, he is an excellent example of a University tutor who cares about his students at a personal level, and I have certainly learned much from him; he has been a constant source of advice. Without his helpful advices, guidance, positive attitude, and encouraging remarks, this thesis could not have been written.

I would like to express my deepest gratitude and appreciation to second supervisor Doctor Jos Vanrenterghem, a lecturer in Biomechanics of Posture and Balance at Liverpool John Moores University, who also cares about his students at a personal level for continued assistance, supportive words, and I appreciate your welcoming spirit and helpful collaboration in the development of this thesis.

I would like to express my best appreciation and appreciation to third supervisor Doctor Malcolm Hawken, an engineer and a registered Clinical Scientist at Liverpool John Moores University, for his continued assistance as I learned much from you, and helpful collaboration in the development of this thesis.

I also extend my gratitude to all the participants who involved in all studies whom without the research would not have been possible, as well as the biomechanics department members for supporting me and create such a great scientific atmosphere.

In addition, I express my profound gratitude to my parents for their prayers and all the sacrifices they have made for me. Great thanks to my wife (Awatef) for her emotional support, encouragement and patience, to my daughter (Aisha) and my son (Gabriel) for

making my life meaningful; brothers and sisters, for their prayers for me. I offer them my heartfelt thanks.

For making the long days seem shorter, the dark days light, and the mundane tasks exciting, my mother and my father, I thank you both for being there and helping me in my times of greatest need. Also, I extend my thanks and gratitude to everyone who has helped me throughout the preparation of this work.

Finally, I am eternally grateful to the Libya Arab Jamahiriya who provided me with much needed funds to maintain my research efforts to undertake my Ph.D. program in the UK.

Dedication

This thesis is dedicated to my father, mother, wife, daughter and son, who taught me what hard work and dedication can accomplish in life, and my brothers and sisters for the everlasting pray, love, support, and encouragement they provide me with.

Declaration

I declare that the work in this thesis is entirely my own. This project was supervised by three members of academic staff (Professor Adrian Lees my Director of Studies, Doctor Jos Vanrenterghem and Doctor Malcolm Hawken). No portion of the work referred to in this thesis has been submitted in support of an application for any another degree or qualification of this or any other university or institute of learning.

List of Abbreviations

List of Abbreviations:

CoM	Centre of Mass
XCoM	Extrapolated Centre of Mass
CoP	Centre of Pressure
BoS	Base of Support
GRF	Ground Reaction Force
ML	Medio-Lateral
AP	Anterior-Posterior
V	Vertical
v	velocity
x	Lateral dimension
y	Anterior-posterior dimension
KE	Kinetic Energy
P	Momentum
I	Impulse
Q	Friction Torque
TTS	Time to Stabilization
DPSI	Dynamic Postural Stability Index
IP	Inverted Pendulum
EO	Eyes Open
EC	Eyes Closed
F_h	Horizontal Ground Forces
F_v	Vertical Ground Forces
Hz	Hertz
N	Newton
s	second

ms	millisecond
m	meter
J	Joule
ft	feet/foot
SD	Standard Deviation
A/D	Analog/digital
ANOVA	Analysis of Variance
CNS	Central nervous system
EMG	Electromyogram
n	Number of subjects
p	p-value = observed significance level
r	Correlation coefficient
RMS	Root mean square
SPSS	Statistical Package for Social Science
df	degrees of freedom

Contents

Table of Contents

CHAPTER (1)

CHAPTER (2)

CHAPTER (3)

CHAPTER (4)

CHAPTER (5)

CHAPTER (6)

CHAPTER (7)

List of Figures:

List of Tables:

Table of Appendices

Chapter (1) Introduction

1. Introduction

1.1. Background

Balance is understood by almost everyone to be a critical component of skilful movement. One definition of balance is a "state of equilibrium" (Grimshaw *et al.*, 2006, p. 161) which can be used to describe the state of a system subjected to opposing forces that balance each other, so that for any small disturbances the mechanical system returns to equilibrium (Zatsiorsky, 2002, p. 199). Balance is also defined as the ability to maintain the body's Centre of Mass over its Base of Support (Woollacott and Shumway-Cook, 2002) whereas a fall is defined by the World Health Organisation as " an event which results in a person coming to rest inadvertently on the ground or floor or other lower level." (WHO, 2010).

An improved understanding of balance control may help prevent falls (Qu and Nussbaum, 2009). The control of balance in human movement activities such as standing (static balance) or walking, jumping or hopping (dynamic balance) involves the moment-to-moment control of forces. For standing and static posture this is often referred to as postural balance (Gill, 2004). Postural balance ability may vary vastly between people. It is commonly evaluated by using functional rating scales e.g. Berg Balance Scale or by recording body sway on a device such as a force platform. Although maintaining a stable upright posture is often considered a simple task, falling is inevitable and occurs throughout our lifespan (Corbeil *et al.*, 2001). Many factors have been identified as influencing balance control, such as aging, body mass and inertial mass distribution properties, carrying additional weight, localized muscle fatigue, and decrements in the quality of sensory input (Jeffrey and Schiffman, 2006).

Typically, the term "body sway" is used to describe the excursions during postural balance of either the Centre of Pressure (CoP) which is defined as the point of application of force within the Base of Support (BoS) that a subject applies to the support surface while attempting to stand still; this movement is displayed as a travelling point between the feet that moves with weight shift or by describing the excursions the Centre of Mass of the body (CoM) which is known as the balancing point of the body which in static standing circumstances means all torques are average to zero (Hamill and Knutzen., 2003, p. 405) while the Base of Support (BoS) can be approximated as the surface area under and between the feet or the area of contact with the support surface (Hof *et al.*, 2005).

One of the most popular computerized laboratory methods for evaluating human postural balance is to measure spontaneous body sway while the subject is standing on a force platform. The basic principle of the force platform test is that movements of the CoP reflect the horizontal location of the CoM, which is considered true for low-frequency components of sway. The frequency of the CoP excursions that accompany body sway for young healthy subjects is below 1 Hz (Era and Heikkinen, 1985), whereas in some elderly subjects there may be additional components between 1 and 3 Hz (Lucy and Hayes, 1985; Hasan *et al.*, 1996; Guerraz *et al.*, 2000). At these higher frequencies the CoP and the CoM cannot be considered equivalent.

Conventional measures of body sway, such as root mean-square (RMS) amplitude of the motion of the CoM or CoP about a mean position, provide single quantities summarizing overall motion of the body. Other typical parameters in platform measurements are the mean CoP position (as a reference point), anterior-posterior and lateral excursions of sway, the length of the sway path, sway velocity and sway area.

Controlling sway relies on sensory information from vision, proprioception and the vestibular system. Body sway has been measured under variable visual and support surface conditions, and measures have been reported to identify sensorimotor deficits as well as to differentiate between functional performance abilities. The Romberg test, which is a clinical test to identify poor balance (Khasnis and Gokula, 2003), specifically identifies the inability to maintain a steady standing posture with the eyes closed compared to eyes opened. Sway has also been analyzed during standing on a foam plastic covered surface to reduce proprioceptive input (Hytönen *et al.*, 1993) under various visual conditions, such as blurred vision or the use of only peripheral or central vision (Geurts *et al.*, 1993).

As noted previously, many studies dealing with postural balance consider the CoP to be coincident with the projected position of the CoM. These studies have some limitations because most of them deal with the body during quiet standing which produces a very low frequency of sway. Hof *et al.* (2005) introduced a novel method for estimating balance during movement (generally, referred to as dynamic balance) and applied it to walking. In this and in sports activities that include rapid movements, such as hopping or jumping, the velocity of the CoM can influence balance behaviour. Hof *et al.* (2005)

introduced a method which is referred to as the "extrapolated Centre of Mass" (XCoM) method and this takes into account the velocity of the CoM with the subject modelled are as an inverted pendulum. Hof defined the XCoM as the position of the vertical projection of the CoM plus a velocity correction factor which together should lie within the BoS.

The XCoM has been studied by Hof in various circumstances such as standing on two feet or one foot, either with feet flat or on tiptoe (Hof et al., 2005). These experiments have shown that the body increases its sway rapidly under unstable condition, especially for the 1 foot tiptoe standing conditions, but has also shown that when balance is maintained the XCoM still stays within the BoS. Hof's method for dealing with high frequency body sway is applicable to various situations, including those in sports, for instance when hopping or jumping, but so far this has not been investigated.

Since balance and stability within sport are important to achieve specific movement patterns (Grimshaw *et al.*, 2006, p. 161) and most sports are dynamic in nature, postural control should be assessed using dynamic tests to ensure the application of results. Furthermore, dynamic balance depends on the relationship between the CoM and the BoS (Kirtley, 2006, p. 172). This relationship needs to be clarified as in dynamic balance the CoM is not in a fixed position relative to the body segments and has velocity as well as a changing the BoS. Therefore, the relationship is dependent not just on the CoM position but also the state of the CoM position and its velocity (Pai, 2003). Oates. (2007) defined dynamic stability as the ability to control a moving CoM within a changing BoS. Consequently, the most important information may not be the current CoM position, but where it will be in the future in relation to the new BoS. If CoM motion cannot be controlled before crossing the BoS boundaries, a step must be taken to maintain stability (Hasson *et al*; 2009). Therefore, the velocity of the CoM should also be considered as well as the changing BoS. Hof *et al.* (2005) clarified that in some circumstances, even though the CoM is above the BoS, balance may be impossible when CoM's velocity is directed outward. The reverse is also possible: even if the CoM is outside the BoS, but CoM's velocity directed towards it, balance can be maintained. Hence, the velocity of the CoM should also be accounted for when evaluating dynamic balance. The XCoM introduced by Hof *et al.* (2005) is a suitable measure for use in the above mentioned circumstances. In summary, evaluating dynamic balance requires understanding the ability of controlling a moving CoM, position-velocity (XCoM), within a changing BoS.

One of the physical factors influencing static and dynamic balance is body mass and mass distribution. This relates to issues of load carriage and obesity. Carrying loads is an everyday task; people carry additional loads at home, at work, items while shopping, and during people's leisure time (e.g. hiking). Many studies have investigated the effect of added weight upon people's balance in static balance (e.g. standing) while fewer studies have been done in dynamic balance (e.g. walking). Some studies have suggested that external loads adversely affect balance control, since such loads resulted in increased postural sway by increasing the CoP sway during quiet erect stance (Ödkvist, 1993). This increase in postural sway indicates that the whole-body CoM gets closer to the boundary of the BoS and thus leads to less stability. Others found that static equilibrium is positively related to mass of the person (Adrian and Cooper, 1995, p. 22). Furthermore, other studies have focused on the effects of the location of external load mass on balance control as well as the percentage of the added weight to the total body mass e.g. 10%, 15% or 20% of total body mass (Singh and Koh., 2009).

Dynamically, most researchers who dealt with loading participants with external mass focused on walking, e.g. schoolchildren (Talbott, 2005) and soldiers (Schiffman *et al.*, 2005). It has been found that increasing mass (e.g. backpack) makes it harder to initiate motion and requires greater moments about the axes of rotation to control motion and alter postural control mechanisms (Maki, 1994), which may lead to the risk of falls and injuries. There appear to be no published studies, which investigate the effect of added mass upon sport related activities such as hopping and jumping. Therefore, a better understanding of the posture and dynamic perturbations induced by additional load carriage in specific populations is an important topic for investigation.

A neuromuscular factor influencing static and dynamic balance is induced muscular fatigue due to exercise. Fatigue is commonly experienced by people in daily life and in sports situations. Fatigue occurs at the time when a target force can no longer be generated or 'a loss of maximal force generating capacity' is discovered (Vollestad *et al.*, 1988; Vollestad, 1997). Miller *et al.* (1995) defined muscle fatigue as the reduction in maximal force generating capability during exercise. In a sport context, fatigue increases the complexity of a balance task because it impairs or reduces the force capacity of muscles and decreases sensitivity of the proprioceptive system (Simoneau *et al.*, 2006). This has been demonstrated by an increase in medio-lateral body sway oscillations during static balance tests in the fatigued state (Corbeil *et al.*, 2003). Nardone *et al.* (1997), using a treadmill based aerobic fatigue protocol, have reported increases of the sway path of the CoP and median frequency of the CoP velocity. This suggests that fatigue induces an increased frequency of actions needed to regulate body sway oscillations. Skilled athletes were less affected by fatigue, suggesting that skill could attenuate the specific effect of fatigue on balance control. Fatigue, therefore, does not always lead to instability. The balance control system is able to compensate for the early acute effects of fatigue by increasing the frequency of actions of the CoP velocity and by allocating a greater proportion of cognitive resources to the balance control task. There is limited information regarding the effect of fatigue on dynamic balance, despite its considerable importance to dynamic activities in sport.

Although many studies have investigated static balance in diverse circumstances, dynamic balance has been discussed mostly based on gait and little has been done on dynamic balance particularly in sport related movements (other than walking). Moreover, there is no information about applying the extrapolated CoM approach in sport related activities (dynamic balance). This project, therefore, aims to determine the characteristics of dynamic balance in sport related activities, typified by hopping and landing from a jump. In addition, it aims to establish the influence on dynamic balance of physical (represented by carrying added weight) and neurophysiological (represented by inducing fatigue) factors.

1.2. Aim of the study

To investigate the characteristics of dynamic balance in sport related activities, with specific reference in the influence of body mass changes and muscular fatigue.

1.3. Objectives

1. To apply the extrapolated Centre of Mass (XCoM) method and other relevant variables for evaluating balance in sport activities such as hopping and jumping;
2. To examine whether the variables developed can reliably characterize dynamic balance characteristics in young adults and to collect baseline data for further studies;
3. To investigate the effects of changing body mass and mass distribution on the static and dynamic balance characteristics of young adults;
4. To investigate the effects of muscular fatigue on the static and dynamic balance characteristics of young adults.

Chapter (2) Review of the Literature

2. Review of the Literature

2.1. Static balance

Static balance has been an important research topic for several decades. It is commonly known from Newton's First Law that when a body is in rest (not moving) or in a state of constant movement (acceleration equal zero), it is also in a state of equilibrium (Grimshaw *et al.*, 2006, p. 156). Stability is defined as the ability of an object or individual to remain in a stable position and is commonly referred to as balance (Hamill and Knutzen, 2003, p. 405). The concept of balance is based on the notion that balance is represented by equilibrium. This definition draws from a balance scale which is used to determine if two items have equal weights, and typically, losing balance means to fall or fail to maintain balance. Being in an off-balance situation means to deviate from the control of balance and inability to control balance. Generally, there are two types of balance, static and dynamic balance.

Static balance is well reported by many researchers considering quiet standing as a "static balance" activity. In fact, the upright posture is a continuum of adjustments that are made in response to a changing environment which is known as body sway (Loram *et al.*, 2007). Internal forces (generated from muscle contraction, ligaments, joint capsules and other connective tissue structures) and external forces (inertia, gravity and ground reaction forces) that are present are constantly monitored and adjusted to prevent movement and maintain posture. To remain in one position, the forces must be in equilibrium, that is, the net effect of all of the forces acting on the body and its segments must be equal to zero (van Asseldonk *et al.*, 2007). It is important to note that the inertial forces relevant to quiet standing are usually ignored when analysing balance. In quiet standing, little or no acceleration is occurring negating the inertia that might be present. The body, however, does undergo a constant swaying motion or postural sway that can be considered an indirect measurement of the stability of an object (Talbot, 2005).

In normal stance, the amount of sway is small and plays a minimal role in altering the position of the body segments. This sway, however, may become greater when the body is unstable as sensory receptors and responding output increase to prevent falls. The line of gravity from the CoM to the axis of a joint determines the internal forces needed to maintain joint position. When the line of gravity passes directly through a joint axis, no gravitational torque is created around the joint and additional forces are not needed to keep the joint in one position. Otherwise, a torque will be developed that will rotate the body segment requiring an opposing torque to maintain balance (Hamill and Knutzen, 2003, p. 405).

2.2. Neuromuscular factors influencing static balance

2.2.1. Sensory systems

To achieve perfect balance it is necessary for several different systems to interrelate. Postural stability may be affected by firstly visual input, secondly the vestibular system, thirdly the proprioceptive inflow and fourthly the locomotor system (Roland *et al.*, 1995). With respect to postural balance, three sensory systems have a main role: proprioception vestibular system, and vision:

Proprioceptors are defined as "nerve terminals found in muscles, tendons and joint capsules, which give information concerning movements and position of the body;

sometimes the receptors in the labyrinth are also considered proprioceptors" (Dorland's Illustrated Medical Dictionary, 2003, p. 124). Receptors "are specialized cells or subcellular structures that change their properties in response to stimuli" (Latash, 1998, p. 112). Their main function is providing information to other neurons, that is, environmental information in addition to information on the body part itself. This information is collected by three kinds of receptors:

- Introceptors: transfers information within the body itself.
- Extraceptors: transfers information from environment.
- Proprioceptors: transfers information about the body segments.

The latter proprioceptors can be found in the muscles, tendons, and joints. Proprioceptors in the muscles are the muscle spindles, which are sensitive to length and velocity of muscle stretch. The proprioceptors located near the junction between tendons and muscle fibres are called Golgi tendon organs, which are due to their specific location in the tendon and their structure's elasticity (Figure 2.1), are perfect in detecting mechanical deformation related to the force stretching the tendon. Therefore, they are known as a force sensor. Another group of proprioceptors are the joint receptors which are known as particular receptors which are fast in transferring signals (80 m/s).

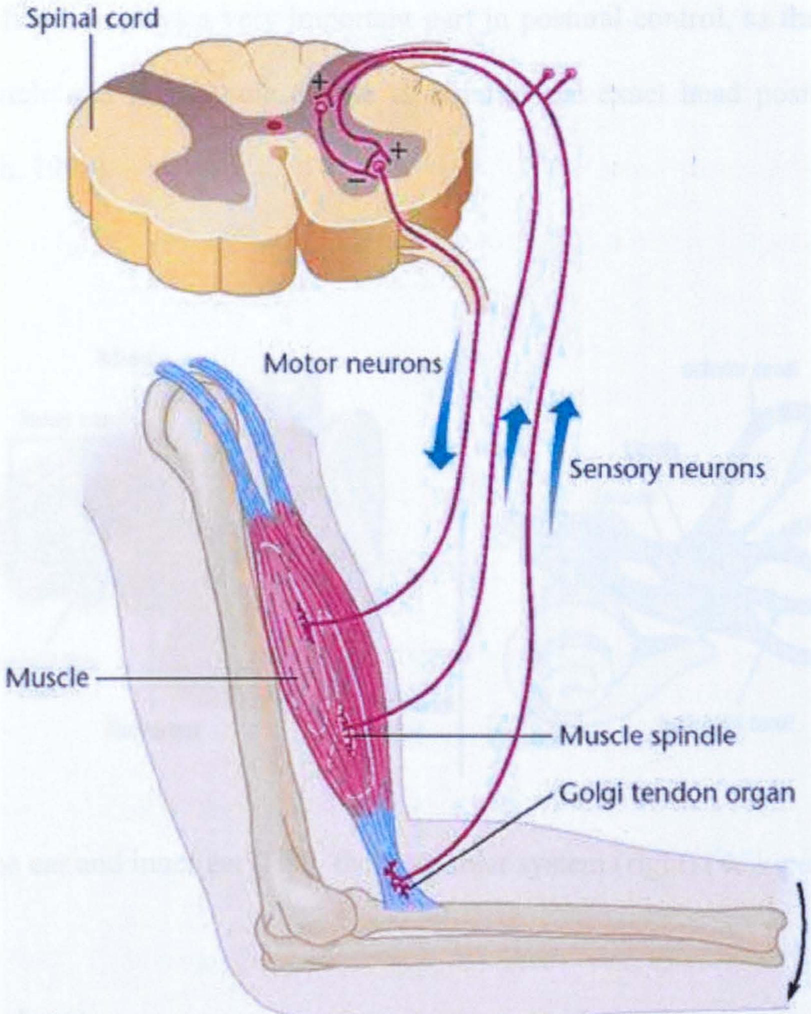


Figure 2.1 location of proprioceptors (Wikipedia, 2010).

The vestibular system is composed of the sense organs of balance (McGinnis, 1999, p. 78). each inner ear (Figure 2.2, right) contains three bony tunnels that are filled with fluid called *endolymph*, which provides signals based on the orientation of the head with respect to the direction of the field of gravity (Latash, 1998, 113). The vestibular system can be divided according to its dynamic and static functions:

- Dynamic function when the semicircular ducts allow tracking of head rotation in space. This is particularly important in controlling the reflex control of eye movements.

- Static function plays a very important part in postural control, as the hair cells in the utricle and the saccule enable to monitor the exact head position in space (Latash, 1998).

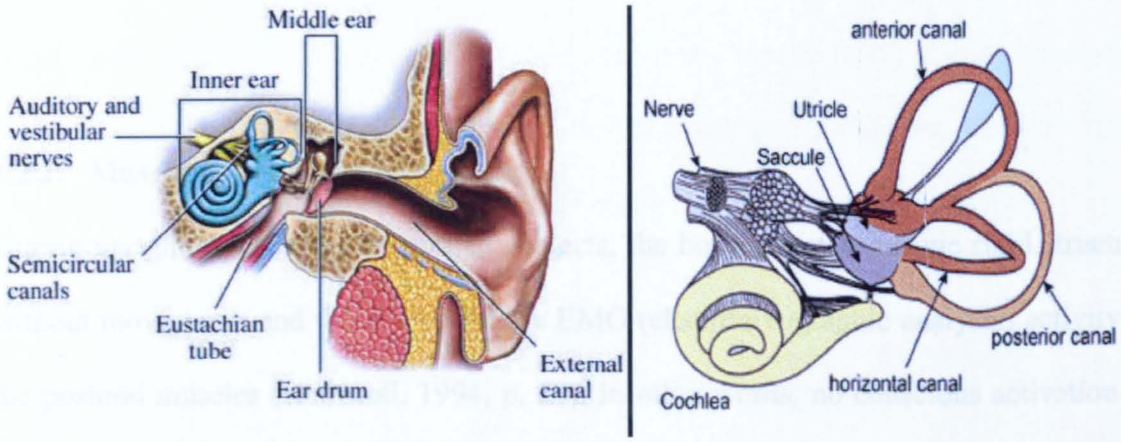


Figure 2.2. The ear and inner ear (left), the vestibular system (right) (Wikipedia, 2010).

Vision and Balance

Vision provides most of the information to the brain which makes it a reliable source of information and plays a direct and important role in stabilizing balance by providing the nervous system with continually updated information regarding the position and movements of body segments in relation to each other and the environment. This visual information is significant in postural control, which can be recognized by bigger sway when people stand with eyes closed compared to standing with eyes open (Redfern *et al.*, 1997). When people stand with their eyes closed, postural sway increases between 20% and 70% (Magnusson *et al.*, 1990; Paulus *et al.*, 1984). It has also been found that moving visual fields can induce a powerful sense of self-motion and misleading visual cues induce significant increases in sway (Lee and Lishman, 1975). Lord. (2005) Individuals with good vision in both eyes have the lowest rate of falls, whereas those with good vision in one eye but only moderate or poor vision in the other had elevated falling rates that were equivalent to those of patients with moderate or poor vision in both eyes. It is clear that information from all three sensory systems need to be integrated to control balance.

2.2.2. Muscular control of static balance

During upright quiet stance of normal subjects, the body parts act as one rigid structure without movements and there is very little EMG (electromyographic analysis) activity in the postural muscles (Rothwell, 1994, p. 59). In other words, no conscious activation of muscles by the nervous system is required to maintain balance (Enoka, 1994). Breathing, heart beats as well as any external force (e.g. gravity) disturbs the equilibrium which moves the CoM continuously in anterior-posterior and medio-lateral directions. Movements can be found at the ankle, hips and neck joints during balance which will correct each other to maintain balance. In an inverted pendulum model where the body pivots around the ankle joint, if the CoM is located exactly above the BoS, then the system is perfectly balanced. However, as the CoM rotates forward around the ankle joint, the body will fall over unless it applies a torque at the ankle joint in the opposite direction (Rothwell, 1994, p. 60). These rotations will stretch the gastrocnemius and soleus muscles and produce an opposing torque at the ankle joint whose effect can be measured by having a subject stand on a force platform (Rothwell, 1994, p. 61).

The reflexes do not contribute directly to the recovery of balance (Kejonen, 2002). The first response against falling is an automatic reaction, as seen in EMG signals, which occurs as a medium-latency muscle response. These reactions are coordinated and conveyed through vestibulospinal reflexes and affect all muscles of the legs, trunk and neck (Allum *et al.*, 1988). In addition to the medium-latency responses, long-latency responses have been found to co-occur in the antagonist muscles (Diener *et al.*, 1986). Automatic responses can be thought of as "long-loop" reflexes that rapidly respond to resisting disturbances (Diener *et al.*, 1986). Automatic reactions are context-dependent and adaptable to the specific balance demands. For example, coordination patterns can be changed, depending on the reliability of the support surface and recent experience.

In feedback loops of the sensory system, there is an important phase lag between the controlled variable and controlling variable. This will have an effect on the dynamics of the system. Typical values of this phase lag for the vestibular or joint proprioceptive reactive control are 150-250 milliseconds (Winter *et al.*, 1998).

2.3. Assessing static balance:

Static balance has been commonly assessed by many researches by using the Romberg test, a clinical test with a specific purpose (Era *et al.*, 1996; Bulbulian and Hargan, 2000) which is clinically based on bipedal stance, standing with the feet together (the standard Romberg test). It can be developed to obtain appropriate information of balance capabilities during standing e.g. with eyes open and eyes closed (Bulbulian and Hargan, 2000), on one foot flat or even one foot tiptoes, either barefoot (Giagazoglou *et al.*, 2009) or shod (Goulding *et al.*, 2003; Ramstrand *et al.*, 2010) or both barefoot and shod (De Wit *et al.*, 2000). Additionally, the surface can also be changed by testing an individual on foam (Davis *et al.*, 2009). Comparisons of force platform measures of sway with subject's performance using other clinical balance tests have been reported by measuring the forces needed to maintain upright stance on a force platform. Karlsson and Frykberg. (2000) found that there was generally a significant correlation ($P < 0.01$) between measures of the standard deviation of the horizontal ground reaction force, the standard deviation of the CoP, and the mean velocity of the CoP.

The range of suitable methods commonly depends on the aims of the investigation and the ability of apparatus which is varied, e.g. functional balance scales are easy to use and suitable for daily clinical use though not always accurate enough, while modern laboratory systems with new technologies may provide more detailed information about postural balance but are expensive. Therefore, there is no single assessment technique that could be used as a true indicator of the overall integrity of the balance control system (Winter *et al.*, 1997).

Balanced stance is based on the coordinated movements of body segments and the neuro-musculo-skeletal system with the interaction of internal and external forces. Therefore, standing balance can be measured in the laboratory derived from kinematic motion analysis systems that capture detailed data of body movements (Winter, 1995) (e.g. Vicon motion analysis system). Kinetically, static balance can be measured by platform measurements that record the forces and the moments of forces developed during movements, and electrically, by recording the bioelectrical changes associated with skeletal muscle activity by the EMG (Kejonen, 2002). These systems can be either used separately or synchronized together (Winter, 1995) in balance measurements, depending on the aim of the study.

The duration of postural stability testing is fundamental in all laboratory-based measurements. Typically, in platform measurements, for example, the most frequently used duration is from 20, 30 or 60 seconds. The measuring time should be long enough to provide a relevant result, but short enough to avoid fatigue due to the measurements. For example, Iverson *et al.* (1990) found a clear decrement in balance times in the Romberg test among subjects aged 60 to 90 years due to the earlier onset of fatigue in these elderly subjects.

2.3.1. Areas of investigations:

Numerous studies have investigated balance in interesting areas. Many researchers investigated the difference between the sexes. For example, some investigations have focused on postural balance in only male populations (e.g. Arokoski *et al.*, 2006) while others have focused on female populations (e.g. Harringe *et al.*, 2008; Ramstrand *et al.*, 2010) and some in both males and females (Roland *et al.*, 1995; Lebiedowska *et al.*, 2009). Kinney LaPier *et al.* (1997) found that differences in body heights of men and women contribute to poorer postural stability of men compared to women. In several balance tasks, men exhibited a statistically significant larger range of CoP displacement than the women ($P < 0.01$). However, after normalising the data for height, other researchers found no gender differences were seen (Bryant *et al.*, 2005).

Balance has also been investigated in varied age populations such as children as young as 3years old (Usui *et al.*, 1995; Deitz *et al.*, 1996), adults and elderly as old as 90 years (Bulbulian and Hargan, 2000; Iverson *et al.*, 1990). Varied age populations can also be informative (Lebiedowska *et al.*, 2009). It has been demonstrated that quiet standing postural control of children improves with age hence studies reported that in static balance control 8-year-old children use fewer muscles at lower amplitudes (EMG) when compared to 4-year-old children (Shambes, 1976). Hytönen et al. (1993) quantified the effect of vision and proprioception function on the postural stability at different ages (ages from 6 to 90 years) and reported that the postural stability is optimal around the ages of 30 to 60 years. In adults the cooperation of vision, vestibular, proprioceptive system has become sophisticated thus creating a stable equilibrium whereas at the age under 10 years, the postural control and synergy are not yet developed and therefore children sway more than adults (Hytönen *et al.*, 1993).

In a sport context, many researchers have investigated static balance in sports groups. Bulbulian and Hargan. (2000) examined postural balance of populations of athlete's and non-athletes. It is commonly known that regular exercises would significantly improve balance ability. If physical exercises could be implemented among non-athletes, it would most certainly improve balance and general health. In addition, improved balance ability would decrease the high incidence of falling and subsequent fractures in the growing population of elderly people. Furthermore, Harringe *et al.* (2008) investigated the postural balance of sport professionals' (top-level gymnasts). Sundstrup *et al.* (2010) reported that lifelong football-trained elderly showed superior rapid muscle force characteristics (faster contraction times) and better postural stability compared with untrained age matched individuals, and moreover no deficit could be detected between old individuals engaged in lifelong football training and the group of untrained youngsters.

In a clinical context, numerous researchers have investigated postural balance, Almost by definition clinical research looks at non-healthy individuals e.g. comparing the behaviour of patients with unstable ankles to that of subjects with healthy ankles during sudden inversion (Vaes *et al.*, 2002), and investigating muscle reaction times in patients with Almost by definition clinical research looks at non-healthy individuals e.g. Chronically unstable ankles (Eechaute *et al.*, 2009). Giagazoglou *et al.* (2009) investigated static balance control in blind and sighted women subjects. The effect of additional mass upon balance is also another topic investigated. In pregnancy, postural equilibrium is significantly affected due to weight gained at the third trimester, hence the total weight that is gained is approximately 12 to 16 kg, which represents a 16% to 23% increase in body weight (Butler *et al.*, 2006). Oliveira *et al.* (2009) reported pregnancy induced significant changes in postural control when pregnant women stood with a reduced BoS or with eyes closed, particularly in the anterior-posterior direction. Furthermore, weight and carrying external weight (e.g. carrying school backpack) significantly altered balance control (Talbot, 2005) as did the position of load carriage in healthy young male participants (Abe *et al.*, 2004). Blaszczyk *et al.* (2009) found that obese individuals in static balance have smaller sway of the CoM than non-obese.

Static balance can also be assessed based on measuring a combination of complex mechanical factors (e.g. CoM, CoP, BoS and XCoM) (Maki, 1994; Winter, 1995;

Woollacott and Shumway-Cook, 2002; Hof *et al.*, 2005) in addition to other mechanical variables (e.g. kinetic energy, momentum, impulse and friction torque).

2.3.2. Balance assessment equipment:

Force platforms:

Humans, in almost all terrestrial movements are acted upon by the ground reaction force (GRF) provided by the surface. This surface may vary e.g. concrete, sandy beach, gymnasium floor, or grass lawn surface (Hamill and Knutzen, 2003). All surfaces provide a reaction force equal to the applied force but opposite in direction. Therefore, studying this phenomenon is fundamental to understand most individual movements. Force platforms have been most commonly used in sports biomechanics to measure the GRF and also to quantify body sway (Nashner and McCollum, 1985; Maki, 1994; Blaszczyk *et al.*, 2000). Force platforms are popular because they are simple to use, very accurate (Bartlett, 2002, p. 208), do not interfere with movement, and are not unpleasant for the patient (Roland *et al.*, 1995). They generally consist of piezo-electric sensors mounted at three or four corners of a plate on which the subject stands. The position of the centre of force is calculated from the forces measured by each transducer.

Many researchers have measured postural stability by using force platforms (Maki, 1994; Era *et al.*, 1996 and Blaszczyk *et al.*, 2000). The force components are usually labelled as Fz, vertical (up), Fy, anterior–posterior (forward-backward) and Fx medial–lateral (side-to-side) (Figure 2.3).

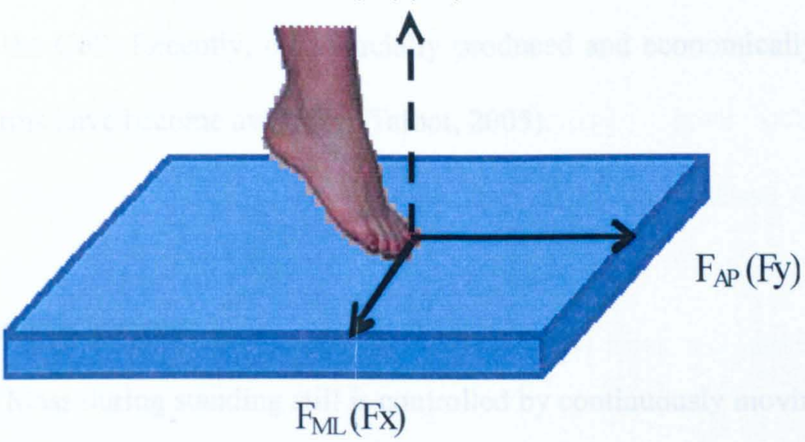


Figure 2.3. The force components, Fz, vertical (F_V, up), Fy, anterior–posterior (F_{AP}, forward-backward) and Fx medial–lateral (F_{ML}, side-to-side). .

According to the standards of the International Society of Biomechanics (ISB) the force components are labelled differently as Fy, vertical (up-down), Fx, anterior–posterior (forward-backward) and Fz medial–lateral (side-to-side). See figure (Figure 2.4).

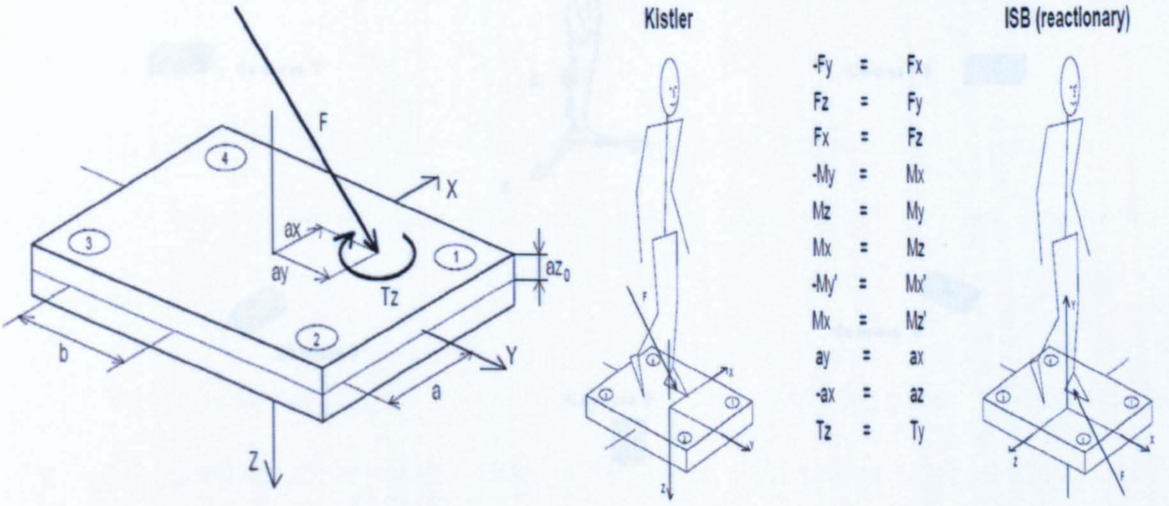


Figure 2.4. Different coordinate system of one force plate, also force component in both Kistler and ISB.

One common procedure to assess balance using a force platform is the calculation of the movement of the CoP. Recently, commercially produced and economically competitive balance platforms have become available (Talbot, 2005).

Kinematic analysis systems:

The Centre of Mass during standing still is controlled by continuously moving. Therefore, computing the CoM has become essential in studying balance as well as in sports biomechanics.

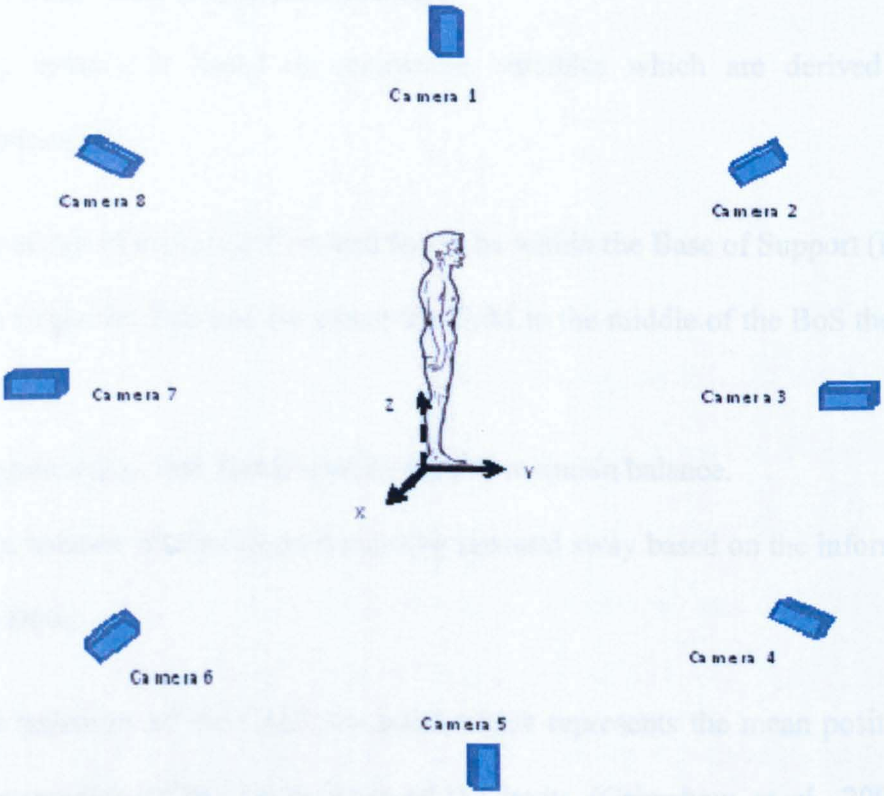


Figure 2.5. 3D Kinematic system (typical optoelectronic camera configuration).

Methods of computing the CoM can be varied. The centre gravity board can easily determine the position of the CoM in static posture. Alternatively, the 3D computation using video digitization of body landmarks can determine CoM position used in the analysis of human movements (Grimshaw *et al.*, 2006, p. 148). The 3D optoelectronic motion analysis systems commonly used in biomechanical laboratories use a series of cameras which project infra-red light onto reflective markers (Figure 3.4). This system provides sophisticated information and tries to reduce the complexity of data collection and speed up the process (Grimshaw *et al.*, 2006, p. 306- 307). It also can be integrated with other apparatuses e.g. force platform, movable platforms and electromyography (EMG) (Colby *et al.*, 2000).

2.3.3. Variables used to quantify balance:

Quantifying balance is based on measuring variables which are derived from the following principles:

i. The center of mass (CoM) which has to be within the Base of Support (BoS).
ii. The larger the BoS and the closer the CoM to the middle of the BoS the better the balance.
iii. Segments (e.g. feet, hands) can be used to maintain balance.

Hence static balance is often characterized by postural sway based on the information that is gathered from:

a) The trajectory of the CoM, the point which represents the mean position for the concentration of the entire mass of the body, (Grimshaw *et al.*, 2006, p. 148) estimated from video-based systems combined with anthropometric information.
b) The Centre of Pressure (CoP) which is defined as the point of application of the ground reaction force under the feet (Winter, 1995)

Both CoM and CoP can be evaluated by the root mean square (RMS) over a specified time period: the CoP trajectory, CoP velocity, range of sway, excursions of sway, the length of the sway path and sway velocity and sway area (Santos *et al.*, 2008). These parameters can be represented in the medio-lateral (ML) and anterior-posterior (AP) directions. The CoP and the CoM are considered equal if the sway velocity is low. Thus, the CoP is frequently used in static balance research because of the ease with which this data can be obtained. Many further variables can be derived from both of the above mentioned variables (CoP and CoM) e.g. the extrapolated Centre of Mass (XCoM), Kinetic Energy (KE), momentum (P) and Friction Torque (Q) which might provide further understanding about static balance. Firstly, The CoM, the BoS and the CoP will be discussed.

Centre of Mass (CoM):

The body's CoM can be considered as the variable controlled in balance (Morasso *et al.*, 1999). The trajectory of the CoM cannot be measured directly but can be estimated using video-based systems combined with anthropometric information based on segmental method of computing the location of the CoM e.g. whole-body gait analysis using retro-reflective markers and a camera system at certain sample rate. The CoM is computed as the centroid of a multi-segments model, a technique commonly used in many studies in biomechanics based on body segments (head, trunk, 3-segment arms, pelvis, and 3-segment legs) (Figure 2.6). (Hamill and Knutzen, 2003, p. 389)

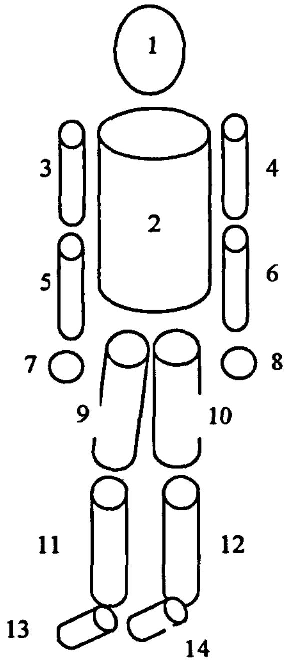


Figure 2.6. An example of 14-Segment model (the Hanavan model).

A video-based system is a time-consuming method to be applied routinely in a clinical setting and requires expensive equipment. An alternative estimation of CoM position can only be achieved when restricting the estimation to the vertically projected CoM. Some studies computed the trajectories of the Centre of Mass based on the calculations of the trajectories of the CoP (Shimba, 1984). Even though this method is reliable (Kingma *et al.*, 1995) it is only applicable in static circumstances as long as the participant is in contact with the force plate. This method is not applicable in testing dynamic balance.

Three approaches have been used to determine the CoM excursion from force-plate data alone. Levine and Mizrahi. (1996) applied a low pass filter to the CoP displacements. Another method is the calculation of the second integral of the acceleration, since the horizontal forces are proportional to the acceleration of the CoM. The difficulty with this method is the estimation of the initial integration constants. Crowe, 1995; Levine and

Mizrahi, 1996; and Zatsiorsky and king, 1998) developed curve-fitting techniques or optimization methods or made some assumptions to successfully solve the double-integration problem. A third consists of using inverse dynamic methods which is based on mechanics equations of motion. Karlsson and Lanshammar (1997) compared the accelerations given by the force plate with those from a kinematic model to study postural movement strategies in the sagittal plane. All these models uniquely provide the horizontal displacements of the vertically projected CoM and were often the results of a planar analysis. The vertical excursions of the CoM were usually considered negligible.

The Base of Support (BoS)

To maintain balance, the CoM must be kept within the BoS. The narrowness of the BoS makes standing upright quite a challenge. It becomes even more challenging when a person stands on a single foot flat or moreover, at some stage when the person stands on tiptoes. Traditionally, the feasible movements which can be made to control balance are described in a single plane related to the horizontal position of the CoM: a person has to confine the projection of the CoM within the BoS in order for the body to remain balanced while standing (Patla *et al.*, 1991). Researchers measure the BoS classically as a fixed area by drawing the outer edges of the feet/ foot (Figure 2.7) or the area of contact between a body and support surface or surfaces (Rothwell, 1994, p. 259).

Figure 2.7. The classical BoS during static balance (two feet flat, eyes open) and during landing in dynamic balance (jumping on tiptoes).

The available BoS has an anterior and posterior limit and a medial/lateral limit which, in standing, correspond to the tips of the toes (anterior), the heels (posterior), and the outer edges of the fifth metatarsal of each foot (medial and lateral) and it can be found by digitization of the footprints (Talbot, 2005). However, Hof *et al.* (2005) described their method of measuring the effective BoS using a foot pressure recording system [Footscan® 3D Balance, (RSscan International, Belgium)] (Figure 2.8) by recording the extreme boundaries of the CoP. The subject stood on one foot and was asked to shift his weight as much as possible laterally, anteriorly, medially and posteriorly and was allowed to lean on a support to maintain balance. In this way the boundary of the BoS is recorded as a loop of the CoP so that the relation between BoS area and foot surface can be seen.

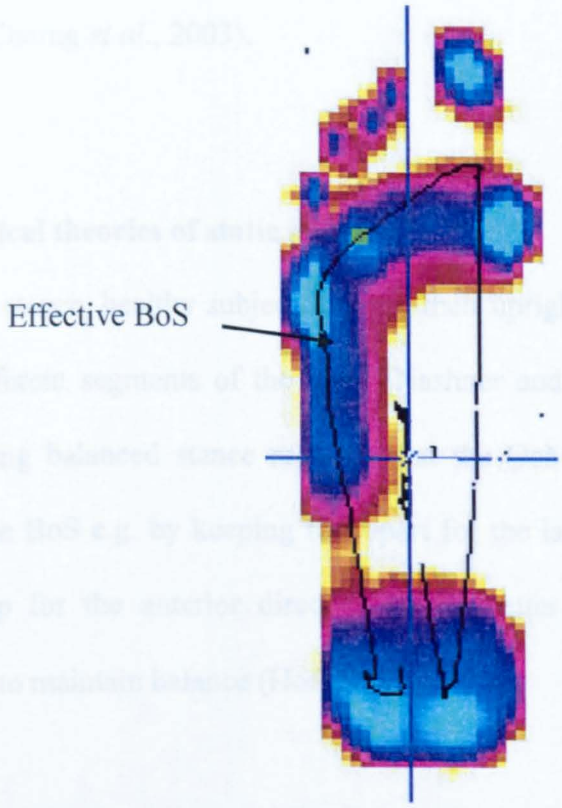


Figure 2.8. The effective BoS while standing on one foot flat is smaller than the outer solid lines representing the classical BoS (Hof *et al.*, 2005).

Centre of Pressure (CoP)

The CoP can be measured using a force platform or a pressure mat. Although researchers have criticised the use of the displacement of the CoP as it merely reflects the response of the neuromuscular system to correct the position of the CoM (Winter, 1995), the CoP is still the most commonly used indicator in clinical tests of sensory interaction on balance, mainly due to the fact that it is easy to measure and analyse (Wrisley and Whitney, 2004). Several balance assessment parameters have been reported using the CoP, focusing on spatial aspects (e.g., average radial displacement) or on spatio-temporal aspects (e.g., path length per second, time to boundary, sway area per second, mean frequency and median frequency) (Cherng *et al.*, 2003).

2.4. Mechanical theories of static balance

During quiet stance, healthy subjects control their upright posture with small movements made by different segments of the body (Nashner and McCollum, 1985). The optimal position during balanced stance requires that the CoM is maintained within the BoS. Increasing the BoS e.g. by keeping feet apart for the lateral direction of body sway and taking a step for the anterior direction, gives better balance. There are three main mechanisms to maintain balance (Hof, 2007):

2.4.1. Mechanism 1: Inverted pendulum theory

The balance of standing humans is usually explained by the inverted pendulum model (Figure 2.9). This model represents the tendency humans have to fall away from their point of support on the ground as a stick or inverted pendulum would do. This model can be used for sagittal plane motion, primarily implying rotation around the ankle joint (plantar-flexion and dorsi-flexion), and in some cases it has been used for the frontal plane motion, primarily implying rotation around the hip joint (abduction and adduction). Figure 2.8 illustrates the inverted pendulum used for static balance when the body is modelled as a single mass m (CoM) balancing on top of a stick with length *l*. Indicated are the CoP (*u*) which is the location of the effective ground reaction force, and the vertical projection of the CoM (*x*), the body mass line (*-mg*) and the vertical ground reaction force (*mg*). The BoS is the area within which the CoP is confined, and roughly equals the area of the foot sole.

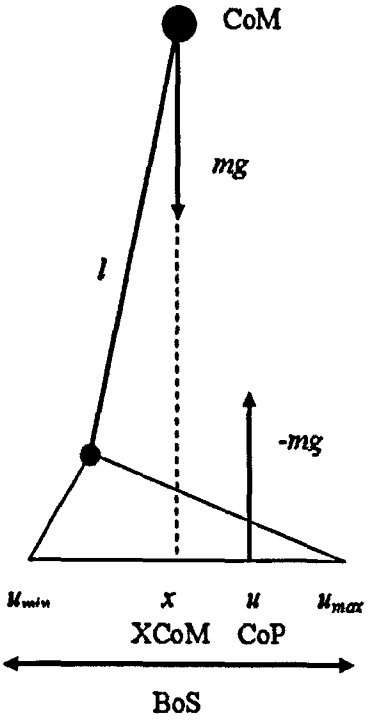


Figure 2.9. Simplified inverted pendulum model for use in static balance (Hof et al., 2005).

People avoid falling by changing the location of the CoP (*u*), i.e. the controlling variable, to correct the position of the CoM (*x*), i.e. the controlled variable (Winter *et al.*, 1998).

The subject moves the CoP under the foot by changing moments of force around the ankle joint, causing the CoP to move in phase with the CoM. Despite its simplicity, the inverted pendulum model has been remarkably successful in many applications (Winter, 1997). This model implies several important assumptions which allow for its simplicity. First, all of the mass of the subject is assumed to be concentrated in one point, that is, the CoM. Second, the height of the CoM is considered constant. Third, the excursion of the CoM over the pendulum is restricted to a small range, such that, within this range the motion of the CoM can be assumed to be horizontal motion. Finally, the ground reaction force (GRF) is the only external force that applies to the body.

2.4.2. Mechanism 2: Counter-rotation of segments

The main situation in which the inverted pendulum model does not apply is when arm or trunk motions are used to aid balance. These motions introduce a shear force (F_h) at the point of the support (Figure 2.10) creating a balance restoring mechanism (Otten, 1999). Therefore, this mechanism is called the counter-rotation mechanism.

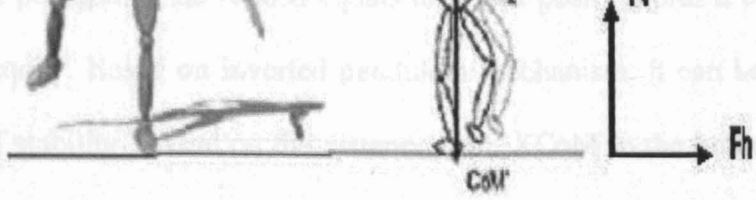


Figure 2.10. The counter-rotation mechanism has a horizontal (Fh) and vertical (Fv) component (Hof, 2007).

During standing, people avoid falling by using fast movements to generate shear forces (F_h) which keeps the CoM within the BoS. Maki and McIlroy (1997) explain the hip strategy in terms of the generation of shear forces at the feet. Such, flexion-extension or adduction-abduction in the hip belong to this mechanism, as well as the arm and leg motions that are seen when balancing on narrow supports (Horak, 1997).

2.4.3. Mechanism 3: External support

The use of an external support can be used to apply an external force for example by leaning against a wall or holding on to a handrail, but also by taking a step (Hof, 2007). These activities have the same purpose, that is, they lead to a change of the BoS within which the subject can keep the CoM.

2.4.4. Advances to the Inverted Pendulum theory: The extrapolated Centre of Mass (XCoM)

The condition for standing balance is usually that the vertical projection of the CoM on the ground should be within the BoS. Hof *et al.* (2005) have recently shown that this condition should be reformulated to take into account not only the CoM position but also its velocity. Hence, the position of the XCoM equals the CoM position plus a correction value related to its velocity. Based on inverted pendulum mechanism, it can be used to determine a 'margin of stability', based on the distance from XCoM to the boundaries of the BoS. In this concept, a greater distance indicates a more stable situation.

Specifically, the $\mathbf{XCoM} = X_0 + \frac{V_0}{\omega_0}$ ... 2.1

where X_0 is the vertical projection of the **CoM**, V_0 is the horizontal velocity of the **CoM** and, ω_0 is the pendulum frequency defined as

$$\omega_0 = \sqrt{\frac{g}{l}} \qquad \text{...2.2}$$

where l is leg length and g is the acceleration due to gravity.

2.4.5. Other mechanical variables used for quantifying balance.

Kinetic Energy (KE):

Energy is defined as the capacity to do work, its unit being joules. Kinetic Energy is a scalar quantity and is the energy of motion. An object which is in motion whether it is vertical or horizontal motion has kinetic energy. There are two forms of kinetic energy:

Linear Kinetic Energy which is based on the linear velocity and the mass of the object and is given by the equation

$$KE_{Lin} = \frac{1}{2} * m * v^2 \qquad \text{... 2.3}$$

Where **m** is the mass and **v** is the magnitude of the linear speed

The second type of Kinetic Energy is the rotational Kinetic Energy which is based on the angular velocity and the moment of inertia of the object and is given by the equation:

$$KE_{rot} = \frac{1}{2} * I * \omega^2 \qquad \text{...2.4}$$

Where **I** is the moment of inertia and **ω** is magnitude of the angular speed

Generally, these equations reveal that the Kinetic Energy of an object is directly proportional to the square of its velocity. The Kinetic Energy is an important mechanical variable to investigate balance, particularly when the body applies a shear force to control velocity, for example when the body decreases its velocity at landing.

Momentum (linear P and angular H):

The key to dynamic stability is the control of the momentum of the CoM. The distribution of body mass is such that two-thirds of mass is in the head, arms, and trunk. Because of the large translational and rotational inertia of the upper body, its position and movement (momentum) can be critical in the overall stability of the upright stance (Winter, 1995). When there is insufficient lower extremity torque generating capacity, the upper body momentum may be used to maintain the stability (Jevsevar *et al.*, 1993; Krebs *et al.*, 1992). There are two forms of momentum: The linear momentum of an object (P) is defined as the product of its mass (m) and linear velocity (v):

$$\mathbf{P} = \mathbf{m} * \mathbf{v} \qquad \text{...2.5}$$

Where **m** is the mass and **v** is the linear velocity

The angular momentum (H) is defined as the product of the object's moment of inertia (I) and its angular velocity (ω):

$$\mathbf{H} = \mathbf{I} * \boldsymbol{\omega} \qquad \text{....2.6}$$

Where **I** is the moment of inertia and **ω** is the angular velocity.

Momentum is a vector quantity.

Impulse (I):

Impulse is defined as "the applied force (F) multiplied by the time (t) of force application" (Grimshaw et al., 2006, p. 81). The impulse either results in the increase of an object's momentum when taking off in jumping or hopping, or a decrease of its momentum when landing from these activities. The linear impulse is related to the changes in linear momentum:

$$\mathbf{F} * \mathbf{t} = \Delta\,(\mathbf{m} * \mathbf{v}) \qquad \ldots 2.7$$

Where **F** is the force, **t** is the time, **m** is the object's mass and **v** is the linear velocity.

The angular impulse is the product of torque (M) and time. Significant changes in the body's angular impulse may result from the action of a large torque over a small time and vice-versa. Since torque is the product of the magnitude of a force and the perpendicular distance of that force to the axis of rotation, both of these factors affect the angular impulse. This is important to keep in mind as the magnitude of a force is measured accurately by the force platform, but the perpendicular distance of the force to the axis of rotation depends on the location of the CoP, which is not as accurately measurable (see later section). This largely prevents this variable from being used in full for balance assessment.

Friction Torque (Q):

As previously noted, quantifying the angular impulse accurately for the whole body is difficult because it requires knowledge of the motion of several body segments to calculate the CoM and accurate measurement of other variables such as the location of the

CoP. However, the angular impulse involves two torque components. The one due to the horizontal friction force applied to the ground can be obtained accurately and is directly related to the counter-rotation mechanism of balance. Hence, calculating the torque (Q) produced by the friction force will provide important information about the force that subjects apply to generate angular impulse of the body (Figure 2.11).

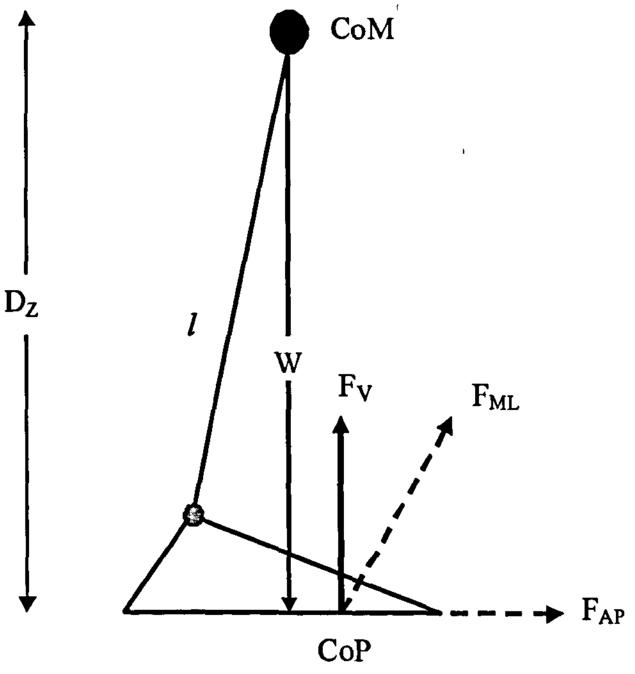


Figure 2.11. Torque due to frictional force is determined by the height of the CoM (Dz) and the horizontal ground reaction force component (F_{ML} and F_{AP}). These components are the most important part of the counter-rotation mechanism to maintain balance.

$$Q = F_{friction} * Dz$$

Where $F_{friction}$ is the friction force which is based on:

$$Q_{ML} = F_{ML(shear\ force)} * Dz \qquad ...2.8$$

$$Q_{ML} = F_{AP\ (shear\ force)} * Dz \qquad ...2.9$$

Where the Medio-lateral force (F_{ML}) is F_x, Anterior-posterior force (F_{AP}) is F_y, and the height of the CoM is Dz.

2.5. Dynamic balance

Dynamic balance is defined as the ability to maintain equilibrium while the body is in motion or changing from one balanced position to another. Also it is defined as "a constant adaptation to forces in order to momentarily attain dynamic equilibrium before adapting and establishing a new equilibrium" (Adrian and Cooper, 1995, p. 22). Like static balance, dynamic balance can also be quantified by measuring the CoM and CoP in both medio-lateral (ML) and anterior-posterior (AP) directions. In addition to these variables many more can be calculated e.g. the extrapolated Centre of Mass (XCoM), Kinetic Energy (KE), momentum (P), time to stabilization (TTS), dynamic postural stability index (DPSI) and Friction Torque (Q) which provide further understanding about dynamic balance.

Conventionally, maintaining balance is described in two dimensional space related to the horizontal position of the CoM, maintaining the projection of the CoM within the BoS in order for the body to remain balanced while standing (Adrian and Cooper, 1995, p. 22; Kuo, 1995). This condition alone, however, is not sufficient to guarantee that standing posture will be sustained. The main difference between the static and dynamic balance is that the CoM travels out of the BoS area and is not anymore within and above it e.g. during walking (Kirtley, 2006, p. 170).

Current studies have considered the horizontal velocity of the CoM in describing the feasible movements for controlling balance (Pai *et al.*, 1992; Hof *et al.*, 2005), as it governs the destiny of the horizontal position of the CoM over the BoS. Standing will not be maintained when a sufficiently large horizontal velocity exists, even though the horizontal CoM is currently located within and over the BoS. On the other hand, even if the CoM is initially located outside the BoS, as in movement termination, upright standing is still achievable (without falling or resorting to taking a step) when a sufficient horizontal CoM velocity is directed toward the BoS (Hof *et al.*, 2005). Therefore, in addition to the position of the CoM with respect to the BoS, the magnitude and the direction (i.e. toward, not away from, the BoS) of its corresponding velocity may also provide critical information pertaining to one's ability to control balance in dynamic situations.

Many studies have investigated static balance while fewer studies have investigated dynamic balance, most of which have focused mainly on gait analysis and rarely dealt with sport activities. Therefore, investigating dynamic balance in sport related activities is important particularly in sport activities such as jumping and hopping.

2.5.1. Variables used for quantifying dynamic balance.

Dynamic Postural Stability Index and Time To Stabilization:

Dynamic measures were developed to overcome the shortcomings of static measures (Reimann *et al.*, 1999). Dynamic tests are varied from 3-20 seconds during jump landings (Wikstrom *et al.*, 2005). A 20 seconds period of time is too long and does not represent sport activities (Wikstrom *et al.*, 2005). Therefore, 10 seconds trial durations are more appropriate to assess the dynamic balance in sport related movements. The dynamic postural stability index (DPSI) can be defined as, an individual's ability to maintain balance while transitioning from a dynamic to a static state (Goldie *et al.*, 1989).

The time to stabilization (TTS) is defined as the time required to minimize resultant ground reaction forces (GRFs) of a jump landing to within a range of the baseline. TTS is an objective postural control measure used in conjunction with a functional jump protocol. TTS has been used to investigative the lower extremity stabilization based on the force measures in various tasks such as forward and medial/lateral drop jumps, and vertical jumps at 50% of maximum height (Colby *et al.*, 1999; Ross, *et al.*, 2005; Wikstrom *et al.*, 2005; Sato *et al.*, 2008).

TTS has been used to evaluate the effects of fatigue. Wikstrom *et al.*, (2004) compared between pre-exercise (baseline) and post-exercise (isokinetic, functional and combined isokinetic and functional fatigue protocols) the vertical time to stabilization (TTS_V), medio-lateral time to stabilization TTS_{ML} and anterior-posterior time to stabilization TTS_{AP}. In TTS_V, there was a significant difference for combined fatigue between baseline, (2201 and 1562 ms respectively) and post-exercise, (2461 and 1350 ms respectively). The other two conditions were not significantly different but there was a trend. This trend was also found in TTS_{ML} and TTS_{AP} measurements. Colby *et al.* (1999) tested TTS during a step down in both healthy subjects and subjects with anterior cruciate ligament (ACL) injury, in healthy subjects (TTS_{AP}, dominant foot = 1419 ms, non-dominant foot = 1877 ms) and for ACL injured subjects (TTS_{AP}, dominant foot = 1998ms, non-dominant foot = 1876 ms). The key finding was that the ACL group needed significantly ($P = <.001$) longer time to stabilize during the step down test, and that TTS is an indication of dynamic balance ability. Sato *et al.* (2008) examined the differences (in TTS) between volleyball players and rugby players in four different hopping tasks (medial, lateral, and two forward hops) onto each foot. They found that the rugby group stabilized more quickly on the right foot, while the volleyball group stabilized more quickly on the left foot in a medial hop task.

2.6. Factors influencing balance

2.6.1. Added weight and balance:

It is known that static equilibrium is positively related to mass of the object (Adrian and Cooper, 1995, p. 22), in other words, the mass of an object affects its stability and the more mass possessed by an object the more force will be required to move or disturb it (Grimshaw *et al.*, 2006, p. 162). Hamill and Knutzen (2003, p. 395) reported that heavier individuals have superior balance; many sports in which stability is critical, take body mass into consideration by dividing the participants into weight divisions. Therefore, in static balance additional carried weight might help people to maintain balance. Blaszczyk *et al.* (2009) found less postural sway in obese subjects and almost all sway indices negatively correlated with body mass. Davis *et al.* (2009) found that obese firefighters had less postural sway, and they compensated posturally when standing on foam by reducing their sway area by 26% as compared to normal weight firefighters. Grimmer *et al.* (2002) revealed that there was a significant relationship between carrying additional weight and posture. Most studies have recommended that 10% or 15% of total body weight load leads to changes in posture mechanisms, and these changes might even occur below these weights (Grimmer *et al.*, 2002). Moreover, the location of the added mass was considered as an important factor that affects the erect posture. Many studies have suggested that the logical choice for the load location would be the closest to the CoM as possible. Grimmer *et al.* (2002) suggested that the location of the adolescent's backpack has to be just at the waist level (CoM location) to minimize postural displacement. This placement would reduce the excess moments about the body's CoM and thus reduce the energy required to carry the load (Johnson, 2000).

Much of the literature, which has dealt with the effects of wearing a backpack on human gait and posture, has focused on children wearing school bags (Talbott, 2005). However, many adult populations either wear a heavy external load such as a backpack or carry extra weight in their torso due to life tasks or obesity. Studies have shown changes in gait because of wearing a heavy backpack in adults (Abe *et al.*, 2004) but few studies have investigated the postural implications. For dynamic conditions, the trunk forward lean increased significantly for the 15% and 20% load conditions compared to the unloaded condition. Furthermore, Qu and Nussbaum. (2009) found that applying external loads (10% or 15% of total body) led to significant changes in several centre of pressure's based measures. Increased mass near the torso may increase the risk of injury due to falling e.g. soldiers, recreational hikers, and even overweight individuals. Carrying additional mass creates many biomechanical and postural challenges for these people (Blaszczyk *et al.*, 2009).

In a clinical context, lightweight individuals generate ankle torque more rapidly and with a much higher rate of torque development to recover balance. Researchers have indicated a potential link between obesity and risk of falling during dynamic circumstances (Wallace *et al.*, 2002). The abdominal circumference, endomorphy and body weight are the most important factors influencing the performance of military recruits on postural tests (Fregly *et al.*, 1968). Moreover, body size and shape influence static postural stability by altering the location of the centre of gravity (Corbeil *et al.*, 2001). It seems logical that the increased antero-posterior sway observed with obesity represents a limitation of the ability to control the inertial properties associated with greater fat mass, rather than an impaired postural control system itself (Hennig *et al.*, 2006). Moreover, an increased postural sway is not usually conclusive evidence for postural instability (Blaszczyk *et al.*, 1994). Gymnasts and professional ballet dancers sway more than control subjects, even though their postural stability control is apparently superior (Blaszczyk *et al.*, 2009). Hence, further investigation of how and why balance control is affected by external loads is necessary, in dynamic activities in particular since most of these studies above have focused on standing posture. One of the main factors influencing balance is the BoS (contact surface) as the larger BoS the more stable the object. Obese people maintain balance by modifying their feet structure (BoS) by increasing the contact area (Matrangola, 2008).

To date, most studies investigating postural control in the obese have employed cross-sectional study designs and have not considered the potentially confounding effects of physical activity. Physical activity status has been shown to have a profound influence on balance performance in adults (Bulbulian and Hargan, 2000), and as such may confuse the effect of obesity on postural control. Goulding *et al.* (2003) reported a significant negative relationship between body weight, body mass index, percentage of fat and total fat mass and a clinical balance score. Obesity modifies body geometry that increases the masses of the different segments, and imposes functional limitations relating to the biomechanics of activities of daily living such as the limitations related to dynamic balance control. This supports the idea that overweight can lead to poorer dynamic balance control in obese people or while carrying additional weight. Given the association between obesity and physical inactivity (Jebb and Moore., 1999), it is unclear whether the additional mass associated with obesity results in reduced postural stability, or the greater adiposity of the obese is the consequence of postural instability and reduced activity (Hennig *et al.*, 2006).

To date few researches have investigated the effect of additional weight on dynamic balance. Moreover, no study has investigated the effect of additional weight on dynamic balance in sport related activities, in particular, jumping and hopping.

2.6.2. Fatigue and balance:

In order to remain in equilibrium, several mechanisms are used by the central nervous system (CNS). Muscular fatigue is commonly associated with physical activities, which the CNS has to take into account (Schieppati *et al.*, 2003). Maintaining balance is mainly the ability to generate forces large enough to maintain stability while performing voluntary movements (Ledin *et al.*, 2004). It has been reported that fatigue causes negative postural control in both elderly and young people as well as in people with neurological disorders (Schieppati *et al.*, 2003). The level of effect depends on the way in which fatigue is induced (Enoka and Stuart., 1992).

Previous studies on the effects of fatigue on postural control showed a significant increase of the CoP sway (Nardone *et al.*, 1997; Winter *et al.*, 1996). It has been demonstrated experimentally that muscle fatigue affects postural control by increasing the static body sway (Nardone *et al.*, 1997; Corbeil *et al.*, 2003; Ledin *et al.*, 2004; Reimer and Wikstrom, 2010). However, the detrimental effect of fatigue on static postural control has been established (Gribble *et al.*, 2004) since fatigue appears to influence dynamic postural control (Gribble *et al.*, 2004). The effects of fatigue on dynamic postural control in sport related movements needs further investigation as little known about how fatigue which is normally induced in sport activities (e.g. jumping and hopping) may influence control of posture. Gribble *et al.* (2004) reported dynamic postural control can be assessed as a moving center of mass controlled while one's BoS is changing.

Since fatigue intensity level in very important, Bizid *et al.* (2009) reported that the duration between the end of the fatiguing task and the initiation of the balance test might not cause disturbed balance. Therefore making a pilot study that determines the proper fatigue intensity protocol is very important as well as assessing the appropriate duration between the end of the fatiguing sessions and the initiation of the balance tests. Wikstrom *et al.* (2004) using healthy subjects failed to observe changes under fatigue conditions. Therefore, examining the effect of intensive localized fatigue may resolve this conflict.

To date few researches have investigated the effect of localized muscle fatigue (lower extremity) on dynamic balance. Moreover, no study has investigated the effect of localized muscle fatigue on dynamic balance in sport related activities, in particular, jumping and hopping.

2.7. Summary

In summary, investigating the characteristics of dynamic balance in sport related activities would appear to be necessary for understanding balance further, by applying the extrapolated Centre of Mass (XCoM) and other relevant variables for evaluating balance in sport activities such as hopping and jumping.

Examining whether the methods developed can reliably characterize dynamic balance characteristics in young adults and collecting baseline data for further studies is warranted. Investigating the effects of changing body mass and the effects of muscular fatigue on the dynamic balance characteristics of young adults would enable the influence of these factors to be clearly established.

Chapter (3) Study 1: Developing the methods for the study of static and dynamic balance

3. Study 1: Developing the methods for the study of static and dynamic balance

3.1. Introduction:

During upright standing, the body sways in the anterior-posterior (AP) and medio-lateral (ML) directions. This sway is characterized by the excursions of the Centre of Pressure (CoP, when using a force platform) and the Centre of Mass (CoM when calculated from motion analysis). In steady standing, both CoP and CoM must be within the Base of Support (BoS) which can be determined dynamically from a pressure mat instead of using a fixed shape which has previously been used.

Other mechanical variables may be related to balance [such as Kinetic Energy (KE), momentum (P), impulse (I) and angular momentum (H)] and these need to be quantified and evaluated in terms of whether they can provide further information about balance. In addition, it is of interest to establish whether the extrapolated Centre of Mass (XCoM) method commonly used for static balance can be extended to evaluate dynamic balance in sport activities such as hopping, and in jumping. Therefore, this study aims to develop methods to evaluate these mechanical variables that are most suited to investigate dynamic balance.

3.1.1. Objectives

1. To develop a suitable methods for studying static and dynamic balance in a sport context;
2. To apply the extrapolated Centre of Mass (XCoM) method to a range of sport activities such as hopping and jumping;

3. To investigate which mechanical variables are most suited to investigate dynamic balance.

3.2. Methods

3.2.1. Participants

The participants in this study were 5 male healthy students at Liverpool John Moores University (Mean ± SD:- age 24.6 years ±4.5, height 177 cm ± 6.3, body mass 72.8 kg ± 6.6). They had no history of problems of postural instability. The main requirement was to perform normal in a set of different balance tests. Each participant signed the consent form that complied with the testing information sheet (Appendix 2). A copy of the consent form was approved by the ethics committee and located in (Appendix 1).

3.2.2. Equipment

The ground reaction force (GRF) during various static and dynamic balance activities was evaluated by using 2 force platforms, the first (Kistler 9281B11, Kistler, Switzerland, dimensions 400 x 600mm) was level with the floor of the laboratory. The participant was required either to stand on this platform during standing tests or to land on it in hopping and jumping tests. The second Kistler force platform (9287B, Kistler, Switzerland, dimensions 600 x 900mm), was 20 cm higher than floor level and positioned next to the built-in platform. It was used for take-off in the hopping and jumping movements. Both force platforms recorded ground reaction forces and CoP at 1000 Hz sampling rate (12 bit A/D conversion). (See Figure 3.1 and Figure 3.4).

Figure 3.1. The force platform (left) and amplifier (right).

The effective BoS was measured by a pressure mat: Dimensions (1 x 0.4 x 0.008 m) with active sensor surface (0.98 x 0.32 m), the number of sensors is 8192, the sensitivity 0.27 - 127 (N/sq.cm) and the maximum sample frequency 500 (Hz). The model used was a Footscan® 3D Balance mat (RSscan International, The Belgium) as shown in Figure 3.2.

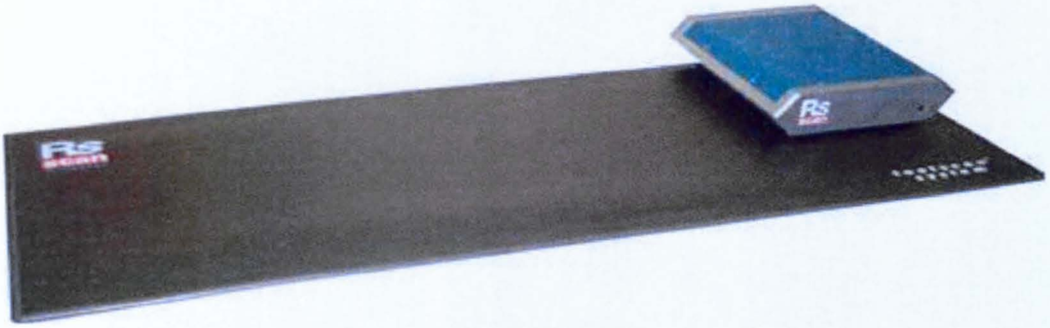


Figure 3.2. The pressure mat used to measure the effective BoS.

Anthropometric measurements were made while the participant stood barefoot with heels 15 cm apart and arms by sides. Foot angle, 15°, was fixed and drawn over the force platform surface that used for standing and landing. Leg length was measured from the sacroiliac joint to the ground level. Elbow, wrist, knee and ankle joints' widths and hand thickness were measured with a calliper. All measurements were made by the same person (the author). Both sides of the extremities were measured in addition to body mass and height.

Whole-body motion analysis was undertaken using 39 (15-mm) retro-reflective markers placed on different anatomical locations (Figure 3.3) of the subject's body. These locations were recorded by a Vicon motion capture system (Figure 3.4) with 8-camera system (Vicon Peak® 512) sampled at 100 Hz. A common, commercially available gait kinematic model was used to compute the CoM (Plug-In-Gait, Vicon Peak®, Oxford, UK). (See Appendix 3)

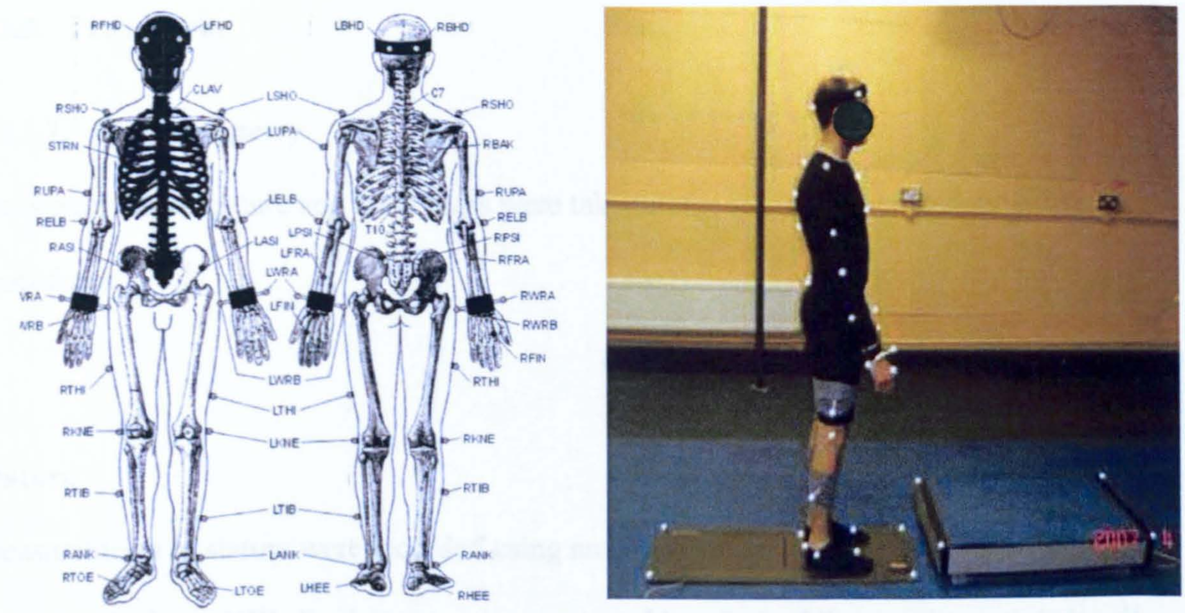
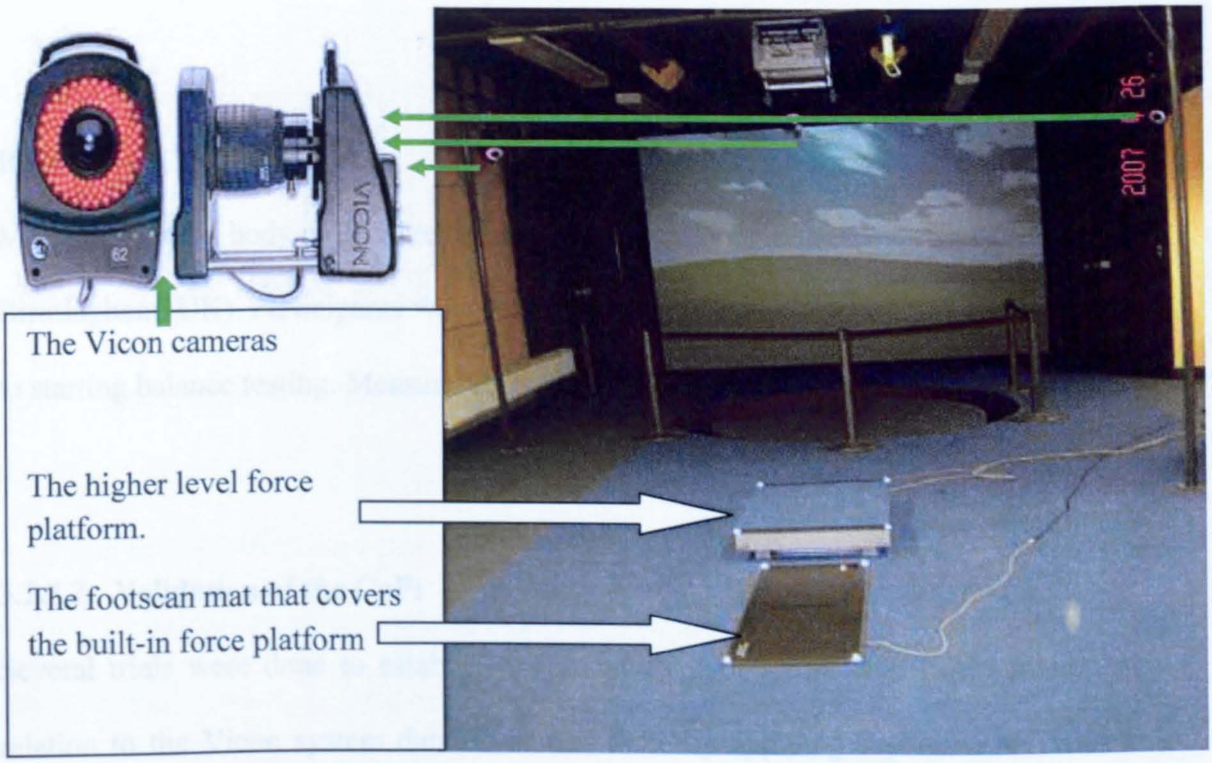


Figure 3.3. The location of markers on the participant's body, following the 39-marker Plug-in-Gait protocol.


The Vicon cameras

The higher level force platform.

The footscan mat that covers the built-in force platform

Figure 3.4. The infrared cameras used to track the markers' locations. In addition, the high and low level force platform, and pressure mat can be seen as part of the set-up.

3.2.3. Procedures

3.2.3.1. Anthropometry

Measurements of stature and body mass were taken in the same manner to standardise procedures:

Stature

Measurements of stature were recorded using analogue Leicester height measure (Seca Ltd., Birmingham, UK). Participants were measured barefoot whilst wearing a stretch suit prior to starting balance testing. Measurements were recorded to the nearest 0.1cm.

Body mass

Measurements of body mass were recorded using analogue Seca scales (Seca Ltd., Birmingham, UK). Participants were measured barefoot whilst wearing a stretch suit prior to starting balance testing. Measurements were recorded to the nearest 0.1kg.

3.2.3.2. Validation of the CoP:

Several trials were done to establish the accuracy of the CoP from force platforms in relation to the Vicon system data. This was done by applying a pointed rod with five reflective markers upon a base which lay on the force platform. The location of the CoP as measured from the GRF was compared with that as calculated from kinematic data of the markers (reconstructing the bottom tip of the rod) through Caltester software (C-Motion, USA). This is shown in Figure 3.5.

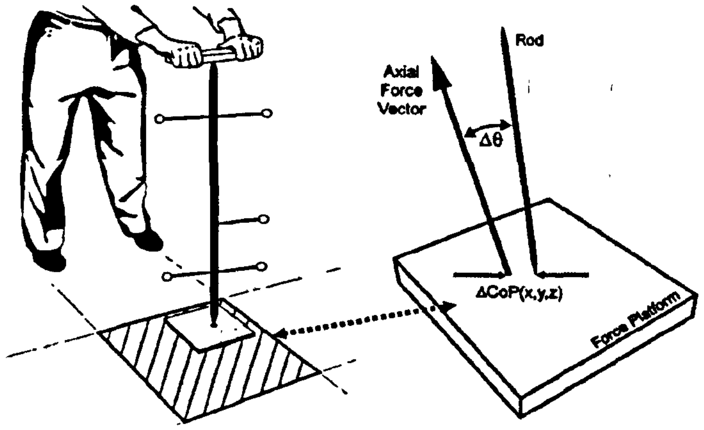


Figure 3.5. Shows the Caltester device (left) and calculated variables: The rod orientations and the bottom tip of the testing rod are calculated from motion capture. The axial force vector (with point of application) is calculated from force measurement.

It was found that there was a consistent but relatively small inaccuracy in the measurement of the CoP. This inaccuracy depended on the amplitude and direction of the horizontal GRF. It was decided that in future studies an algorithm would have to be used to correct for this inaccuracy.

Spatial synchronization of forces and motion capture

An important methodological aspect when applying the inverted pendulum theory is the spatial synchronization between the point of application of forces (CoP) and kinematics (CoM). Figure 3.6 (A and B) shows both in one graph. Although, the time profiles were alike (Figure 3.6A), there was a constant shift of the CoP relative to the CoM. This was found to average 4 mm, and was due to an inaccuracy of the force platform coordinate system in relation to the kinematic coordinate system. Because of the difference between the CoP and the CoM, the absolute CoP location becomes an unreliable variable when used in some calculations, such as the angular impulse variable as previously described. The CoP can be re-trended to best match the CoM data. This is done in Figure 3.6 B.

The correction was made by adding the mean differences between the origins of the CoP and the CoM to the CoP data. This offers a better figure for comparison of the CoP and the CoM in static balance data, whereas in dynamic balance the method of correction was not suitable due to the change of the location of the CoP in addition to the impact magnitude. Consequently, in dynamic balance these variables are represented uncorrected.

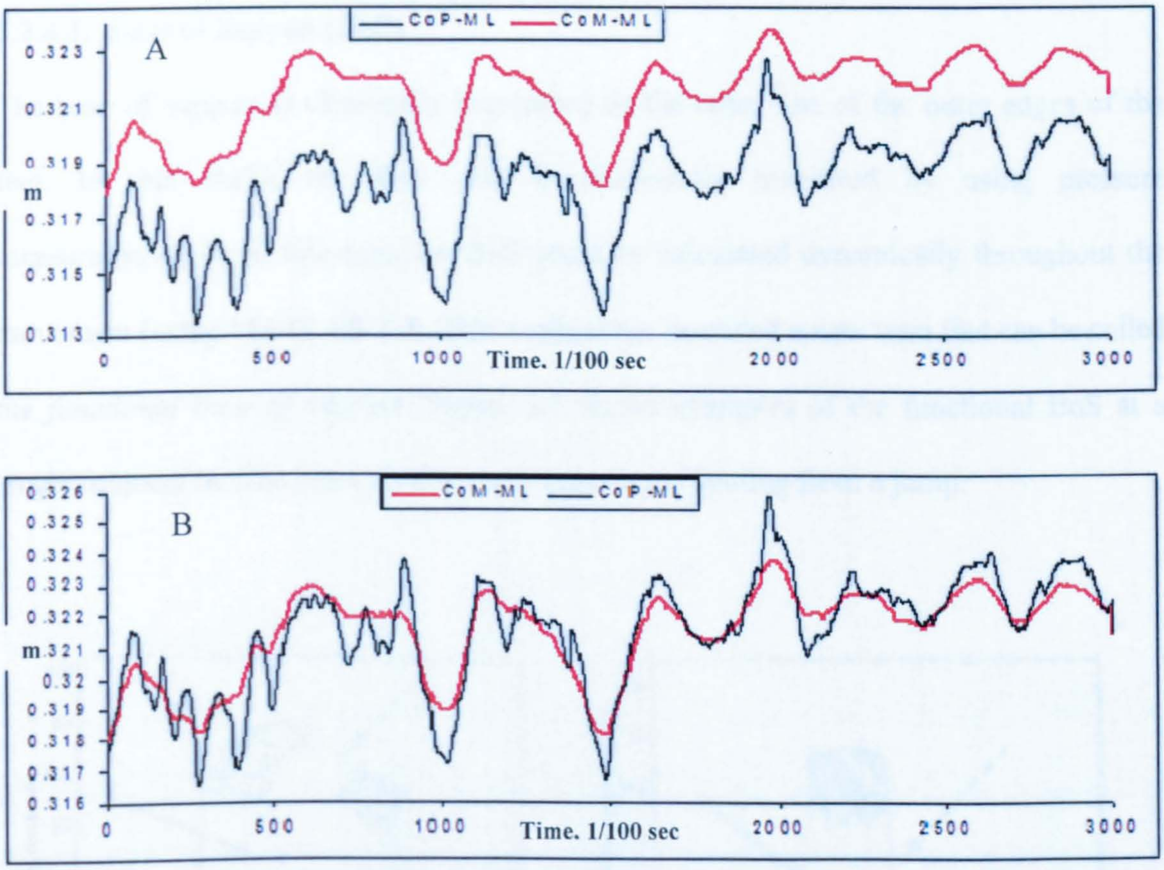


Figure 3.6. A and B) An example (standing, two feet flat, eyes open) of the inaccuracy in spatial synchronization between kinetic and kinematic coordinate systems, shown through systematic shift between CoP and CoM in ML direction (A, top graph). This can be corrected for static balance measurements by re-trending the CoP data (B, bottom graph) (units = m)

3.2.4. Pilot work

A few pilot experiments were undertaken to examine the apparatus's functions such as testing the synchronisation between systems e.g. kinematic system (Vicon), kinetic system (force platforms) and pressure mat (RS scan); establishing the time required for each participant e.g. pre testing (calibration and preparing markers). In addition, data were computed to that from the literature in order to ensure its validation.

3.2.4.1. Base of Support (BoS)

The base of support is classically interpreted as the outer line of the outer edges of the feet. In this study, the BoS was simultaneously measured by using pressure measurements. From this data, the BoS could be calculated dynamically throughout the movement (using MATLAB 7.0). This method has provided a new term that can be called *the functional base of support*. Figure 2.7 shows examples of the functional BoS at a single moment in time from standing and from tiptoe landing from a jump.

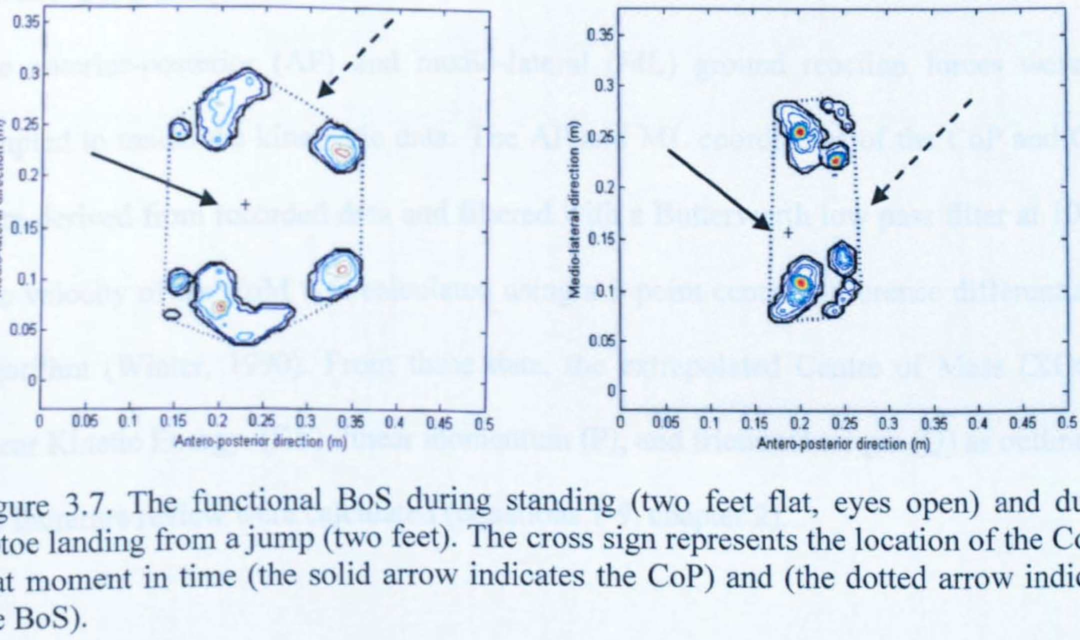


Figure 3.7. The functional BoS during standing (two feet flat, eyes open) and during tiptoe landing from a jump (two feet). The cross sign represents the location of the CoP at that moment in time (the solid arrow indicates the CoP) and (the dotted arrow indicates the BoS).

3.2.4.2. Data collection

Data were recorded over 30s for two feet flat standing test and 10s for two feet tiptoe jumping. Standardized instructions and explanations were given to the participant. The participant was given an opportunity to practice prior to the measurements. The BoS was determined by recording the extreme boundaries of the CoP using the RSscan pressure mat while the subject stood on either two feet flat or two feet tiptoe, and was asked to lean as much as possible laterally, anteriorly, medially and posteriorly. This was done both with and without available support.

The balance variables were evaluated under the following conditions;

i. Static: Romberg test with two feet flat, eyes open.

ii. Dynamic: jumping (two feet, take-off) and landing on tiptoes with eyes open.

A series of 3 trials of each activity were performed.

3.2.4.3. Data analysis:

The anterior-posterior (AP) and medio-lateral (ML) ground reaction forces were re-sampled to match the kinematic data. The AP and ML coordinates of the CoP and CoM were derived from recorded data and filtered with a Butterworth low pass filter at 10 Hz. The velocity of the CoM was calculated using a 3-point central difference differentiation algorithm (Winter, 1990). From these data, the extrapolated Centre of Mass (XCoM), linear Kinetic Energy (KE), linear momentum (P), and frictional torque (Q) as outlined in the literature review were calculated (equations 1-9. chapter 2).

Treating data from the output of analysis systems was complex. Microsoft Excel 2003 was used to process both force plate data (e.g. Forces and CoP) and the CoM data. Microsoft Office Excel 2003 was used to apply a customized routine for filtering raw data, re-sampling the data frequencies of the CoP data (1000 Hz) to match the CoM data (100Hz). A spreadsheet application was written which ran all calculations, plotted graphs, while arranging and re-trending data was done by a macro program.

All parameters of static and dynamic postural balance tests were analysed by Microsoft Excel 2003 software.

Statistical analysis:

For static balance, the mean and RMS values over the three trials were calculated for each subject as well as the grand mean and standard deviation for each condition.

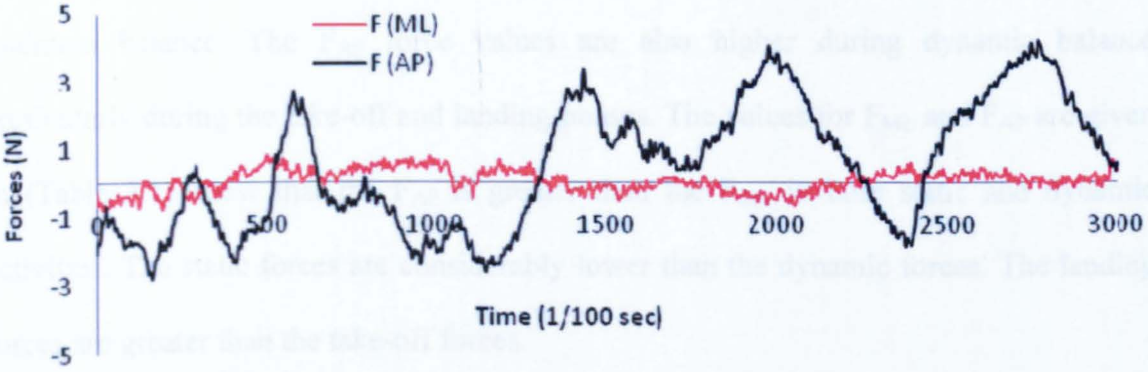
For dynamic balance, the mean of peak horizontal forces (F_{ML} and F_{AP}), Kinetic Energy (KE_{total}, KE_{ML}, KE_{AP}), Momentum (P) and Friction Torque (Q) and the mean of range of the CoM, XCoM and CoP of the three trials were calculated for each subject in both ML and AP directions as well as the grand mean and standard deviation for each condition.

3.3. Results:

3.3.1.1. Ground reaction force (GRF)

Typical graphical displays are given in Figure 3.8 for shear forces in both F_{ML} and F_{AP} directions during static balance (2-feet flat eyes open) and dynamic balance (jumping on tip toes).

- **Static balance**



- **Dynamic balance**

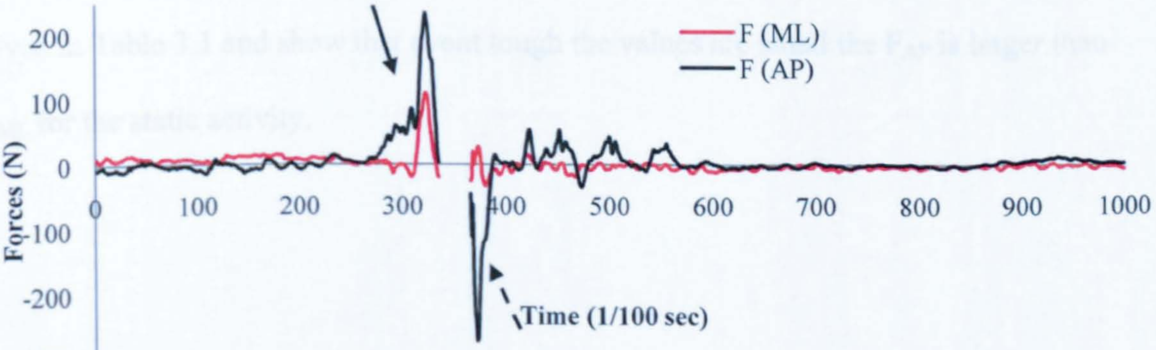


Figure 3.8. Illustrates the F_{ML} and F_{AP} in two conditions: static balance (2-feet flat eyes open) and dynamic balance (Jumping on tip toes). (Units = N)

In static balance, both the medio-lateral (F_{ML}) and anterior-posterior (F_{AP}) forces fluctuate around a constant level (nominally zero). These force values are lower in static balance than in dynamic balance. The F_{ML} and F_{AP} charts are similar for the static balance but are different in profile and in values for the dynamic balance. During take-off (solid arrow) and landing (dotted arrow) stages in this activity the F_{ML} and F_{AP} change their shape. The F_{ML} curve increases during take-off to shift body weight above the preferred take-off foot for landing. After landing, there is a marked oscillation from positive to negative values before settling down, indicating a period of instability. The F_{AP} curve increases as body weight is shifted forward during take-off with a reverse force created during landing to maintain balance. The F_{AP} force values are also higher during dynamic balance particularly during the take-off and landing phases. The values for F_{ML} and F_{AP} are given in (Table 3.1) show that the F_{AP} is greater than the F_{ML} in both static and dynamic activities. The static forces are considerably lower than the dynamic forces. The landing forces are greater than the take-off forces.

In static balance (2-feet flat eyes open), the mean of the RMS values for F_{ML} and F_{AP} are given in Table 3.1 and show that event tough the values are small the F_{AP} is larger than F_{ML} for the static activity.

In dynamic balance test (Jumping on tip toes), the peaks values for F_{ML} and F_{AP} are also given in Table 3.1 and show that the F_{AP} is larger than F_{ML} for in both take-off and landing phases due to the nature of the event (direction of the jump)

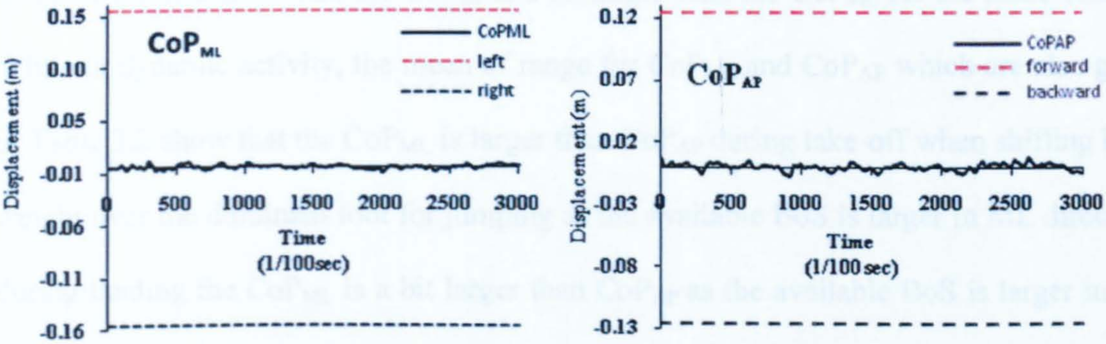
Table 3.1. Mean of RMS of 3 trials (n = 5) of forces in both medio-lateral (ML) and anterior-posterior (AP) directions for static balance (2-feet flat eyes open) and the mean of peaks of F_{ML} and F_{AP} for dynamic balance (Jumping on tip toes). (Units = N)

Subjects	**Static (RMS)**		**Dynamic (peak)**			
	F_{ML} (N)	**F_{AP} (N)**	**Take-off**		**Landing**	
			F_{ML} (N)	**F_{AP} (N)**	**F_{ML} (N)**	**F_{AP} (N)**
Subject 1	0.32	3.121	43.07	175.9	86.66	245.8
Subject 2	0.37	2.970	37.13	178.3	88.03	255.1
Subject 3	0.28	3.020	46.18	181.3	85.83	251.2
Subject 4	0.311	3.050	41.79	176.8	80.87	240.0
Subject 5	0.291	2.885	42.57	175.4	85.63	248.5
Grand Mean	**0.314**	**3.009**	**42.15**	**177.5**	**85.40**	**248.1**
SD	**0.035**	**0.088**	**3.26**	**2.3**	**2.70**	**5.7**

3.3.1.2. Centre of Pressure (CoP)

Typical graphs Figure 3.9 illustrate the Centre of Pressure in both mideo-lateral (CoP_{ML}) and in anterior-posterior (CoP_{AP}) directions during static balance (2 feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes) in relation to the functional BoS (straight dotted lines).

- **Static balance**



- **Dynamic balance**

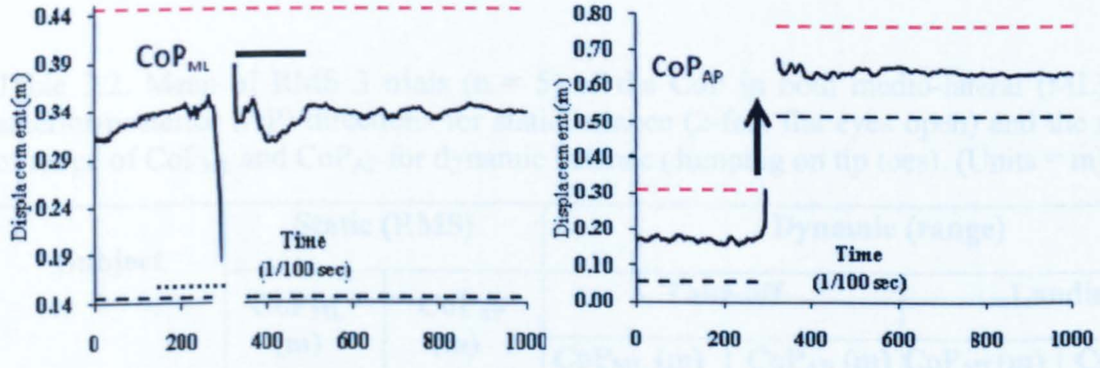


Figure 3.9. Illustrates the variables COP_{ML} and COP_{AP} in both in both static balance (2-feet flat eyes open) and dynamic balance (jumping on tip toes) and the functional BoS (dotted line). (Units= m).

The absolute CoP values depend on where the feet are placed on the force platform. The vertical arrow in the dynamic CoP_{AP} (see figure) represents a shift in feet placement. The range of CoP_{ML} values is lower in static balance than in dynamic balance. The CoP_{ML} and CoP_{AP} ranges are similar for static balance and represent the steady changes of application of force to maintain balance. During take-off and landing stages in dynamic balance the CoP_{ML} and the CoP_{AP} change their shape. The CoP_{ML} curve fluctuates during the take-off due to shifting body weight between feet (dotted line). At landing, the other foot absorbs the impact (solid line) before settling down. The CoP_{AP} curve increases while shifting the body weight forward during take-off and show a reverse in direction during landing to maintain balance. The mean of the RMS values for CoP_{ML} and CoP_{AP} are given in Table 3.2 and show that the CoP_{AP} is a bit larger than the CoP_{ML} for the static activity. While in dynamic activity, the mean of range for CoP_{ML} and CoP_{AP} which are also given in Table 3.2 show that the CoP_{ML} is larger than CoP_{AP} during take-off when shifting body weight over the dominant foot for jumping as the available BoS is larger in ML direction, during landing the CoP_{ML} is a bit larger than CoP_{AP} as the available BoS is larger in ML direction and individual use this obtainable BoS to maintain balance.

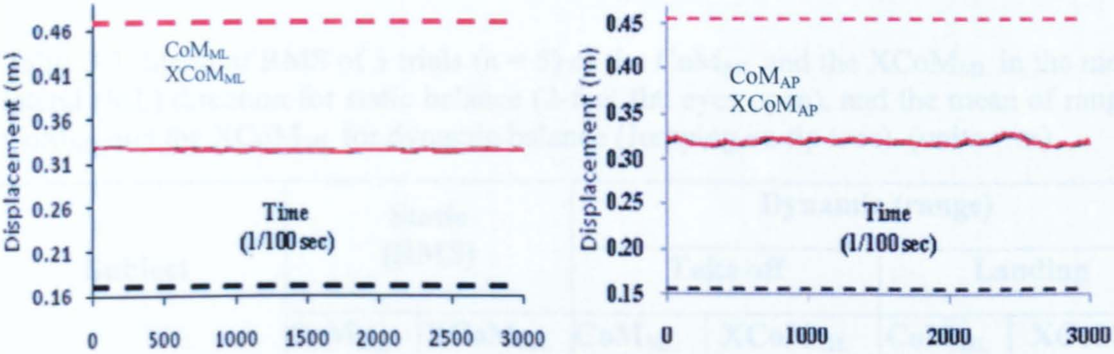
Table 3.2. Mean of RMS 3 trials (n = 5) of the CoP in both medio-lateral (ML) and anterior-posterior (AP) directions for static balance (2-feet flat eyes open) and the mean of range of CoP_{ML} and CoP_{AP} for dynamic balance (Jumping on tip toes). (Units = m)

Subject	**Static (RMS)**		**Dynamic (range)**			
	CoP_{ML} (m)	**CoP_{AP} (m)**	**Take-off**		**Landing**	
			CoP_{ML} (m)	**CoP_{AP} (m)**	**CoP_{ML}(m)**	**CoP_{AP} (m)**
Subject 1	0.008	0.014	0.073	0.169	0.074	0.148
Subject 2	0.010	0.013	0.096	0.199	0.065	0.144
Subject 3	0.009	0.016	0.085	0.124	0.076	0.159
Subject 4	0.011	0.012	0.098	0.128	0.073	0.161
Subject 5	0.012	0.017	0.094	0.099	0.084	0.168
Grand Mean	**0.010**	**0.014**	**0.089**	**0.144**	**0.074**	**0.156**
SD	**0.002**	**0.002**	**0.010**	**0.040**	**0.007**	**0.010**

3.3.1.3. Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM)

Typical graphs Figure 3.10 illustrate the horizontal components of the Centre of Mass in the medio-lateral CoM_{ML} and anterior-posterior CoM_{AP} together with the extrapolated Centre of Mass ($XCoM_{ML}$, $XCoM_{AP}$) respectively during static balance (2 feet flat eyes open) and dynamic balance (jumping on feet flat) in relation to the functional BoS (dotted line).

- Static balance



- Dynamic balance

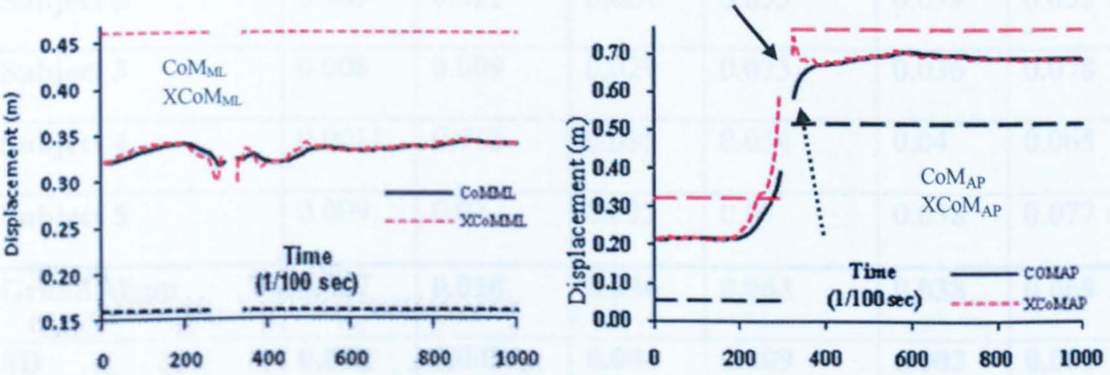


Figure 3.10. Illustrates the variables CoM and the XCoM in both directions: in static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes) and the extreme Base of Support (dotted line). (Units= m).

In static balance, the CoM_{ML} and the $XCoM_{ML}$ are similar in range and are very similar in pattern, although the $XCoM_{ML}$ has a greater excursion at peaks and troughs of movements. In dynamic balance, this excursion is amplified particularly for fast movements (indicated by arrows particularly during take-off (AP) and landing (ML). The CoM and the XCoM values are higher in dynamic balance as balanced is being maintained and movement velocity increases. In static balance, the grand mean of RMS values for CoM_{ML} and XCoM_{ML} are given in (Table 3.3) and show that the XCoM_{ML} is a bit larger than the CoM_{ML} for the static activity and obviously both the CoM and XCoM trajectory is considerably lower than the dynamic CoM and the XCoM trajectories.

Table 3.3. Mean of RMS of 3 trials (n = 5) of the CoM_{ML} and the XCoM_{ML} in the medio-lateral (ML) direction for static balance (2-feet flat eyes open), and the mean of range of CoM_{ML} and the XCoM_{ML} for dynamic balance (Jumping on tip toes). (units = m)

Subject	**Static (RMS)**		**Dynamic (range)**			
			Take off		**Landing**	
	CoM_{ML}	**XCoM_{ML}**	**CoM_{ML}**	**XCoM_{ML}**	**CoM_{ML}**	**XCoM_{ML}**
Subject 1	0.007	0.008	0.03	0.062	0.037	0.067
Subject 2	0.009	0.011	0.024	0.055	0.039	0.059
Subject 3	0.008	0.009	0.029	0.073	0.036	0.078
Subject 4	0.0011	0.012	0.035	0.054	0.04	0.065
Subject 5	0.009	0.01	0.032	0.07	0.038	0.077
Grand Mean	**0.007**	**0.010**	**0.030**	**0.063**	**0.038**	**0.069**
SD	**0.003**	**0.002**	**0.004**	**0.009**	**0.002**	**0.008**

In dynamic balance, the XCoM_{ML} is much greater than the CoM_{ML} during both take-off and landing phases due to the accelerated CoM in take-off and CoM in landing; also the landing CoM trajectories are greater than the take-off. The mean of range for CoM_{ML} and XCoM_{ML} which are also given in (Table 3.3) show that the XCoM_{ML} is larger than

CoM_{ML} during take-off when shifting body weight over the dominant foot for jumping as the available BoS is larger in ML direction, and also during landing the $XCoM_{ML}$ is also larger than CoM_{ML} as it travels on available BoS in ML direction which individual use this obtainable BoS to maintain balance. During landing, the values of mean of range are larger than take-off values as the landing trajectories excurse larger. The mean of range for CoM_{AP} and $XCoM_{AP}$ which are also given in (Table 3.4) show that the $XCoM_{AP}$ is larger than CoM_{AP} during take-off when shifting body weight over the dominant foot for jumping as the available BoS is larger in ML direction, the $XCoM_{AP}$ is also larger than CoM_{AP} nearly reaches the available BoS in AP direction that individual use for maintaining balance.

Table 3.4 Mean of RMS of 3 trials (n = 5) of the CoM_{AP} and the $XCoM_{AP}$ in the anterior-posterior (AP) direction for static balance (2-feet flat eyes open), and the mean of range of CoM_{AP} and the $XCoM_{AP}$ for dynamic balance (Jumping on tip toes). (Units = m)

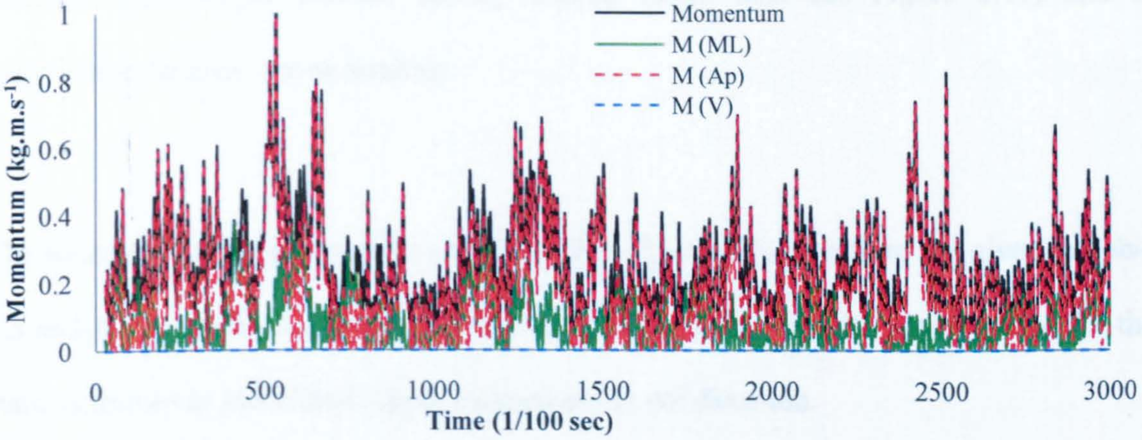
Subject	**Static (RMS)**		**Dynamic (range)**			
			Take off		**Landing**	
	CoM_{AP}	**$XCoM_{AP}$**	**CoM_{AP}**	**$XCoM_{AP}$**	**CoM_{AP}**	**$XCoM_{AP}$**
Subject 1	0.008	0.012	0.257	0.524	0.163	0.196
Subject 2	0.009	0.014	0.28	0.55	0.155	0.179
Subject 3	0.0011	0.015	0.273	0.6	0.148	0.158
Subject 4	0.01	0.016	0.303	0.61	0.137	0.167
Subject 5	0.012	0.017	0.263	0.594	0.146	0.167
Grand Mean	**0.008**	**0.015**	**0.275**	**0.576**	**0.150**	**0.173**
SD	**0.004**	**0.002**	**0.018**	**0.037**	**0.010**	**0.015**

*note: the landing locations are varied from take-off.

3.3.1.4. Momentum (P)

Typical graphs Figure 3.11 illustrate the total momentum P and its components P_{ML} and P_{AP} in both directions during static balance (standing 2 feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes).

- Static balance



- Dynamic balance

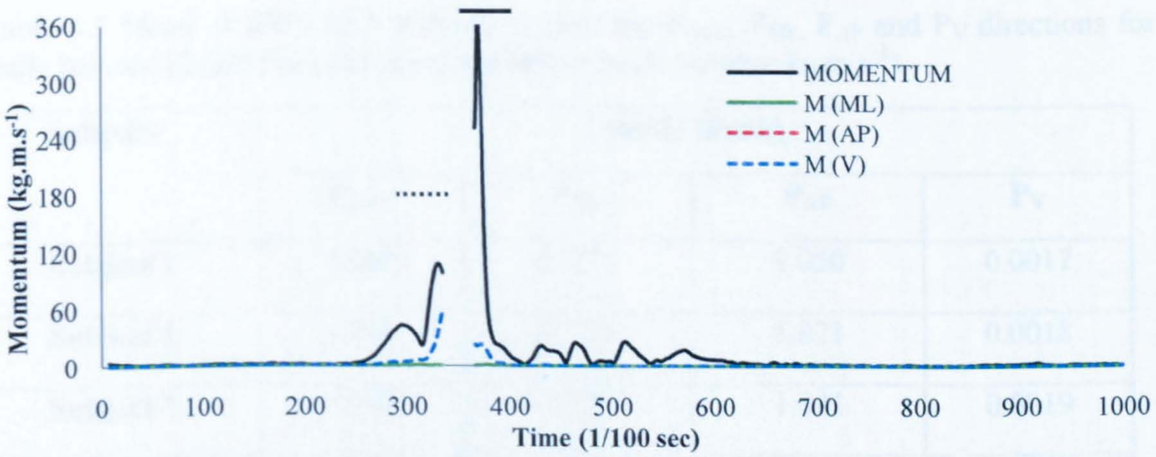


Figure 3.11. Illustrates the P_{total} and the P_{ML-AP} in both static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes). (Units= $kg.m.s^{-1}$).

In static balance, the subject has a low velocity and so the total momentum is low. These values increase during the dynamic balance particularly during take-off and landing phases. In dynamic balance the P_{total} is high due to the subject needs for a high velocity during take-off. The P_{AP} is much higher than the P_{ML} because subject's velocity in anterior-posterior direction is greater than in medio-lateral direction. The P_{ML} curve increases during the take-off when subjects accelerate their CoM_{ML} to shift body weight above the preferred take-off foot (dotted line, see Figure 3.11) and at landing when absorbing the impact before settling to a steady value. The P_{AP} curve increases while shifting body weight forward during landing (solid line, see Figure 3.11) and in maintaining balance during landing.

The mean of RMS of peaks values for P_{Total}, P_{ML}, P_{AP} and P_V directions are given in Table 3.5 and show that the P_{total} is greater than the P_{ML} and P_V and nearly equals the P_{AP} for the static activities as individuals apply momentum in AP direction.

Table 3.5 Mean of RMS of 3 trials (n = 5) of the P_{Total}, P_{ML}, P_{AP} and P_V directions for static balance (2-feet flat eyes open) variable = peak. (Units= kg.m.s^{-1}).

Subjects	**Static (Peak)**			
	P_{Total}	P_{ML}	P_{AP}	P_V
Subject 1	1.068	0.377	1.050	0.0017
Subject 2	1.066	0.399	1.021	0.0018
Subject 3	1.068	0.370	1.041	0.0019
Subject 4	1.068	0.360	1.039	0.0020
Subject 5	1.069	0.380	1.061	0.0023
Grand Mean	**1.068**	**0.377**	**1.043**	**0.0019**
SD	**0.001**	**0.014**	**0.015**	**0.0002**

The mean of range of peaks values for P_{Total}, P_{ML} P_{AP} and P_V for the dynamic balance are given in Table 3.6 show that. The landing momentum values are larger than the take-off; in take-off phase, the P_{total} is greater than the P_{ML} and the P_{AP} and P_V are nearly equals to the P_{total} for the take-off phase as individuals apply large momentum in AP direction and in V direction due to the nature of event (jumping from higher force platform). In landing phase, the P_{total} is greater than the P_{ML} and the P_{AP} though it is higher than P_{ML}, while the P_V are nearly equals to the P_{total} as individuals apply large momentum in V direction due to the nature of event (jumping from higher force platform).

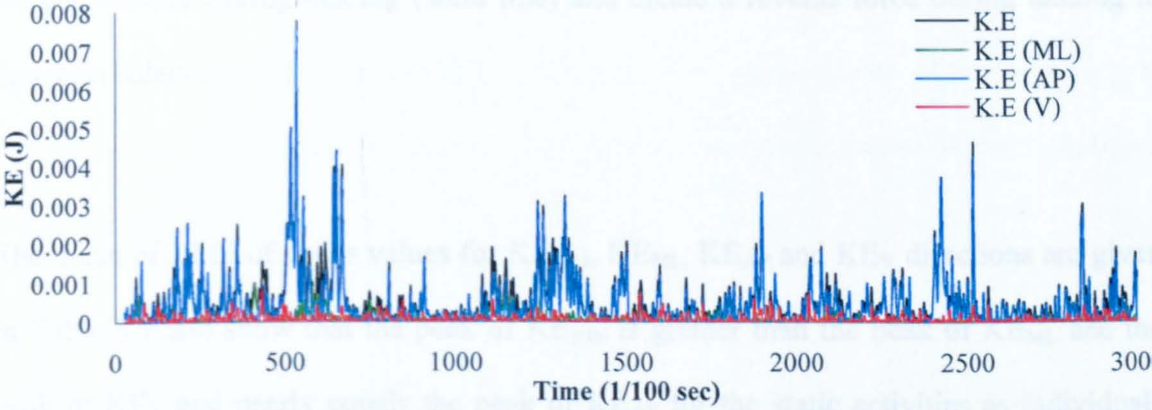
Table 3.6.Mean of range of peaks of 3 trials (n = 5) of the of the P_{Total}, P_{ML} P_{AP} and P_V directions for dynamic balance (Jumping on tip toes) variable = peak. (Units= $kg.m.s^{-1}$).

Subjects	**Dynamic (Peak)**							
	Take-off				**Landing**			
	P_{Total}	**P_{ML}**	**P_{AP}**	**P_V**	**P_{Total}**	**P_{ML}**	**P_{AP}**	**P_V**
Subject 1	79.08	0.323	29.41	55.71	368.1	0.959	22.27	290.9
Subject 2	81.77	0.381	27.85	56.90	378.5	0.939	25.22	298.7
Subject 3	81.08	0.352	26.01	54.09	367.1	1.019	24.91	295.2
Subject 4	78.21	0.342	28.50	59.29	363.5	0.993	24.73	301.6
Subject 5	81.42	0.374	27.44	58.88	373.1	1.039	23.99	299.3
Grand Mean	**80.31**	**0.353**	**27.84**	**56.97**	**370.1**	**0.990**	**24.23**	**297.2**
SD	**1.573**	**0.033**	**1.264**	**2.175**	**5.853**	**0.041**	**1.183**	**4.176**

3.3.1.5. Kinetic Energy (KE)

Typical graphs Figure 3.12 illustrate the KE_{total} and its components the KE_{ML} and the KE_{AP} in both directions during static balance (standing 2 feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes).

- Static balance



- Dynamic balance

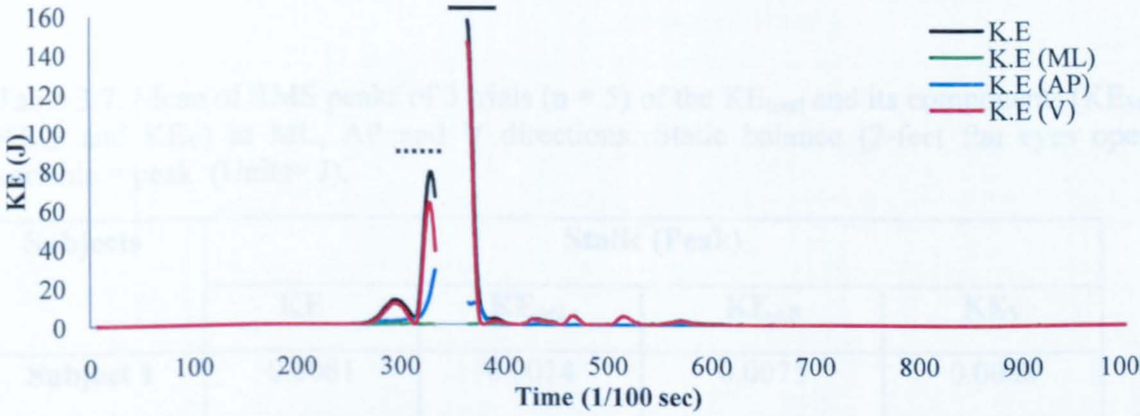


Figure 3.12. Illustrates the KE_{total}, KE_{ML} and KE_{AP} in both static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes). (Units= J).

In static balance, the velocity of the Centre of Mass in the medio-lateral and the anterior-posterior are effectively very small and so values for the KE_{total} and for the KE_{ML} and the KE_{AP} are also small and represent the state of stability in this condition. In dynamic balance the KE_{total} is higher due to the subject's velocity particularly in KE_{AP} because the subject's velocity is higher in the anterior-posterior direction, particularly during take-off and landing phases. The KE_{ML} curve increases during the take-off when subjects accelerate their Centre of Mass in medio-lateral direction while shifting their body weight between feet (dotted line) and at the landing phase when absorbing the impact before settling to a steady value. The KE_{AP} fluctuation increase when subjects shift their body weight forward during landing (solid line) and create a reverse force during landing to maintain balance.

The mean of RMS of peaks values for KE_{total}, KE_{ML}, KE_{AP} and KE_V directions are given in Table 3.7 and show that the peak of KE_{total} is greater than the peak of KE_{ML} and the peak of KE_V and nearly equals the peak of KE_{AP} for the static activities as individuals apply momentum in AP direction

Table 3.7. Mean of RMS peaks of 3 trials (n = 5) of the KE_{total} and its components (KE_{ML}, KE_{AP} and KE_V) in ML, AP and V directions. Static balance (2-feet flat eyes open) variable = peak. (Units= J).

Subjects	**Static (Peak)**			
	KE	KE_{ML}	KE_{AP}	KE_V
Subject 1	0.0081	0.0014	0.0075	0.0008
Subject 2	0.0079	0.0016	0.0080	0.0007
Subject 3	0.0078	0.0012	0.0077	0.0008
Subject 4	0.0077	0.0010	0.0079	0.0009
Subject 5	0.0078	0.0011	0.0078	0.0008
Grand Mean	**0.0078**	**0.0011**	**0.0078**	**0.0008**
SD	$\mathbf{0.098 \times 10^{-3}}$	$\mathbf{0.085 \times 10^{-3}}$	$\mathbf{0.179 \times 10^{-3}}$	$\mathbf{0.051 \times 10^{-3}}$

The mean of range of peaks values for KE_{Total}, KE_{ML} KE_{AP} and KE_{V} for the dynamic balance are given in Table 3.8 show that. The landing Kinetic Energy values are larger than the take-off; in take-off phase, the KEtotal is greater than the KE_{ML}, and the KE_{AP} and KE_{V} are nearly equals to the Ptotal for the take-off phase as individuals apply large Kinetic Energy in AP direction and in V directions due to the nature of event (jumping from higher force platform). In landing phase, the KEtotal is greater than the KE_{ML} and the KE_{AP} though it is higher than KE_{ML}, while the KE_{V} are nearly equals to the KE_{total} as individuals apply large Kinetic Energy in V direction due to the nature of event (jumping from higher force platform)

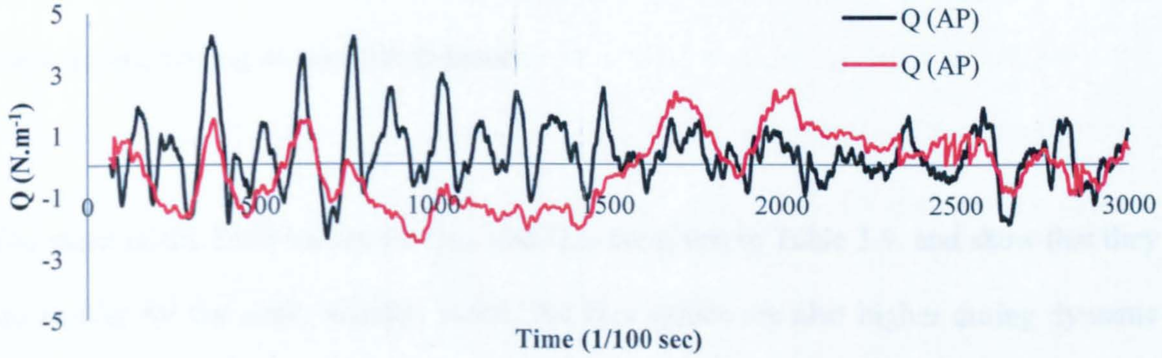
Table 3.8. Mean of range of peaks of 3 trials (n = 5) of the KE_{total} and its components (KE_{ML}, KE_{AP} and KE_{V}) in ML, AP and V directions. Dynamic balance (Jumping on tip toes). (Units= J).

Subjects	**Dynamic (Peak)**							
	Take-off				**Landing**			
	KE	**KE_{ML}**	**KE_{AP}**	**KE_{V}**	**KE**	**KE_{ML}**	**KE_{AP}**	**KE_{V}**
Subject 1	79.08	0.32	29.41	63.25	156.6	0.496	12.14	148.5
Subject 2	81.77	0.38	27.85	62.28	157.9	0.563	11.14	145.7
Subject 3	81.08	0.35	26.01	65.25	157.4	0.470	11.62	151.2
Subject 4	78.21	0.34	28.50	64.28	161.6	0.481	12.70	155.5
Subject 5	81.42	0.37	27.44	67.00	161.5	0.566	11.99	115.5
Grand Mean	**80.31**	**0.35**	**27.84**	**64.41**	**159.0**	**0.515**	**11.92**	**143.3**
SD	**1.57**	**0.03**	**1.26**	**1.82**	**2.4**	**0.046**	**0.58**	**16.0**

3.3.1.6. The Friction Torque (Q)

Typical graphs Figure 3.13 illustrate the Friction Torque Q_{ML} and the Q_{AP} directions during static balance (standing 2 feet flat eyes open) and dynamic balance (jumping tip toes).

- Static balance



- Dynamic balance

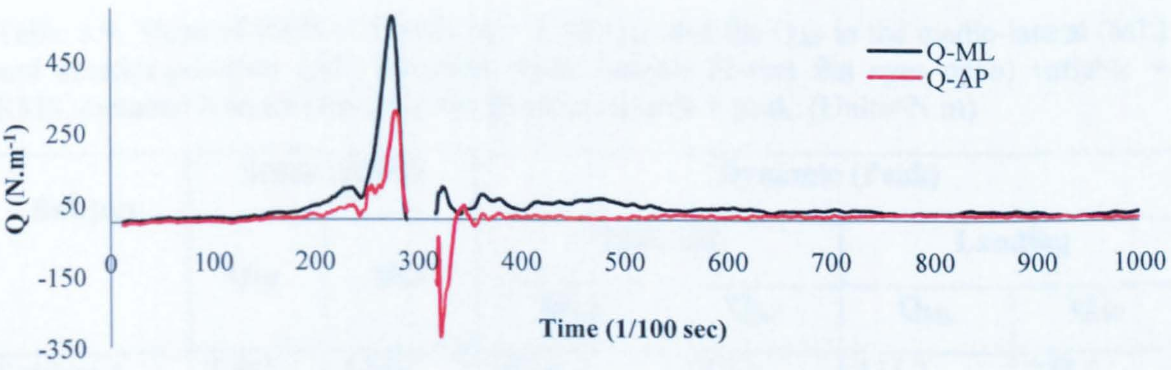


Figure 3.13. Illustrates the Q_{ML} and Q_{AP} in both static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes) (Units=N.m)

In static balance, the velocity of the Centre of Mass in the medio-lateral and the anterior-posterior is very small. These represent the state of stability in this condition (2-feet flat eyes open) and indicate that an ankle strategy is used. In dynamic balance, Q_{AP} is higher due to the subject's velocity particularly in the anterior-posterior direction, when the subject applies horizontal forces during dynamic balance during the take-off and landing phases. The Q_{ML} curve increases during the take-off when subjects accelerate their CoM_{ML} to shift body weight between their feet (dotted line) and at the landing phase when absorbing the impact before settling to a steady value. The Q_{AP} curve increases when shifting body weight forward during take-off (solid line) and creating a reverse force during landing to maintain balance.

The mean of the RMS values for Q_{ML} and Q_{AP} are given in Table 3.9. and show that they are similar for the static activity, while, the Q_{AP} values are also higher during dynamic balance particularly during the take-off and landing phases. The range of peaks values for Q_{ML} and Q_{AP} are given in (Table 3.9.) show that they are similar during take-off phase while Q_{AP} is greater than the Q_{ML} during landing.

Table 3.9. Mean of RMS of 3 trials (n = 5) of Q_{ML} and the Q_{AP} in the medio-lateral (ML) and anterior-posterior (AP) direction Static balance (2-feet flat eyes open) variable = RMS, dynamic balance (Jumping on tip toes) variable = peak. (Units=N.m)

Subject	**Static (RMS)**		**Dynamic (Peak)**			
			Take-off		**Landing**	
	Q_{ML}	**Q_{AP}**	**Q_{ML}**	**Q_{AP}**	**Q_{ML}**	**Q_{AP}**
Subject 1	2.485	2.169	187.6	189.5	135.2	273.1
Subject 2	2.316	1.988	185.1	192.3	136.0	295.7
Subject 3	2.375	2.124	181.1	181.7	137.9	284.5
Subject 4	2.416	2.028	190.1	190.1	135.9	297.8
Subject 5	2.316	1.985	188.3	189.7	139.5	293.6
Grand Mean	**2.382**	**2.059**	**186.4**	**188.6**	**136.9**	**288.9**
SD	**0.072**	**0.083**	**3.456**	**4.044**	**0.512**	**10.221**

3.4. Discussion:

The first objective of the study was to develop the methodology for studying balance; there are several methodological issues that were addressed. The subjects were five healthy adult students at Liverpool John Moores University. For the purpose of this study, the type of subject was not the most critical point. In previous studies concerning the methodological aspects of balance measurements with motion analysis, the number used have commonly been similar to that used in this study (e.g. Moraes and Patla, 2005 n = 8, Aramaki *et al.*, 2001; n =6, Latash *et al.*, 2003; n = 10). Small subject numbers are appropriate for this methodological study in order to get a balance between data from a variety of subject and processing time.

Technically, all the measurements went well, despite some problems (e.g. disappearing markers) during landing from jumping when the subject hits the ground. Fast reviews of the data were done to see every single marker, whether it was still attached or had fallen from its location. In addition, extra trials were recorded for each condition which allowed the best to be chosen for analysis.

In this study a systematic shift of the CoP signals from the original location was found in both the medio-lateral (ML) and the anterior-posterior (AP) directions. Several Caltester experiments were done to improve the accuracy of the CoP. Eventually; it was shown that the CoP did not accurately represent the point of application of force (e.g. Figure 3.6 A and Figure 3.6 B) relative to the CoM where the average difference was up to 4mm. Whether the CoP or the CoM was inaccurate was not possible to evaluate within the scope of this study. However, correcting for these differences was possible in static balance. The same method of correction was not applicable to dynamic balance because of change in position of the feet. The consequences of this were that the CoP remains a useful variable when used alone, but it cannot be easily included into other calculations (e.g. angular impulse).

Estimation of the CoM of the multi-segment human body requires kinematic measurement of all body segment displacements and an anthropometric model of the body (Winter, 1990). The trajectory of the CoM is estimated using a video-based system combined with anthropometric information and a multi-segment human body method for calculating the CoM. Individual body segments can be different depending on individual subject's anthropometric information. The CoM was calculated using a commercially available method (Plug-in Gait marker set, Vicon, UK). Consequently, this method would be expected to produce some error in the location of the CoM as it does not reflect individual differences. This way have let to the above mentioned difference between the CoP and CoM, but nevertheless, the CoP and the CoM move in harmony tracking each other (fig 3.6 B). The CoM velocity was considered more important than its exact location for calculating the following variables: The extrapolated Centre of Mass (XCoM), the momentum (P) and the Kinetic Energy (KE) which are assumed to be indicators for assessing balance all of which use the velocity. This is important as most studies pay no attention to these variables.

The second objective of the study was to apply the (XCoM) method used by Hof *et al.* (2005) on static balance to dynamic balance. This implementation was found to be practical for evaluating both static and dynamic balance and provided the expected results: in static balance, the XCoM was within the BoS when the subject maintained balance, while in dynamic balance, it came close to or exceeded the BoS during take-off and landing stages which represented the imbalance status at these stages. The level of destabilisation gradually increased when the BoS decreased. In other words, the XCoM and the CoM are identical during steady standing while the XCoM diverges from the CoM at take-off and landing.

The third objective of the study was to investigate other mechanical variables suitable for the study of dynamic balance in addition to the CoP, the CoM and the XCoM. These mechanical variables were: The momentum (P) and its components (ML and AP), the Kinetic Energy (KE) and its components (ML and AP) and Friction Torque (Q) and its components (ML and AP) and were found to offer suitable variables for interpreting mechanisms while attempting to maintain balance, whereas the angular impulse was not considered suitable due the shift issue mentioned previously consequently this uses not evaluated. The Friction Torque (torque produced by the friction forces) provides important information about the horizontal force that subjects apply for controlling the angular impulse of the CoM, which is strongly related to the second balance mechanism noted in the literature review.

Although calculating the KE and P was achieved, the results showed that the KE and P are alike. Also, these variables were demonstrated by the vertical component. Because this leads to further calculation, calculating these variables was not thought to be important for future studies.

3.5. Conclusion:

The results indicate that the motion analysis system, force platform and the pressure mat can be synchronised for collecting data in static and dynamic balance.

- The CoP, the CoM, the XCoM and Q are more informative than the other variables (e.g. KE, and P) during static and dynamic balance providing additional information about the postural control mechanisms.
- The XCoM method was found to be applicable to dynamic balance as well as static balance.
- The functional BoS may be measured synchronously with other variables by using the RSscan mat over the force platform.
- The friction force (Q) seems to be a good indicator for assessing dynamic balance, though it is susceptible to systematic errors in forces which are particularly important for static balance.

Chapter (4) Study 2: Evaluating the baseline characteristics of static and dynamic balance in young adults

4. Study2: Evaluating the baseline characteristics of static and dynamic balance in young adults

4.1. Introduction:

Quiet standing is widely considered by many researchers as a (static) task, an event involving no activity. In reality, the upright posture is a continuum of adjustments (correctional movements) that are made in response to a changing environment. Physiological activities are ongoing and internal and external forces that are present are constantly monitored and adjusted to prevent movement and maintain posture. These body adjustments in anterior-posterior (AP) and medio-lateral (ML) directions are dramatically increased in some circumstances, e.g. on a narrow Base of Support (BoS), a moving platform, with eyes closed, or in sport related activities such as landing from jumping or hopping.

External forces acting on the body include gravity and ground reaction forces while internal forces are generated from muscle contraction and/or passive tension in tendons, ligaments, joint capsules and other connective tissue structures. To remain stable, the forces must be in equilibrium, that is, all of the forces acting on the body and its segments must be equal to zero (Talbott, 2005).

In quiet standing, the body undergoes a constant swaying motion or postural sway that can be considered as an indirect measurement of stability. In normal stance, such as standing on two feet flat eyes open, the amount of sway is small and plays a minimal role in altering the position of the body segments compared to harder conditions e.g. standing on one foot tip toes with eyes open. This sway, however, may become greater when the body is under unstable situations particularly, when the BoS gets smaller and whilst eyes are closed.

The mechanical variables which are needed to evaluate static balance, such as Centre of Pressure (CoP), Centre of Mass (CoM), Friction Torque (Q) as well as the extrapolated Centre of Mass (XCoM), can be extended to evaluate dynamic balance in sport activities such as hopping and jumping in order to provide a better understanding of the dynamic balance phenomenon. Previous studies have examined these variables only in static conditions which offer some data which can be used for comparative purposes, but no study has evaluated and quantified these variables in dynamic conditions in sport related activities such as hopping and jumping. Moreover, evaluating these selected variables on a sufficiently large population (e.g. 20 healthy males) generates baseline data for future studies. In general, baseline studies help researchers to gain a deeper understanding of the phenomenon they are investigating and the values of the variables which quantify that phenomenon.

Treating data from the output of analysis systems is complex. Study 1 was a methodological study which was based on a small population (5 healthy males). Microsoft EXCEL was suitable to deal with this kind of study e.g. filtering, the retrend of the CoP data to match the CoM data, run calculations, plot and save files. In this study, advanced analytical software scripts (MATLAB® 7.4.0, R2007a, The Math Works™) were necessary for analyzing numerous data files and creating informative plots as well as organizing structures which are useful in the current study and in future works.

4.1.1. Objectives

1. To implement Matlab procedures for quantifying selected static and dynamic balance variables;
2. To establish baseline data of selected variables which characterize static and dynamic balance activities in a population of healthy young adult males;
3. To examine the trial effect on selected variables which characterize static and dynamic balance.

4.2. Methods

4.2.1. Participants

The participants in this study were 20 healthy male students at Liverpool John Moores University (age 25.4 ± 4.5 years, height 179 ± 7.2 cm, body mass 73.4 ± 7.2 kg). They had no history of problems of postural instability, passed the stereovision test which meant that they had no gross problem with stereopsis and fine depth perception (Figure 4.1). The main requirement was to perform normal balance in a set of different balance tests. Each participant signed the consent form that complied with the testing information sheet (Appendix 2). A copy of the consent form was approved by the ethics committee and located in (Appendix 1).

4.2.2. Equipment:

Two force platforms were used as detailed in study 1: the first was a Kistler 9281B11, Kistler, Switzerland (dimensions 400 x 600mm) which was built-in and levelled with the floor of the laboratory. It was used in standing tests or for landing in the hopping and jumping tests. The second was Kistler 9287B, Kistler, Switzerland (dimensions 600 x 900mm), whose surface was 20 cm higher than floor level and positioned next to the built-in platform. This was used for take-off in the hopping and jumping movements. Both force platforms recorded ground reaction forces and the CoP at 1000 Hz (12 bit A/D conversion). Additional markers on the 5th metatarsal joints of the feet/foot were used for providing the BoS.

Whole-body kinematic analysis using 41 retro-reflective markers and eight cameras system (Vicon Peak® 512) was performed at 100 Hz wherein the CoM was defined by using a common, commercially available gait kinematic model was used (Plug-In-Gait, Vicon Peak®, Oxford, UK).

Anthropometric measurements were made by the same person as documented in study 1. Both sides of the extremities were measured, but only the right-side values were presented. Body mass and height were also measured as detailed in study 1.

4.2.2.1. Stereo Fly Test:

This test is designed for the evaluation of both gross stereopsis and fine depth perception because if individuals experience visual problems they have unstable postural control. The Stereo Fly test *(Stereo Optical Company. Inc Chicago, IL 60631 USA)* is used as a standard in stereo testing. Participants were required to wear specific glasses because the test only works with the use of the stereo glasses. This helps prevent guessing and creates a more reliable stereo vision test. The targets test was used in this study (left top of the book, Figure 4.1).

Figure 4.1. Illustrates the Stereovision equipment, Stereo Optical Company. Inc Chicago, IL 60631 USA.

4.2.2.2. Questionnaire:

For standardizing participants and avoiding abnormal individuals, a copy of personal medical history and physical activity assessment questionnaire was handed to the participant 2 days before the testing day (Appendix 4).

4.2.3. Procedures:

4.2.3.1. Anthropometry

Similar to the previous study, measurements of stature and body mass were taken in the same manner to standardise procedures:

Stature

Measurements of stature were recorded using analogue Leicester height measure (Seca Ltd., Birmingham, UK). Participants were measured barefoot whilst wearing a stretch suit prior to starting balance testing. Measurements were recorded to the nearest 0.1cm.

Body mass

Measurements of body mass were recorded using analogue Seca scales (Seca Ltd., Birmingham, UK). Participants were measured barefoot whilst wearing a stretch suit prior to starting balance testing. Measurements were recorded to the nearest 0.1kg.

4.2.3.2. Activities:

Balance variables were evaluated under the following conditions; standing with two feet flat, on one foot flat, on one foot and two feet tip-toes, and at the start and end of hopping and jumping manoeuvres. Standardized instructions and explanations were given to the participant as in study 1 for these activities. The participant was given an opportunity to practice prior to the measurements.

- Statically, subjects were required to stand with two feet flat, on one foot flat and on one and then two feet tiptoes (four conditions). A series of 3 trials of each activity were performed with eyes open as well as with eyes closed.
- Dynamically, subjects were required to jump and land with two feet flat and on two feet tiptoes (two conditions) and hop from the higher platform to the lower platform with one foot flat and on one foot-tiptoes (two conditions). A series of 3 trials of each activity were performed only with eyes open.

4.2.3.3. Data collection:

Data were recorded over 60s for two feet flat standing, 15s for two feet tiptoe and one foot flat for both conditions eyes open and eyes closed, and 10s for jumping and hopping tests. The BoS was determined using the RSscan pressure mat which recorded the image of the area of contact between foot/feet and the mat.

Data analysis:

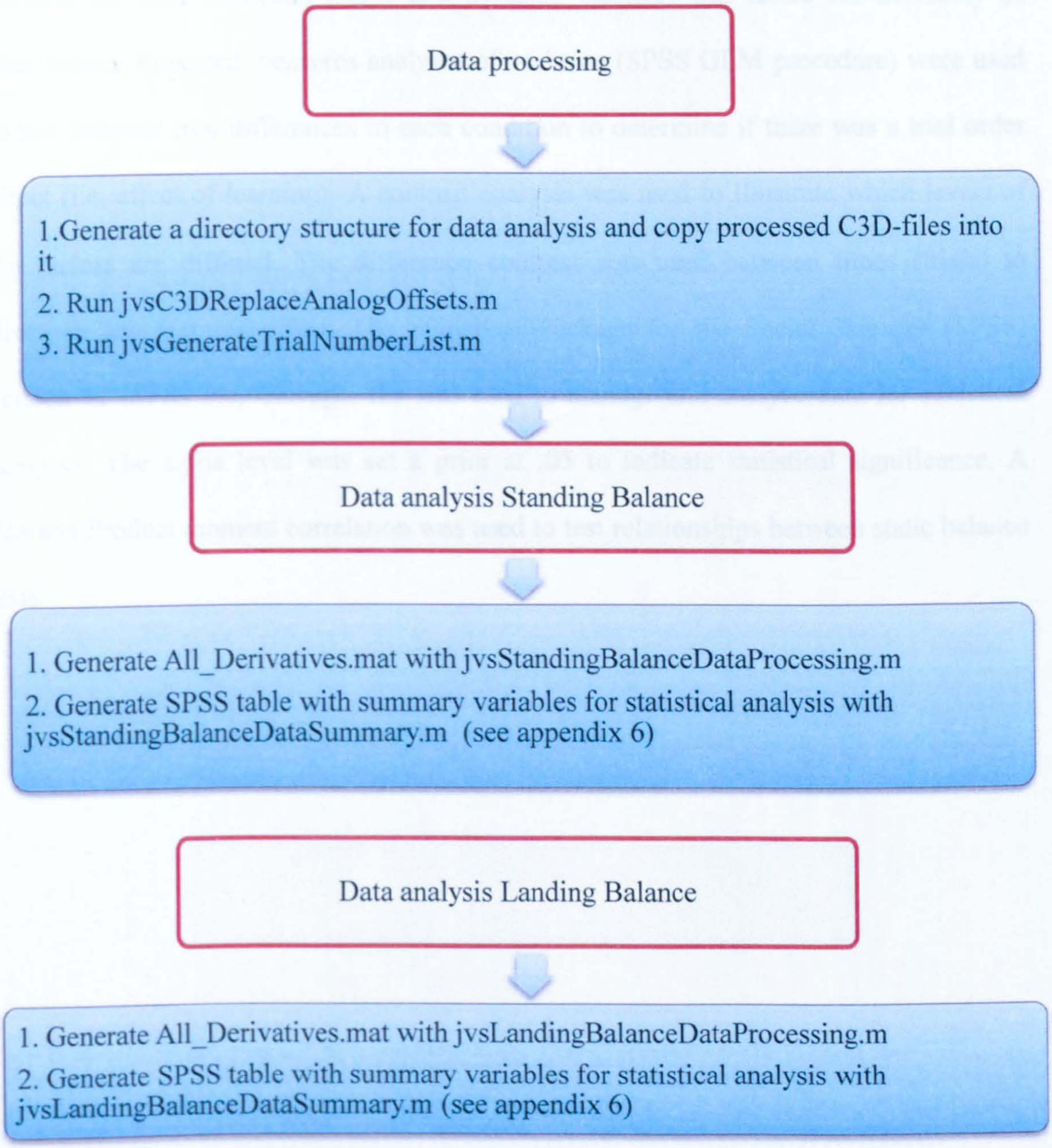
The (AP) and (ML) coordinates of the CoP and the CoM were derived from recorded data and filtered using low pass Butterworth 10 Hz. The velocity of the CoM was calculated using a 3-point central difference differentiation algorithm (Winter, 1990). From these data.

- For static balance, the mean of the RMS values over the period of data collection of (F, CoM, XCoM and CoP in both ML and AP directions) for the three trials were calculated for each subject in each condition.
- For dynamic balance, the mean of the peaks of horizontal forces (F_{ML} and F_{AP}), and Friction Torque (Q) and the mean of the range of the CoM, XCoM and CoP of the three trials were calculated for each subject in both ML and AP directions.

Matlab scripts (Matlab 7.4.0, R2007a) were developed in conjunction with laboratory staff (setting the force platform accurately to minimize the shift between the CoP and CoM which was achieved by computing each mean of (CoP and CoM), and removing the difference and then replacing it with the calculated value. Also Matlab was used to create organized functions for analyzing data. These functions can be used with large volumes of data for creating informative organized structures including plots, and all treated output can be saved as SPSS compatible files.

Matlab flow diagram:

Matlab processing data flow is given in the following diagram.



Data processing

1.Generate a directory structure for data analysis and copy processed C3D-files into it

2. Run jvsC3DReplaceAnalogOffsets.m

3. Run jvsGenerateTrialNumberList.m

Data analysis Standing Balance

1. Generate All_Derivatives.mat with jvsStandingBalanceDataProcessing.m

2. Generate SPSS table with summary variables for statistical analysis with jvsStandingBalanceDataSummary.m (see appendix 6)

Data analysis Landing Balance

1. Generate All_Derivatives.mat with jvsLandingBalanceDataProcessing.m

2. Generate SPSS table with summary variables for statistical analysis with jvsLandingBalanceDataSummary.m (see appendix 6)

Figure 4.2. Matlab processing data flow is given in the following diagram.

*code complied by the author is located in appendix 6 (2 examples are given)

Statistical analysis:

To analyze the postural balance parameters during static and dynamic testing, each variable for each condition (static and dynamic balance) was tested for normality of distribution. Repeated measures analyses of variance (SPSS GLM procedure) were used to test between trial differences in each condition to determine if there was a trial order effect (i.e. effect of learning). A contrast analysis was used to illustrate which levels of the factors are differed. The difference contrast was used between times (trials) to illustrate any learning effect. The Statistical Package for the Social Sciences (SPSS) version 17 (*SPSS Inc*, Chicago, IL*)* was used to manage and analyze data for statistical analyses. The alpha level was set a prior at .05 to indicate statistical significance. A Pearson Product moment correlation was used to test relationships between static balance tests.

4.3. Results:

4.3.1. The Stereo Fly test

All participants' answers were correct and therefore they passed the test for evaluating the both gross stereopsis and fine depth perception and did not experience any visual problems that relates to unstable postural control.

4.3.2. Static balance

4.1.2.1. Base of Support (BoS):

The (BoS) is widely interpreted as the outer line of the outer edges of the feet or the area of contact between a body and support surface or surfaces (Rothwell, 1994, p. 259; Hof *et al.*, 2005) (Figure 4.3).

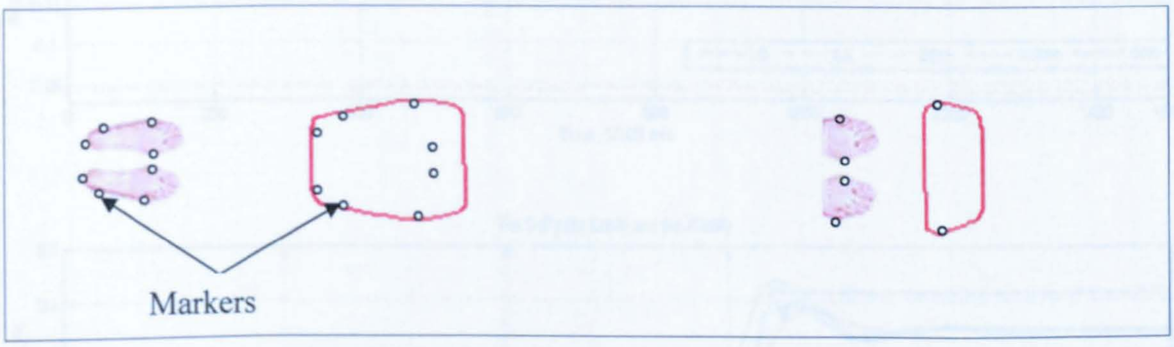
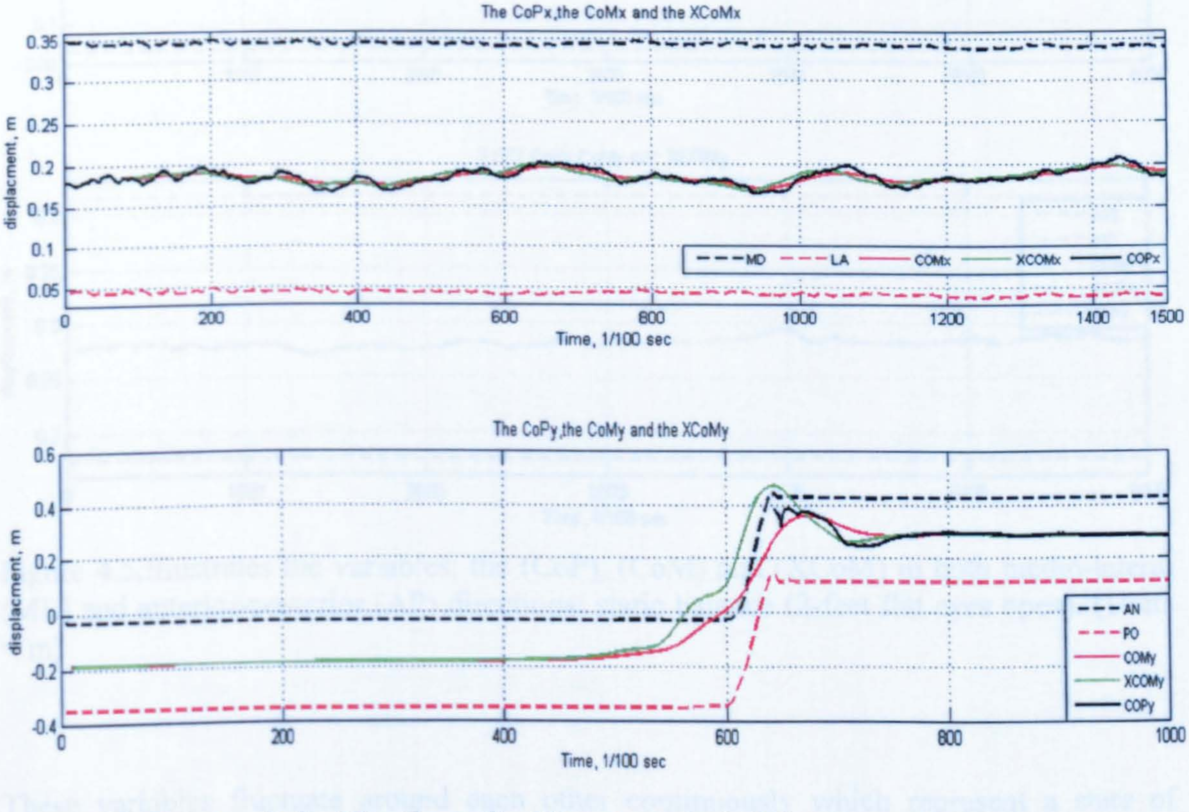


Figure 4.3. Displays an example of the BoS during static balance (two feet flat, eyes open) and the BoS during landing in dynamic balance (jumping on tiptoes), the markers are used as the BoS boundaries.

In this study, the BoS was simultaneously measured by using the feet/foot markers as references and so could be calculated dynamically throughout the movements. Although, the RSscan method gives a more detailed representation of the functional BoS, using, the anatomical plug-in gait feet/foot markers provide similar information about the BoS (See Appendix 3). This anatomical plug-in gait feet/foot markers method is useful to determine the BoS and its boundaries, indicating during dynamic activities how the BoS (see Table 4.3). All markers represented the location of the boundary except the big toe markers used in a calculation based on their location plus a correction (based on the draw of outline of the feet/ foot in anterior direction)

The figure below shows an examples of the dynamic BoS for the ML and AP directions at a single moment in time for standing on two feet flat (left) and when landing from a jump on two feet flat (right).



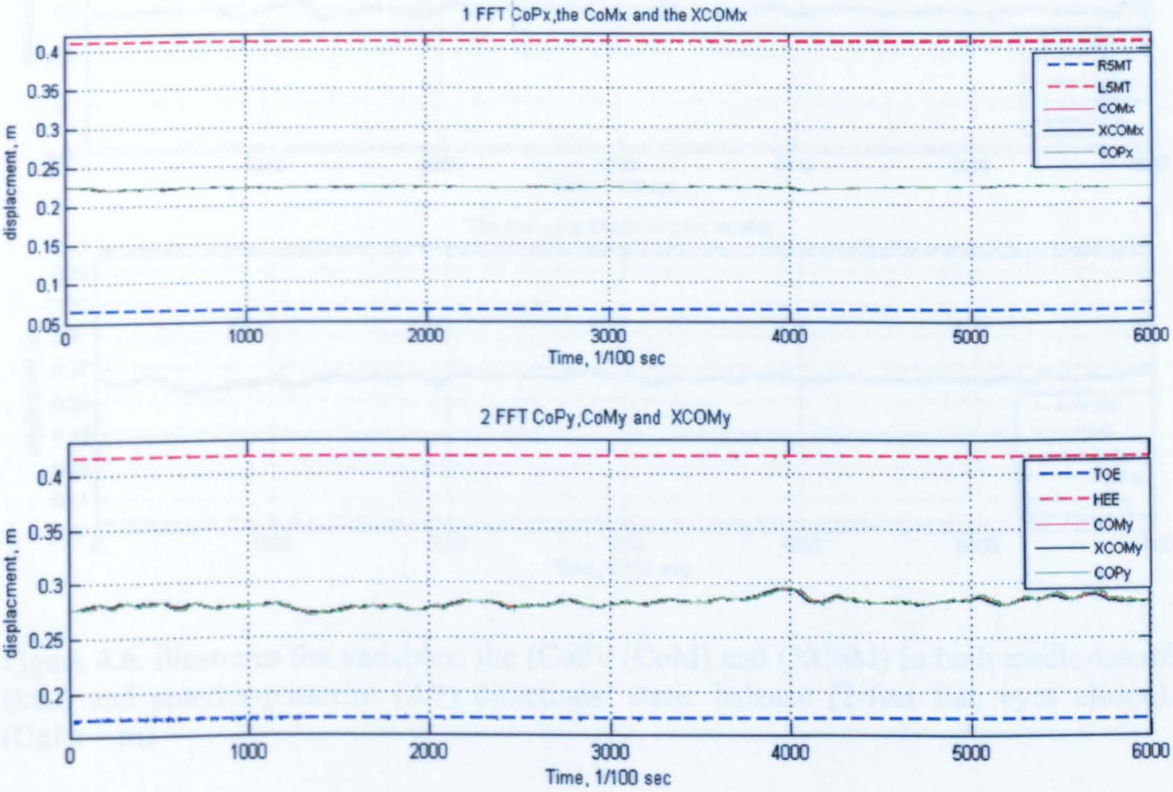
Legend: MD = (medial), LT= (lateral), AN = (anterior), PO = (posterior).

Figure 4.4. Illustrates the medio-lateral (left) and the anterior-posterior (right) BoS (indicated by arrows) during standing (two feet flat, eyes open) and during tiptoe landing from a jump (two feet, right) in relation to the CoP, CoM and XCoM at that moment in time.

4.3.2.2. Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM): for static balance.

Static Balance (2-feet flat, eyes open)

Typical graphical displays are given in Figure 4.5 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML (x) and AP (y) during static balance (2-feet flat, eyes open) in relation to the functional BoS (straight dotted line).


1 FFT CoPx,the CoMx and the XCOMx

2 FFT CoPy,CoMy and XCOMy

Figure 4.5.Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (2-feet flat eyes open). (Units = m)

These variables fluctuate around each other continuously which represent a state of equilibrium but are easily controlled within the BoS.

Static Balance (2-feet flat, eyes closed)

Typical graphical displays are given in Figure 4.6 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML (x) and AP (y) during static balance (2-feet flat, eyes closed) in relation to the functional BoS (dotted line).

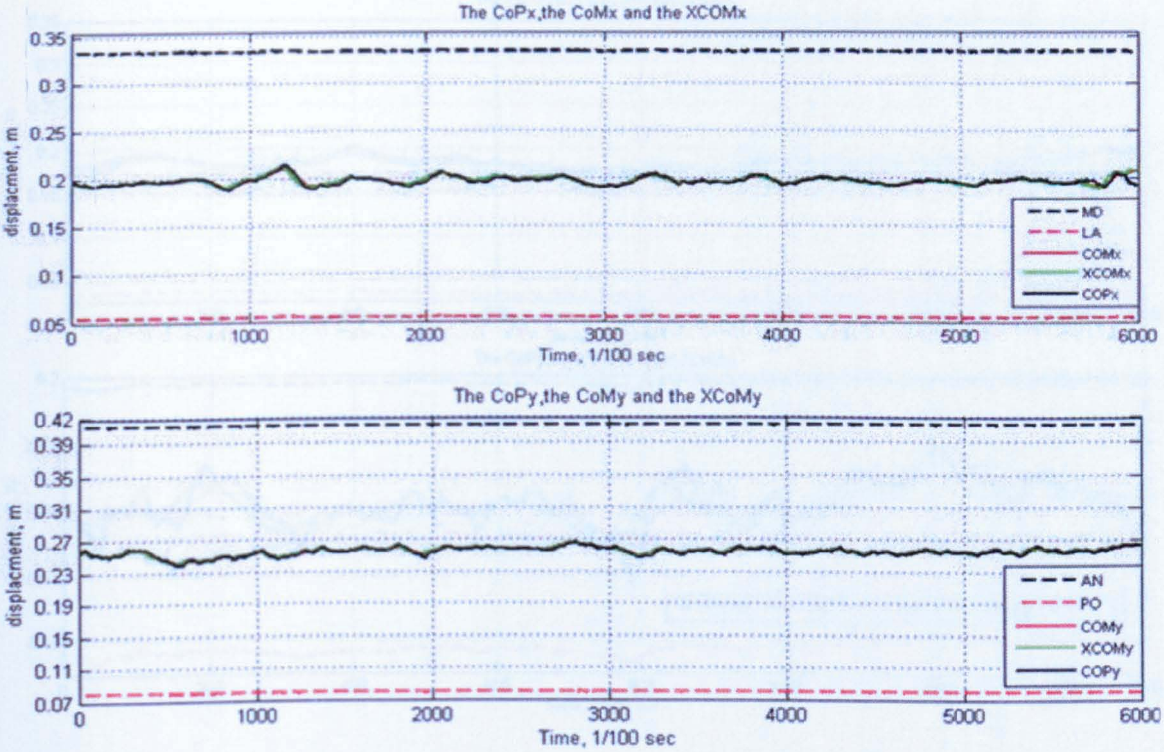


Figure 4.6. illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (2-feet flat, eyes closed). (Units = m)

These variables fluctuate around each other continuously as noted for two feet flat eyes open except there is noticeably more variation.

Static Balance (2-feet tiptoes, eyes open)

Typical graphical displays are given in Figure 4.7 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML (x) and AP (y) during static balance (2-feet tiptoes, eyes open) in relation to the functional BoS (dotted line).

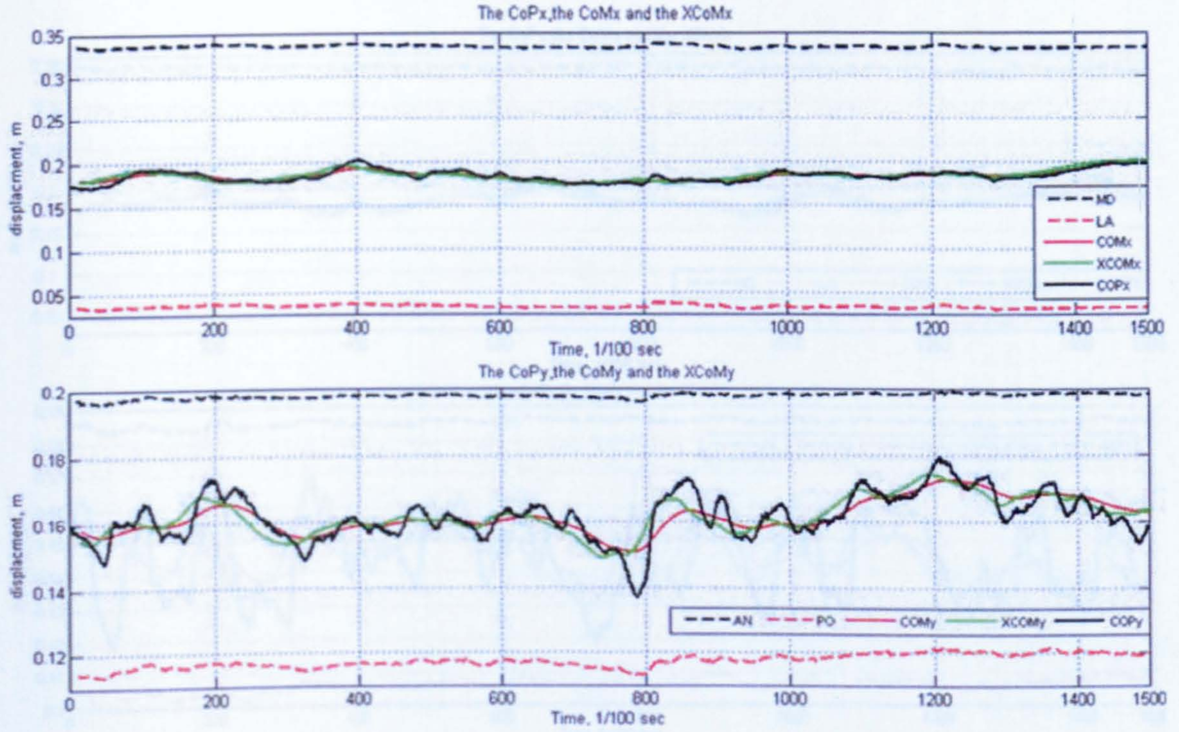
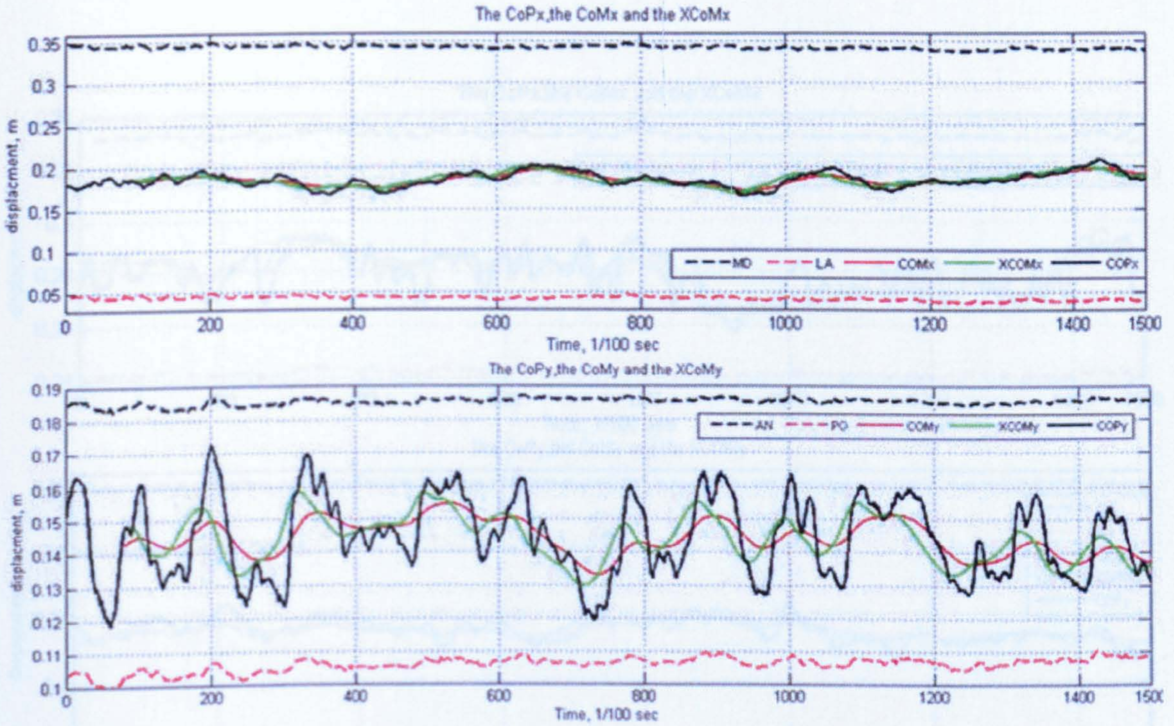


Figure 4.7. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (2-feet tiptoes eyes open). (Units = m).

The charts above illustrate good stability in the (CoP), (CoM) and (XCoM) in the medio-lateral (ML) during static balance while the anterior-posterior (AP) shows large fluctuations due to the small available size of the BoS there are perturbations. These variables fluctuate around each other continuously which represent a state of equilibrium.

Static Balance (2-feet tiptoes, eyes closed)

Typical graphical displays are given in Figure 4.8 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML (x) and AP (y) during static balance (2-feet tiptoes, eyes closed) in relation to the functional BoS (dotted line).


The CoPx,the CoMx and the XCoMx

The CoPy,the CoMy and the XCoMy

Figure 4.8. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (2-feet tiptoes eyes closed). (Units = m).

There was small perturbation in the ML direction due to the nature of the event (eyes closed), whereas as a result of the small available size of the BoS in the AP direction these variables fluctuate widely around each other. Particularly the CoP_{AP} diverges to control the other variables.

Static Balance (1-foot flat, eyes open)

Typical graphical displays are given in Figure 4.9 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML (x) and AP (y) during static balance (1-foot flat, eyes open) in relation to the functional BoS (dotted line).

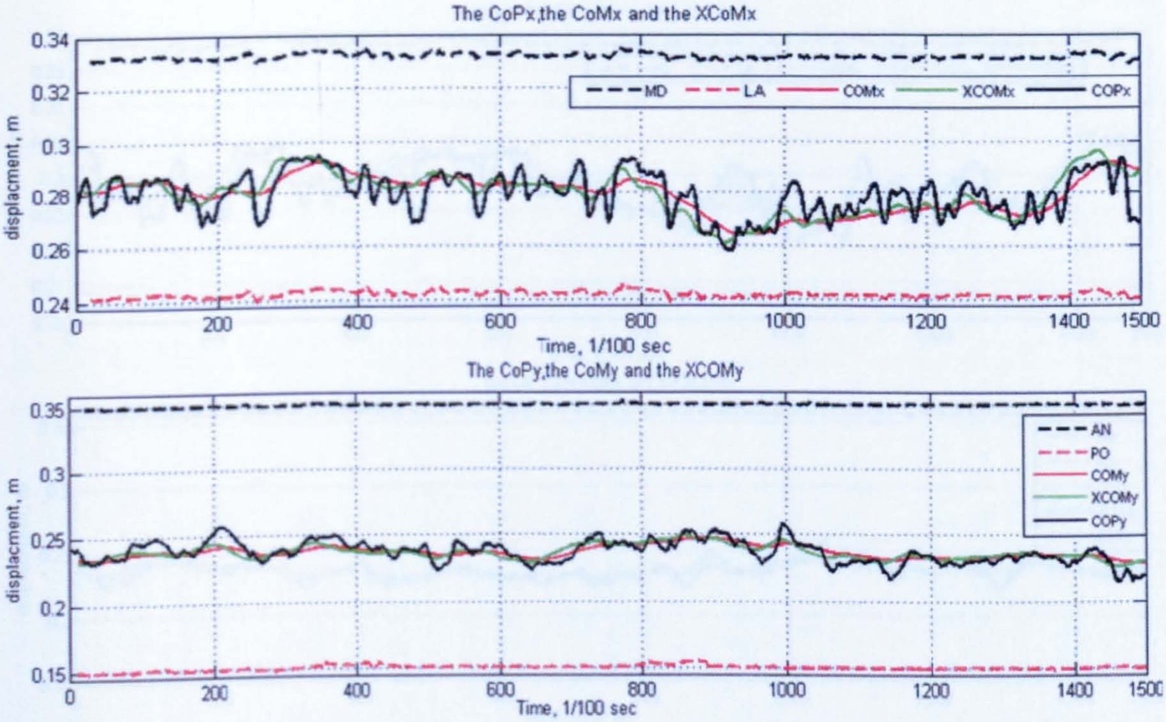


Figure 4.9. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (1-foot flat eyes open). (Units = m).

As a result of the small available size of the BoS in the ML direction there were larger fluctuations. These variables fluctuate widely around each other particularly the CoP_{ML} diverges far away to control the other variables. There was smaller perturbation in the AP direction due to the available size of the BoS (one foot open).

Static Balance (1-foot flat, eyes closed)

Typical graphical displays are given in Figure 4.10 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML (x) and AP (y) during static balance (1-foot flat, eyes closed) in relation to the functional BoS (dotted line).

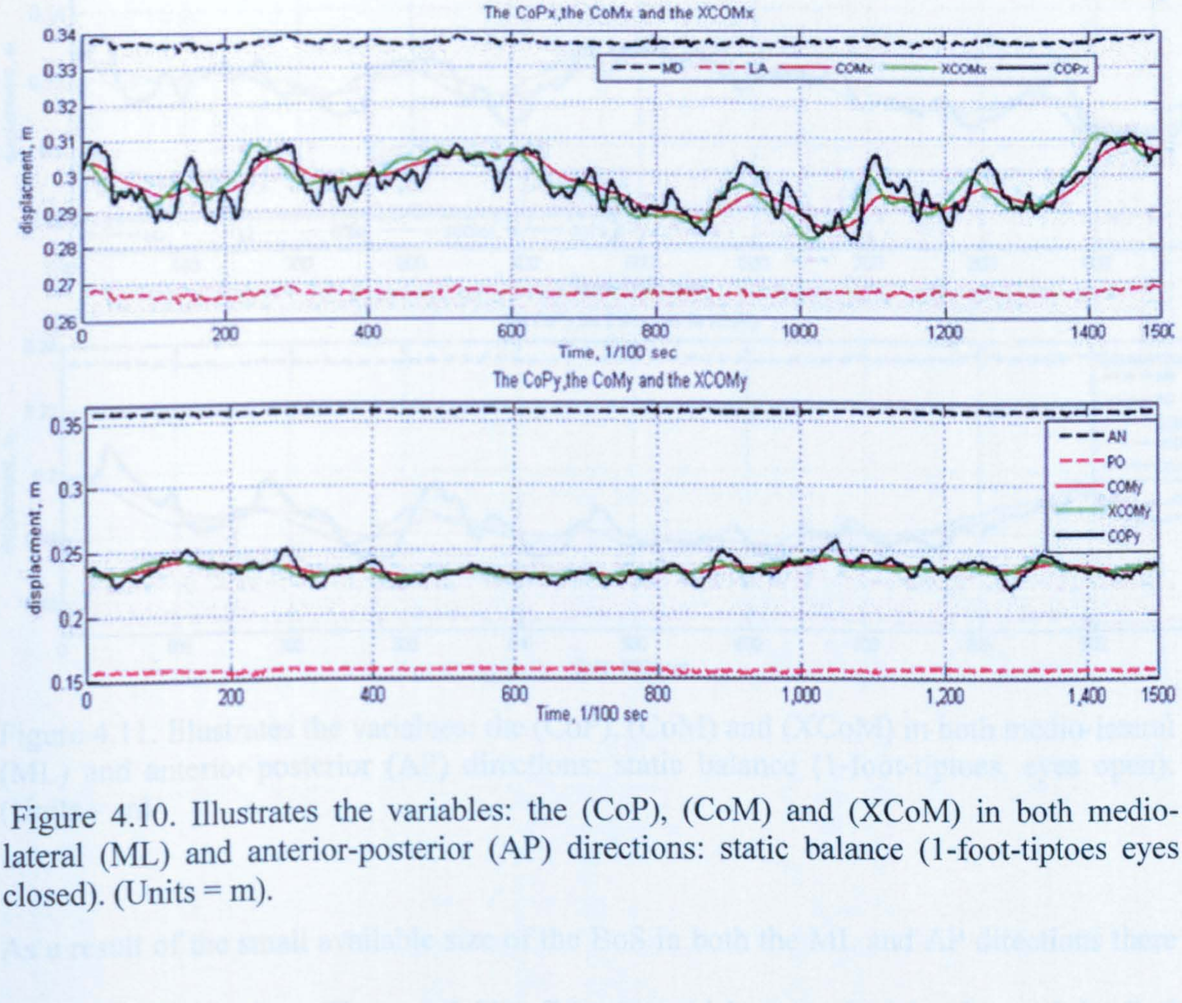


Figure 4.10. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (1-foot-tiptoes eyes closed). (Units = m).

As a result of the small available size of the BoS in the ML direction there were larger fluctuations. These variables fluctuate widely around each other particularly the CoP_{ML} diverges far away to control the other variables. There was smaller perturbation in the AP direction due to the available size of the BoS (one foot).

Static Balance (1-foot-tiptoes, eyes open)

Typical graphical displays are given in Figure 4.11 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML *(x)* and AP *(y)* during static balance (1-foot-tiptoes, eyes open) in relation to the functional BoS (dotted line).

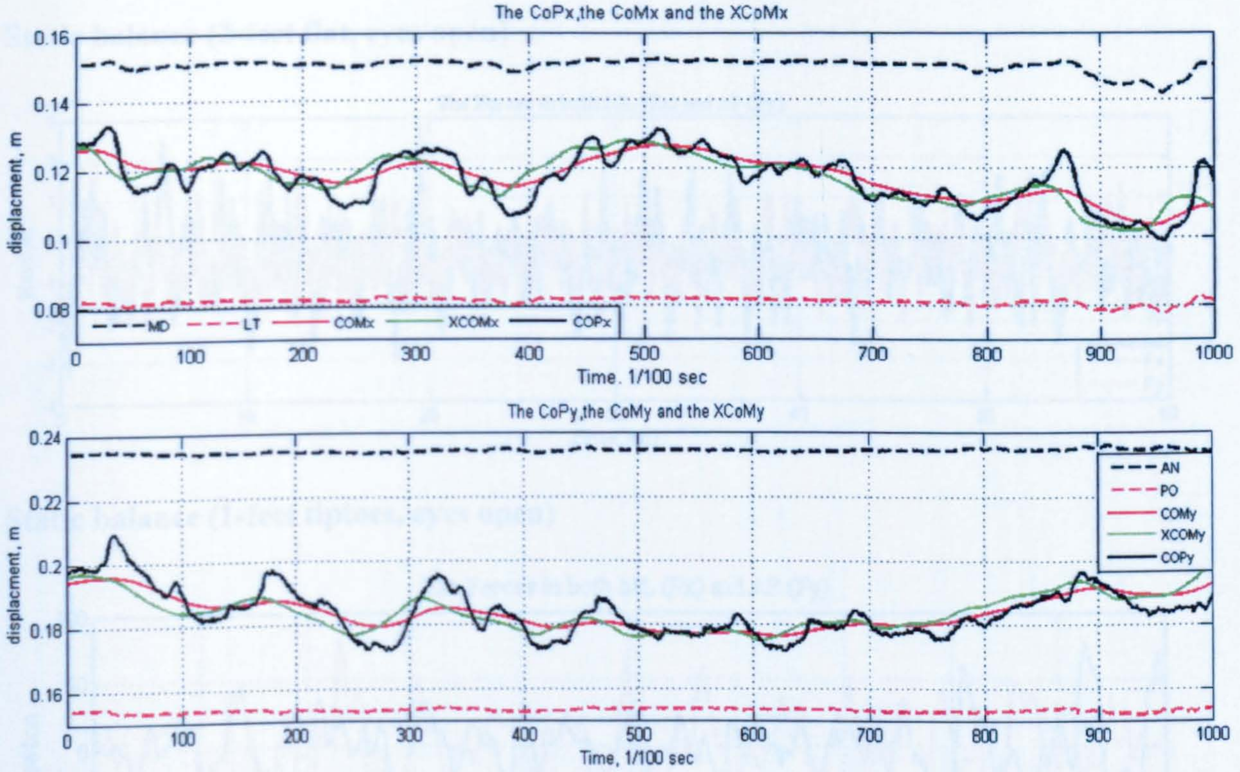


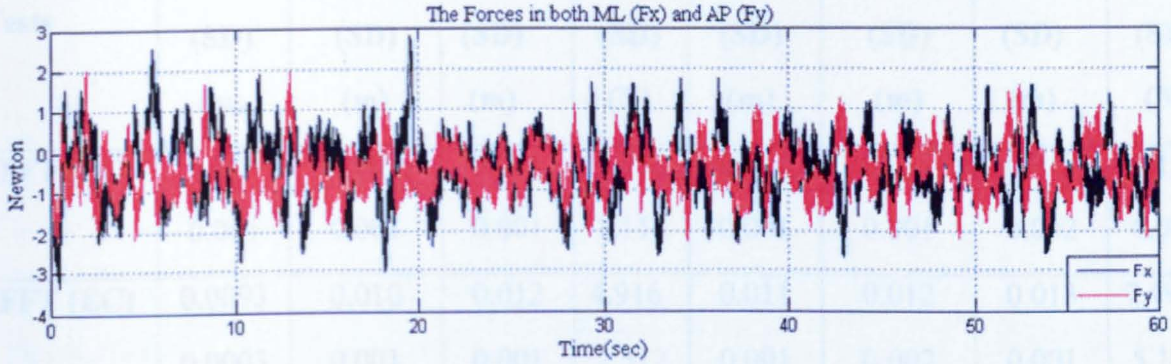
Figure 4.11. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral (ML) and anterior-posterior (AP) directions: static balance (1-foot-tiptoes, eyes open). (Units = m)

As a result of the small available size of the BoS in both the ML and AP directions there were large fluctuations. These variables fluctuate widely around each other and the CoP diverges far away to control and other variables.

4.3.2.3. Ground reaction force (GRF) for static balance

Typical graphical displays are given in Figure 4.12 for the shear force in both F_{ML} (F*x*) and F_{AP} (F*y*) directions during static balance. These forces fluctuate around a constant level (nominally zero) which represents a state of equilibrium. In static balance, the ranges (double arrow) of the forces F_{ML} and F_{AP} are shown.

Static balance (2-feet flat, eyes open)



Static balance (1-feet tiptoes, eyes open)

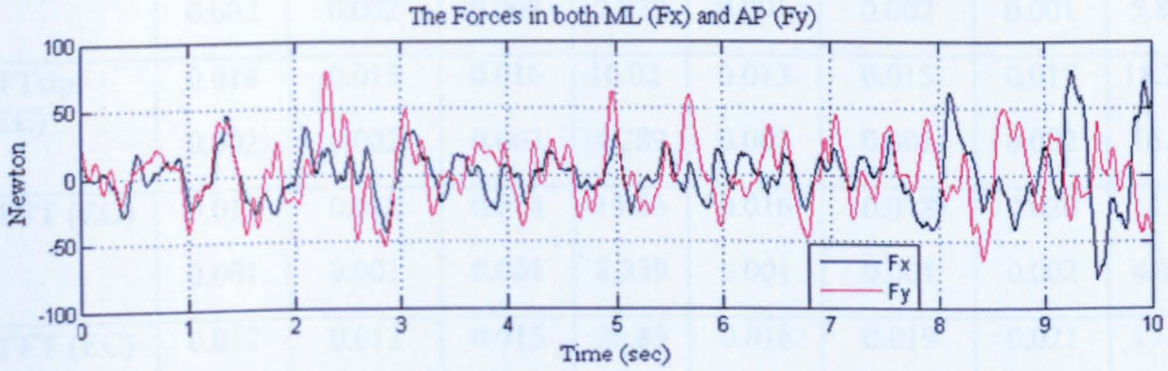


Figure 4.12. Illustrates the applied forces in both the F_{ML} and F_{AP} directions in static balance (Romberg 2-feet flat) and (Romberg 1-foot-tiptoes). (Units = N)

The applied forces in F_{ML} and F_{AP} values were small, (range < 10 Newton) during 2-feet flat standing, while the applied forces in F_{ML} and F_{AP} values were larger (range ≥ 100 Newton) during 1-foot-tiptoes standing.

4.3.2.4. Numerical data

The mean and standard deviations of the RMS of the CoM, XCoM, CoP and F are given in Table 4.1.

Table 4.1.The mean and the SD of the RMS of the CoM, XCoM, CoP and F in both medio-lateral (ML) and anterior-posterior (AP) directions in static balance (mean of 20 subjects and 3 trials)

Tests	**$\mathrm{CoM}_{\mathrm{ML}}$ Mean (SD) (m)**	**$\mathrm{XCoM}_{\mathrm{ML}}$ Mean (SD) (m)**	**$\mathrm{CoP}_{\mathrm{ML}}$ Mean (SD) (m)**	**F_{ML} Mean (SD) (N)**	**$\mathrm{CoM}_{\mathrm{AP}}$ Mean (SD) (m)**	**$\mathrm{XCoM}_{\mathrm{AP}}$ Mean (SD) (m)**	**$\mathrm{CoP}_{\mathrm{AP}}$ Mean (SD) (m)**	**F_{AP} Mean (SD) (N)**
2FFT (EO)	0.008	0.009	0.011	3.750	0.010	0.011	0.012	6.152
	0.001	0.001	0.001	1.118	0.001	0.001	0.002	4.080
2FFT (EC)	0.0093	0.010	0.012	4.916	0.011	0.012	0.013	7.498
	0.0003	0.001	0.001	2.512	0.001	0.002	0.001	5.100
2FTtip (EO)	0.013	0.014	0.015	7.993	0.011	0.014	0.015	11.94
	0.002	0.002	0.002	2.979	0.001	0.002	0.001	5.850
2FTtip (EC)	0.014	0.015	0.016	10.02	0.013	0.015	0.017	18.26
	0.002	0.002	0.002	4.289	0.001	0.001	0.002	16.81
1FFT (EO)	0.011	0.012	0.014	13.56	0.016	0.018	0.020	11.22
	0.001	0.001	0.001	8.339	0.001	0.001	0.002	4.459
1FFT (EC)	0.012	0.013	0.015	26.89	0.018	0.019	0.021	17.65
	0.001	0.001	0.001	20.47	0.001	0.001	0.002	10.69
1FTtip (EO)	0.009	0.010	0.011	32.50	0.035	0.037	0.039	27.08
	0.001	0.001	0.001	17.22	0.001	0.002	0.002	14.87
1FTtip (EC)	**	**	**	**	**	**	**	**

** Most participants lost balance.

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat), 1FFT = (2 foot-tiptoes), and EO = (eyes open), EC = (eyes closed)

4.3.2.5. Trial effects

Centre of Mass;

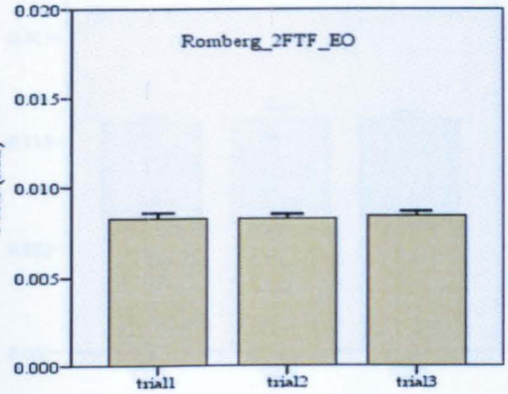
The results in Table 4.2 for a one way repeated measures ANOVA with one within subject factor (TRIAL, 3 levels) showed that there was no significant main effect of trials neither in eyes open nor eyes closed conditions for the medio-lateral (ML) and anterior-posterior (AP) directions. Specific trial-by-trial comparisons are displayed in Figure 4.13

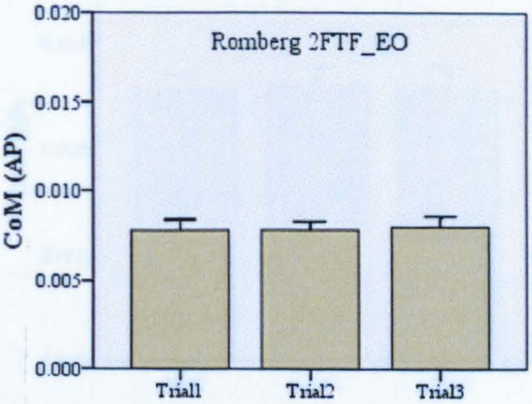
Table 4.2. Illustrates the F values associated with trial effects of the Centre of Mass variable in all static balance test in both eyes open and eyes closed conditions and in both medio-lateral (ML) and anterior-posterior (AP) directions.

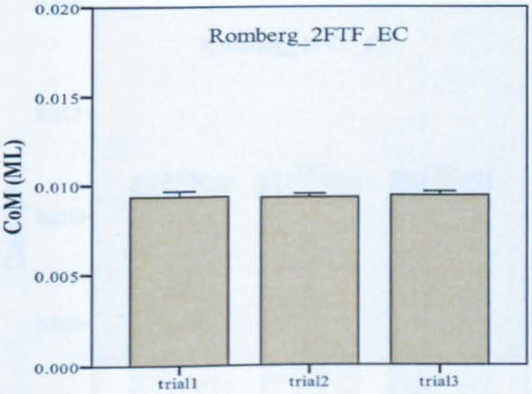
Conditions	CoM_{ML}	CoM_{AP}
2FFT (EO)	$F_{(1.998, 37.956)} = 1.349, p > .05$	$F_{(1.884, 35.789)} = 1.483, p > .05$
2FFT (EC)	$F_{(1.855, 35.244)} = 1.316, p > .05$	$F_{(1.792, 34.041)} = 1.915, p > .05$
2FTtip (EO)	$F_{(1.910, 36.290)} = 1.355, p > .05$	$F_{(1.841, 34.976)} = 1.088, p > .05$
2FTtip (EC)	$F_{(1.862, 35.378)} = 1.293, p > .05$	$F_{(1.978, 37.582)} = 1.142, p > .05$
1FFT (EO)	$F_{(1.966, 37.362)} = 1.593, p > .05$	$F_{(1.905, 36.196)} = 1.957, p > .05$
1FFT (EC)	$F_{(1.982, 37.655)} = 1.302, p > .05$	$F_{(1.750, 33.251)} = 1.814, p > .05$
1FTtip (EO)	$F_{(1.596, 30.325)} = 2.158, p > .05$	$F_{(1.632, 31.015)} = 1.186, p > .05$

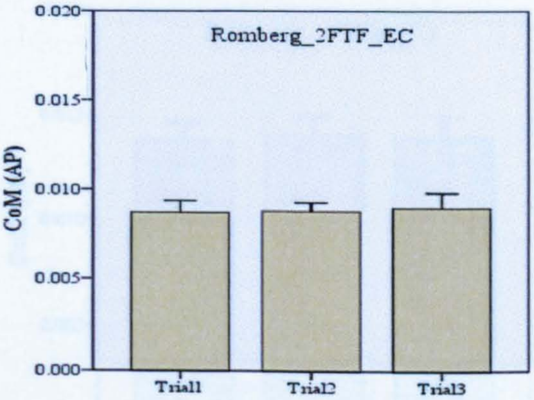
Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat), 1FFT = (2 foot-tiptoes), and EO = (eyes open), EC = (eyes closed)

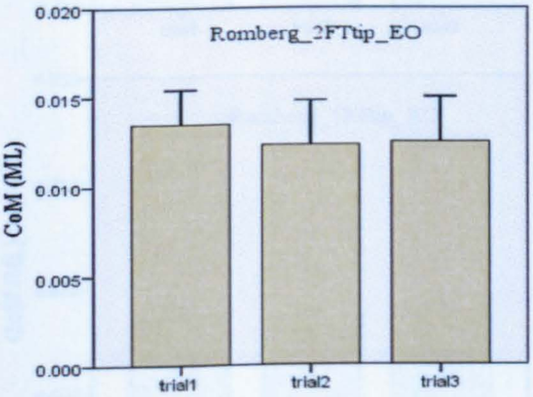
Centre of Mass: (CoM)

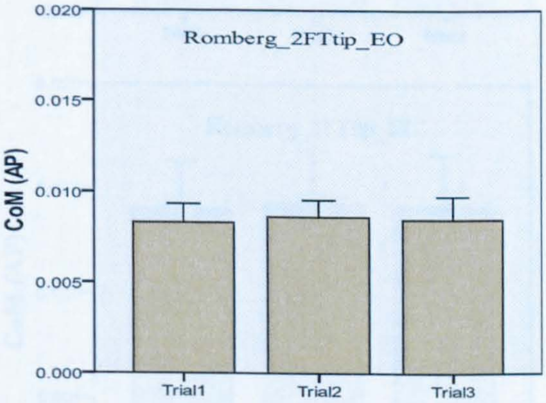


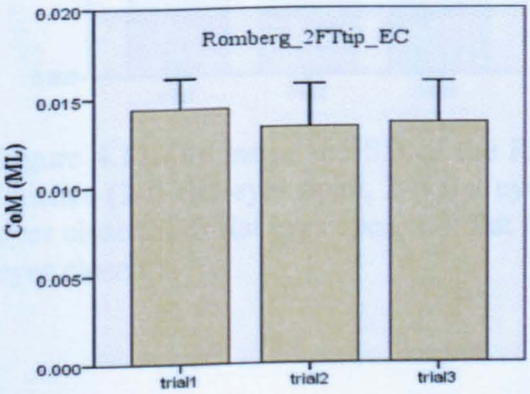


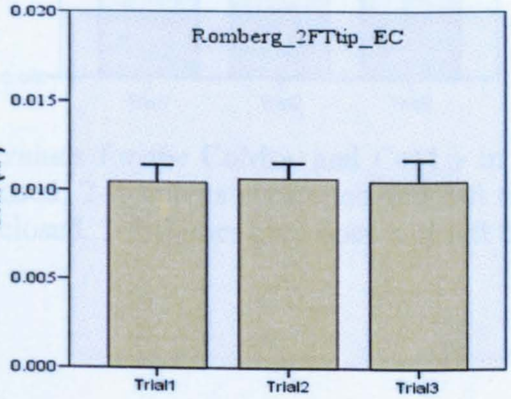












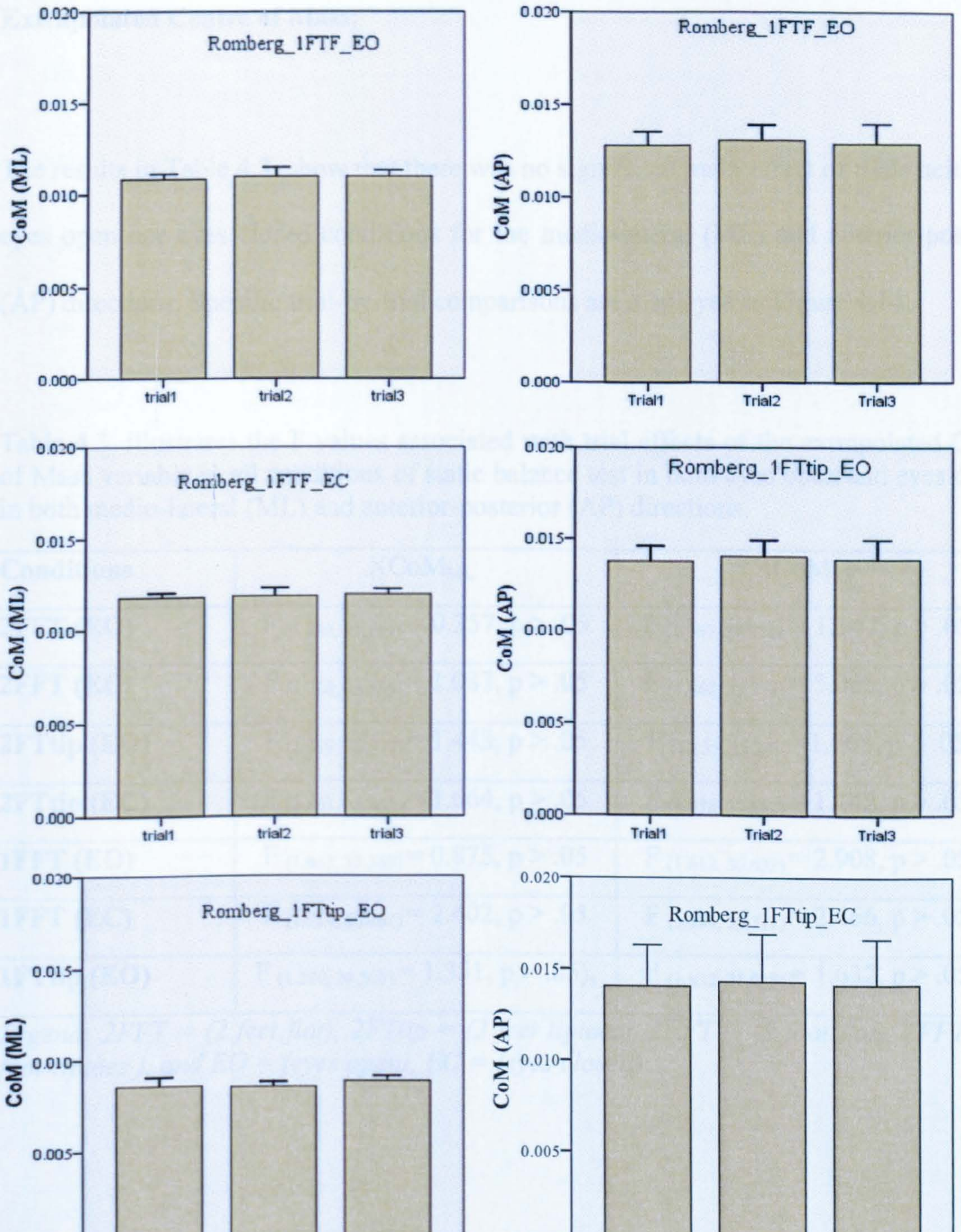


Figure 4.13.The mean and SD of the RMS values for the CoM_{ML} and CoM_{AP} in static balance (2-ft flat eyes open, 2-ft flat eyes closed, 2-ft tiptoes eyes open and 2-ft tiptoes eyes closed, 1-ft flat eyes open, 1-ft flat eyes closed, 1-ft tiptoes eyes open and 1-ft tiptoes eyes closed).

Extrapolated Centre of Mass;

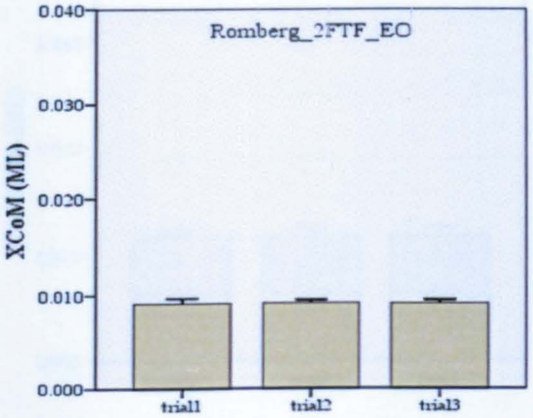
The results in Table 4.3 show that there was no significant main effect of trials neither in eyes open nor eyes closed conditions for the medio-lateral (ML) and anterior-posterior (AP) directions. Specific trial-by-trial comparisons are displayed in Figure 4.14.

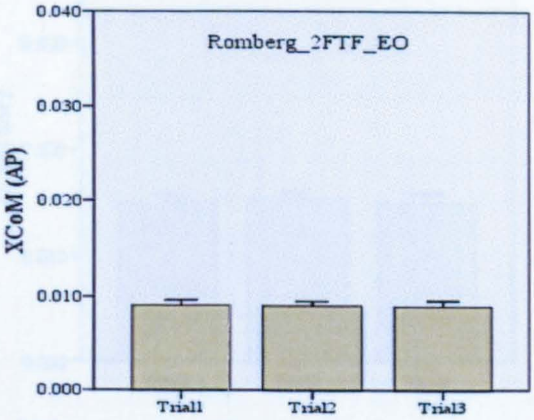
Table 4.3. illustrates the F values associated with trial effects of the extrapolated Centre of Mass variable in all conditions of static balance test in both eyes open and eyes closed in both medio-lateral (ML) and anterior-posterior (AP) directions.

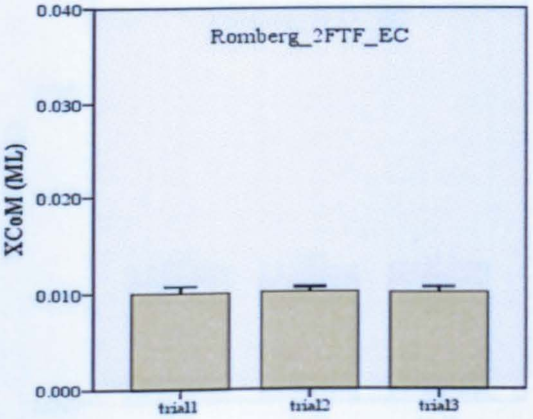
Conditions	$\mathrm{XCoM}_{\mathrm{ML}}$	$\mathrm{XCoM}_{\mathrm{AP}}$
2FFT (EO)	$F_{(1.850, 35.149)} = 0.357, p > .05$	$F_{(1.967, 37.376)} = 1.347, p > .05$
2FFT (EC)	$F_{(1.768, 33.595)} = 1.087, p > .05$	$F_{(1.862, 35.373)} = 3.065, p > .05$
2FTtip (EO)	$F_{(1.899, 36.077)} = 1.443, p > .05$	$F_{(1.855, 35.241)} = 1.668, p > .05$
2FTtip (EC)	$F_{(1.861, 35.363)} = 1.664, p > .05$	$F_{(1.978, 37.582)} = 1.142, p > .05$
1FFT (EO)	$F_{(1.967, 37.369)} = 0.875, p > .05$	$F_{(1.612, 30.632)} = 2.908, p > .05$
1FFT (EC)	$F_{(1.919, 36.461)} = 2.402, p > .05$	$F_{(1.880, 35.712)} = 2.466, p > .05$
1FTtip (EO)	$F_{(1.290, 24.507)} = 1.351, p > .05)$,	$F_{(1.632, 31.015)} = 1.632, p > .05$

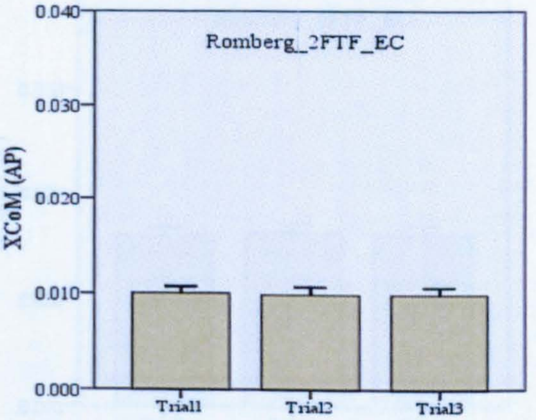
Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat), 1FFT = (2 foot-tiptoes), and EO = (eyes open), EC = (eyes closed)

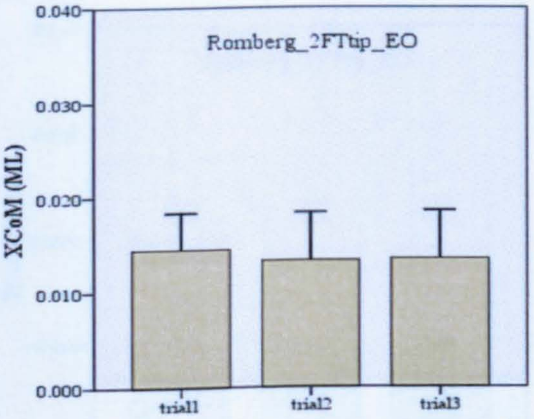
Extrapolated Centre of Mass: (XCoM)

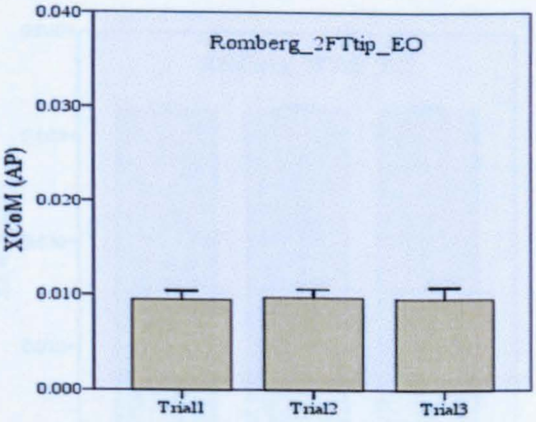


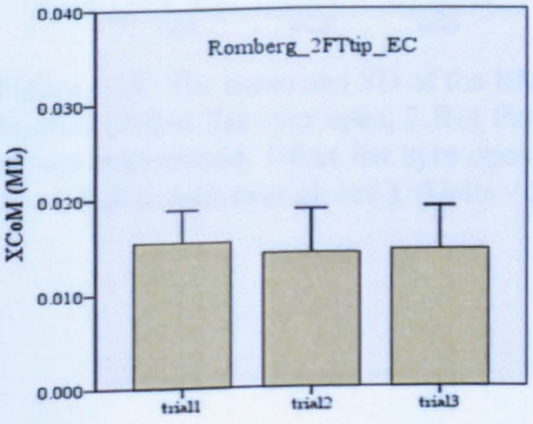


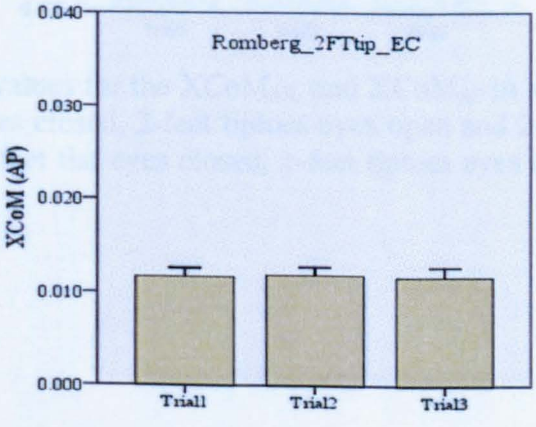












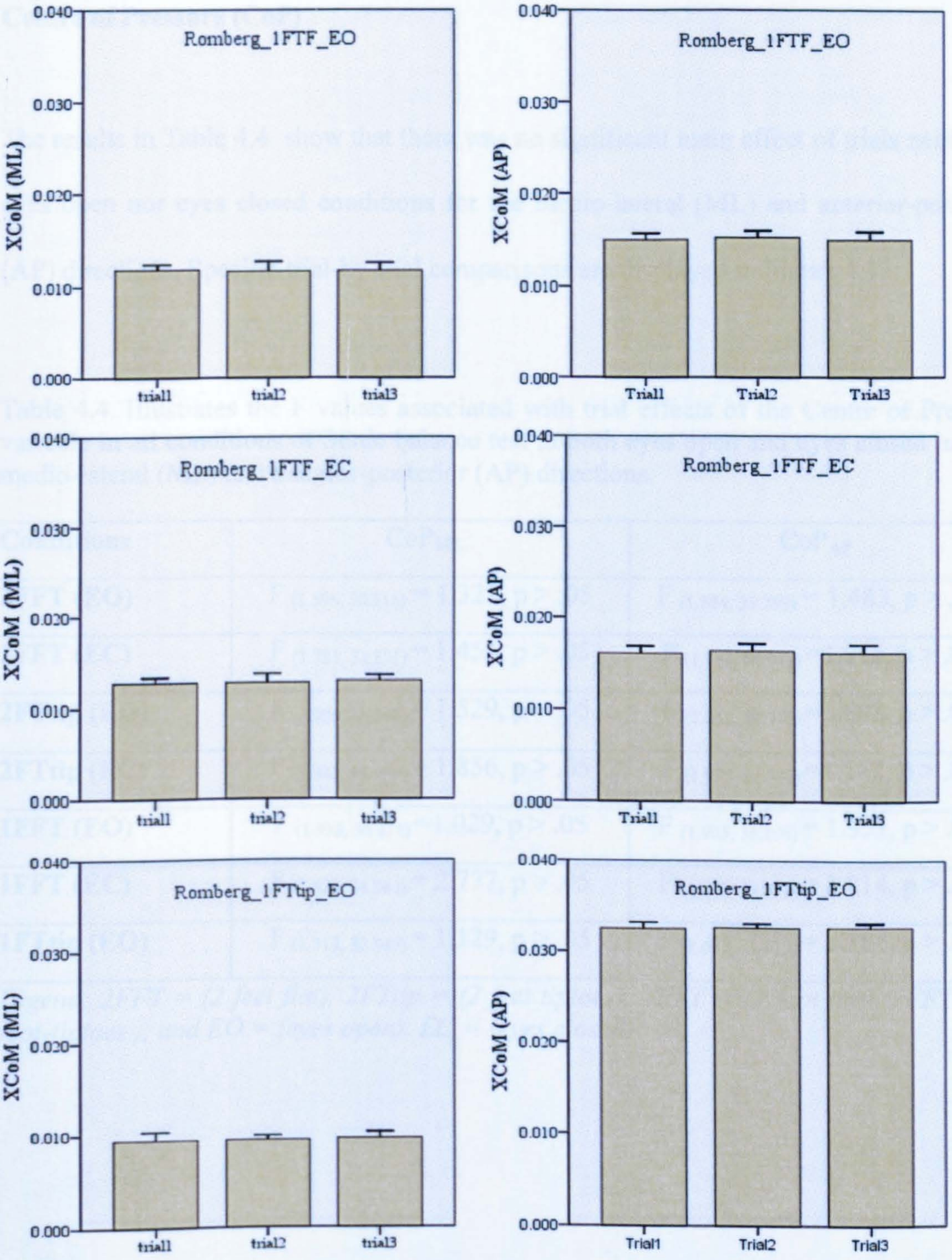


Figure 4.14. The mean and SD of the RMS values for the $XCoM_{ML}$ and $XCoM_{AP}$ in static balance (2-feet flat eyes open, 2-feet flat eyes closed, 2-feet tiptoes eyes open and 2-feet tiptoes eyes closed, 1-feet flat eyes open, 1-feet flat eyes closed, 1-feet tiptoes eyes open and 1-feet tiptoes eyes closed). (Units = m)

Centre of Pressure (CoP)

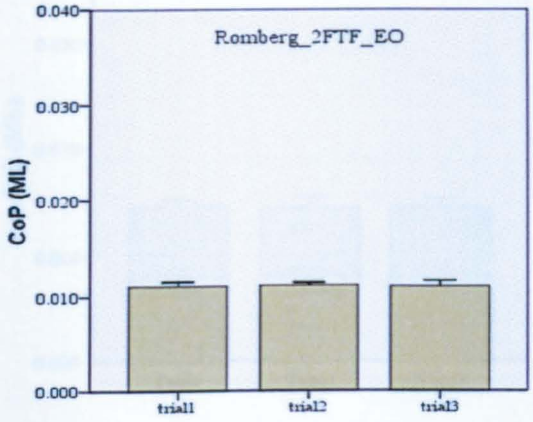
The results in Table 4.4 show that there was no significant main effect of trials neither in eyes open nor eyes closed conditions for the medio-lateral (ML) and anterior-posterior (AP) directions. Specific trial-by-trial comparisons are displayed in Figure 4.15.

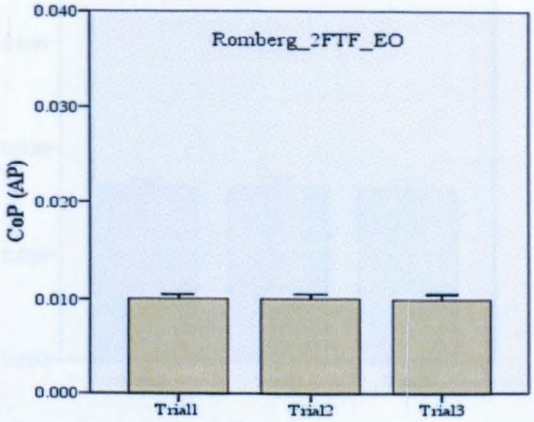
Table 4.4. Illustrates the F values associated with trial effects of the Centre of Pressure variable in all conditions of Static balance test in both eyes open and eyes closed in both medio-lateral (ML) and anterior-posterior (AP) directions.

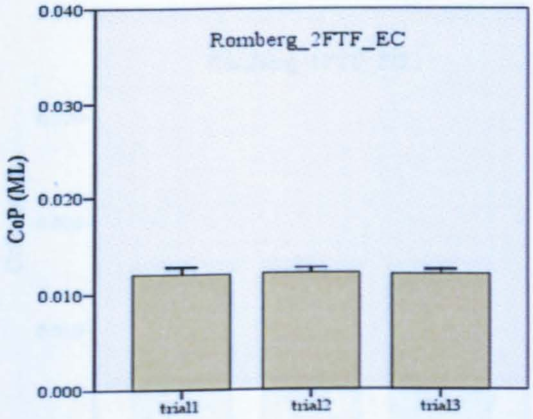
Conditions	CoP_{ML}	CoP_{AP}
2FFT (EO)	$F_{(1.596, 30.316)} = 1.321, p > .05$	$F_{(1.884, 35.789)} = 1.483, p > .05$
2FFT (EC)	$F_{(1.781, 33.831)} = 1.451, p > .05$	$F_{(1.792, 34.041)} = 1.915, p > .05$
2FTtip (EO)	$F_{(1.908, 36.248)} = 1.529, p > .05$	$F_{(1.841, 34.976)} = 1.088, p > .05$
2FTtip (EC)	$F_{(1.842, 34.999)} = 1.856, p > .05$	$F_{(1.978, 37.582)} = 1.142, p > .05$
1FFT (EO)	$F_{(1.938, 36.818)} = 1.029, p > .05$	$F_{(1.905, 36.196)} = 1.957, p > .05$
1FFT (EC)	$F_{(1.829, 34.743)} = 2.777, p > .05$	$F_{(1.750, 33.251)} = 1.814, p > .05$
1FTtip (EO)	$F_{(1.313, 32.945)} = 1.129, p > .05$	$F_{(1.632, 31.015)} = 1.186, p > .05$

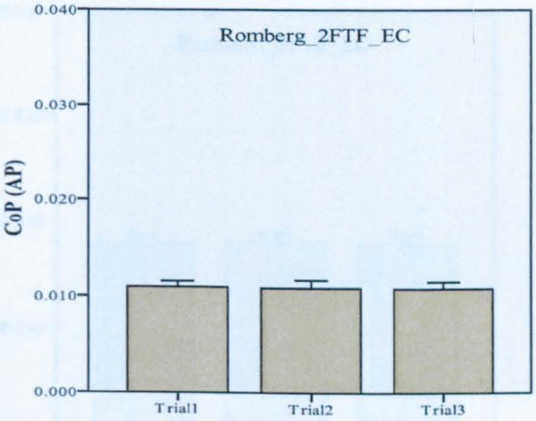
Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat), 1FFT = (2 foot-tiptoes), and EO = (eyes open), EC = (eyes closed)

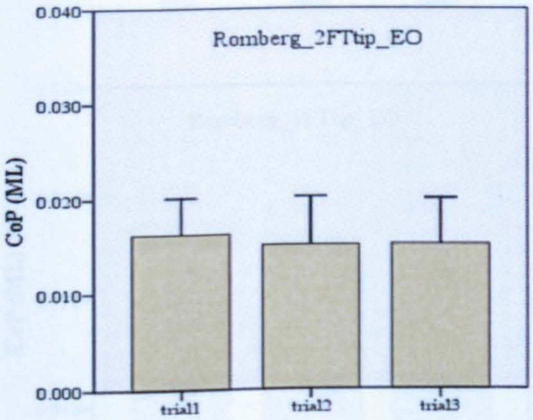
<u>Centre of pressure: (CoP)</u>

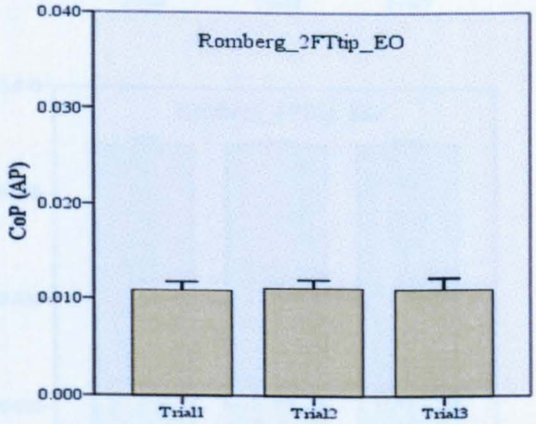


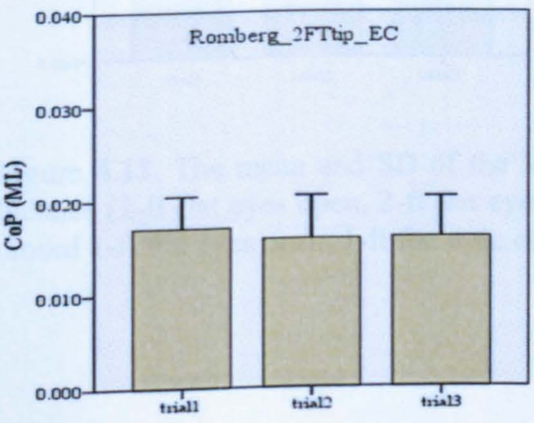


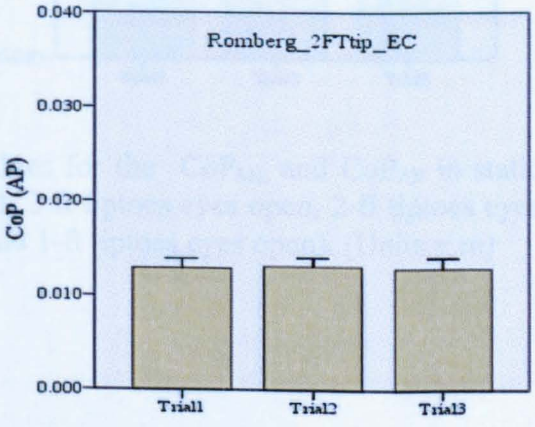












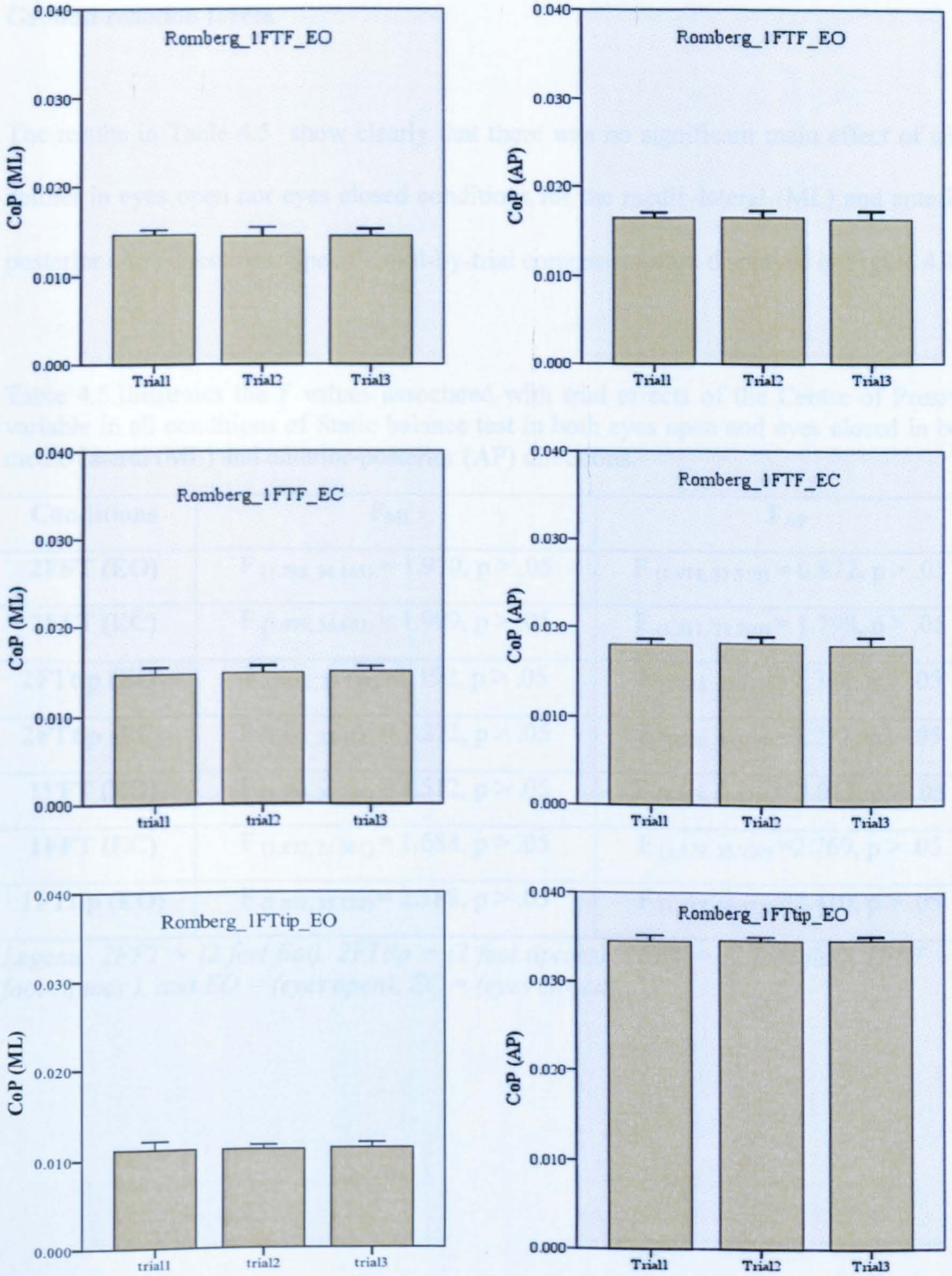


Figure 4.15. The mean and SD of the RMS values for the CoP_{ML} and CoP_{AP} in static balance (2-ft flat eyes open, 2-ft flat eyes closed, 2-ft tiptoes eyes open, 2-ft tiptoes eyes closed 1-ft flat eyes open, 1-ft flat eyes closed, and 1-ft tiptoes eyes open). (Units = m)

Ground reaction forces

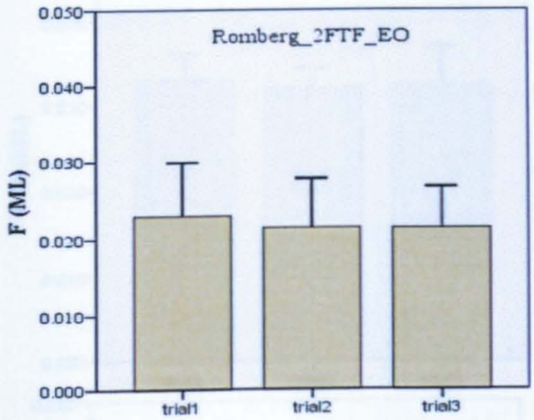
The results in Table 4.5 show clearly that there was no significant main effect of trials neither in eyes open nor eyes closed conditions for the medio-lateral (ML) and anterior-posterior (AP) directions. Specific trial-by-trial comparisons are displayed in Figure 4.16.

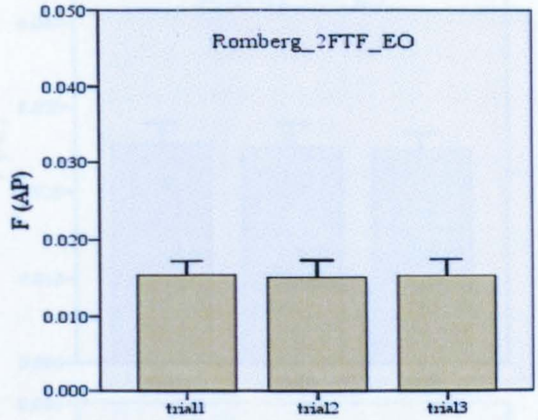
Table 4.5.Illustrates the F values associated with trial effects of the Centre of Pressure variable in all conditions of Static balance test in both eyes open and eyes closed in both medio-lateral (ML) and anterior-posterior (AP) directions.

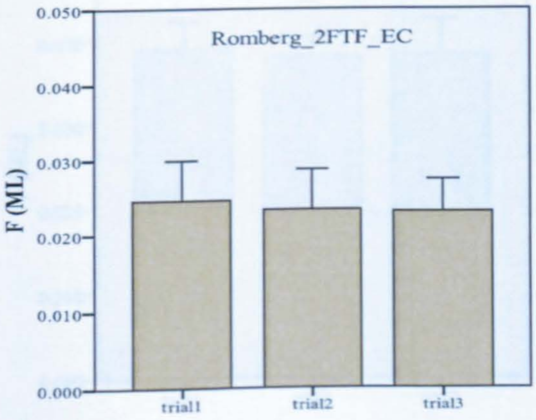
Conditions	F_{ML}	F_{AP}
2FFT (EO)	$F_{(1.798, 34.165)} = 1.970, p > .05$	$F_{(1.974, 37.510)} = 0.872, p > .05$
2FFT (EC)	$F_{(1.979, 36.602)} = 1.999, p > .05$	$F_{(1.511, 28.700)} = 1.798, p > .05$
2FTtip (EO)	$F_{(1.851, 35.177)} = 1.192, p > .05$	$F_{(1.585, 30.121)} = 1.344, p > .05$
2FTtip (EC)	$F_{(1.852, 35.182)} = 1.272, p > .05$	$F_{(1.580, 30.028)} = 1.271, p > .05$
1FFT (EO)	$F_{(1.904, 36.184)} = 1.512, p > .05$	$F_{(1.835, 34.872)} = 2.015, p > .05$
1FFT (EC)	$F_{(1.872, 35.561)} = 1.688, p > .05$	$F_{(1.879, 35.700)} = 2.769, p > .05$
1FTtip (EO)	$F_{(1.852, 35.182)} = 2.188, p > .05$	$F_{(1.917, 36.432)} = 2.410, p > .05$

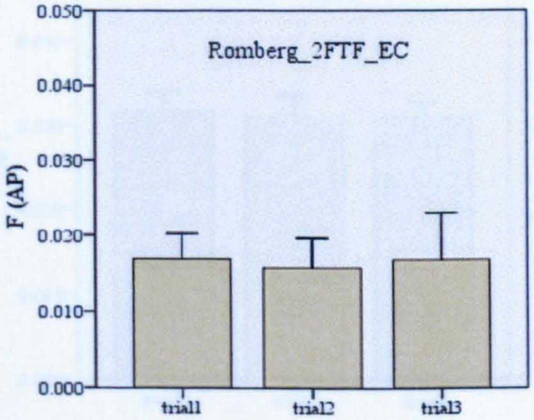
Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat), 1FFT = (2 foot-tiptoes), and EO = (eyes open), EC = (eyes closed)

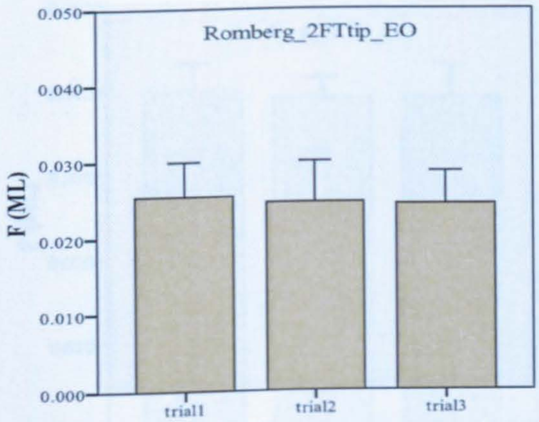
Ground reaction forces: (GRF)

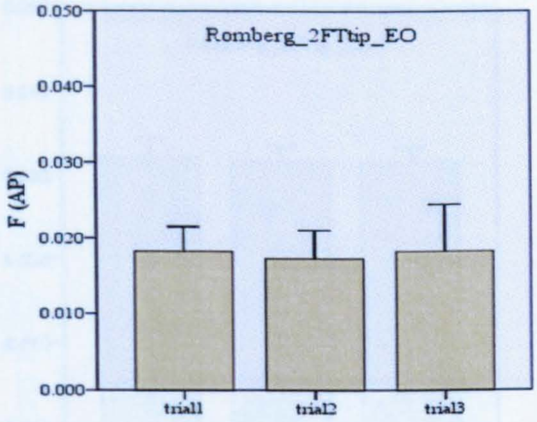


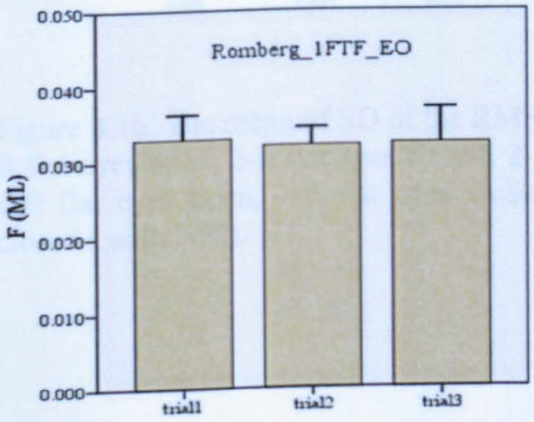


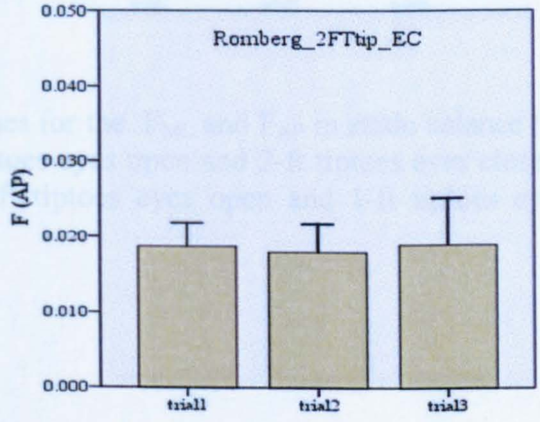












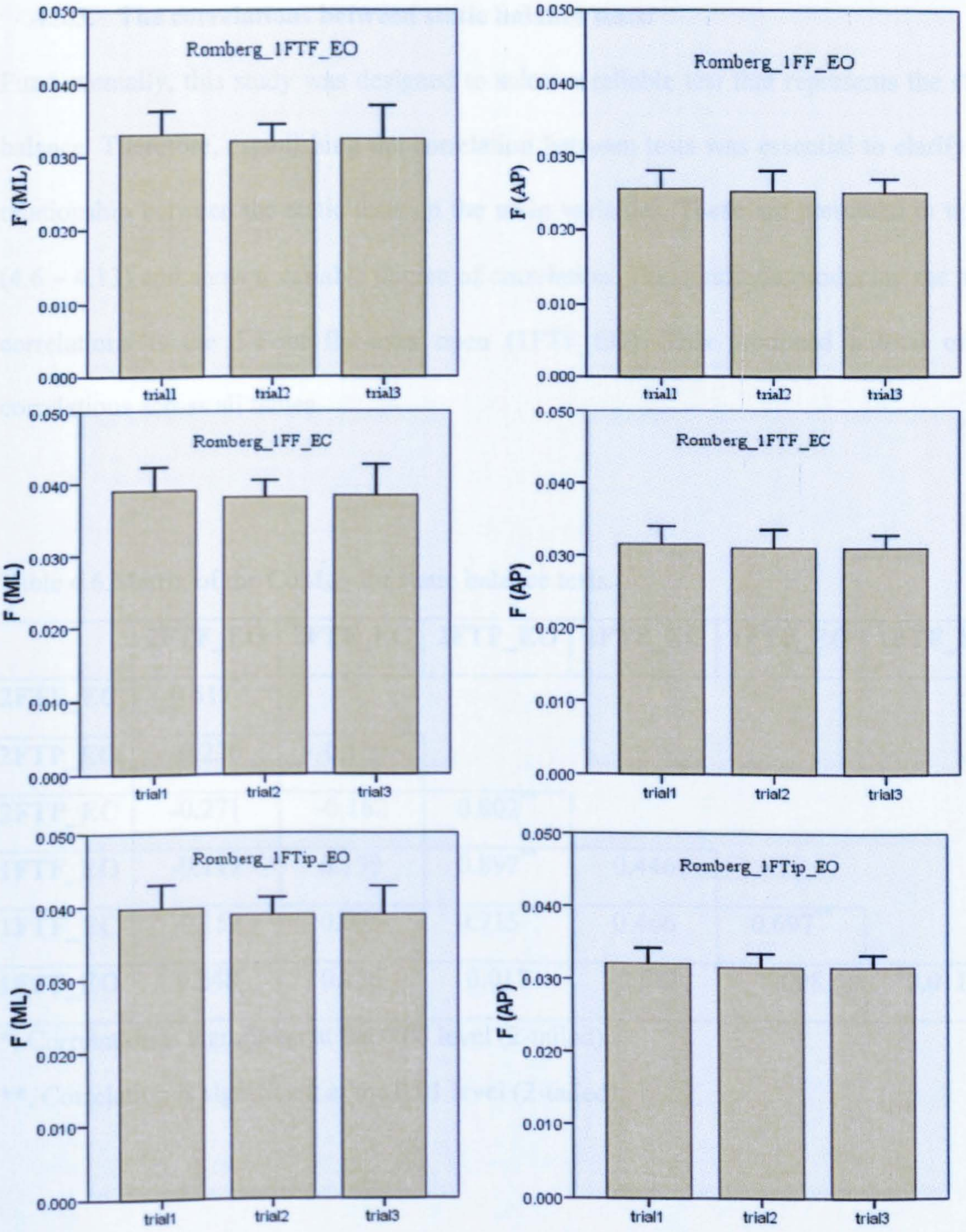


Figure 4.16. The mean of SD of the RMS values for the F_{ML} and F_{AP} in static balance (2-ft flat eyes open, 2-ft flat eyes closed, 2-ft tiptoes eyes open and 2-ft tiptoes eyes closed, 1-ft flat eyes open, 1-ft flat eyes closed, 1-ft tiptoes eyes open and 1-ft tiptoes eyes closed.(units = N).

4.3.3. The correlations between static balance tests:

Fundamentally, this study was designed to select a reliable test that represents the static balance. Therefore, establishing the correlation between tests was essential to clarify the relationship between the static tests on the main variables. These are presented in tables (4.6 – 4.13) and show a variable degree of correlation. The condition producing the most correlations is the 1-Foot flat-eyes open (1FTF_EO). This produced a total of 19 correlations across all tables.

Table 4.6.Matrix of the CoM_{ML} for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.517*					
2FTP_EO	-0.230	-0.129				
2FTP_EC	-0.271	-0.162	0.802**			
1FTF_EO	-0.119	0.139	0.897**	0.446		
1FTF_EC	-0.152	0.075	0.715**	0.466	0.697**	
1FPT_EO	0.248	0.136	0.017	-0.081	0.008	0.011

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.7. Matrix of the CoM_{AP} for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.743^{**}					
2FTP_EO	-0.213	0.144				
2FTP_EC	-0.184	0.175	0.752^{**}			
1FTF_EO	-0.458^{*}	-0.325	0.733^{**}	0.750^{**}		
1FTF_EC	-0.453^{*}	-0.277	0.693^{**}	0.632^{**}	0.671^{**}	
1FPT_EO	0.719^{**}	0.735^{**}	0.021	0.083	-0.134	-0.094

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.8. Matrix of the XCoM_{ML} for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.303					
2FTP_EO	-0.322	0.134				
2FTP_EC	-0.113	0.159	0.267			
1FTF_EO	-0.186	-0.171	0.488^{*}	0.266		
1FTF_EC	0.003	-0.434	-0.121	-0.496^{*}	0.408	
1FPT_EO	0.256	-0.016	0.083	-0.174	0.368	0.017

*. Correlation is significant at the 0.05 level (2-tailed).

Table 4.9. Matrix of the XCoM$_{AP}$ for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.141					
2FTP_EO	0.014	-0.323				
2FTP_EC	-0.163	0.029	-0.059			
1FTF_EO	-0.123	-0.391	0.553^{*}	0.243		
1FTF_EC	-0.188	-0.346	0.186	0.733^{**}	0.452	
1FPT_EO	0.541^{*}	0.263	-0.084	0.072	-0.417	-0.125

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.10. Matrix of the CoP$_{ML}$ for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.425					
2FTP_EO	-0.273	0.218				
2FTP_EC	-0.217	0.079	0.926^{**}			
1FTF_EO	0.047	-0.250	-0.447^{*}	-0.483^{*}		
1FTF_EC	0.003	-0.473^{*}	-0.189	-0.055	0.401	
1FPT_EO	0.246	0.052	-0.205	-0.229	0.235	0.121

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.11. Matrix of the CoP_{AP} for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.203					
2FTP_EO	-0.029	-0.217				
2FTP_EC	-0.086	-0.083	0.619^{**}			
1FTF_EO	-0.128	-0.236	0.742^{**}	0.539^{*}		
1FTF_EC	-0.199	-0.378	0.566^{**}	0.124	0.508^{*}	
1FPT_EO	0.395	0.323	0.011	0.075	-0.334	-0.121

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.12. Matrix of the F_{ML} for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.522^{*}					
2FTP_EO	0.487^{*}	0.275				
2FTP_EC	0.526^{*}	0.507^{*}	0.363			
1FTF_EO	-0.108	-0.023	0.650^{**}	0.260		
1FTF_EC	-0.237	0.351	0.087	0.301	0.270	
1FPT_EO	-0.455^{*}	0.113	-0.141	-0.070	0.315	0.355

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.13. Matrix of the F_{AP} for static balance tests.

	2FTF_EO	2FTF_EC	2FTP_EO	2FTP_EC	1FTF_EO	1FTF_EC
2FTF_EC	0.432					
2FTP_EO	-0.014	0.441				
2FTP_EC	0.173	0.689**	0.328			
1FTF_EO	0.522*	0.564**	0.540*	0.216		
1FTF_EC	0.343	0.455*	0.254	0.329	0.486*	
1FPT_EO	0.474*	0.410	0.181	0.584**	0.765**	0.423

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

The above tables (4.6-4.13) show correlation matrixes of the main variables (CoM, XCoM, CoP and F) in both in both medio-lateral (ML) medio-lateral and anterior-posterior (AP) directions in static balance tests (standing on two feet flat, two feet tiptoes, one feet flat and one foot tiptoes) in both conditions eyes open and eyes closed tests.

4.3.4. Dynamic balance

Effect of learning (between trials) is established in this study, and an example of three trials of 2FT_HJ is shown in appendix 7

4.3.4.1. Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM): for dynamic balance.

Dynamic balance (2-feet flat horizontal jump)

Typical graphical displays are given in Figure 4.17, Figure 4.18, and Figure 4.19. for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in both directions ML *(x)* and AP *(y)* during dynamic balance (for 2-feet flat horizontal jump, 2-feet tiptoes horizontal jump, 1-foot flat horizontal hop). The 1-foot-tiptoes horizontal hop could not be achieved by most of the participants.

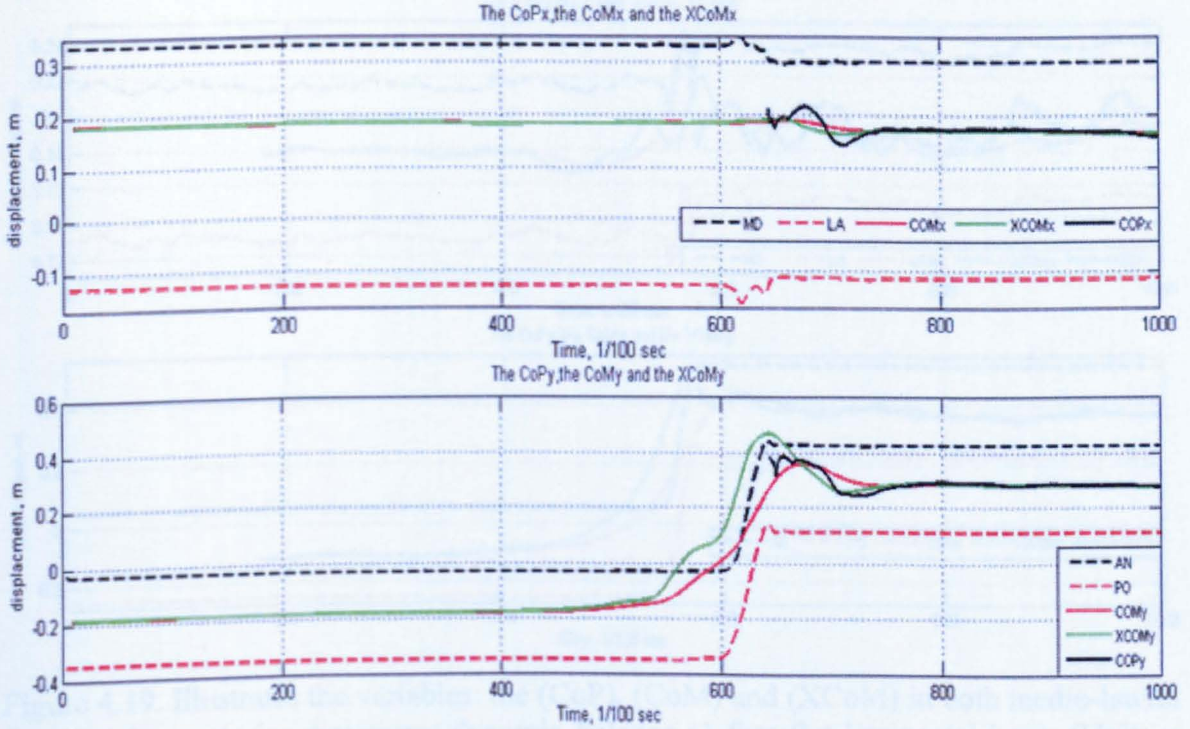


Figure 4.17. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral and anterior-posterior directions. (Units = m)

Dynamic balance (2-feet tiptoes horizontal jump)

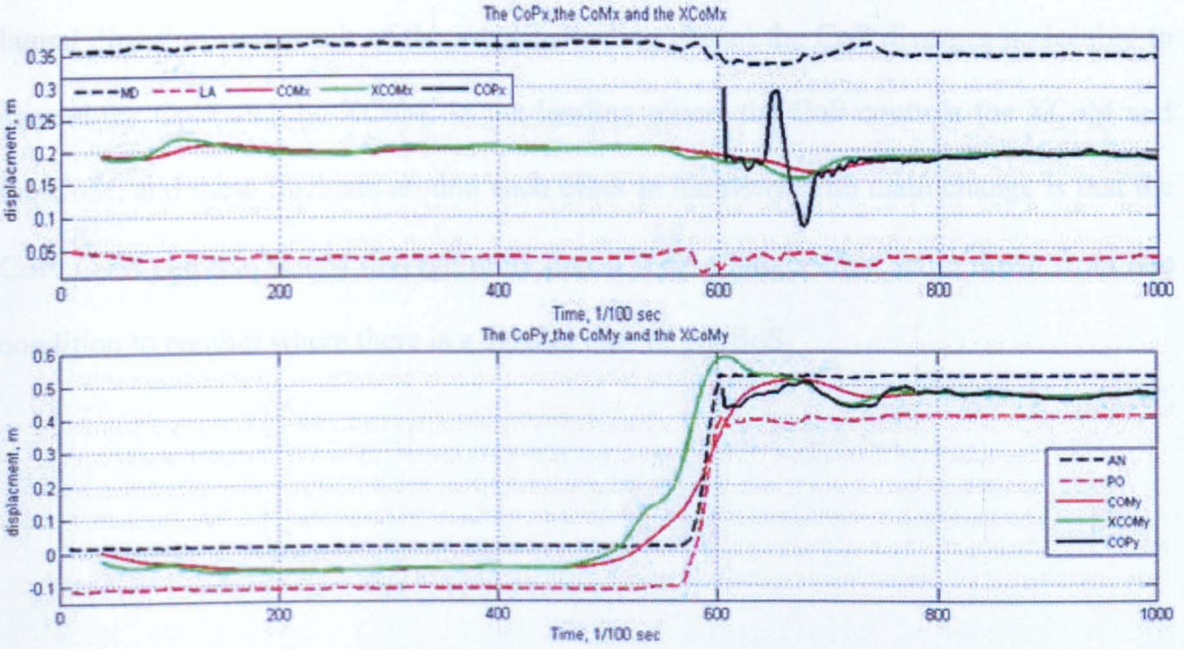


Figure 4.18. Illustrate the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral and anterior-posterior directions. (Units = m)

Dynamic balance (1-foot flat horizontal hop)

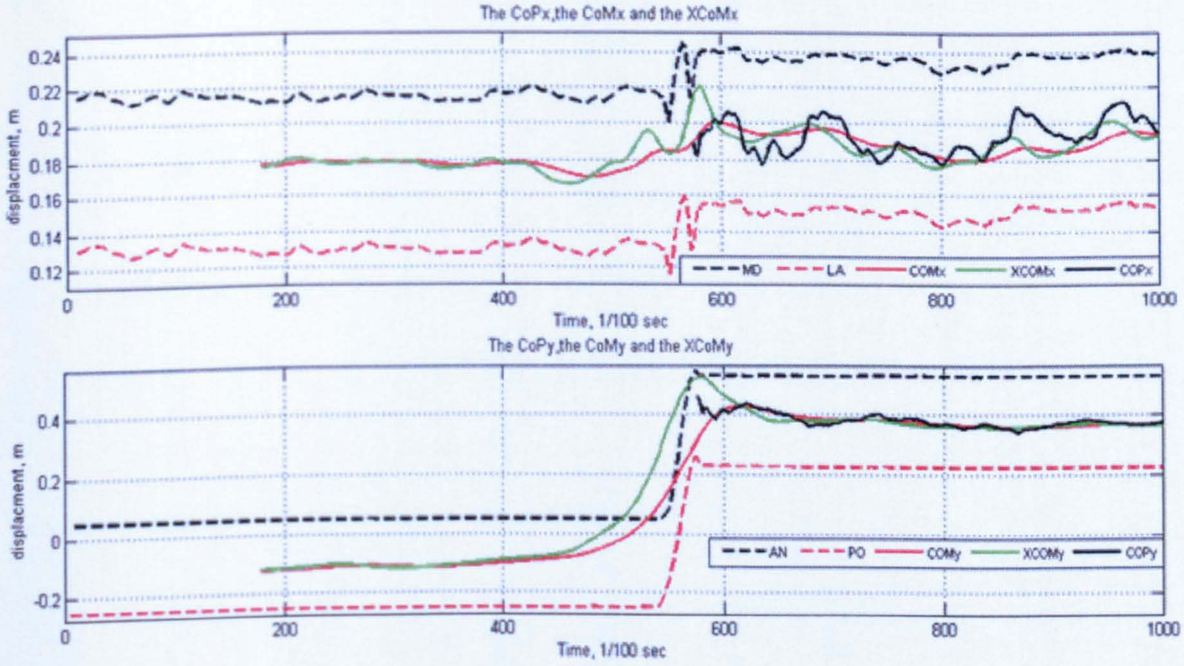


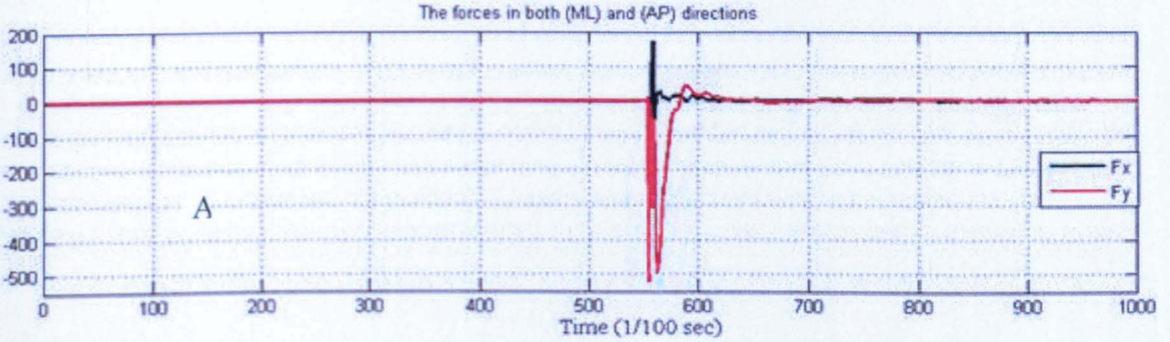
Figure 4.19. Illustrates the variables: the (CoP), (CoM) and (XCoM) in both medio-lateral and anterior-posterior directions: dynamic balance (1-feet flat horizontal hop). (Units = m)

The charts above (Figure 4.17, Figure 4.18, and Figure 4.19) illustrate that in the medio-lateral direction, as a result of the impact (landing phase) the CoP diverges noticeably to control the CoM and the XCoM. In the landing phase, the CoP controls the XCoM and the CoM, and these fluctuate around each other in harmony. The main change is that the CoP, CoM and the XCoM diverge more and it took a longer time settle down from one condition to another where there is a smaller size of the BoS.

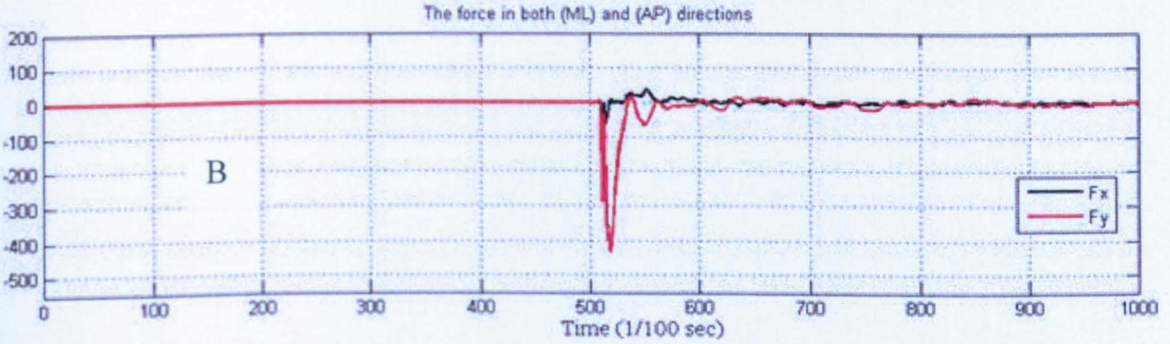
4.3.4.2. Ground reaction force (GRF) for dynamic balance

Typical graphical displays are given in Figure 4.20 for the shear force in both F_{ML} (Fx) and F_{AP} (Fy) directions during dynamic balance activities. These forces fluctuate around a constant level (nominally zero) which represents a state of equilibrium.

Horizontal jump on 2 feet flat



Horizontal jump on 2 feet tiptoes



Horizontal jump hop on 1 foot flat

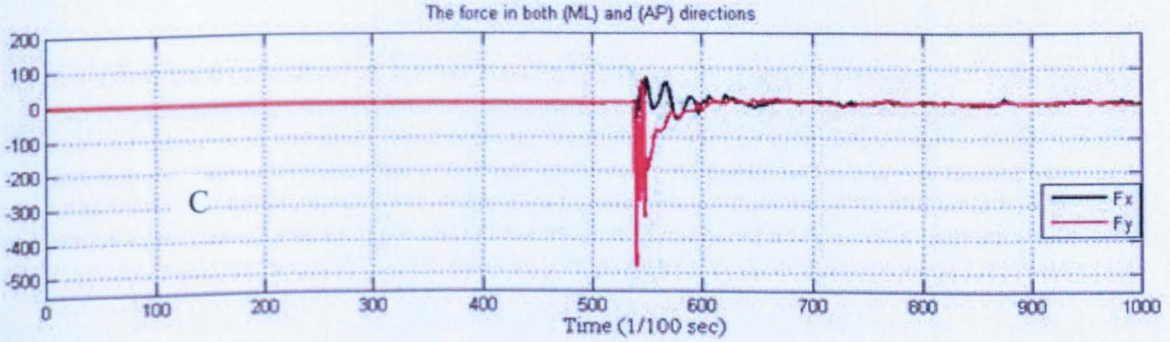


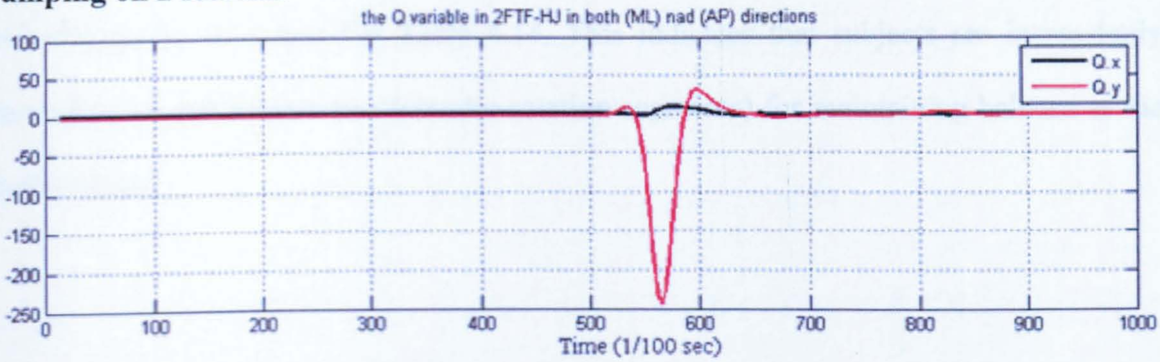
Figure 4.20. Illustrates the applied forces in both the F_{ML} and F_{AP} directions in both medio-lateral (ML) and anterior-posterior (AP) directions: Dynamic balance (2-feet flat jumping, two feet tip toes jumping) and (1-foot flat hopping). Landing occurs at the first deviation from zero. (Units = N)

Landing in dynamic balance requires the ability to maintain balance. Therefore, during landing the applied forces in F_{ML} and F_{AP} are used in correcting the upright position. In Jumping on 2-feet flat, the forces were mostly at the landing impact and settled down after that for the rest of the activity (Figure 4.20A) when there was no necessity for large forces.

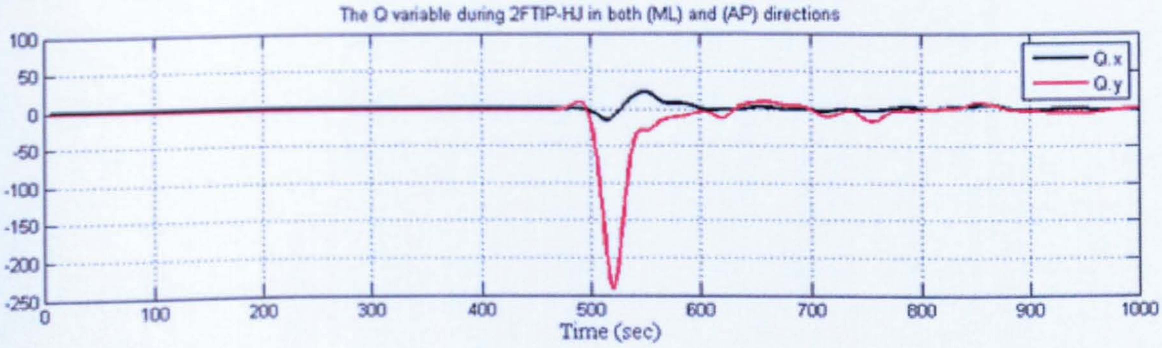
4.3.4.3. The Friction Torque (Q);

Typical graphical displays are given in Figure 4.21 for the shear force in both Q_{ML} (Qx) and Q_{AP} (Qy) directions during dynamic balance (2-feet horizontal Jump). These forces fluctuate around a constant level (nominally zero) which represents a state of equilibrium.

Jumping on 2 feet flat



Jumping on 2 feet tiptoes



Hopping on 1 foot flat

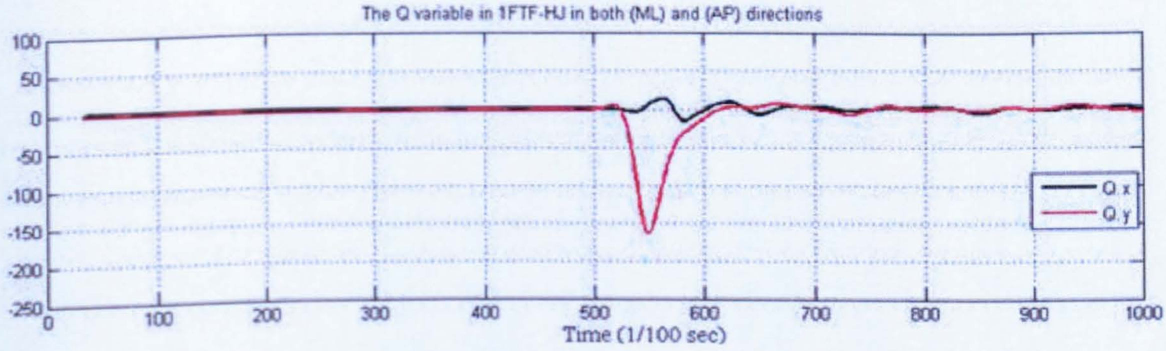


Figure 4.21. Illustrates the applied forces in both the Q_{ML} and Q_{AP} directions in both medio-lateral (ML) and anterior-posterior (AP) directions: Dynamic balance (2-feet flat jumping, two feet tip toes jumping) and (1-foot flat hopping). (Units = N.m)

Landing in dynamic balance requires the ability to maintain balance. Therefore, during landing the applied torque in Q_{ML} and Q_{AP} are used to correct the upright position. In Jumping on 2-feet flat, the forces were mostly at the impact and landing phases and settled down after that for the rest of the activity when there was no necessity for large forces. In contrast, it took a longer time to settle down when jumping on 2-feet tiptoe and even longer in on 1-foot flat Table 4.14. This indicates that subjects are increasingly dependent on mechanism two (counter-rotation segments) for maintaining balance as the BoS reduced.

4.3.4.4. Numerical data

The mean and standard deviations of the range of the CoM, XCoM, CoP, and the mean and standard deviations of the peak of the F and Q are given in Table 4.14.

Table 4.14. The mean and the SD of the range of the CoM, XCoM and CoP in both medio-lateral and anterior-posterior directions in dynamic balance, also the peak forces and friction torques in both medio-lateral and anterior-posterior directions

Tests	CoM_{ML} Mean (SD) (m)	XCoM_{ML} Mean (SD) (m)	CoP_{ML} Mean (SD) (m)	F_{ML} Mean (SD) (N)	Q_{ML} Mean (SD) (N.m)	CoM_{AP} Mean (SD) (m)	XCoM_{AP} Mean (SD) (m)	CoP_{AP} Mean (SD) (m)	F_{AP} Mean (SD) (N)	Q_{AP} Mean (SD) (N.m)
2FFT	0.018	0.028	0.164	18.86	144.3	0.102	0.148	0.171	237.5	639.4
	0.004	0.008	0.039	4.236	37.52	0.020	0.030	0.040	46.48	91.89
2FTtip	0.022	0.037	0.180	18.82	67.57	0.140	0.121	0.140	205.9	569.7
	0.008	0.013	0.058	9.714	26.37	0.043	0.031	0.043	56.45	105.2
1FFT	0.043	0.057	0.066	29.75	272.6	0.190	0.182	0.155	231.2	498.6
	0.023	0.031	0.025	9.015	115.4	0.101	0.130	0.036	34.2	65.5
1FTtip	**	**	**	**	**	**	**	**	**	**

** Most participants lost balance

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat).

4.3.4.5. Trial effects

Centre of Mass

The results in Table 4.15 show that there was no significant main effect of trials for all conditions in both medio-lateral (ML) and anterior-posterior (AP) directions. Mean and SD of range of data for each trial for all tests are illustrated in Figure 4.22.

Table 4.15. Illustrates the trial effects of the Centre of Mass variable between trials in all conditions of horizontal jump tests in both medio-lateral (ML) and anterior-posterior (AP) directions.

Conditions	**CoM_{ML}**	**CoM_{AP}**
2FFT	$F_{(1.926, 36.586)} = 0.324, p > .05$	$F_{(1.336, 25.376)} = 0.189, p > .05$
2FTtip	$F_{(1.760, 33.446)} = 1.657, p > .05$	$F_{(1.631, 30.997)} = 1.379, p > .05$
1FFT	$F_{(1.738, 33.030)} = 3.130, p > .05$	$F_{(1.548, 29.416)} = 0.969, p > .05$

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat).

Centre of Mass: (CoM)

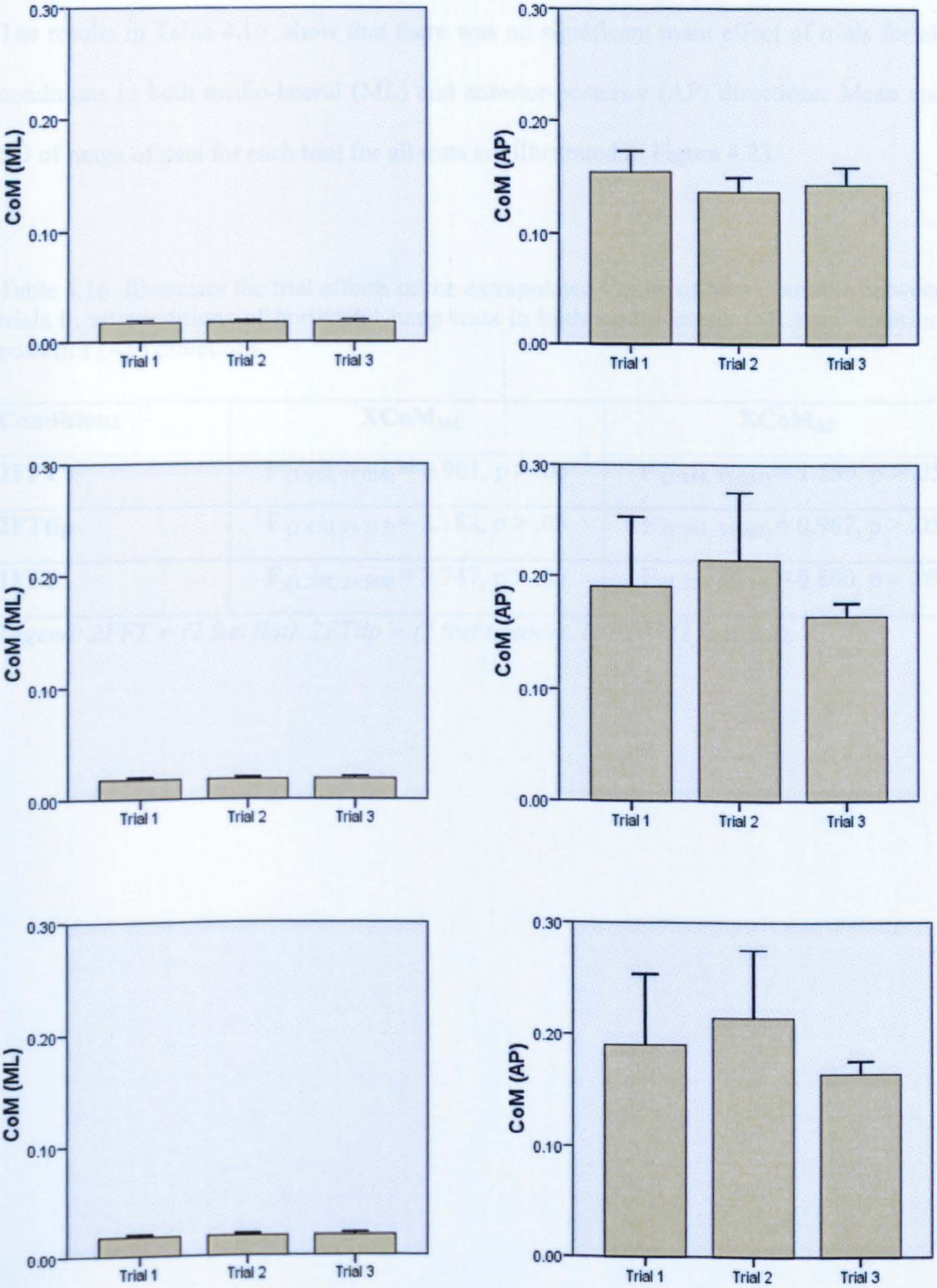


Figure 4.22. The mean and SD of the CoM_{ML} and CoM_{AP} in dynamic balance (2-ft flat and 2-feettiptoes horizontal jump, and 1-ft flat). (Units = m)

Extrapolated Centre of Mass

The results in Table 4.16 show that there was no significant main effect of trials for all conditions in both medio-lateral (ML) and anterior-posterior (AP) directions. Mean and SD of range of data for each trial for all tests are illustrated in Figure 4.23.

Table 4.16. Illustrates the trial effects of the extrapolated Centre of Mass variable between trials in all conditions of horizontal jump tests in both medio-lateral (ML) and anterior-posterior (AP) directions.

Conditions	**$XCoM_{ML}$**	**$XCoM_{AP}$**
2FFT	$F_{(1.949, 37.036)} = 0.901, p > .05$	$F_{(1.844, 35.033)} = 1.559, p > .05$
2FTtip	$F_{(1.670, 31.733)} = 2.182, p > .05$	$F_{(1.841, 34.985)} = 0.967, p > .05$
1FFT	$F_{(1.767, 33.568)} = 2.747, p > .05$	$F_{(1.370, 26.039)} = 0.800, p > .05$

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat).

Extrapolated Centre of Mass: (XCoM)

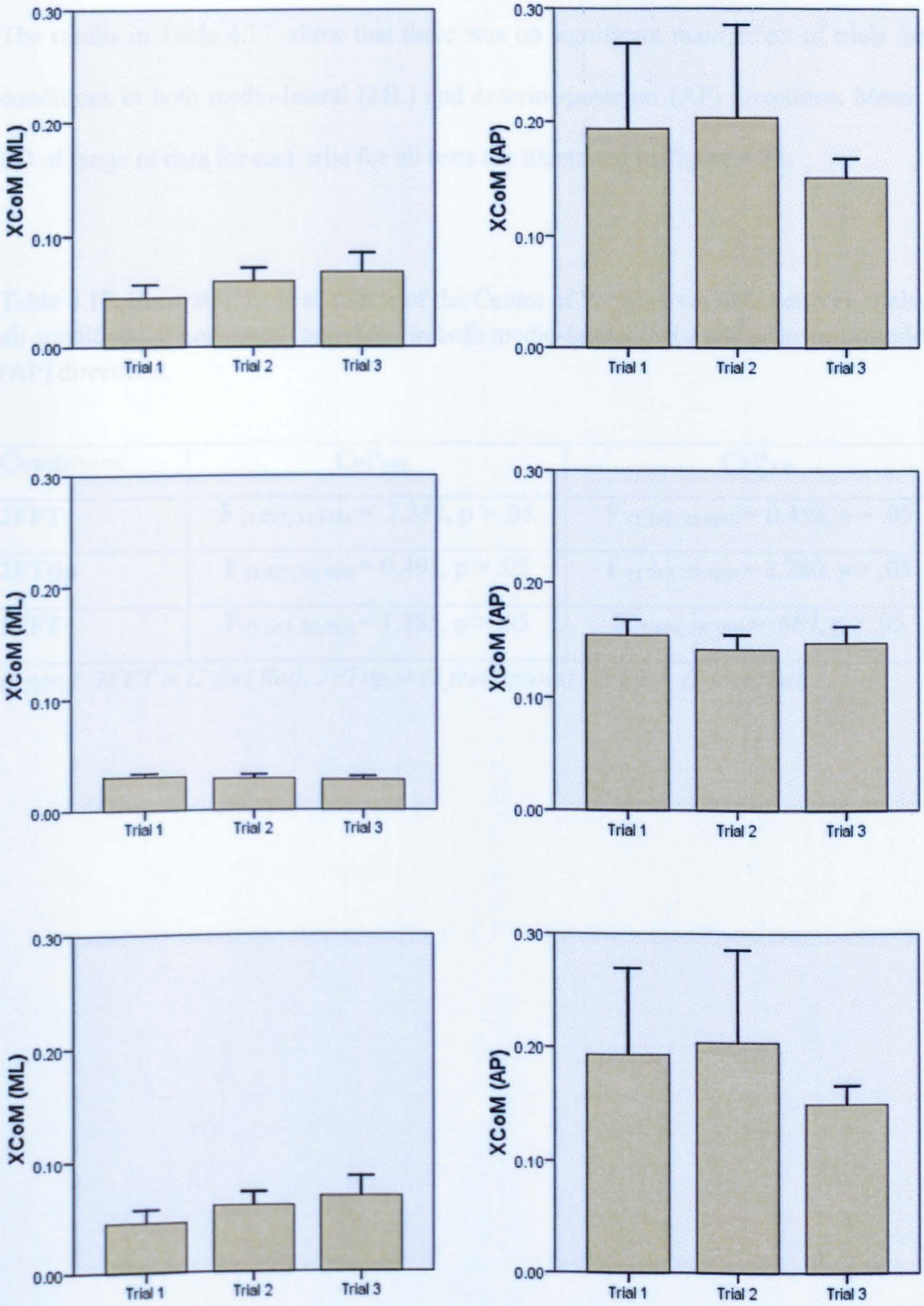


Figure 4.23. The mean and SD of the XCoM$_{ML}$ and XCoM$_{AP}$ in both medio-lateral and anterior-posterior directions: Dynamic balance (2-ft flat and 2-feet tiptoes horizontal jump, and 1-ft flat). (Units = m)

Centre of pressure

The results in Table 4.17 show that there was no significant main effect of trials for all conditions in both medio-lateral (ML) and anterior-posterior (AP) directions. Mean and SD of range of data for each trial for all tests are illustrated in Figure 4.24.

Table 4.17. Illustrates the trial effects of the Centre of Pressure variable between trials in all conditions of horizontal jump tests in both medio-lateral (ML) and anterior-posterior (AP) directions.

Conditions	**CoP_{ML}**	**CoP_{AP}**
2FFT	$F_{(1.797, 34.144)} = 2.238, p > .05$	$F_{(1.385, 25.809)} = 0.458, p > .05$
2FTtip	$F_{(1.615, 30.686)} = 0.491, p > .05$	$F_{(1.993, 37.869)} = 2.280, p > .05$
1FFT	$F_{(1.617, 30.720)} = 1.285, p > .05$	$F_{(1.494, 28.390)} = .669, p > .05$

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat).

Centre of pressure: (CoP)

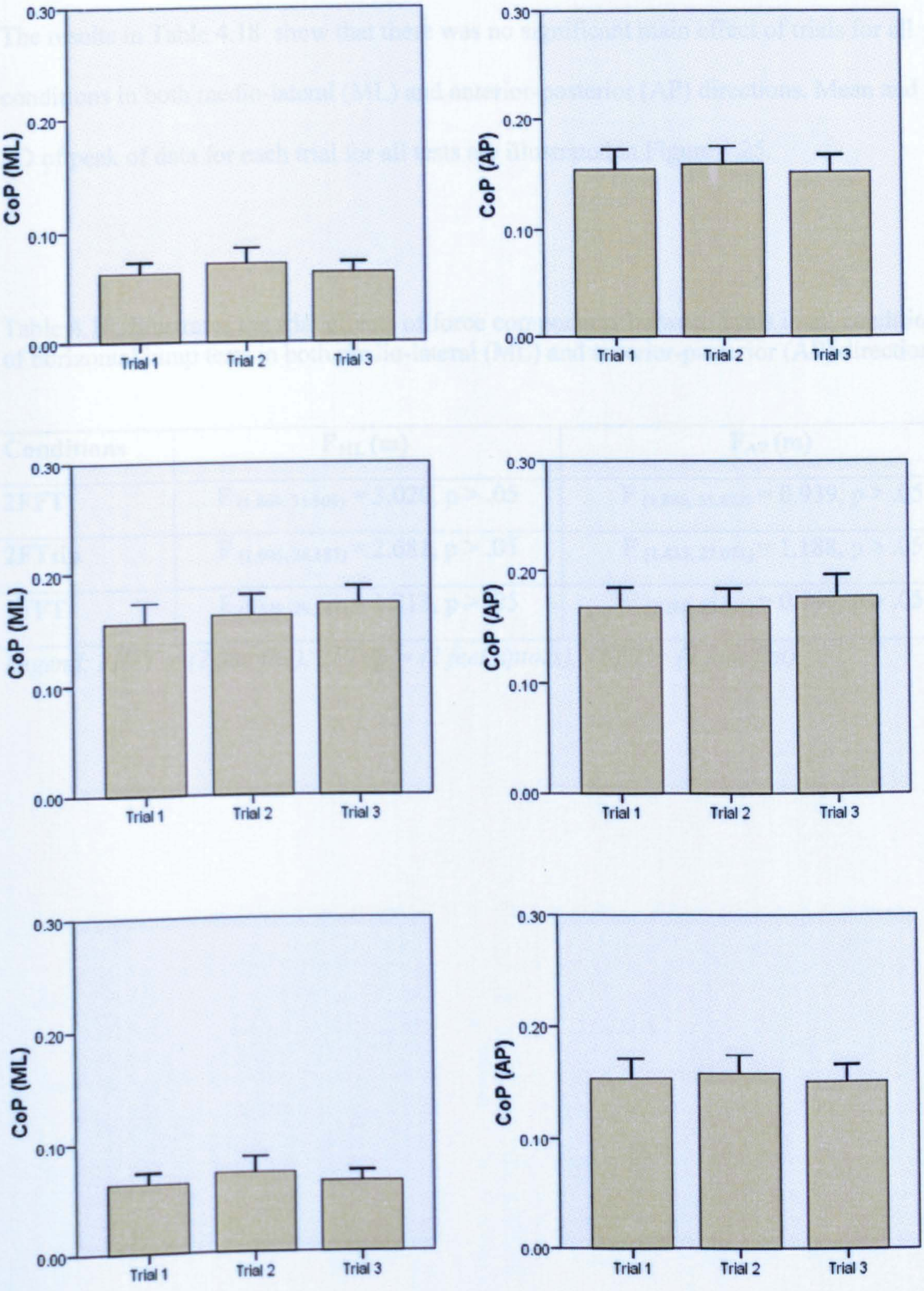


Figure 4.24. The mean and SD of the CoP_{ML} and CoP_{AP} in both medio-lateral and anterior-posterior directions: Dynamic balance (2-ft flat and 2-feet tiptoes horizontal jump, and 1-ft flat). (Units = m)

Ground reaction forces

The results in Table 4.18 show that there was no significant main effect of trials for all conditions in both medio-lateral (ML) and anterior-posterior (AP) directions. Mean and SD of peak of data for each trial for all tests are illustrated in Figure 4.25.

Table 4.18. Illustrates the trial effects of force components between trials in all conditions of horizontal jump tests in both medio-lateral (ML) and anterior-posterior (AP) directions.

Conditions	**F_{ML} (m)**	**F_{AP} (m)**
2FFT	$F_{(1.869, 35.509)} = 3.020, p > .05$	$F_{(1.886, 35.832)} = 0.939, p > .05$
2FTtip	$F_{(1.905, 36.187)} = 2.681, p > .05$	$F_{(1.425, 27.071)} = 1.188, p > .05$
1FFT	$F_{(1.539, 29.241)} = 1.213, p > .05$	$F_{(1.260, 23.941)} = 0.799, p > .05$

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat).

Ground reaction forces: (GRF)

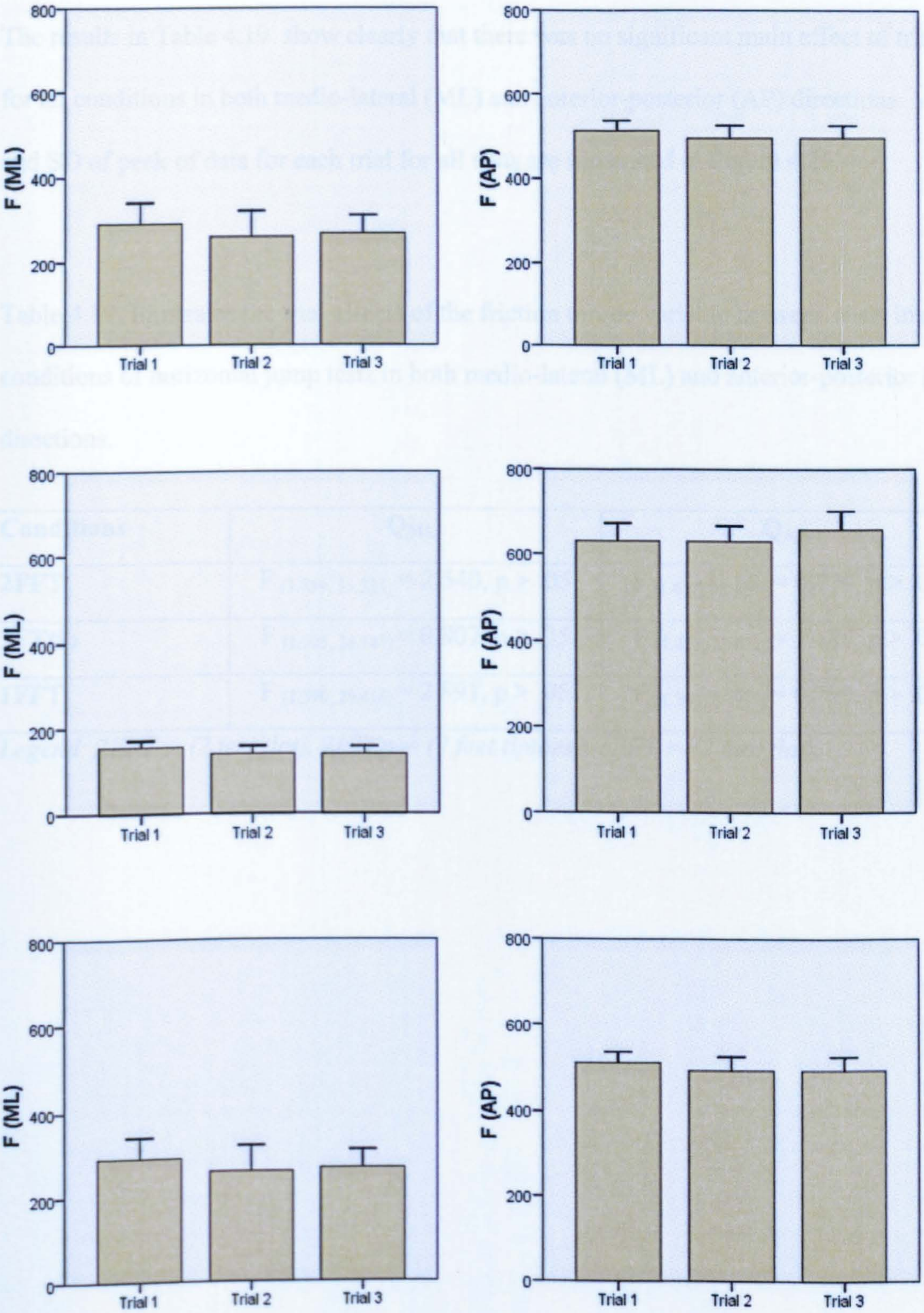


Figure 4.25. The mean and SD of the peak F_{ML} and F_{AP} in dynamic balance (2-ft flat and 2-feet tiptoes horizontal jump, and 1-ft flat). (Units = N)

Friction torque

The results in Table 4.19 show clearly that there was no significant main effect of trials for all conditions in both medio-lateral (ML) and anterior-posterior (AP) directions. Mean and SD of peak of data for each trial for all tests are illustrated in Figure 4.26.

Table 4.19. Illustrates the trial effects of the friction torque variable between trials in all conditions of horizontal jump tests in both medio-lateral (ML) and anterior-posterior (AP) directions.

Conditions	Q_{ML}	Q_{AP}
2FFT	$F_{(1.859, 35.324)} = 2.540, p > .05$	$F_{(1.602, 30.430)} = 0.779, p > .05$
2FTtip	$F_{(1.905, 36.187)} = 0.807, p > .05$	$F_{(1.425, 27.071)} = 1.188, p > .05$
1FFT	$F_{(1.390, 26.416)} = 2.891, p > .05$	$F_{(1.260, 23.941)} = 0.799, p > .05$

Legend: 2FFT = (2 feet flat), 2FTtip = (2 feet tiptoes), 1FFT = (2 foot flat).

Friction torque: (Q)

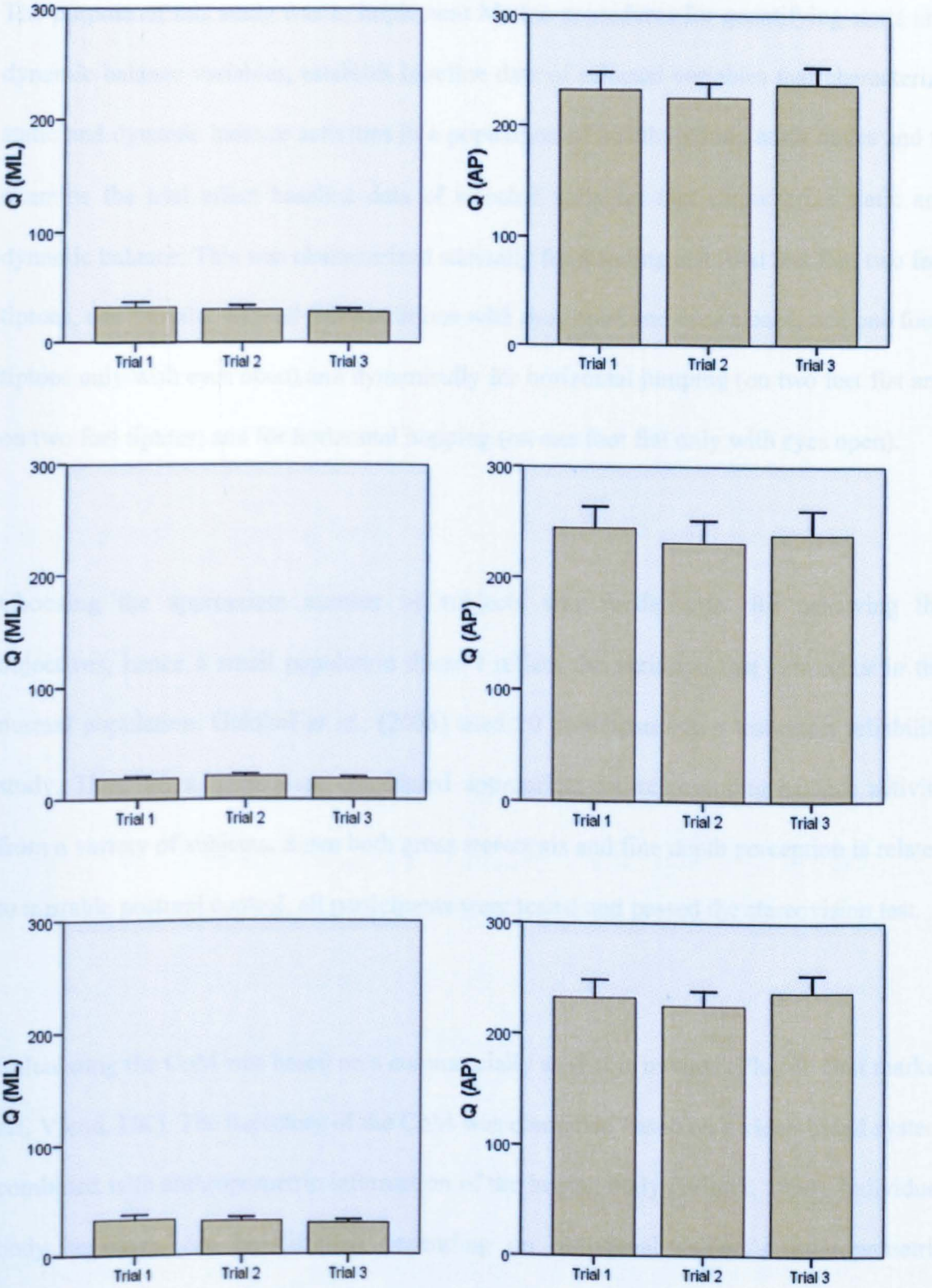


Figure 4.26. The mean and SD of the peak of Q_{ML} and Q_{AP} in dynamic balance (2-ft flat and 2-feet tiptoes horizontal jump, and 1-ft flat). (Units = $N.m^{-1}$)

4.4. Discussion:

The purpose of this study was to implement Matlab procedures for quantifying static and dynamic balance variables, establish baseline data of selected variables that characterize static and dynamic balance activities in a population of healthy young adult males and to examine the trial effect baseline data of selected variables that characterize static and dynamic balance. This was characterized statically for standing test (two feet flat, two feet tiptoes, one foot flat with all test conditions with eyes open and eyes closed, and one foot-tiptoes only with eyes open) and dynamically for horizontal jumping (on two feet flat and on two feet tiptoes) and for horizontal hopping (on one foot flat only with eyes open).

Choosing the appropriate number of subjects was fundamental for achieving the objectives, hence a small population doesn't reflect the variation that can occur in the normal population. Geldhof *et al.*, (2006) used 20 participants in a test-retest reliability study. Thus, 20 subjects were considered appropriate for representing balance activity from a variety of subjects. Since both gross stereopsis and fine depth perception is related to unstable postural control, all participants were tested and passed the stereovision test.

Calculating the CoM was based on a commercially available method (Plug-in Gait marker set, Vicon, UK). The trajectory of the CoM was computed based on a video-based system combined with anthropometric information of the human body (Winter, 1990). Individual body segments can be different depending on individual subject's anthropometric information. The Plug-in Gait model is widely accepted as a biomechanical model in both clinical and research settings for evaluating gait dynamics (Gutierrez-Farewik *et al.*,

2006) as well as static and dynamic balance (Reevesa *et al.*; 2008). Although, The CoM displacement based on the Plug-in-Gait model has been analysed recently in many studies (Brostrom *et al.*, 2007; Orendurff *et al.*, 2004) it does not consider the asymmetry of the human body particularly in the anterior-posterior direction. Talbott (2005) avoided this issue by representing a plot of the CoM and matching them by displaying the CoP displacement data on a secondary axis. Consequently, in this study a Matlab script was used to shift mathematically the CoM toward the CoP to provide assured agreement between the CoP and CoM data.

A novel method of computing the BoS dynamically was established by adding markers to the subjects' feet/foot, which were tracked during the tests in both static and dynamic conditions. This provided a convenient way of establishing the BoS without the need for additional equipment and data processing.

Basically, this study was designed to implement Matlab procedures for quantifying selected static and dynamic balance variables. The developed Matlab code can treat numerous files at once and creates figures in a standardised way. Many individual and generic Matlab functions were written for processing data and to create SPSS output which can be then statistically treated.

To establish baseline data of selected variables which characterize static and dynamic balance activities in a population of healthy young adult males, it was fundamental to test many static and dynamic conditions but necessary to reduce these for further studies.

Vision is a very important factor in sport activities and testing with eyes open is essential. Therefore, the eyes closed tests will not be undertaken in future tests. Standing on two feet flat is an easy task while standing on one foot tiptoes is very difficult. Standing on one foot flat is challenging enough and commonly used in testing postural balance. Therefore, standing on one foot flat can be used as a representative test for static balance that is supported and clarified by establishing a correlation between static tests on the main variables (e.g. CoM, XCoM, CoP and F) tables (Table 4.6– Table 4.13). This is supported by the fact that this test condition had the highest number of correlations with other tests (Table 4.6 to Table 4.13). Therefore, the one foot flat, eyes open test can be used to represent static balance in the forthcoming study.

For testing dynamic balance the existing horizontal jumping tests are useful for establishing baseline data of selected variables which characterize dynamic balance activities in a population of healthy young adult males. Due to the complexity of jumping on tiptoes and most subjects found this difficult and therefore failed to execute it successfully, the two feet tiptoe horizontal jump will not be used in the forthcoming study. instead vertical jumps (e.g. 2 feet flat vertical jump and one foot flat vertical hop) will be used which will widen the investigating into dynamic balance. An interesting pattern emerged when generally comparing jumping (two feet flat) and hopping (one foot flat). In one foot flat horizontal jump, the excursions of CoM, XCoM, and CoP were larger than in two feet flat horizontal jump, suggesting that the one foot flat condition is a less stable condition. However, shear forces and Q were smaller in one foot flat compared to two feet flat, suggesting that in one foot flat mechanism two (counter rotating segments) is utilized to a lesser extent to recover balance. This indicates interesting differential effects of condition (one foot flat versus two feet flat) related to the different balance mechanisms.

The trial effect (baseline data) of selected variables (CoM, CoP, XCoM, F) which characterize static and dynamic balance was established by testing the differences between the trials. The results show clearly that there was no significant main effect of trials neither in eyes open, eyes closed conditions nor in medio-lateral (ML) and anterior-posterior (AP) directions. In other words, participants replicate similarly in each trial which means the mean of the trials can be used for analysis.

4.5. Conclusion

The main finding can be summarized as following:

- Using Matlab procedures for quantifying selected static and dynamic balance is practical for handling such large data (e.g. analysis, plotting and producing SPSS output)
- Baseline data of selected variables which characterize static and dynamic balance activities was established for a population of healthy young adult males.
- No significant trial effect was found between repetitions on selected variables which characterize static and dynamic balance.
- The functional BoS can be measured by using additional markers to the feet/ foot.
- Testing with eyes open is related to sport activity. Furthermore, one foot flat is a representative test of static balance.
- Tiptoes tests, either in static or dynamic balance are too challenging for most participants in normal circumstances.
- An interesting differential effect of condition (one foot flat versus two feet flat) was observed related to the utilization of different balance mechanisms.
- The results of this study can be used for the comparative purpose in the forthcoming study.

Chapter (5) Study 3: The effects of adding external mass and fatigue upon static and dynamic balance

5. Study 3: The effects of adding external mass and fatigue upon static and dynamic balance

5.1. Introduction

One of the physical factors influencing static and dynamic balance is body mass and mass distribution e.g. carrying loads and obesity. The effects of carrying external mass on static and dynamic balance has been investigated in many studies mostly in children population (e.g. carrying school's backpack, Singh and Koh., 2009), fewer studies have investigated that in adult populations (Grimmer *et al.*, 2002) and in these some have dealt with military manoeuvres (Heller *et al.*, 2009). Since jumping and single-leg hop stabilization tests are challenging and most closely mimic athletic performance (Wikstrom *et al.*, 2004) and no study has yet investigated adding external mass in relation to a sport activity (jumping / hopping), it makes this a suitable topic for further studies.

Fatigue is one of the main factors influencing balance. Fatigue is commonly experienced by people in daily life and in medical situations. Miller *et al.* (1995) defined muscle fatigue as the reduction in maximal force generating capability during exercise. In a sport context, fatigue increases the complexity of a balance task since it impairs or reduces the force capacity of muscles, decreases sensitivity of the proprioceptive system, and increases body sway (Simoneau *et al.*, 2006). There is limited information regarding the effect of fatigue on dynamic balance, despite its considerable importance to dynamic activities in sport. Therefore the aim of this study was investigating the effects of adding external mass and inducing localised fatigue on static and dynamic balance.

5.1.1. Objectives

1. To investigate the effect of carrying additional weight (15% of total weight) upon static and dynamic balance activities in healthy young adult males ;
2. To investigate the effect of inducing intensive localized fatigue (lower extremity) upon static and dynamic balance activities in healthy young adult males.

5.2. Method

5.2.1. Participants

The participants in this study were twenty healthy males (age 23.9 ± 5.5 years, height 178 ± 5.8 cm, body mass 74.1 ± 5.7 kg), of which 6 participants took part in the previous study (study 2). They had neither history of problems of postural instability nor gross problem with stereopsis and fine depth perception, and the main requirement was to perform normal balance in a set of different balance tests.

Participants were required to avoid strenuous exercise for at least forty eight hours prior testing to avoid fatigue. Any participants who had experienced previous lower extremity surgical repair and/or current injury or pain affecting the lower extremity that altered participation were excluded from the study. Each participant signed the consent form that complied with the testing information sheet (Appendix 2). A copy of the consent form was approved by the University Ethics Committee and located in (Appendix 1).

5.2.2. Instrumentation

Two force platforms were used as detailed in study 1 and 2: the first was a Kistler 9281B11, Kistler, Switzerland (dimensions 400 x 600mm) which was built-in and levelled with the floor of the laboratory. It was used in the standing tests or for landing in the hopping and jumping tests. The second was Kistler 9287B, Kistler, Switzerland (dimensions 600 x 900mm), whose surface was 20 cm higher than floor level and positioned next to the built-in platform, and was used for take-off in the hopping and jumping movements. Both force platforms recorded ground reaction forces and the CoP at 1000 Hz (12 bit A/D conversion) and were time synchronised with the Vicon motion analysis system (See Figure 3.1 and Figure 3.4).

Anthropometric measurements were made by the same person as documented in study 1 and 2. Both sides of the limbs were measured. These values were essential to compute the Centre of Mass. Body mass and height were also measured as detailed in study 1 and 2. A total of eight high resolution cameras (100 Hz) were used to track the reflective markers during the test to calculate the CoM which was calculated using a commercially available method (Plug-in-Gait marker set, Vicon, UK) as detailed in study 2 (Figure 3.4). They were also used to track the dynamic trajectories of the BoS during the events. The BoS was measured using additional feet markers developed in study 2 (see Appendix 3).

5.2.3. Procedures

5.2.3.1. Anthropometry

Similar to previous studies, measurements of stature and body mass were taken in the same manner to standardise procedures:

Stature

Measurements of stature were recorded using analogue Leicester height measure (Seca Ltd., Birmingham, UK). Participants were measured barefoot whilst wearing a stretch suit prior to starting balance testing. Measurements were recorded to the nearest 0.1cm.

Body mass

Measurements of body mass were recorded using analogue Seca scales (Seca Ltd., Birmingham, UK). Participants were measured barefoot whilst wearing a stretch suit prior to starting balance testing. Measurements were recorded to the nearest 0.1kg.

5.2.3.2. Jump Height Assessment:

Standardization is essential in testing, in horizontal jumping tests, participants were instructed to take-off and land on a fixed location. Also in vertical jumping tests they were asked to jump to a certain height (75% of maximum jump) which was determined as follow:-

After a warm up, vertical jump trials were assessed by using a simplified vertical jump measurement method (Figure 5.1), based on three concepts **A**: *standing height*, **B**: *the maximum jump* and **C**: *75% of maximum jump*.

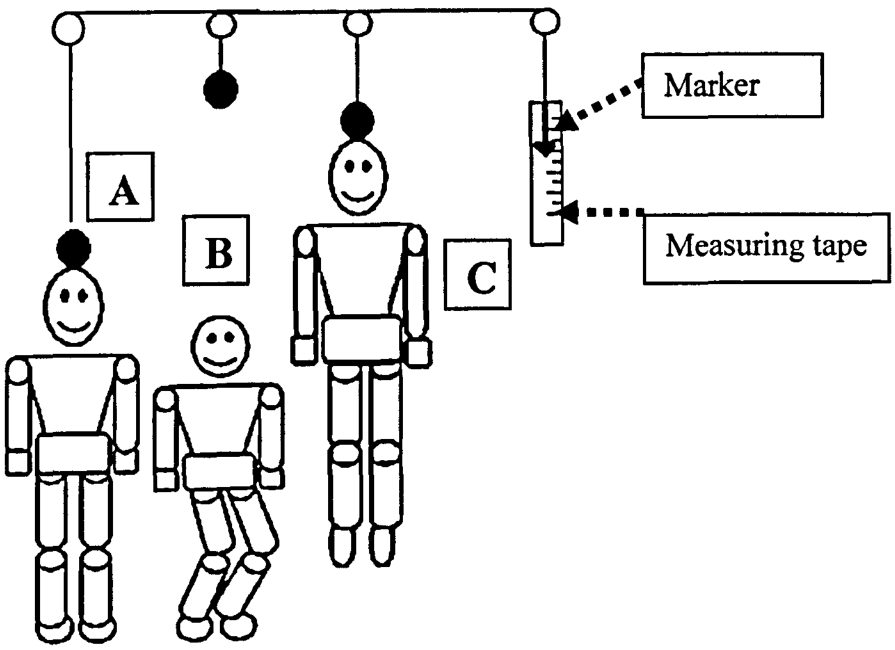


Figure 5.1. Shows the determination of the 75% of max VJ.

Steps to find the 75% of maximum vertical jump:

A. Stand underneath a ball (at the height of subject), and record the measurement on the measuring tape (A).
B. Raise the ball above the subject, and ask him to perform maximum jumps (bringing the ball to a height at which the subject reaches the ball at the apex of flight by the tip of the head). This is the 100% maximum jump.
C. Work out the difference, and only use 75% of the maximum jump.

This method has been used in previous study related to vertical jumping (Vanrenterghem *et al.*, 2004).

After finding the maximum vertical jump height, 75% of this distance was calculated and used in all vertical trials. This procedure was used for every individual participant to standardize the efforts of jumping. The average maximum vertical jump performance for the participants was 42.1 ± 8.9 cm (range 32 cm to 53.5 cm).

5.2.3.3. Added weight Protocol

A weighted vest was prepared for carrying the added loads (Figure 5.2). After establishing the participant's total body mass, 15% of that mass was calculated (to nearest 0.45 kg), then added to the weighted vest. Loads were added into the pocket of the vest about the estimated location of the Centre of Mass (about 57% of the total height). This vest was tightened enough to ensure the constancy of the markers on its locations. On account of the weighted jacket, some markers were positioned as required in Plug-in Gait but on the jacket instead. These markers are: [the C7 (Back of neck), the T10 (Upper back), the RBAK (Right back) which is optional, the RSHO and the LSHO (right and left shoulder)].

Figure 5.2. Shows both the weighted vest and the participant while wearing it loaded.

5.2.3.4. Fatigue protocol:

The participants were required to warm up prior to undertaken the fatigue protocol. The warm up consisted of pedalling on a cycle ergo-meter at a self-selected light intensity for five minutes followed by higher intensity for three minutes.

The participants were then instructed to perform 16 maximum effort non-stop vertical jumps; 8 squats while lifting a weight followed by 8 calf-raise exercises while still having the weight on shoulder. After that, the participants were then instructed to lunge 8 times 8 on each foot while holding dumbbells. These exercises were repeated 3 times. Although the subjects were encouraged to perform the whole session they were asked to inform the experimenter if they have felt they had already reached the target of fatigue on the Borg scale of 17-20 Appendix 5 (Borg, 1998).

5.2.3.5. Questionnaire:

A copy of personal medical history and physical activity assessment questionnaire was handed to the participant 2 days before the testing day (see Appendix 4). This was identical to the one used in study 2.

5.2.4. Pilot work

A few pilot experiments were undertaken to examine weight carrying manoeuvres and periods of time for the fatigue protocol. Also, establishing estimated time for each participant to complete the tests.

5.2.5. Data collection:

5.2.6. Activities and Testing Protocol:

Standardized instructions and explanations were given to the participant as in study 1 and 2. Each participant was given an opportunity to practice prior to the measurements, and perform three trials for all conditions:

- *statically*: standing still on one foot flat for 35s eyes open (Rom, 1FFT)
- *dynamically*:
    a) Vertical jumps/ hops: two feet flat vertical jump (2FFT-VJ) and One-foot flat vertical hop (1FFT-VJ) conditions, take-off and landing on the same force platform. To standardise efforts, the height of approximately 75% of subject's maximum vertical jump was required.

    b) Horizontal jumps/ hops: two feet horizontal jump (2FFT-HJ) and one foot horizontal hop (1FFT-HJ) both conditions take-off from the higher force platform to land on the lower built-in force platform at a specified location (standardising efforts).

Unsuccessful trials that included loss of balance, extreme asymmetry, or other procedural errors were kept for future work in order to give further information about balance and falls in sport related activities. Only correct trials were computed in this study.

5.2.6.1. Randomization:

To avoid bias, a Latin square was used to counterbalance the conditions (Figure 5.3) which provide a unique order for administrating tests.

Baseline	S 1	S 2	S 3	S 4	S 5	**Weighted**	S 1	S 2	S 3	S 4	S 5	**Fatigue**	S 1	S 2	S 3	S 4	S 5
Rom 1ft	1	2	3	4	5	2ft VJ	1	2	3	4	5	1ft HJ	1	2	3	4	5
1ft VJ	2	3	4	5	1	1ft HJ	2	4	1	5	3	Rom1ft	2	3	5	1	4
1ft HJ	3	4	5	1	2	Rom 1ft	3	5	4	2	1	2ft HJ	3	5	4	2	1
2ft VJ	4	5	1	2	3	2ft HJ	4	1	5	3	2	1ft VJ	4	1	2	5	3
2ft HJ	5	1	2	3	4	1ft VJ	5	3	2	1	4	2ft VJ	5	4	1	3	2

Figure 5.3. Shows the table of the Latin square for 5 participants of 5 tests in 3 conditions.

Note: the above table is an example and was changed for every single participant.

5.2.7. Data analysis:

The (AP) and (ML) coordinates of the CoP and the CoM were derived from recorded data and low pass filtered at 10 Hz. The velocity of the CoM was calculated using a 3-point central difference differentiation algorithm (Winter, 1990). From these data;

- For static balance, the mean of the RMS values of all variables (CoM, XCoM and CoP in both ML and AP directions) for the three trials were calculated for each subject as well as the grand mean and standard deviation for each condition.
- For dynamic balance, the mean of peaks of horizontal forces (F_{ML} and F_{AP}), and Friction Torque (Q), and the mean of the range of the CoM, XCoM and CoP of the three trials were calculated for each subject in both ML and AP directions. In addition the mean and SD of Dynamic Postural Stability Index and Time to Stabilization were computed.

5.2.7.1. Stability indices:

For dynamic trials, stability indices are based on the RMS deviation of the force variable from its baseline value (nominally equal to zero) for the medio-lateral, anterior-posterior, and body weight (BW) for the vertical force. These are universal calculations of dynamic stability and sensitive to changes in all 3 directions:

Generally, $PSI = \sqrt{[\Sigma(0 - X)^2/n]}$, or = RMS (X)

For component forces: - $PSI_{ML} = \sqrt{[\Sigma (0 - F_{ML})^2 / n]}$,

$PSI_{AP} = \sqrt{[\Sigma (0 - F_{AP})^2 / n]}$,

$PSI_{V} = \sqrt{[\Sigma (BW - F_{V})^2 / n]}$,

Where n is the number of data points. This gives the Dynamical Postural Stability Index (DPSI) as:

$$DPSI = \sqrt{[\Sigma (0 - F_{ML})^2 / n] + [\Sigma (0 - F_{AP})^2 / n] + [\Sigma (BW - F_{V})^2 / n]}$$

(Wikstrom *et al.*, 2005)

Calculation of DPSI was based on 3s data post-landing (touchdown force platform). The average values from the 3 successful trials of each of the dependent variables were presented.

5.2.7.2. Computing Time to stabilization (TTS):

For dynamic trials, stabilization time for each of the forces (F_{ML}, F_{AP} and F_{v}) and CoP signals was calculated using the technique of sequential estimation from time of landing. The algorithm calculated a cumulative average of the data points in a series by successively adding 1 point at a time. So after the first point, the average of the first 2 data points was calculated; then the average of the first 3 data points was calculated, and so on. The last calculation was simply the mean of all points in the series. At the time the sequential average remained within one quarter of the SD of the overall series, the participant was considered to be stable. The stabilization time, was selected as the point where this occurred. This calculation is based on sequential analysis of data points within the first 3s after touchdown on the force platform (Colby *et al.*, 1999; Wikstrom *et al.*, 2005).

Computing TTS was based on a Matlab script which dealt with the whole set of force data, this method was suitable with horizontal activities (jumping and hopping) whereas in vertical activities (jumping and hopping) where participants start from the same force platform, calculating the TTS was not applicable and required a complex routine to start computing TTS after the flight phase.

5.2.7.3. Using Matlab

Matlab scripts (Matlab 7.4.0, R2007a, .m files) were developed in conjunction with laboratory staff in order to create organized functions for analyzing data. These functions can be used with numerous data for creating informative organized structures including plots, and all treated outputs were saved as SPSS files.

5.2.7.4. Statistical Analysis

To analyse the postural balance parameters during static and dynamic testing, each variable for each condition (baseline, added weight and post fatigue) was tested for normality of distribution. If data were found to be non-normal or skewed, a log transformation was used to correct it. Repeated measures analyses of variance (SPSS GLM procedure) were used to test between trial differences in each condition to determine if there was a trial order effect (i.e. effect of learning). The statistical model was a repeated measures of ANOVA with two within subject factors [CONDITION, 3 levels] and [TRIAL, 3 levels]. If there was a significant main effect a contrast analysis was used to illustrate which levels of the factors differed.

The simple contrast was used to compare between the reference value (baseline) with the other conditions (added weight and post fatigue) whereas the difference contrast was used between times (trials) to illustrate any learning effect.

The Statistical Package for the Social Sciences (SPSS) version 17 (*SPSS Inc*, Chicago, IL*)* was used to manage and analyze data. The alpha level was set at .05 to indicate statistical significance.

5.3. Results:

5.3.1. Static balance

5.3.1.1. Standing balance test (1-foot flat)

Typical graphical displays are given in Figure 5.4 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in medio-lateral (ML) and anterior-posterior (AP) directions during static balance (1foot flat, eyes open). These variables were characterised by the mean and standard deviation of the RMS values for each variable and are given in Table 5.1.

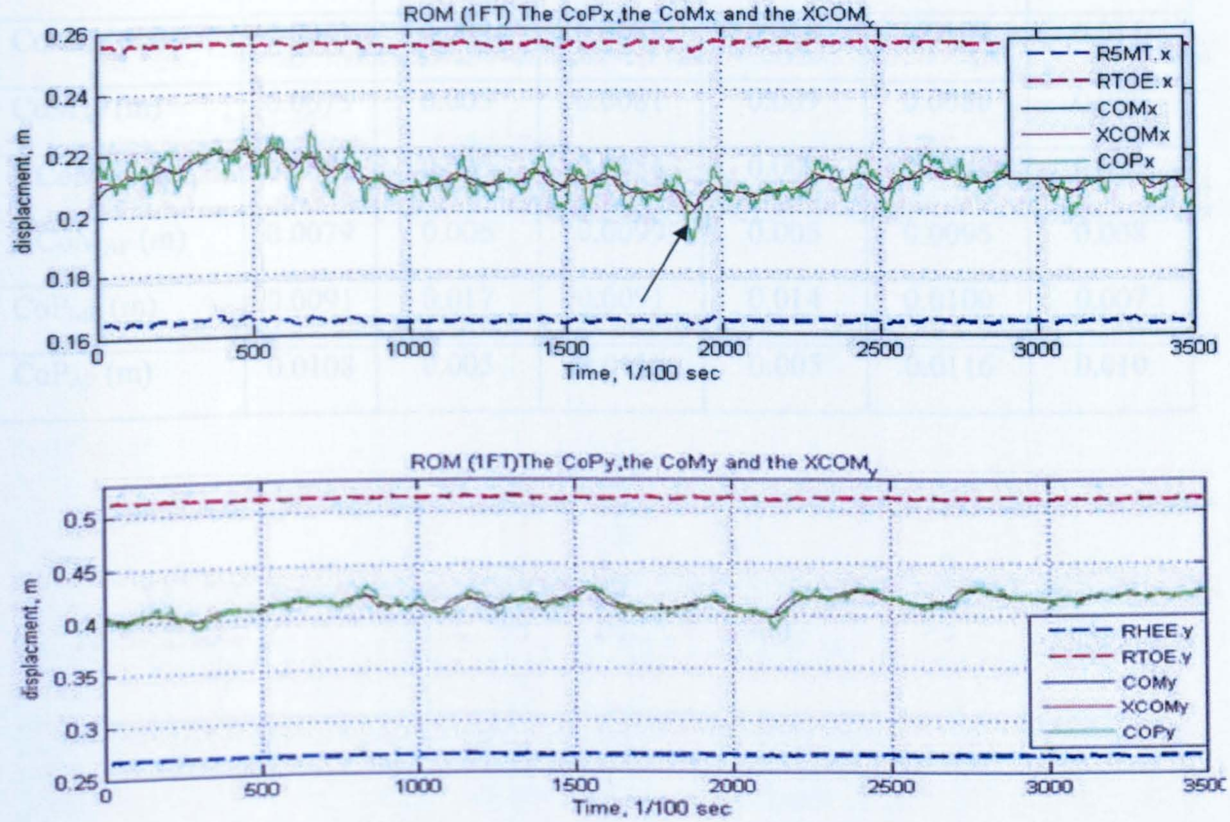


Figure 5.4 The variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for static balance (1-foot flat, eyes open). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BOS)

The above figures illustrate a static balance condition (1-foot flat, eyes open). It is seen that the CoP (green line) follows the other variables (XCoM and CoM) during the whole event, but sometimes the XCoM is slightly separated from the CoM where there is a fast correction was used by the CoP which is indicated by the arrow (Figure 5.4). Otherwise, (for this slow movement) they are close together to represent stable circumstances.

Table 5.1. Mean and standard deviation of the RMS value of each variable in both the medio-lateral (ML) and anterior-posterior (AP) directions during static balance (1-foot flat, eyes open) for baseline, added weight and fatigue conditions.

Variables	Baseline		Added weight		Fatigue	
	Mean	SD	Mean	SD	Mean	SD
CoM_{ML} (m)	0.0081	0.008	0.0079	0.018	0.0104	0.011
CoM_{AP} (m)	0.0073	0.005	0.0081	0.009	0.0080	0.008
$XCoM_{ML}$ (m)	0.0082	0.005	0.0086	0.009	0.0089	0.007
$XCoM_{AP}$ (m)	0.0079	0.006	0.0099	0.005	0.0095	0.008
CoP_{ML} (m)	0.0091	0.017	0.0091	0.014	0.0100	0.007
CoP_{AP} (m)	0.0108	0.005	0.0115	0.005	0.0116	0.010

Figure 5.5 illustrates the data for the Postural Stability Index.

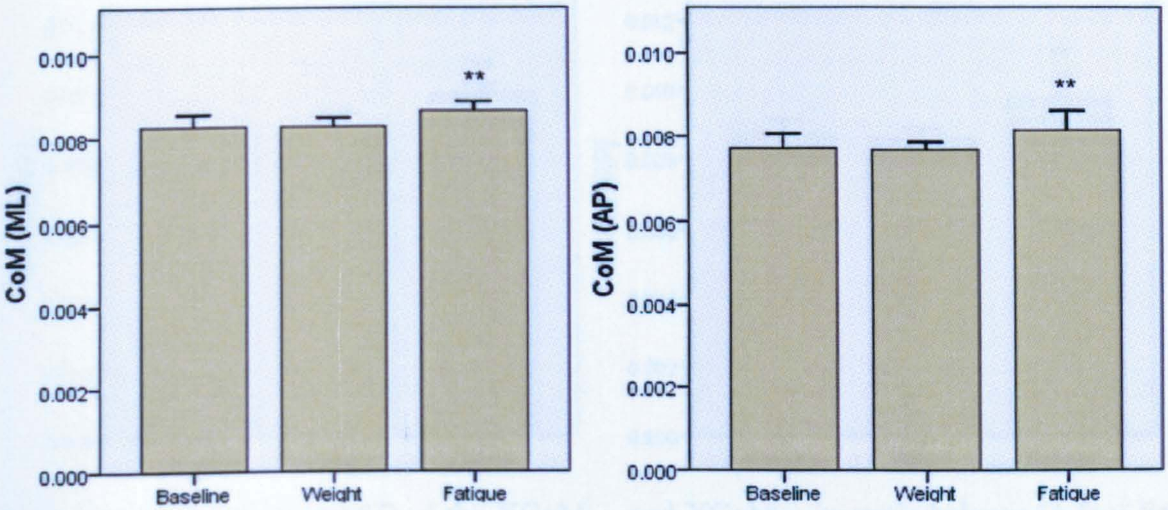


Figure 5.5. The mean and SD of the CoM_{ML} and CoM_{AP} in static balance (1-foot flat eyes open). (Units = m) (** indicates a significant differences from baseline at $p < .01$)

For the variable CoM_{ML}, contrast analyses showed that there was a significant main effect of condition ($F_{(1.774, 33.701)} = 32.349$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 41.467$, $p < .01$). Added weight did not differ from baseline ($F_{(1, 19)} = 0.339$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoM_{AP}, contrast analyses showed that there was a significant main effect of condition ($F_{(1.581, 30.030)} = 11.229$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 11.056$, $p < .01$). Added weight did not differ from baseline ($F_{(1, 19)} = 0.282$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.6 illustrates the data for the Extrapolated Centre of Mass:

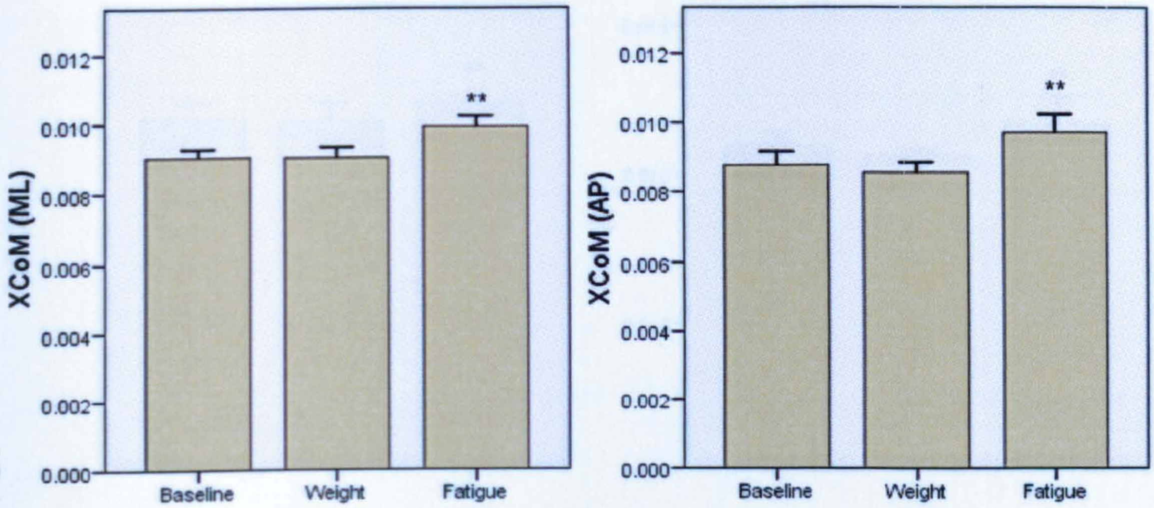


Figure 5.6. The mean and SD of the $XCoM_{ML}$ and $XCoM_{AP}$ in static balance (1-foot flat eyes open). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable $XCoM_{ML}$, contrast analyses showed that there was a significant main effect of condition ($F_{(1.996,\ 37.916)} = 60.860$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 92.754$, $p < .01$). Added weight did not differ from baseline ($F_{(1,\ 19)} = 0.033$, $p > .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable $XCoM_{AP}$, contrast analyses showed that there was a significant main effect of condition ($F_{(1.756,\ 33.372)} = 33.120$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 32.772$, $p < .01$). Added weight did not differ from baseline ($F_{(1,\ 19)} = 3.428$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.7 illustrates the data for the Centre of pressure:

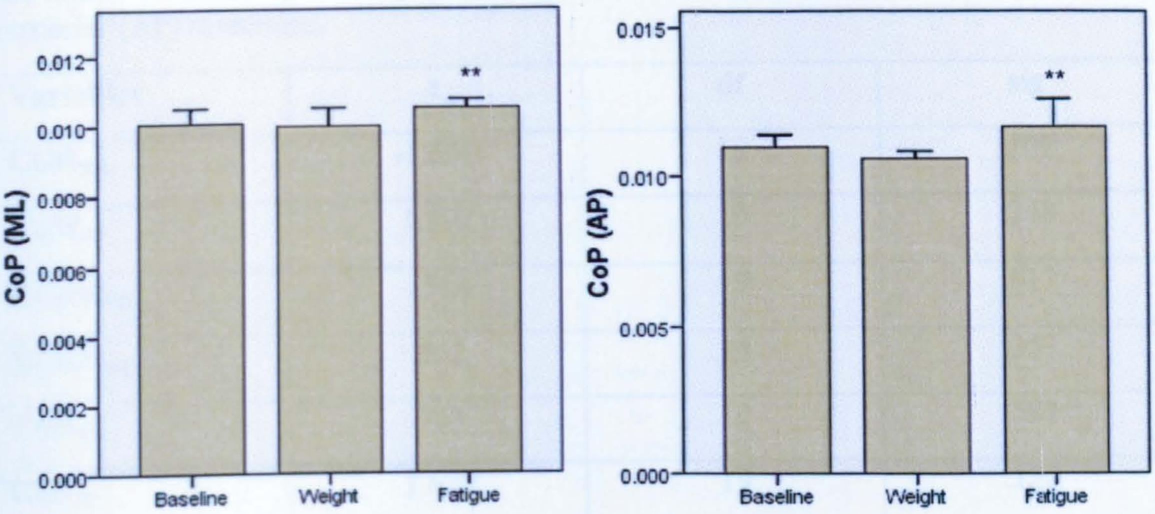


Figure 5.7. The mean and SD of the CoP_{ML} and CoP_{AP} in static balance (1-foot flat eyes open). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoP_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.465, 27.841)} = 15.529$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 21.531$, $p < .01$). Added weight did not differ from baseline ($F_{(1, 19)} = 1.337$, $p > .05$). There was no significant main effect of trial for the baseline, added weight nor fatigue conditions.

For the variable CoP_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.089, 20.691)} = 15.235$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 13.756$, $p < .01$). Added weight did not differ from baseline ($F_{(1, 19)} = 1.646$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Table 5.2. The agreement between the main variables in study 2 (baseline) and study 3 in the same condition (Romberg- 1foot flat) in both medio-lateral (ML) and anterior-posterior (AP) directions.

Variables	**t**	**df**	**sig**
CoM_{ML}	-1.690	19	.107
CoM_{AP}	1.192	19	.248
$XCoM_{ML}$	-.514	19	.613
$XCoM_{AP}$	.952	19	.353
CoP_{ML}	.553	19	.587
CoP_{AP}	1.629	19	.120

The above table (Table 5.2) shows no significant differences between the result of the two studies (study 2 and study 3) in all main variables in both medio-lateral (ML) and anterior-posterior (AP) directions. Therefore, data of study 3 represents typical data in investigating static balance.

5.3.2. Dynamic balance

Effect of carrying additional weight and localised muscle fatigue (between conditions) is established in this study, and an example of three trials is shown in appendix 8.

5.3.2.1. Two feet horizontal jump (dynamic balance)

Typical graphical displays are given in Figure 5.8 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in medio-lateral (x) and anterior-posterior (y) directions during dynamic balance (2 feet horizontal jump). These variables were characterised by their range.

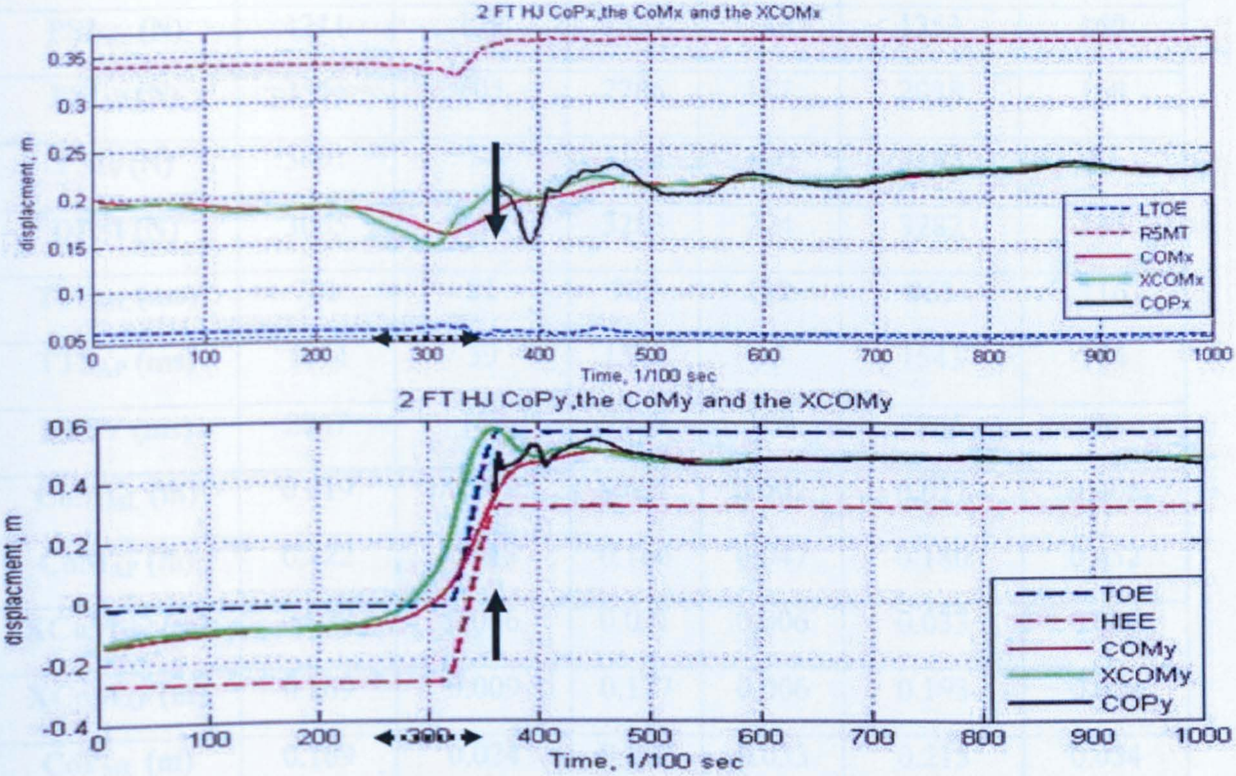


Figure 5.8. The variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for dynamic balance (2-feet flat horizontal jump). (Units = m) Dashed lines indicate the boundaries of the Base of Support (BOS)

The above figures illustrate the whole event (for 2 feet horizontal jump). The solid arrows indicate the start of landing phase. Due to nature of the event (horizontal jump), the

XCoM diverges away from the CoM during take-off phase which represents its nature (rapid movement ◄····►). After the landing (↑), the XCoM start gradually to close with the CoM which also represents its nature (slow movement). These movements necessitate the CoP to follow them to be stable. Mean and standard deviation of the standard deviation across time for each variable are given in Table 5.3.

Table 5.3. Mean and standard deviation of the range of each variable in both the medio-lateral (ML) and anterior-posterior (AP) directions during dynamic balance (Two feet horizontal jump) for baseline, added weight and fatigue conditions.

Variables	**Baseline**		**Added weight**		**Fatigue**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
PSI$_{ML}$ (N)	1211	128	1327	143	1353	169
PSI$_{AP}$ (N)	2551	105	2786	117	2938	168
PSI$_{V}$ (N)	3001	74	3194	190	3192	87
DPSI (N)	3065	158	3283	224	3282	135
TTS$_{ML}$ (ms)	701	81	905	112	963	116
TTS$_{AP}$ (ms)	1494	59	1539	95	1543	104
TTSV (ms)	2847	162	2938	109	2966	90
CoM$_{ML}$ (m)	0.019	0.002	0.021	0.002	0.021	0.002
CoM$_{AP}$ (m)	0.122	0.013	0.166	0.047	0.180	0.052
XCoM$_{ML}$ (m)	0.028	0.006	0.031	0.006	0.033	0.006
XCoM$_{AP}$ (m)	0.169	0.009	0.177	0.006	0.193	0.029
CoP$_{ML}$ (m)	0.169	0.024	0.202	0.033	0.215	0.034
CoP$_{AP}$ (m)	0.163	0.017	0.178	0.024	0.202	0.022
Q$_{ML}$ (N.m)	16.86	2.666	18.46	3.208	19.91	3.501
Q$_{AP}$ (N.m)	263.8	26.94	283.8	24.84	316.5	35.04
F$_{ML}$ (N)	125.4	45.35	155.8	50.69	175.9	53.62
F$_{AP}$ (N)	682.1	90.41	773.7	114.4	879.1	160.2

Figure 5.9 illustrates the data for the Postural Stability Indices.

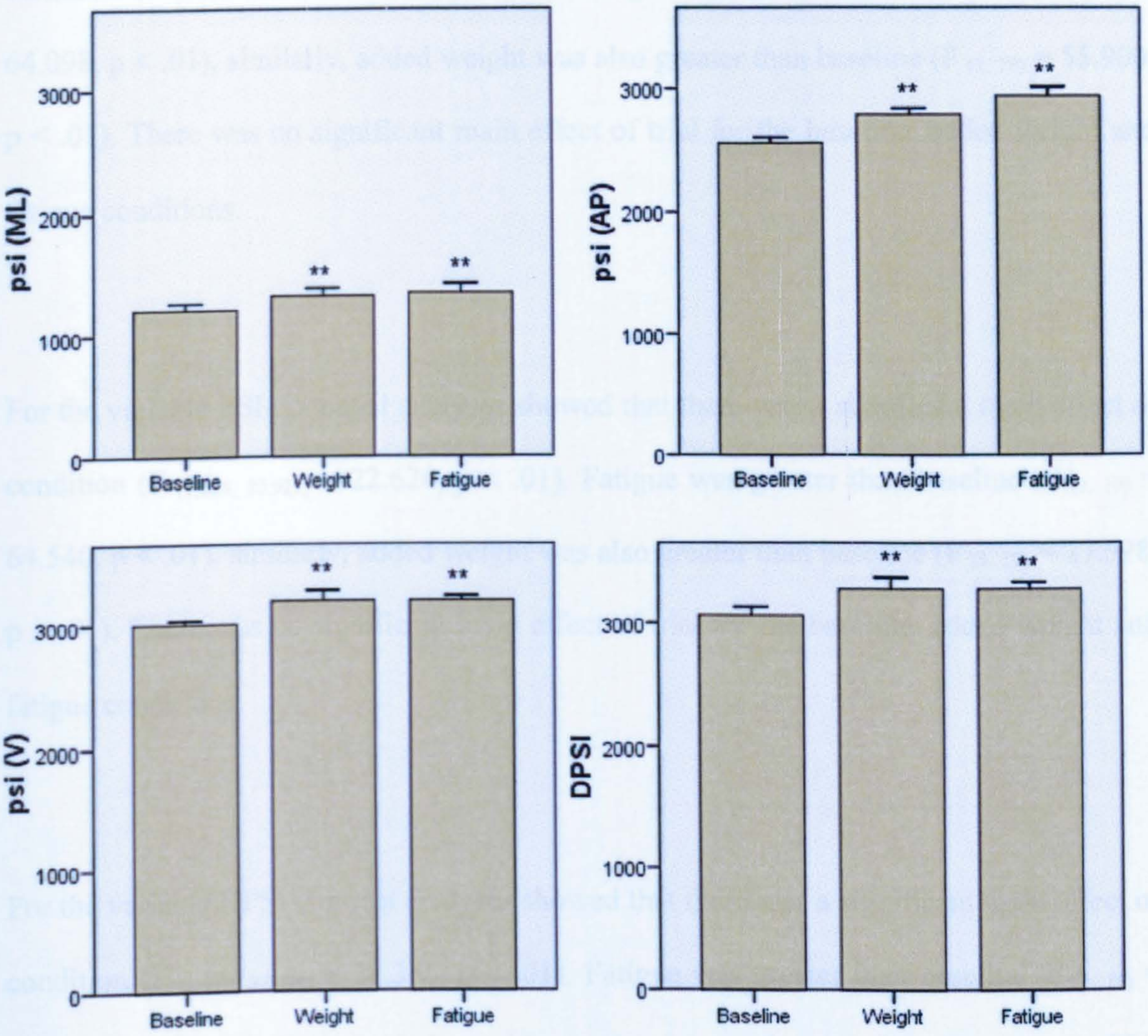


Figure 5.9. The Postural Stability Index (PSI_{ML}, PSI_{AP}, PSI_{V} and DPSI) and Dynamic Postural Stability Index (DPSI) in dynamic balance (2-feet flat horizontal jump). (** indicates a significant difference from baseline at $p < .01$)

For the variable PSI_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.723,\ 32.729)} = 8.634$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 12.411$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 16.899$, $p < .01$). There was no significant main effect of trial for the baseline, added weight and fatigue conditions.

For the variable PSI_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.592, 30.249)} = 48.339$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 64.098$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 55.900$, $p < .01$). There was no significant main effect of trial for the baseline, added weight and fatigue conditions.

For the variable PSI_V contrast analyses showed that there was a significant main effect of condition ($F_{(1.628, 30.927)} = 22.620$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 64.540$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 27.598$, $p < .01$). There was no significant main effect of trial for the baseline, added weight and fatigue conditions.

For the variable DPSI contrast analyses showed that there was a significant main effect of condition ($F_{(1.973, 37.494)} = 21.355$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 33.632$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 34.381$, $p < .01$). There was no significant main effect of trial for the baseline, added weight and fatigue conditions.

Figure 5.10 illustrates the data for the time to stabilization.

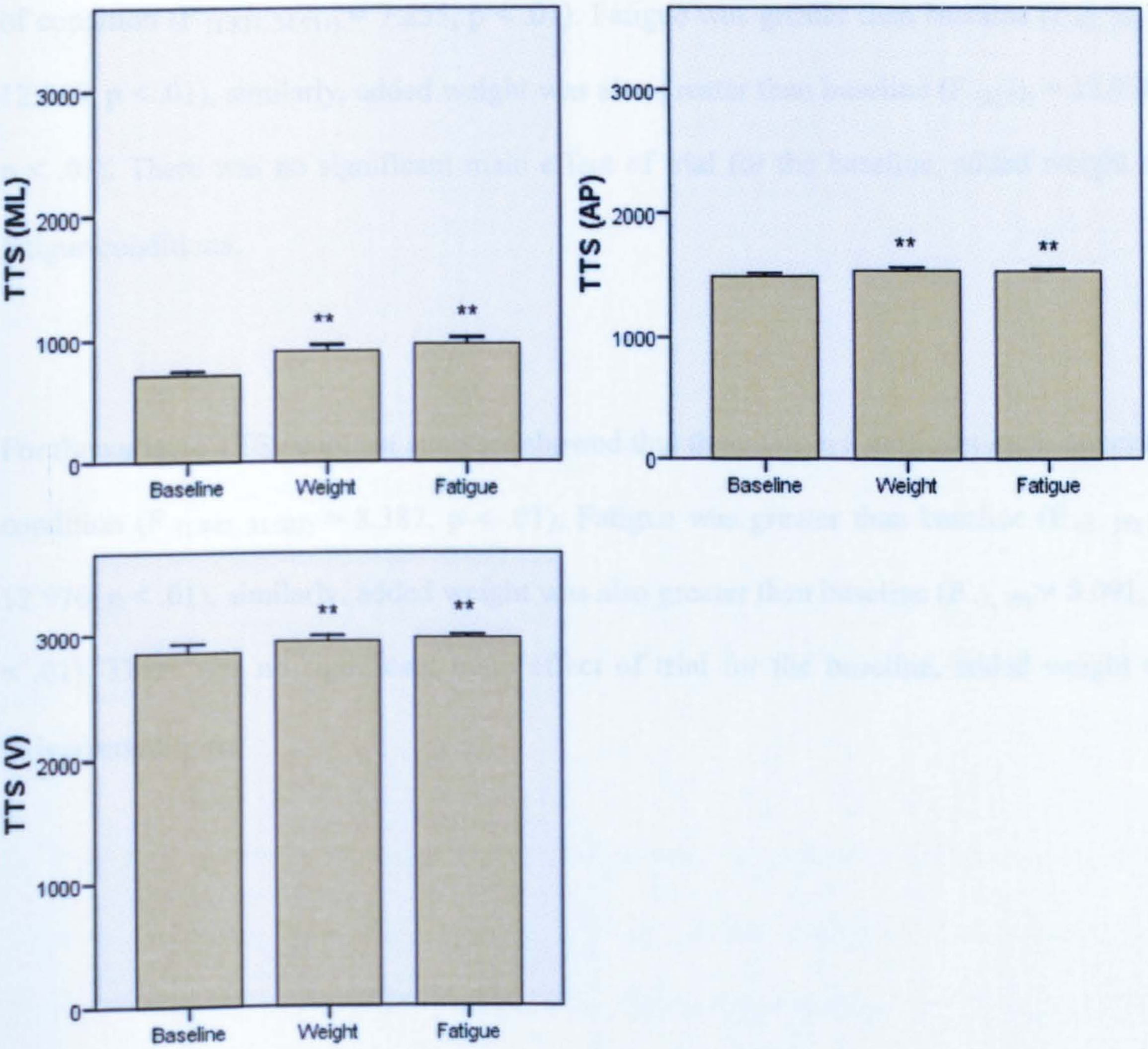


Figure 5.10. The Time to Stabilization (TTS_{ML}, TTS_{AP} and TTS_{V}) in dynamic balance (2-feet flat horizontal jump). (Units = s). (** indicates a significant difference from baseline at $p < .01$)

For the variable TTS_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.846, 35.067)} = 38.427$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 85.440$, $p < .001$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 46.980$, $p < .001$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable TTS_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.837, 34.911)} = 7.255, p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 12.068, p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 12.938, p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable TTS_V contrast analyses showed that there was a significant main effect of condition ($F_{(1.842, 35.002)} = 8.387, p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 12.970, p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 8.091, p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.11 illustrates the data for the Centre of Mass.

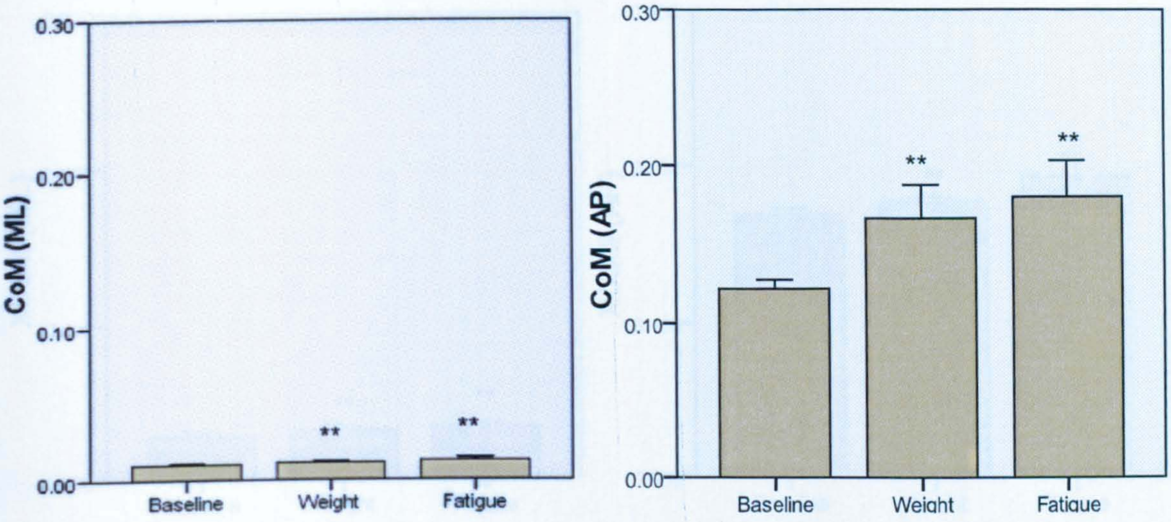


Figure 5.11. The range of the Centre of Mass (CoM_{ML}) and (the CoM_{AP}) in dynamic balance (2-feet flat horizontal jump). (Units = m). (** indicates a significant difference from baseline at $p < .01$)

For the variable CoM_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.581,\ 30.043)} = 44.277$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 83.096$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 28.701$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoM_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.105,\ 20.997)} = 21.285$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 27.003$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 18.018$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.12 illustrates the data for the extrapolated Centre of Mass.

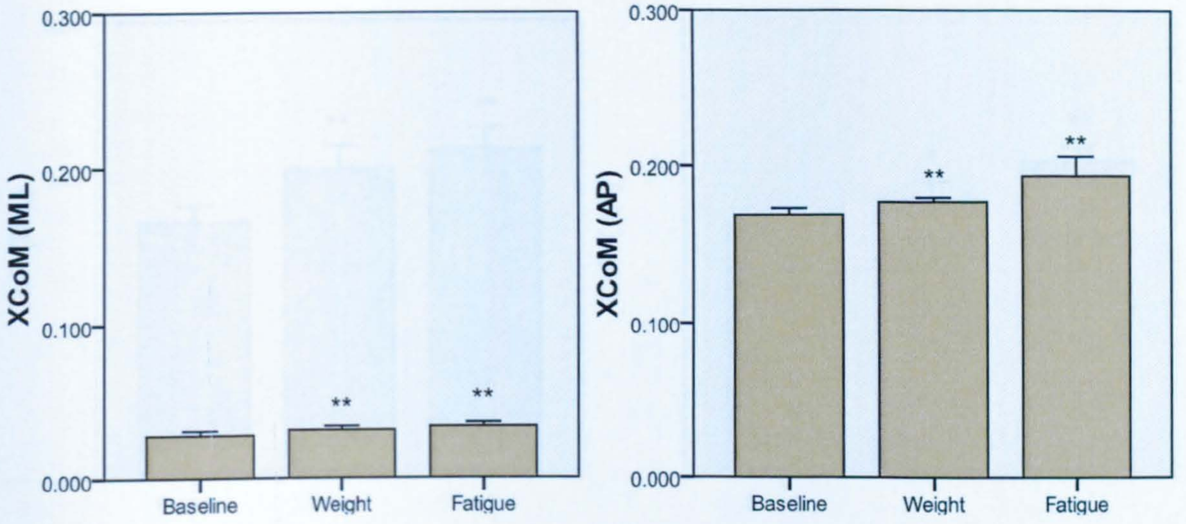


Figure 5.12. The range of the XCoM_{ML} and XCoM_{AP} in dynamic balance (2-feet flat horizontal jump). (Units = m/s) (** indicates a significant difference from baseline at $p < .01$)

For the variable XCoM_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.258,\ 23.904)} = 17.061$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 19.138$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 16.130$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable XCoM_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.160,\ 22.038)} = 10.522$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 10.312$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 12.907$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.13 illustrates the data for the centre of pressure.

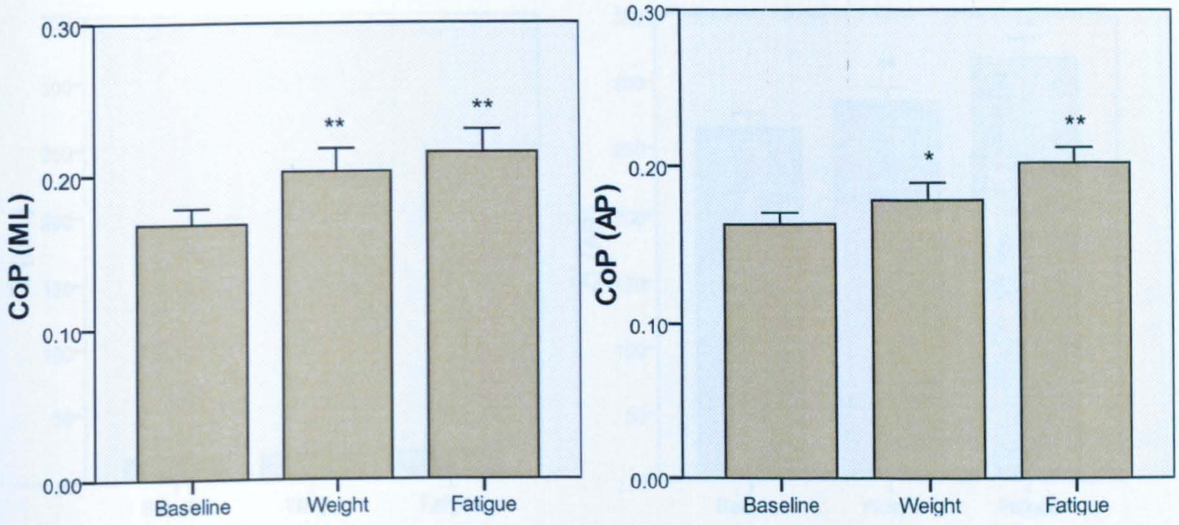


Figure 5.13. The range of the CoP_{ML} and CoP_{AP} in dynamic balance (2-feet flat horizontal jump). (Units = m/s) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoP_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.929, 36.658)} = 33.787$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 35.145$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 32.527$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoP_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.789, 33.990)} = 34.441$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 85.428$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 7.585$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.14 illustrates the data for the friction torque.

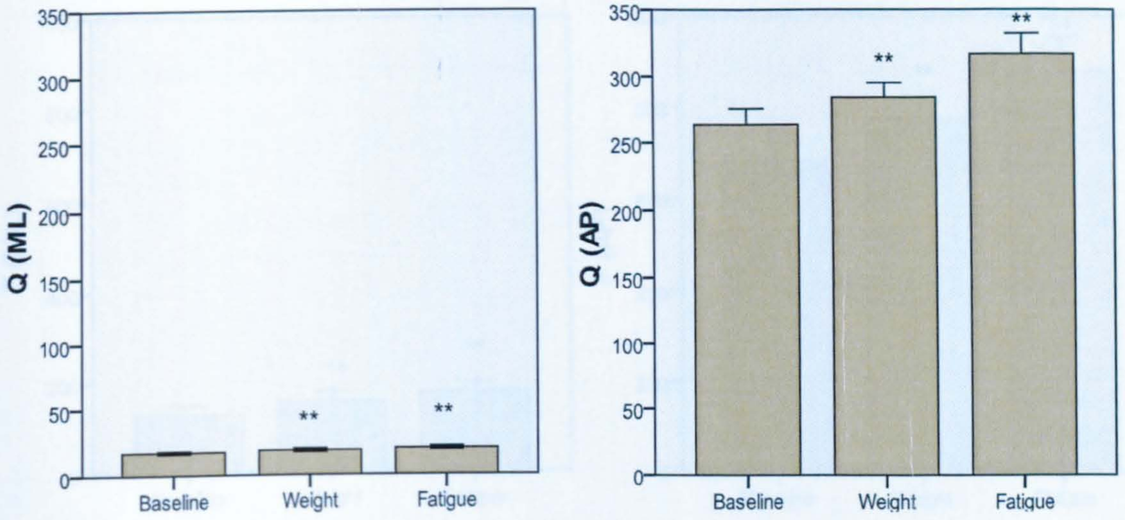


Figure 5.14. The peak of the Q_{ML} and Q_{AP} in dynamic balance (2-feet flat horizontal jump). (Units = N.m) (** indicates a significant difference from baseline at $p < .01$)

For the variable Q_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.284,\ 24.390)} = 47.472$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 65.616$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 27.349$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable Q_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.660,\ 31.546)} = 26.112$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 38.321$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 8.872$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.15 illustrates the data for the ground reaction forces.

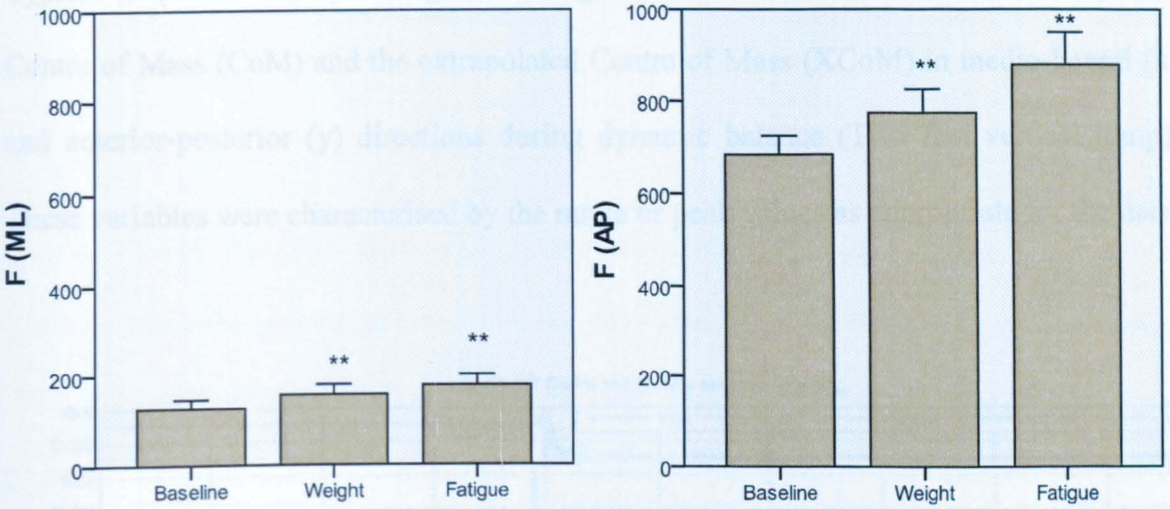


Figure 5.15. The peak of the F_{ML} and F_{AP} in dynamic balance (2-feet flat horizontal jump). (Units = N) (** indicates a significant difference from baseline at $p < .01$)

For the variable F_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.533, 29.136)} = 31.430.795$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 37.735$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 24.144$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable F_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.566, 29.752)} = 35.269$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 36.410$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 31.661$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

5.3.2.2. Two feet vertical jump (dynamic balance)

Typical graphical displays are given in Figure 5.16 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in medio-lateral (x) and anterior-posterior (y) directions during dynamic balance (Two feet vertical jump). These variables were characterised by the range or peak values as appropriate for the data.

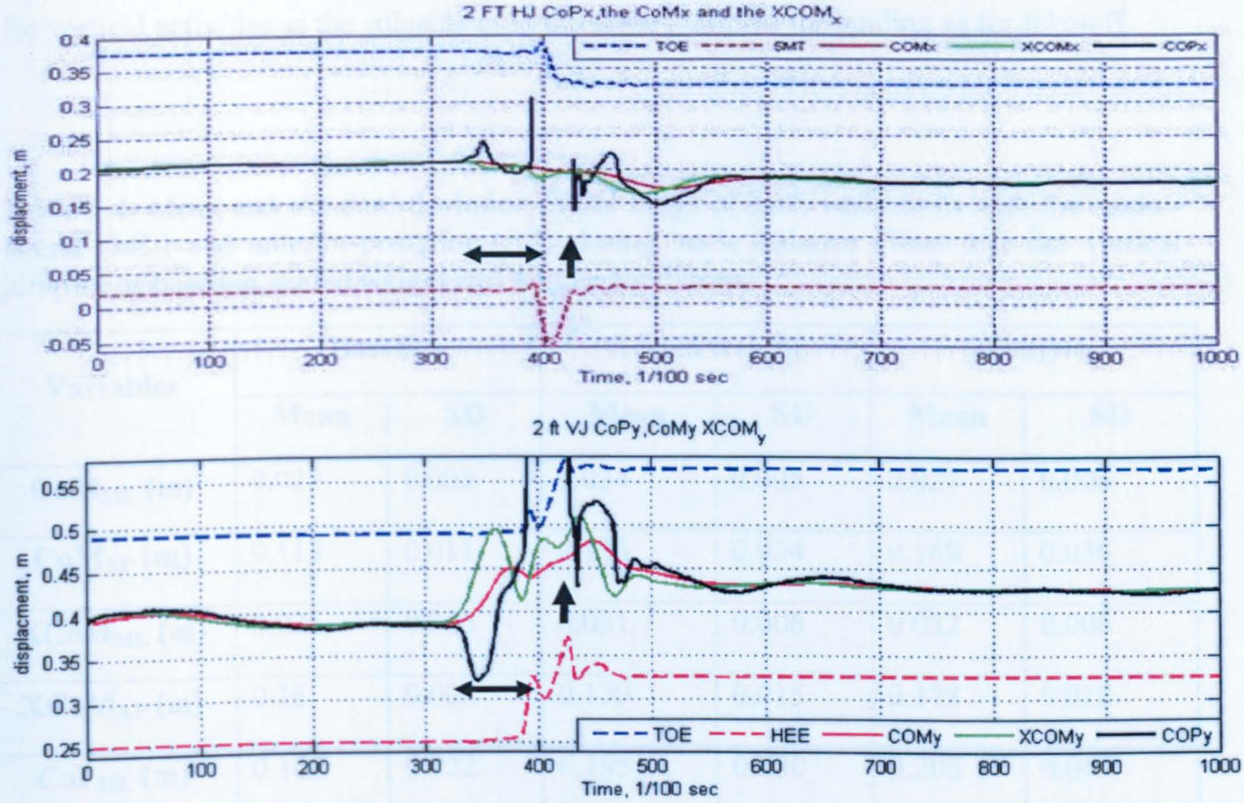


Figure 5.16. The variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for dynamic balance (2-feet flat vertical jump). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BoS)

The above figures illustrate the whole event (for 2 feet vertical jump). The single arrows indicate the start of landing phase. Due to nature of the event (vertical jump), the XCoM diverges away from the CoM during take-off phase which represents its nature (rapid movement ↔), after the landing phase (↑), the XCoM start gradually to close with the

CoM which also represents its nature (slow movement). These movements necessitate the CoP to follow them to be stable. Mean and standard deviation for each variable are given in Table 5.4.

Due to Matlab functions that were written based on whole set of data of one force platform (used for landing in horizontal activities) the DPSI and TTS were not computed for vertical activities as the subjects used the same platform for landing as for take-off.

Table 5.4. Mean and standard deviation of the range of each variable in both the medio-lateral (ML) and anterior-posterior (AP) during static balance (Two feet flat vertical jump). For baseline, added weight and fatigue conditions.

Variables	**Baseline**		**Added weight**		**Fatigue**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
CoM_{ML} (m)	0.022	0.005	0.024	0.005	0.027	0.006
CoM_{AP} (m)	0.118	0.011	0.153	0.034	0.169	0.036
$XCoM_{ML}$ (m)	0.026	0.005	0.031	0.006	0.032	0.006
$XCoM_{AP}$ (m)	0.16	0.008	0.170	0.015	0.178	0.018
CoP_{ML} (m)	0.162	0.022	0.195	0.030	0.205	0.04
CoP_{AP} (m)	0.159	0.016	0.181	0.021	0.194	0.021
Q_{ML} (N.m)	15.859	2.545	18.41	3.125	19.33	4.025
Q_{AP} (N.m)	203.7	20.39	288.0	28.94	292	26.44
F_{ML} (N)	105.3	45.73	152.4	49.89	163.7	45.99
F_{AP} (N)	582.1	90.9	778.3	121.7	796.5	118.6

Note: neither the TTS nor the DPSI was evaluated for subjects in vertical events.

Figure 5.17 illustrates the data for the Centre of Mass.

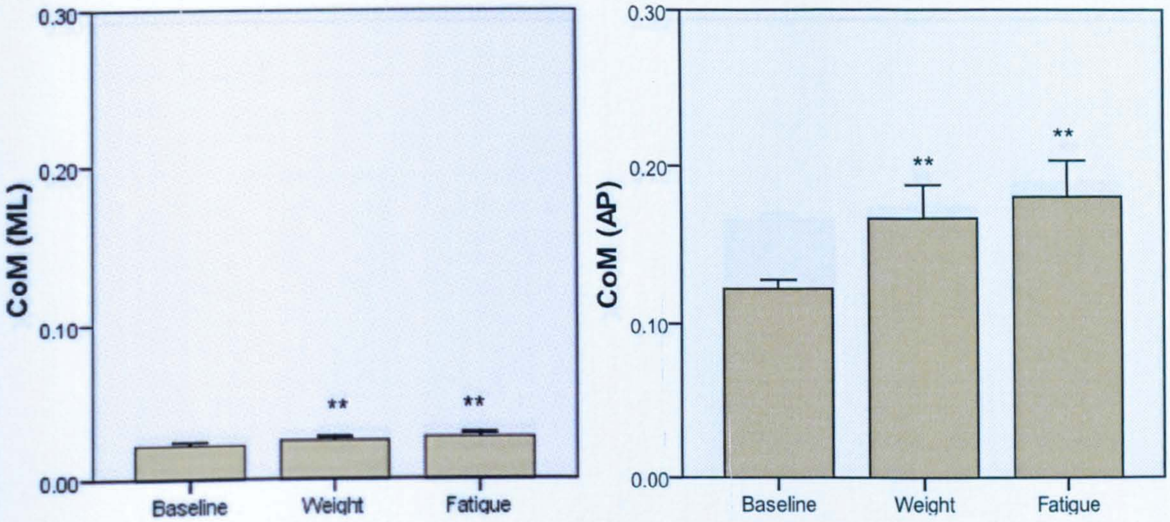


Figure 5.17. The CoM_{ML} and CoM_{AP} in dynamic balance (2-feet vertical jump). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoM_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.453,\ 27.598)} = 27.755$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 37.171$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 18.855$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoM_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.657,\ 31.\ 479)} = 45.117$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 75.271$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 20.823$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.18 illustrates the data for the extrapolated Centre of Mass.

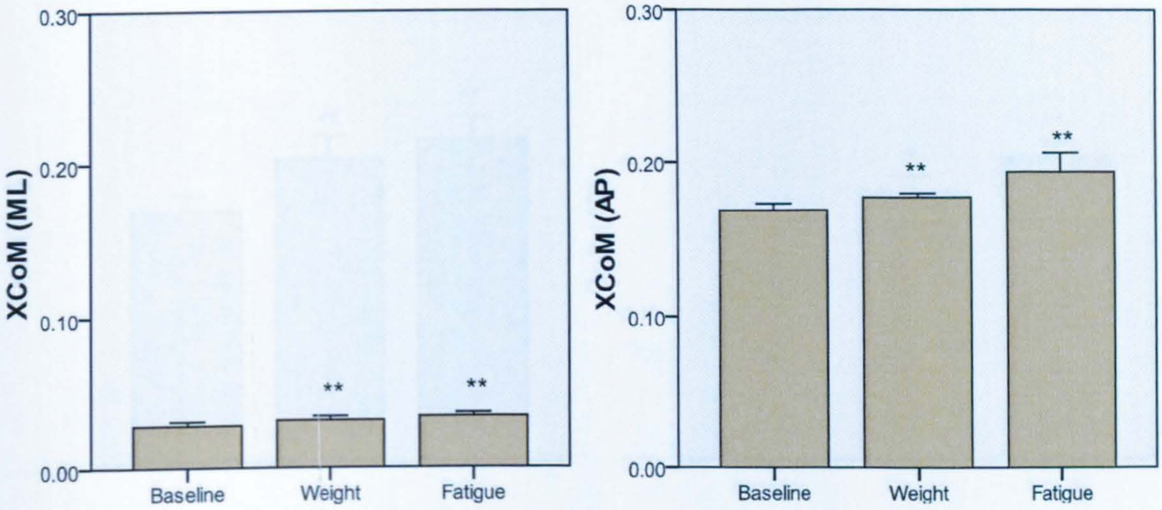


Figure 5.18. The $XCoM_{ML}$ and $XCoM_{AP}$ in dynamic balance (2-feet flat vertical jump). (Units = m/s) (** indicates a significant difference from baseline at $p < .01$)

For the variable $XCoM_{ML}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.258, 23.904)} = 17.061$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 16.130$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 19.138$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable $XCoM_{AP}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.160, 22.038)} = 10.522$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 10.313$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 12.907$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.19 illustrates the data for the centre of pressure.

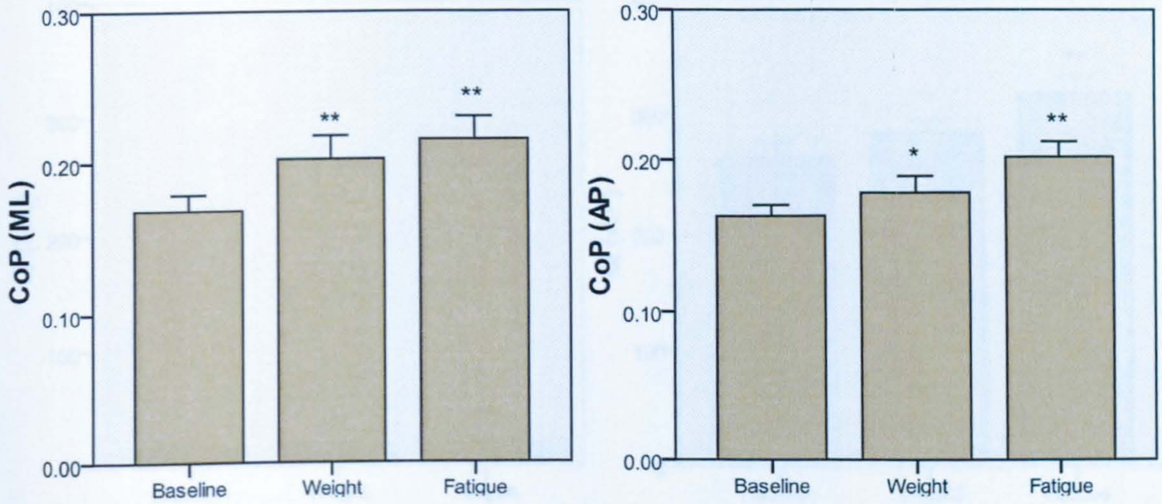


Figure 5.19. The CoP_{ML} and CoP_{AP} in dynamic balance (2-feet flat vertical jump). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoP_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.929, 36.658)} = 33.787$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 35.145$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 32.527$, $p > .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoP_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.789, 33.990)} = 34.411$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 85.428$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 7.585$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.20 illustrates the data for the friction torque.

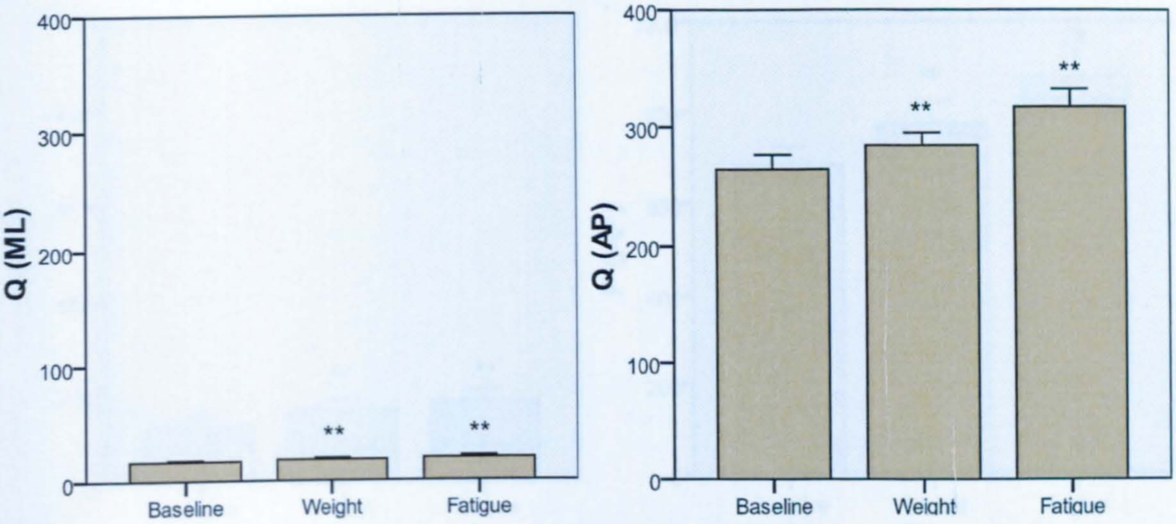


Figure 5.20. The peak of the Q_{ML} and Q_{AP} in dynamic balance (2-feet flat horizontal jump). (Units = N.m^{-1}) (** indicates a significant difference from baseline at $p < .01$)

For the variable Q_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.284,\ 24.390)} = 47.472$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 65.616$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 27.349$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable Q_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.660,\ 31.546)} = 26.112$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 38.321$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 8.872$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.21 illustrates the data for the ground reaction forces.

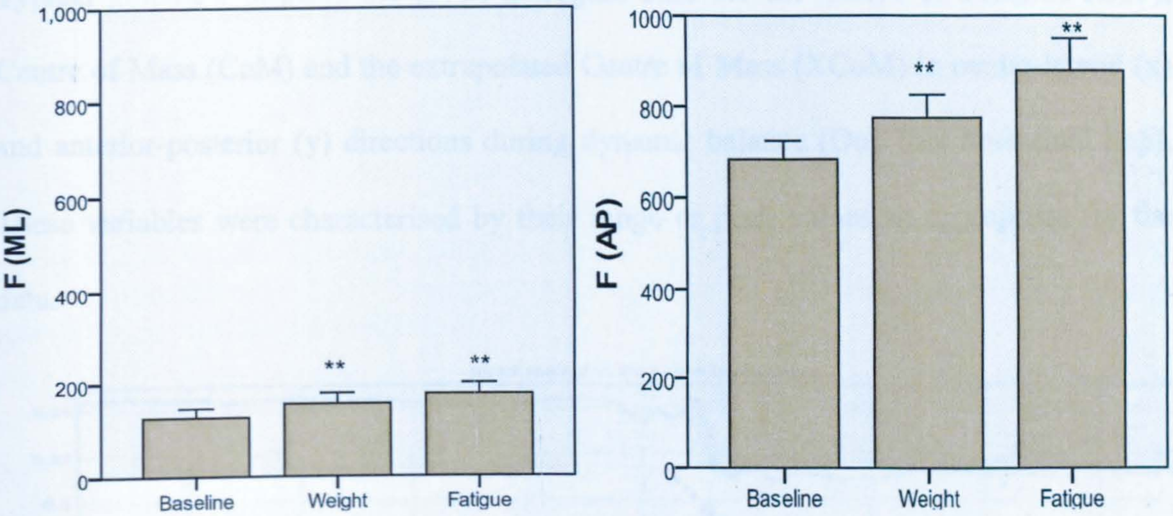


Figure 5.21. The F_{ML} and F_{AP} in dynamic balance (2-feet flat vertical jump). (Units =N) (** indicates a significant difference from baseline at $p < .01$)

For the variable F_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.533, 29.136)} = 31.430$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 37.735$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 24.144$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable F_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.566, 29.752)} = 35.269$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 36.410$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 31.661$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

5.3.2.3. One foot horizontal hop (dynamic balance)

Typical graphical displays are given in Figure 5.22 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in medio-lateral (x) and anterior-posterior (y) directions during dynamic balance (One foot horizontal hop). These variables were characterised by their range or peak values as appropriate for the data.

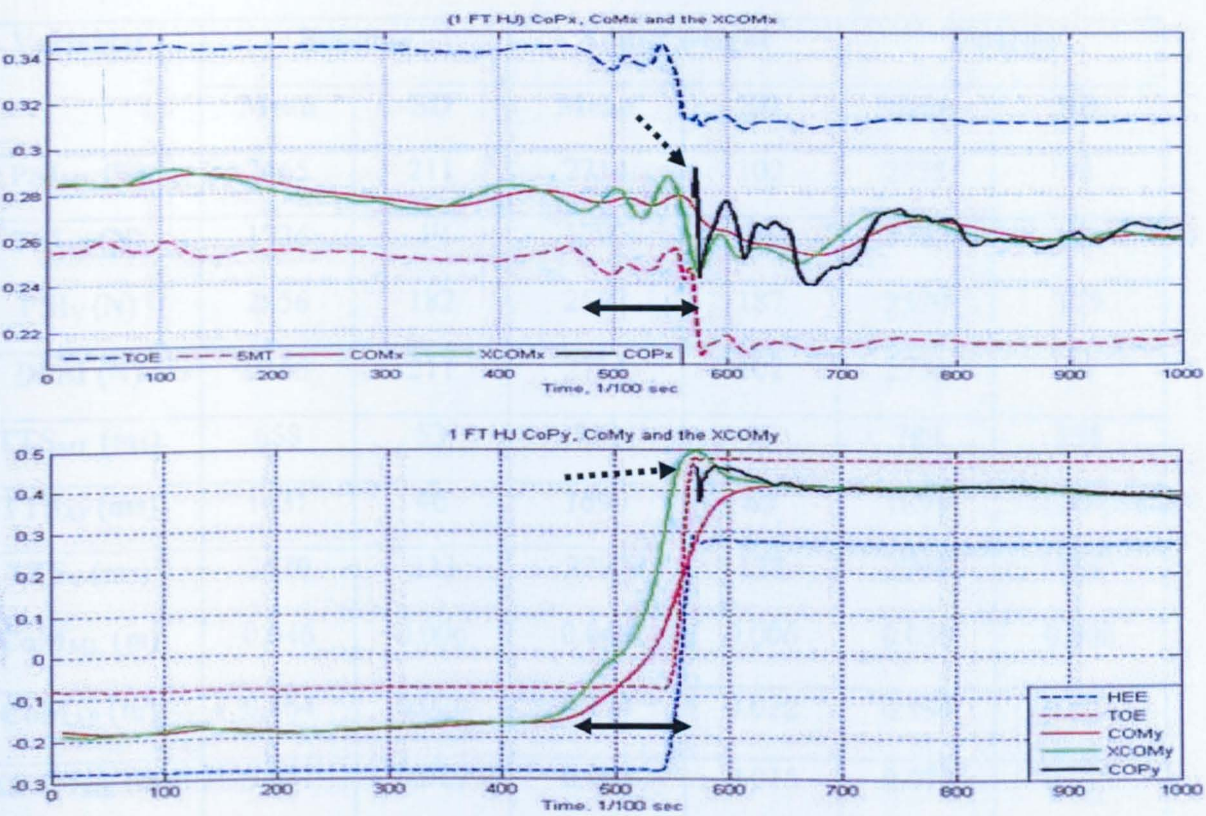


Figure 5.22. Illustrates the variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for dynamic balance (1-foot flat horizontal hop). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BoS)

The above figures illustrate the whole event (for 1 foot horizontal hop). The single-dotted arrow indicates the start of landing phase. Due to nature of the event (horizontal jump), the XCoM diverges away from the CoM during take-off phase which represents its nature (rapid movement ↔), after the landing phase (⇡), the XCoM start gradually to close with the CoM which also represents its nature (slow movement). These movements' necessitate the CoP to follow them to be stable. Mean of the standard deviation for each variable are given in Table 5.5.

Table 5.5. Mean and standard deviation of each variable in both the medio-lateral (ML) and anterior-posterior (AP) during static balance (One foot horizontal hop). For baseline, added weight and fatigue conditions.

Variables	**Baseline**		**Added weight**		**Fatigue**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
PSI_{ML} (N)	2465	211	2714	102	2755	94
PSI_{AP} (N)	1726	49	1792	36	1797	46
PSI_{V} (N)	2456	182	2597	187	2579	179
DPSI (N)	2465	211	2714	102	2755	94
TTS_{ML} (ms)	658	53	732	99	789	138
TTS_{AP} (ms)	1631	46	1690	49	1699	37
TTS_{V} (ms)	2670	223	2797	137	2799	166
CoM_{ML} (m)	0.046	0.006	0.048	0.006	0.050	0.006
CoM_{AP} (m)	0.164	0.020	0.174	0.022	0.194	0.023
$XCoM_{ML}$ (m)	0.057	0.017	0.065	0.015	0.077	0.013
$XCoM_{AP}$ (m)	0.143	0.016	0.161	0.014	0.177	0.012
CoP_{ML} (m)	0.169	0.024	0.202	0.033	0.214	0.034
CoP_{AP} (m)	0.155	0.023	0.173	0.022	0.193	0.025
Q_{ML} (N.m)	28.84	7.695	34.22	7.205	37.84	10.83
Q_{AP} (N.m)	227.0	29.46	247.2	31.30	258.0	32.67
F_{ML} (N)	242.9	93.40	264.8	93.57	292.1	86.35
F_{AP} (N)	460.8	55.70	501.1	53.22	532.6	66.37

Figure 5.23 illustrates the data for postural stability indices.

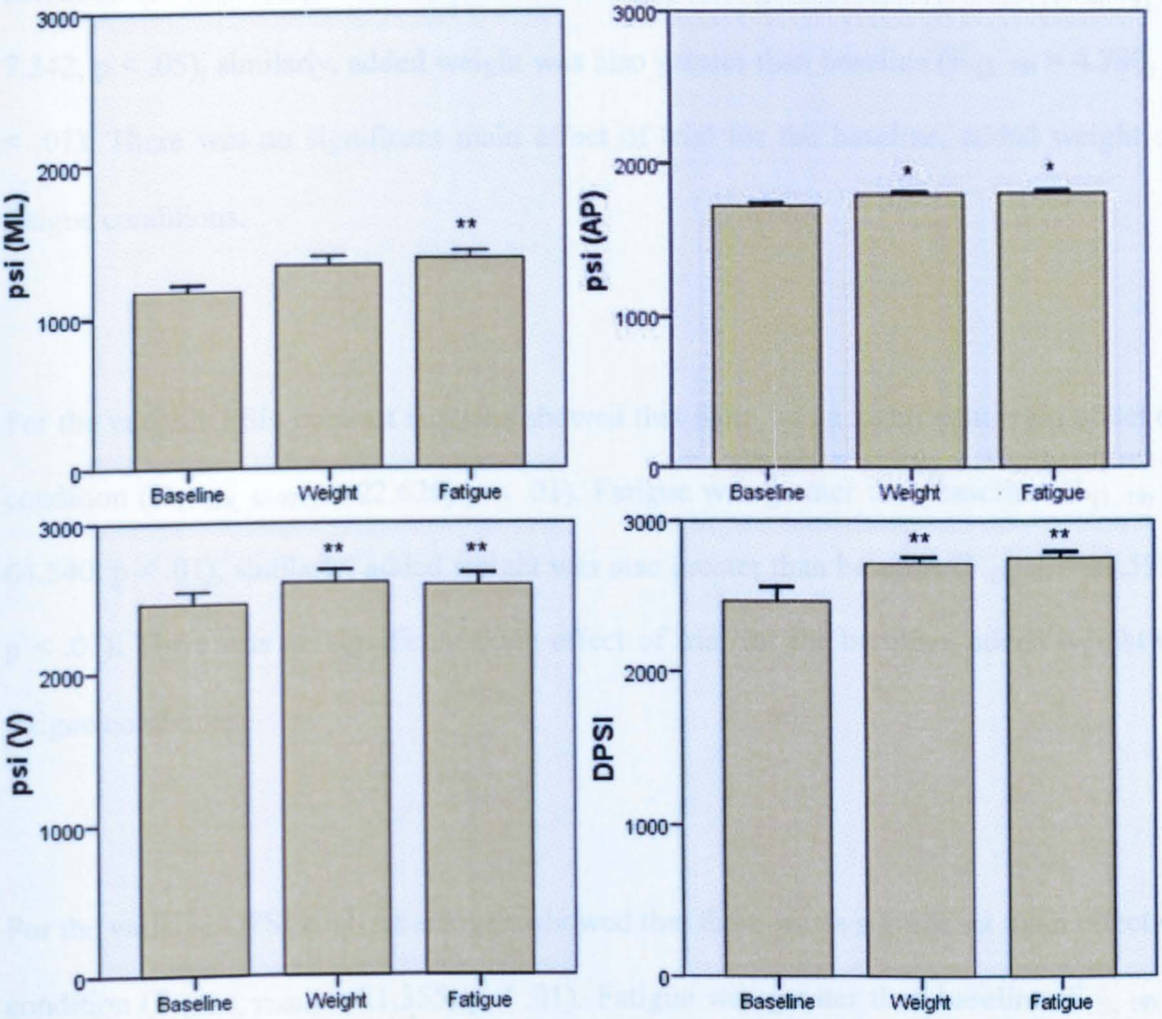


Figure 5.23. The Postural Stability Index (PSI_{ML}, $PSI_{AP,}$ PSI_V and DPSI) and Dynamic Postural Stability Index (DPSI) in dynamic balance (1-foot horizontal hop). (** indicates a significant difference from baseline at $p < .01$ and * indicates a significant differences from baseline at $p < .05$)

For the variable PSI_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.952,\ 37.084)} = 9.582$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 19.048$, $p < .01$). Added weight did not significantly differ from baseline ($F_{(1,\ 19)} = 1.660$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable PSI_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.300, 24.709)} = 5.572$, $p < .05$). Fatigue was greater than baseline ($F_{(1, 19)} = 7.342$, $p < .05$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 4.780$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable PSI_V contrast analyses showed that there was a significant main effect of condition ($F_{(1.628, 30.927)} = 22.620$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 64.540$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 27.598$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable DPSI contrast analyses showed that there was a significant main effect of condition ($F_{(1.973, 37.494)} = 21.355$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 33.632$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 34.381$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.24 illustrates the data for the time to stabilization.

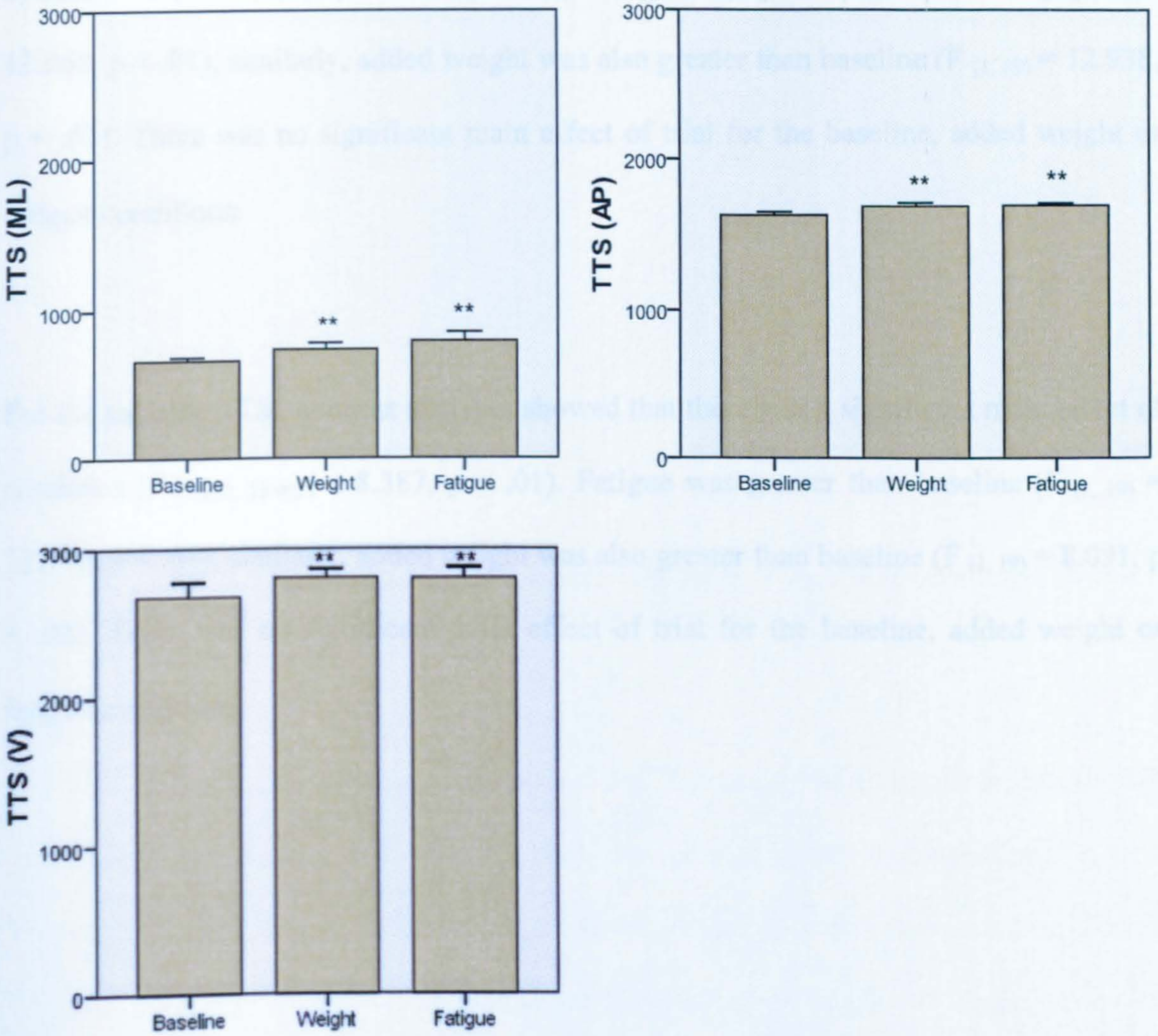


Figure 5.24. The Time to Stabilization (TTS_{ML}, TTS_{AP} and TTS_{V}) in dynamic balance (1foot horizontal hop). (Units = s). (** indicates a significant difference from baseline at $p < .01$)

For the variable TTS_{ML} contrast analyses showed that there was no significant main effect of conditions ($F_{(1.846, 35.67)} = 38.427$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 85.440$, $p < .05$), whereas added weight did not significantly differ from baseline ($F_{(1, 19)} = 46.980$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable TTS_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.837, 34.911)} = 7.255$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 12.068$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 12.938$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable TTS_{V} contrast analyses showed that there was a significant main effect of condition ($F_{(1.842, 35.002)} = 8.387$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 12.970$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 8.091$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.25 illustrates the data for the Centre of Mass.

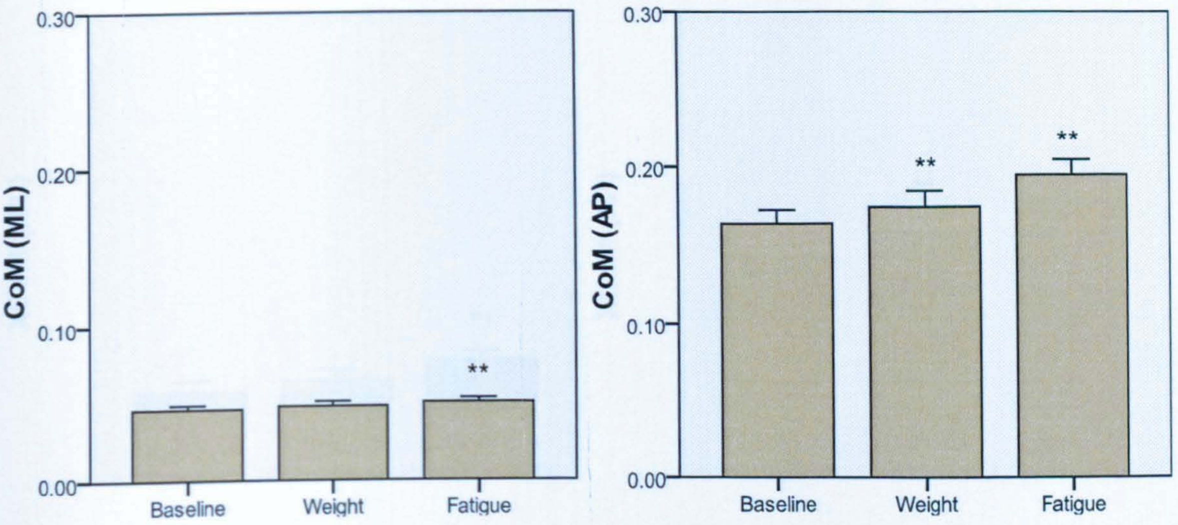


Figure 5.25. The CoM$_{ML}$ and CoM$_{AP}$ in dynamic balance (1-feet horizontal hop). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoM$_{ML}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.401, 26.625)} = 11.259$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 39.134$, $p < .01$). Whereas added weight did not significantly differ from baseline ($F_{(1, 19)} = 3.252$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoM$_{AP}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.399, 26.581)} = 78.394$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 86.055$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 46.166$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.26 illustrates the data for the extrapolated Centre of Mass.

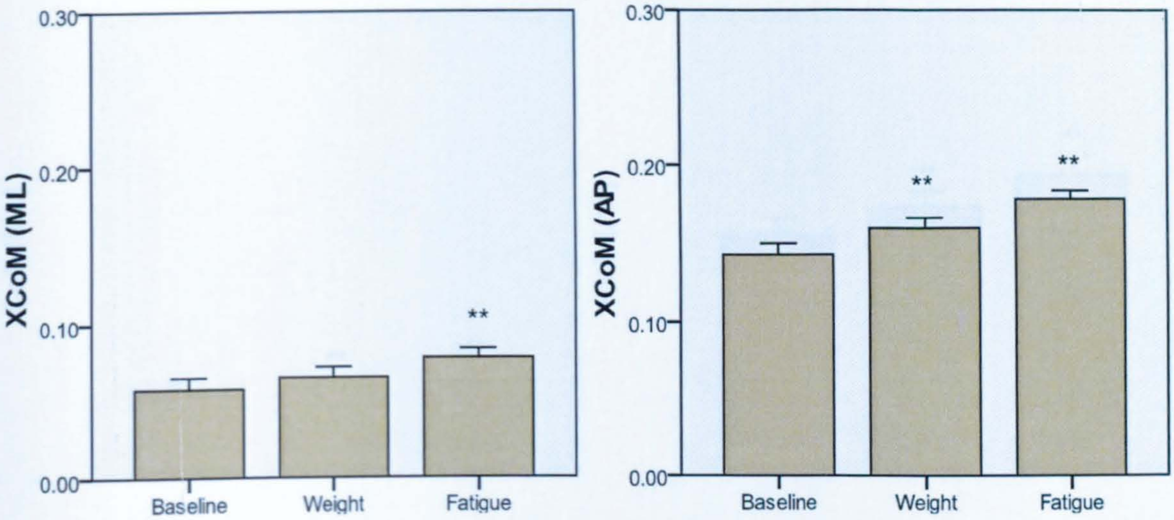


Figure 5.26. The $XCoM_{ML}$ and $XCoM_{AP}$ in dynamic balance (1-foot flat horizontal hop). (Units = m/s) (** indicates a significant difference from baseline at $p < .01$ and * indicates a significant differences from baseline at $p < .05$)

For the variable $XCoM_{ML}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.853, 35.205)} = 10.017$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 20.083$, $p < .01$). Whereas added weight did not significantly differ from baseline ($F_{(1, 19)} = 2.561$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable $XCoM_{AP}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.835, 36.693)} = 60.388$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 87.401$, $p < .01$). Added weight was also greater than baseline ($F_{(1, 19)} = 33.966$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.27 illustrates the data for the centre of pressure.

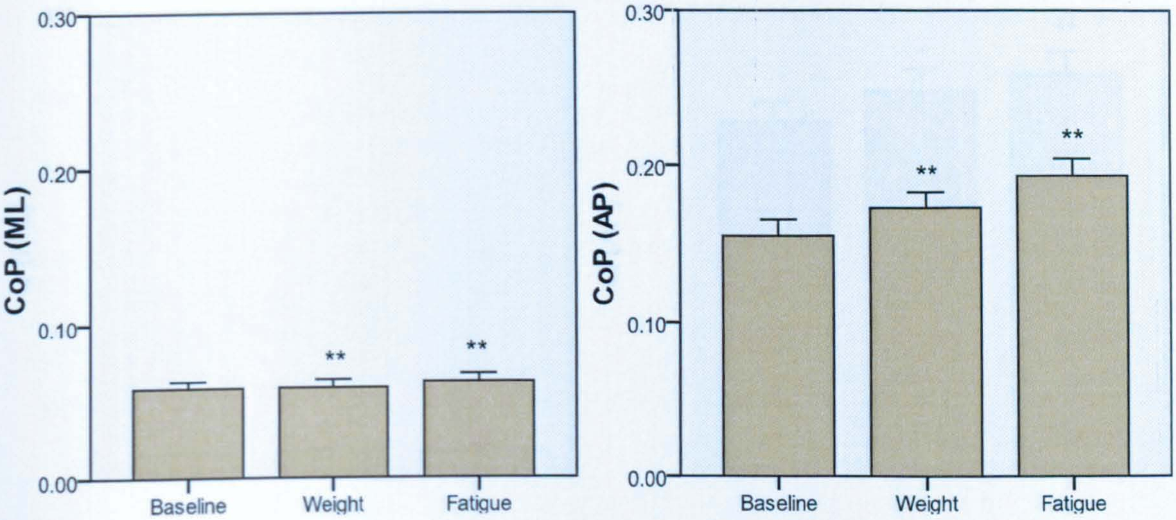


Figure 5.27. The CoP$_{ML}$ and CoP$_{AP}$ in dynamic balance (1-foot flat horizontal jump). (Units = m) (** indicates a significant difference from baseline at p < .01 and * indicates a significant differences from baseline at p < .05)

For the variable CoP$_{ML}$ contrast analyses showed that there was a significant main effect of condition (F $_{(1.929\ 36.658)}$ = 33.787, p < .01). Fatigue was greater than baseline (F $_{(1,\ 19)}$ = 35.145, p < .01). Added weight was also greater than baseline (F $_{(1,\ 19)}$ = 33.527, p > .01). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoP$_{AP}$ contrast analyses showed that there was a significant main effect of condition (F $_{(1.732,\ 32.916)}$ = 30.602, p < .01). Fatigue was greater than baseline (F $_{(1,\ 19)}$ = 34.642, p < .01), similarly, added weight was also greater than baseline (F $_{(1,\ 19)}$ = 21.479, p < .01). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.28 illustrates the data for the friction torque.

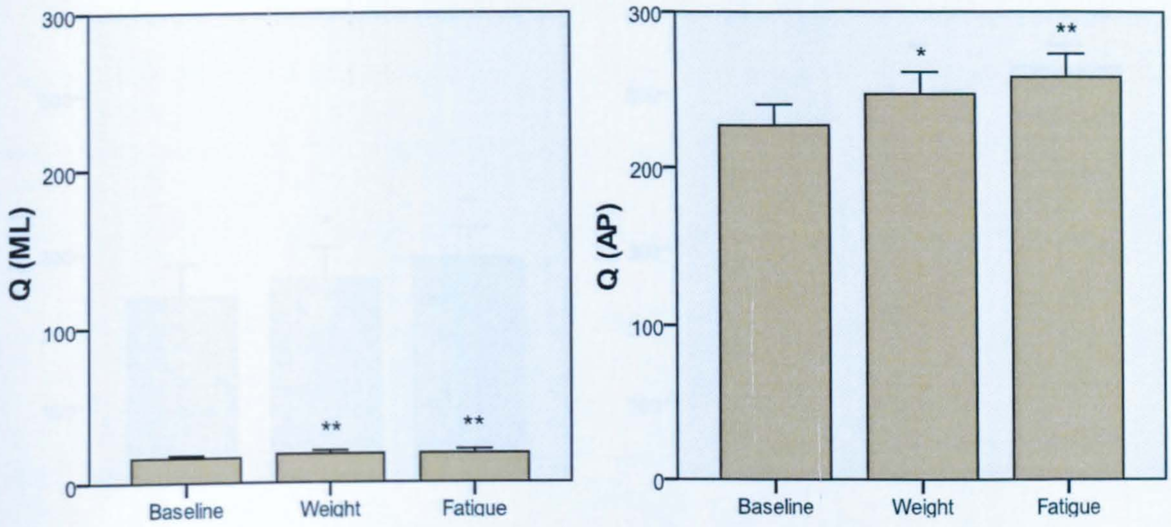


Figure 5.28. The peak of the Q_{ML} and Q_{AP} in dynamic balance (2-feet flat horizontal jump). (Units = $N.m^{-1}$) (** indicates a significant difference from baseline at $p < .01$)

For the variable Q_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.776,\ 33.740)} = 10.192$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 10.275$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 10.044$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable Q_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.660,\ 31.546)} = 10.831$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 15.913$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 7.416$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.29 illustrates the data for the ground reaction forces.

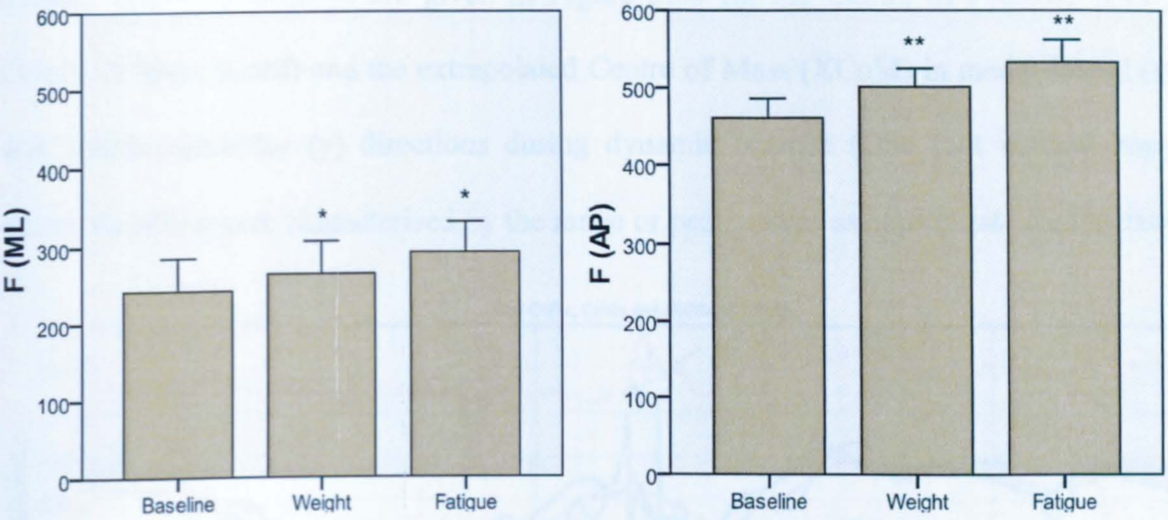


Figure 5.29. The F_{ML} and F_{AP} in dynamic balance (1-foot flat horizontal jump). (Units = N) (** indicates a significant difference from baseline at $p < .01$)

For the variable F_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.639,\ 31.134)} = 6.593$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 7.218$, $p < .05$). Added weight was also greater than baseline ($F_{(1,\ 19)} = 4.878$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable F_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.603,\ 30.462)} = 16.007$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 14.719$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 19.795$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

5.3.2.4. One foot flat vertical hop (dynamic)

Typical graphical displays are given in Figure 5.30 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in medio-lateral (x) and anterior-posterior (y) directions during dynamic balance (One foot vertical hop). These variables were characterised by the range or peak values as appropriate for the data.

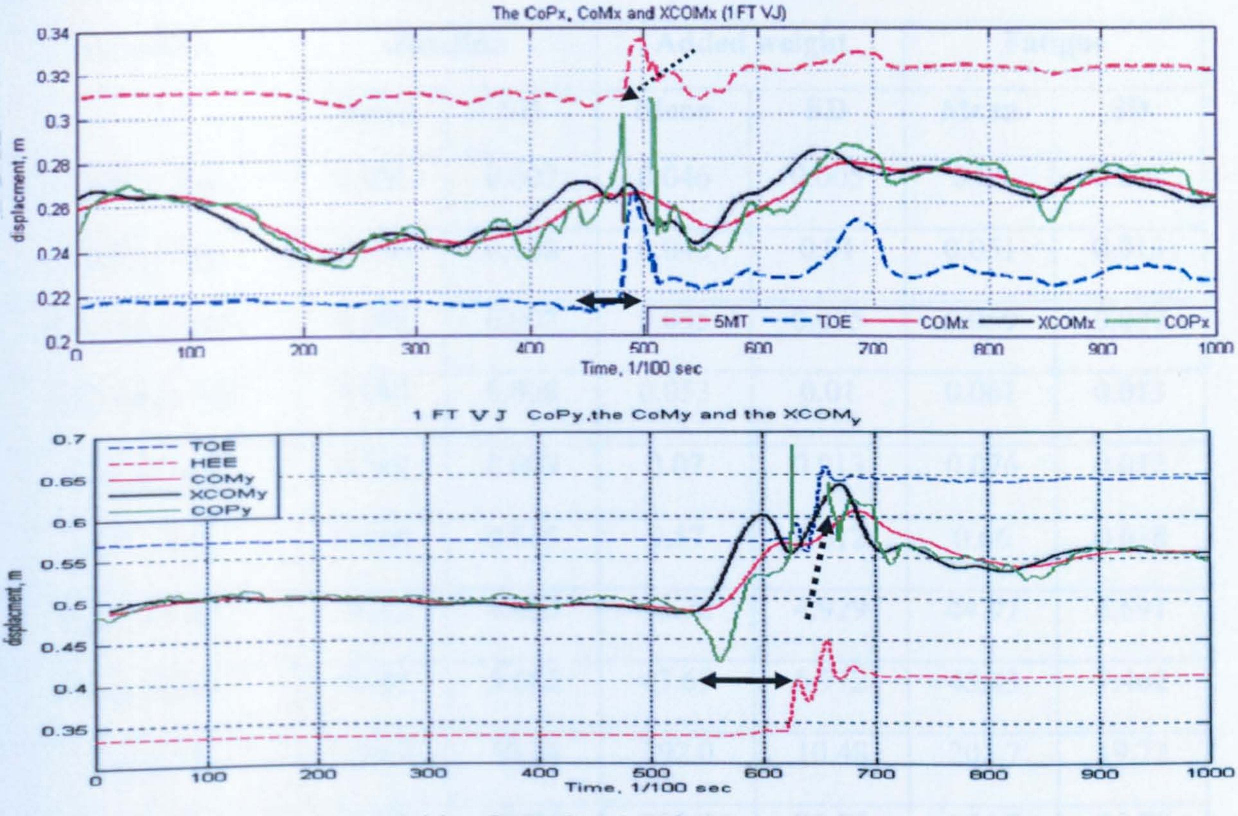


Figure 5.30. Illustrates the variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for dynamic balance (1-foot flat vertical hop). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BoS).

The above figures illustrate the whole event (for 1 foot flat vertical hop). The single-dotted arrow indicates the start of landing phase. Due to nature of the event (vertical jump), the XCoM diverges away from the CoM during take-off phase which represents its nature (rapid movement ↔) even out of the BoS instantly at the flight phase. After the landing phase (↑), the XCoM start gradually to close with the CoM which also represents its nature (slow movement). These movements' necessitate the CoP to follow them to be stable. Mean of the standard deviation for each variable are given in Table 5.6.

Table 5.6. Mean and standard deviation of range of the variables in both the medio-lateral (ML) and anterior-posterior (AP) during dynamic balance (One foot flat vertical hop) for baseline, added weight and fatigue conditions.

Variables	**Baseline**		**Added weight**		**Fatigue**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
CoM_{ML} (m)	0.035	0.007	0.046	0.005	0.05	0.007
CoM_{AP} (m)	0.036	0.008	0.045	0.01	0.051	0.013
$XCoM_{ML}$ (m)	0.045	0.007	0.055	0.005	0.059	0.007
$XCoM_{AP}$ (m)	0.046	0.008	0.053	0.01	0.061	0.013
CoP_{ML} (m)	0.068	0.009	0.07	0.013	0.076	0.012
CoP_{AP} (m)	0.048	0.015	0.57	0.012	0.66	0.018
Q_{ML} (N.m)	36.12	4.423	40.72	4.929	44.97	6.691
Q_{AP} (N.m)	40.01	5.685	43.67	6.772	45.43	7.462
F_{ML} (N)	180.8	10.14	192.0	10.48	201.7	19.72
F_{AP} (N)	312.4	33.86	333.4	39.75	354.7	35.79

Note: neither the TTS nor the DPSI was evaluated for subjects in vertical events.

Figure 5.31 illustrates the data for the Centre of Mass.

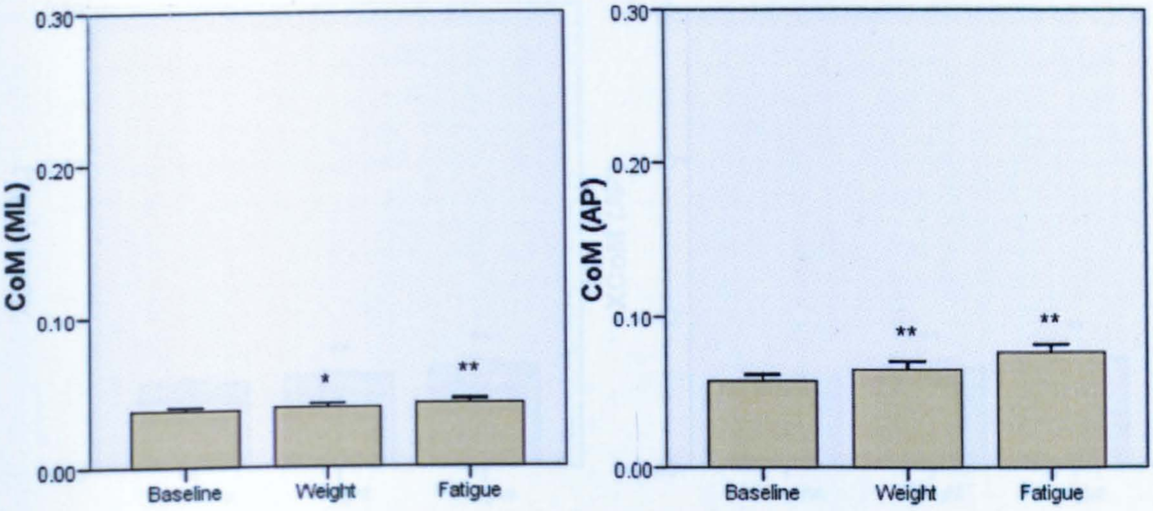


Figure 5.31. Illustrates the mean and SD of the CoM$_{ML}$ and CoM$_{AP}$ directions in dynamic balance (1-feet vertical jump). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoM$_{ML}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.750,\ 33.360)} = 15.386$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 19.757$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 7.484$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoM$_{AP}$ contrast analyses showed that there was a significant main effect of condition (F (1.842, 35.002) = 31.024, $p < .01$). Fatigue was greater than baseline (F (1, 19) = 61.476, $p < .01$). Added weight was also greater than baseline (F (1, 19) = 8.694, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.32 illustrates the data for the extrapolated Centre of Mass.

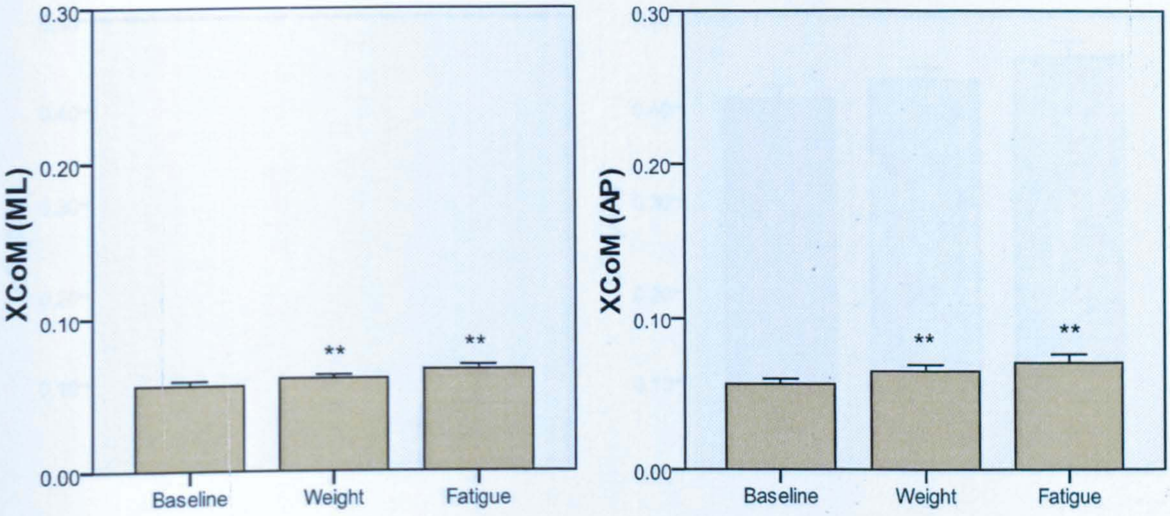


Figure 5.32. The $XCoM_{ML}$ and $XCoM_{AP}$ in dynamic balance (2-feet flat vertical jump). (Units = m/s) (** indicates a significant difference from baseline at $p < .01$)

For the variable $XCoM_{ML}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.747,\ 33.194)} = 92.800$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 39.148$, $p < .01$). Added weight was also greater than baseline ($F_{(1,\ 19)} = 14.251$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable $XCoM_{AP}$ contrast analyses showed that there was a significant main effect of condition ($F_{(1.770,\ 33.622)} = 27.185$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 26.634$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 28.311$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.33 illustrates the data for the centre of pressure.

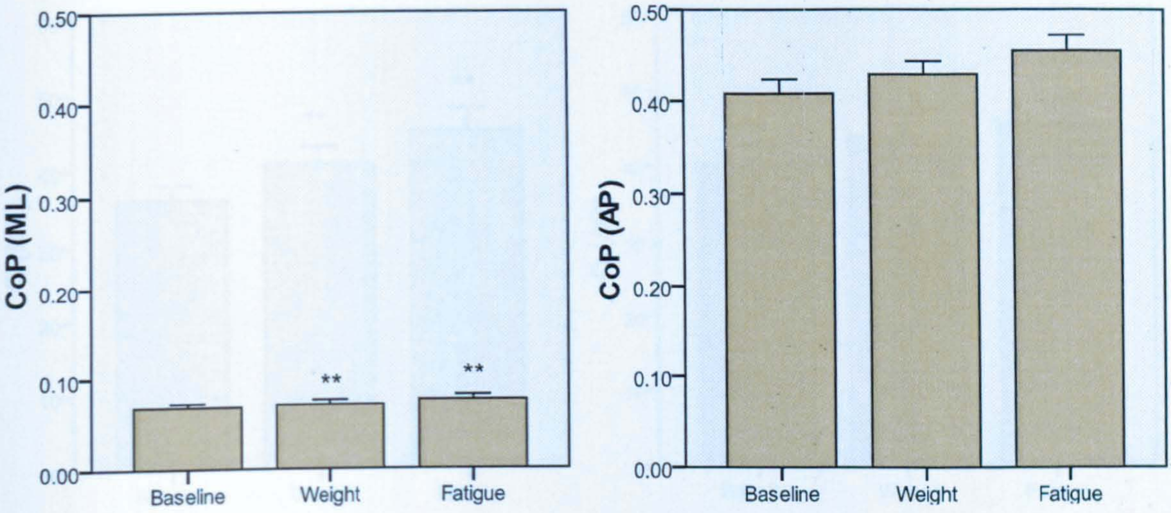


Figure 5.33. The CoP_{ML} and CoP_{AP} in dynamic balance (1-foot flat vertical hop). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

For the variable CoP_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.277,\ 24.449)} = 6.113$, $p < .05$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 6.848$, $p < .05$), whereas added weight did not significantly differ from baseline ($F_{(1,\ 19)} = 2.901$, $p > .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable CoP_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.708,\ 32.449)} = 37.920$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 53.763$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1,\ 19)} = 17.763$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.34 illustrates the data for the friction torque.

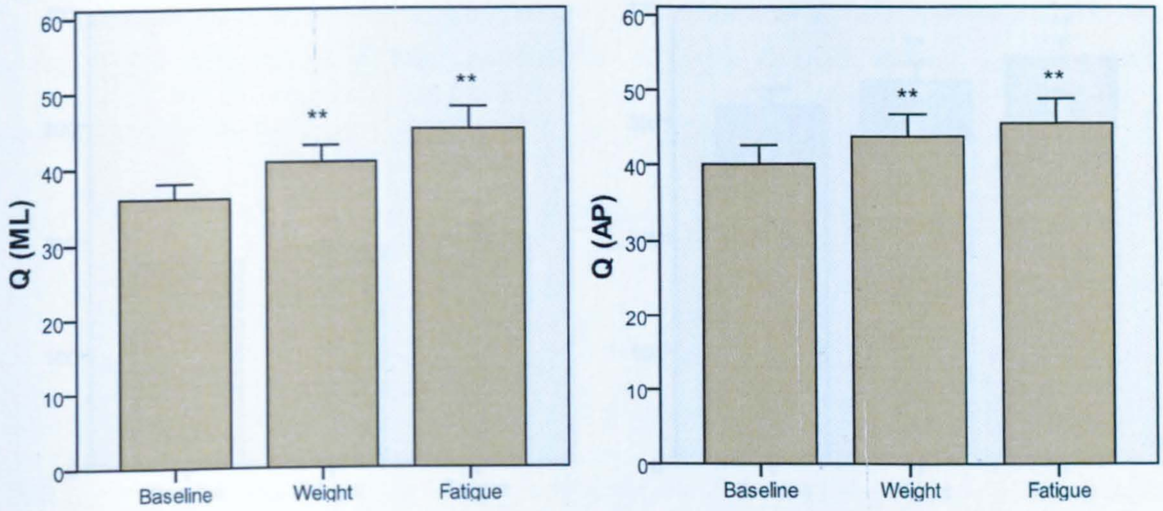


Figure 5.34. The peak of the Q_{ML} and Q_{AP} in dynamic balance (1-feet flat vertical jump). (Units = $N.m^{-1}$) (** indicates a significant difference from baseline at $p < .01$)

For the variable Q_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.461, 27.757)} = 56.359$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 58.211$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 51.908$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable Q_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.696, 32.232)} = 24.597$, $p < .01$). Fatigue was greater than baseline ($F_{(1, 19)} = 24.600$, $p < .01$), similarly, added weight was also greater than baseline ($F_{(1, 19)} = 24.593$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

Figure 5.35 illustrates the data for the ground reaction forces.

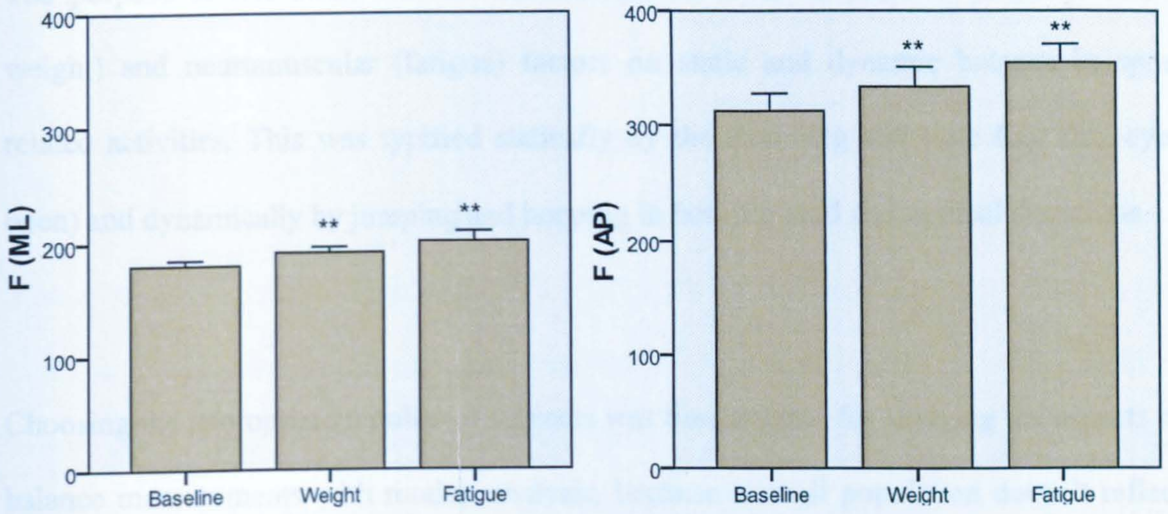


Figure 5.35 The peak of the F_{ML} and F_{AP} in dynamic balance (1-foot flat vertical hop). (Units = N) (** indicates a significant difference from baseline at $p < .01$)

For the variable F_{ML} contrast analyses showed that there was a significant main effect of condition ($F_{(1.196,\ 22.719)} = 17.122$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 13.469$, $p < .01$). Added weight was also greater than baseline ($F_{(1,\ 19)} = 53.779$, $p < .05$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

For the variable F_{AP} contrast analyses showed that there was a significant main effect of condition ($F_{(1.479,\ 28.092)} = 11.457$, $p < .01$). Fatigue was greater than baseline ($F_{(1,\ 19)} = 11.704$, $p < .01$). Added weight was also greater than baseline ($F_{(1,\ 19)} = 10.759$, $p < .01$). There was no significant main effect of trial for the baseline, added weight or fatigue conditions.

5.4. Discussion:

The purpose of this study was to establish the influence of physical (external added weight) and neuromuscular (fatigue) factors on static and dynamic balance in sport related activities. This was typified statically by the Romberg test (one foot flat, eyes open) and dynamically by jumping and hopping in both forward and vertical directions.

Choosing the appropriate number of subjects was fundamental for studying the aspects of balance measurements with motion analysis, because a small population doesn't reflect the variation that can occur in the normal population. Many studies have used numbers of subjects similar to this study (e.g. Wikstrom et al., 2005; n=18, Qu and Nussbaum, 2009; n= 12, Singh and Koh, 2009; n=17, Arellano *et al.*, 2009; n=23). Thus, 20 subjects were considered appropriate for representing balance activity from a variety of subjects.

Choosing the appropriate added mass to be carried by participants was important. Some studies have loaded recreational hikers with 12% to 47% of their total body mass (Lobb 2004), others recommended using 10%, 15% or 20% of total body weight (BW) (Cheung and Hong, 2001; Abe *et al.*, 2004; Singh and Koh, 2009; Arellano *et al.*, 2009), most of which indicate significant changes. The lack of an effect on postural stability when carrying lighter loads has been reported by others (Palumbo *et al.*, 2001) and may be due to the ability of the body to adjust to the smaller load. Therefore, the added weight was considered to be appropriate to elicit a suitable balance response which was 15% of total body weight.

Deciding the appropriate effective fatigue such as type (concentric), location (lower extremity), duration (short period) was also important. Many studies indicated that fatiguing the lower extremity was associated with significant increases in postural sway (Ochsendorf *et al.*, 2000; Ramsdell *et al*, 2001; Gribble and Hertel, 2004). Davidson *et al.* (2004) found that the duration of the induced fatigue effects on postural control have varied from near immediate recovery extended to 10–20 min after the end of the fatiguing exercise for lower extremity fatigue. Moreover, many studies assessing the impact of fatigue on postural control have focused primarily on the induction of fatigue through relatively short-duration exercise (Dickin, 2007). Therefore, this study was designed to determine the effect of short-duration intensive fatiguing exercise localized at the lower extremity, and that within 10 minutes after the fatiguing exercise.

5.4.1. Statically

In the static balance test (one foot flat, eyes open), the present findings are in agreement with previous results (Blaszczyk *et al.*, 2009). Although by adding weight sway did not significantly differ from baseline, there was a trend in that participants' postural sway in the AP direction reduced while carrying added mass. The $XCoM_{AP}$ decreased by -2.51%, the CoP_{AP} by -3.64%. The degree of stability is higher when the body mass is greater (Ribas and Guirro, 2007). This mechanically is due to increase of inertia and therefore postural balance may well be preserved (Blaszczyk *et al.*, 2009). Increasing mass (e.g. backpack) makes it harder to initiate motion and requires greater moments about the axes of rotation to control motion and alter postural control mechanisms (Maki, 1994). As a consequence, AP postural stability is not necessarily better despite reduced sway.

While an increase of body mass resulted in a small functional adaptation of the control of the erect posture, participants' postural sway increased post fatigue in both medio-lateral and anterior-posterior directions. The CoM_{ML} increased by 4.5% and the CoM_{AP} by 5.6%; the $XCoM_{ML}$ increased by 8.9%; and the $XCoM_{AP}$ by 10.6%; the CoP_{ML} increased by 4.4% and the CoP_{AP} by 6.0%. Fatigue increases the complexity of a balance task because it impairs or reduces the force capacity of muscles, decreases sensitivity of the proprioceptive system, and increases body sway (Simoneau *et al.*, 2006). The results agreed with other studies which found an increase in body sway oscillations during static balance tests in the fatigued state (Nardone *et al.*, 1997; Corbeil *et al.*, 2003). Increased postural sway is an indication of perturbed balance. Consequently, fatigue negatively affected postural stability.

In summary, carrying additional weight increased subject's inertia and tended to decrease their sway amplitude and therefore stabilized them in static conditions. In contrast, fatigue increased subjects sway indicating greater instability.

4.3.2. Dynamically

In summary, the differences between the baseline and the added weight condition were as follows: The CoM_{ML} increased by 27.3% and the CoM_{ML} by 2.2%; the $XCoM_{ML}$ increased by 7.9%, and the $XCoM_{AP}$ by 2.4%; the CoP_{ML} increased by 24.9% and the CoP_{AP} 15.3%. Also, the other related variables were affected during dynamic balance e.g. the time to stabilization increased by 29.1%. In post-fatigue, the differences between the baseline and the fatigue condition were as follows: The CoM_{ML} increased by 32.9% and the CoM_{AP} by 2.5%; the $XCoM_{ML}$ increased by 19.1%, and the $XCoM_{AP}$ by 3.3%; also the CoP_{ML} was increased by 30.2% and the CoP_{AP} 19.7%. Time to stabilization was also affected during dynamic balance as the time to stabilization increased by 37.3%. In other words, both added weight and fatigue seemed to lead to reduce stability. However, as will be described below, a more detailed interpretation reveals some interesting concepts.

Results for vertical and horizontal jumping/hoping were similar, but more explicitly evident for the horizontal jumping/hopping. As expected, the main differences between horizontal and vertical jumping were in the AP direction. The variables CoM, XCoM, CoP, Q and F were all larger in horizontal jump than in vertical jump, both at baseline and under added weight or fatigued conditions. In horizontal jumping and hopping, there were significant differences between baseline and added weight. The larger main effect of condition was found in the antero-posterior direction during the landing phase (Figure 5.8, Figure 5.16, Figure 5.22 and Figure 5.30). The translation of the CoM considerably increases its velocity which is important considering the feasible movement for the control of one's balance (Pai *et al.*, 1992). During the take-off phase, the body generates velocity required for flight. As a matter of fact, it creates a significantly diverged $XCoM_{AP}$ that exceeds the boundaries of the BoS at take-off (due to nature of movement). Pai and Patton (1997) reported that forward movement (e.g. take-off of jumping or hopping) would be initiated if the CoM exceeds the boundaries of the BoS. Even though the $XCoM_{ML}$ did not exceed the boundaries of the BoS it also diverged away from it as subjects move their CoM_{ML} laterally at take-off as well as after landing. Upon landing, the movements must be decelerated to stabilize the body's CoM. Although this can be easily achieved in normal circumstances (baseline), in the added weight condition the

XCoM instantly travels outside the BoS particularly in the AP direction ($XCoM_{AP}$). Consequently, the CoP excursion was significantly larger in added weight compared to baseline, but insufficient to recover balance. Dragging the XCoM back within the BoS necessitates the body to generate shear forces at the BoS that are used to decelerate and stabilize the CoM. This was found to be the case at baseline and increasingly under added weight. The larger main effects of added weight on shear force were also found in the two feet horizontal jump. For the two feet horizontal jump added weight condition TTS was also significantly greater than baseline. In other words, subjects require longer time of force production than in the normal condition to remain in equilibrium by dragging and holding the CoM within and over the BoS.

The differences between baseline and lower extremity fatigue were similar to those reported above for added weight. The larger main effect of condition was found in the AP direction due to large and fast movement of the CoM during take-off to landing phase. During the take-off phase, the $XCoM_{AP}$ exceeds the boundaries of the BoS though the $XCoM_{ML}$ did not exceed the boundaries of the BoS. During landing, to stabilize the body's CoM which can be easily achieved in normal circumstances (baseline), after inducing fatigue the XCoM was initially outside the BoS particularly in the AP direction. Consequently, the CoP excursion was significantly larger in post fatigue compared to baseline. In order to recover balance, considerable shear forces had to be generated at the BoS to decelerate and stabilize the CoM. TTS was also significantly greater than baseline indicating that more time was needed to maintain balance.

5.5. Conclusion:

The investigation of the effect of carrying additional mass (15% of total body mass) and inducing intensive localized fatigue (lower extremity) upon static and dynamic balance variables in healthy young adult males was informative in different ways.

Added weight (15% of total body weight):

- *Statically,* decreased body sway in AP direction though not significant. Indication that increased inertia impacts on behaviour of the mechanical system rather than behaviour of neurophysiological system.
- *Dynamically,* significantly increased body sway in both ML and AP directions as an indication of instability. This challenges mechanism one (seen through increased CoP excursion) and requires utilization of mechanism two in order to maintain balance (seen through increased shear forces and Q).

Fatigue (localized at the lower extremity):

- *Statically,* fatigue significantly increased body sway indicating greater instability while primarily utilizing mechanism one. This is an Indication of neurophysiological adaptation.
- *Dynamically,* significantly increased body sway in both ML and AP directions as an indication of instability. Advanced utilization of mechanism two is demonstrated through increased shear forces and Q, as well as increased TTS.

Chapter (6) General discussion and Future work

6. General discussion and Future work

6.1. General discussion

This thesis presented a number of discrete studies, which investigated characteristics of static and dynamic balance in sport related activities and eventually the effects of physical (carrying additional weight) and neuromuscular (effect of localized muscular fatigue) factors influencing these characteristics.

In study 1, methods incorporating mechanical variables to quantify static and dynamic balance were developed. This was achieved in a sport context, applying the XCoM method to activities ranging from standing still to jumping and hopping. It was established that CoP, CoM, and XCoM are informative on mechanism 1 (inverted pendulum). This can be facilitated through measuring RMS during static balance, and measuring excursion range during more dynamic activities such as hopping and jumping. In the latter dynamic activities, shear forces and their respective moments were found to be informative measures on mechanism 2 (counter rotating segments) for maintaining balance after landing. Implementation of the XCoM was practical for evaluating both static and dynamic balance and provided the expected results: in static balance, the XCoM was within the BoS when the subject maintained balance, while in dynamic balance it travels close to the boundaries of the BoS during take-off and landing stages.

In study 2, the baseline characteristics of static and dynamic balance in young adults in sport related activities were evaluated. This was achieved by establishing baseline data of selected variables which characterize static and dynamic balance activities in a population of healthy young adult males and examining the trial effect on these variables. Matlab procedures were developed and used for quantifying selected static and dynamic balance variables.

No significant trial effect was found between repetitions. It was established that the functional BoS can also be measured by using additional markers to the feet/ foot, and that using Matlab procedures for quantifying the selected variables for static and dynamic balance is practical for handling large data sets (e.g. analysis, plotting and producing SPSS output). Moreover, it was found that testing with eyes open is related to sport activity and standing one foot flat is a representative test for static balance while standing on tiptoes tests, either in static or dynamic balance, are too challenging for most participants in normal circumstances. The baseline data from this study was considered suitable for comparative purposes in the forthcoming study.

In study 3, the investigation presented the establishment of the influence of physical (carrying an external added weight of 15% of total body mass) and neurophysiological (fatigue induced to the lower extremities) factors on static and dynamic balance in sport related activities. Overall, the effect on static balance of carrying additional weight was that it increased subjects' inertia, tended to decrease their sway, and therefore stabilizes them in static conditions. In contrast, the effect of fatigue on static balance was that it led to increased sway as an indication of reduced stability. These effects on static balance seemed to largely confirm previous findings. A key innovative aspect of this thesis was applying the XCoM in sport related activities such as jumping and hopping. Here, it was found that upon landing XCoM exceeded the BoS boundaries both under added weight and fatigue. If only mechanism one (inverted pendulum) applied, the participants would lose their balance. However, considering that in all trials participants did not lose their balance and did not alter their BoS (either through taking a step or using an external support), this was an indication that participants had to use mechanism two (counter rotating segments) to maintain their balance. Interestingly, a differential adaptation for each of these mechanisms was found between one foot flat and two feet flat conditions, such that participants relied more heavily on mechanism one in the one foot flat conditions and relied more on mechanism two in the two feet flat conditions.

6.2. Summary points:

- This thesis provided substantial insight in evaluating static (standing) and dynamic balance(jumping and hopping) in sport related activities
- The CoP, the CoM, the XCoM, shear forces, and their respective moments are more informative than other variables (e.g. KE, and P) during both static and dynamic balance providing valuable information about the postural control mechanisms,
- The investigations showed that there was a significant difference in static balance tests between normal circumstances and post fatigue, when there was no significant difference in static balance test between normal circumstances and carrying 15% of the total body mass.
- The investigations showed also a significant difference in dynamic balance between normal circumstances and both while participants carrying 15% of total body mass and post fatigue.

It is suggested that results from this thesis aid toward advancing the understanding of balance in sport related activities, and can provide an initial foundation for future work in this area.

6.3. Future work

The key findings of this thesis provide valuable insights into the application of the XCoM approach for assessing balance in a sports context.

Adaptations due to training can now be investigated through a focused methodology. For example, comparison can be made between non-trained population and athletes who undergo inherent balance training as part of their sports discipline (e.g. ballet dancers, gymnasts).

The focused study of balance during specific technical skills in sport (e.g. side cutting manoeuvres, standing reception in volleyball, and floor routines in gymnastics) can now be undertaken. The importance of accurate recordings, quantifying relevant variables, supplying sufficiently synchronised and automated data processing routines, and appropriate interpretation in terms of the available balance mechanisms was demonstrated in this thesis. This serves as a solid starting point towards studying balance in more sport specific technical skills.

It is expected that future developments of the methodology may require advanced complexity, for example by measuring the CoP through a combination of pressure and force platform recordings, by measuring the Base of Support through a combination of pressure and kinematic recordings, or by simultaneously recording muscle activation patterns through surface electromyography. Regarding the latter, there is scope for associating muscle activation patterns of ankle plantar flexors and dorsiflexors to findings related to mechanism one, and for associating muscle activation patterns of hip extensors and flexors to findings related to mechanism two.

Chapter (7) References

7. References

Abe, D., Yanagawab, K., and Niihata, S. (2004). Effects of load carriage, load position, and walking speed on energy cost of walking, *Applied Ergonomics*, **35**, 329–335.

Adrian, M. J., and Cooper, J. M. (1995). *Biomechanics of human movement*, second edition, McGraw-Hill.

Allum, J. H, Keshner, E. A., Honegger, F., and Pfaltz, C. R. (1988). Organization of leg-trunk-head equilibrium movements in normals and patients with peripheral vestibular deficits, *Progress in Brain Research*, **76**, 277–290.

Aramaki, Y., Nozaki, D., Masani, K., Sato, T., Nakazawa, K., and Yano, H. (2001). Reciprocal angular acceleration of the ankle and hip joints during quit standing humans, *Experimental Brain Research*, **136**, 463-473.

Arellano, C.J., Layne, C.S., O'Connor, D.P., Scott-Pandorf, M., and Kurz, M. J. (2009). Does Load Carrying Influence Sagittal Plane Locomotive Stability? *Medicine and Science in Sports and Exercise*, **41**, 620-627.

Bartlett, G. (2002). Introduction to sports biomechanics, fourth edition, Spon press.

Bizid, R., Jully, J. L., Gonzalez, G., Francois, Y., Dupuic, P., and Paillard, T. (2009). Effects of fatigue induced by neuromuscular electrical stimulation on postural control, *Journal of Science and Medicine in Sport*, **12**, 60-66.

Blaszczyk, J. W., Lowe, F., and Hansen, P. D. (1994). Ranges of postural stability and their changes in the elderly, *Gait and Posture*, **2**, 11-17.

Blaszczyk, J. W., Prince, F., Raiche, M., and Hebert, R. (2000). Effect of ageing and vision on limb load asymmetry during quiet stance, *Journal of Biomechanics,* **33,** 1243-1248.

Blaszczyk, J. W., Cieslinska-Swider, J., Plewa, M., Zahorska-Markiewicz, B. and Markiewicz, A. (2009). Effects of excessive body weight on postural control, *Journal of Biomechanics*, **42**, 1295–1300.

Borg, G. (1998). *Borg's perceived exertion and pain scales.* Stockholm: Human Kinetics.

Brostrom, E., Ortqvist, M., Haglund-Akerlind, Y., Hagelberg, S., and Gutierrez-Farewik, E. M. (2007). Trunk and center of mass movements during gait in children with juveline idiopathic arthritis, *Human Movement Science*, **26**, 296–305.

Bryant, E. C., Trew, M. E., Bruce, A. M., Kuisma, R.M.E., and Smith, A.W. (2005). Gender differences in balance performance at the time of retirement, *Clinical Biomechanics*, **20**, 330-335.

Bulbulian, R., and Hargan, M. L. (2000). The effect of activity history and current activity on static and dynamic postural balance in older adults, *Physiology and Behaviour*, **70**, 319–325.

Butler, E., Colón, I., Druzin, M., and Rose, J. (2006). Postural equilibrium during pregnancy: Decreased stability with an increased reliance on visual cues, *American Journal of Obstetrics and Gynecology*, **195**, 1104-1108.

Cherng, R. J., Lee, H. Y., and Su, F. C. (2003). Frequency spectral characteristics of standing balance in children and young adults, *Journal of Biomedical Engineering*, **25**, 509–515

Cheung, K., and Hong, Y. (2009). The effect of load carriage on gait pattern and trunk posture in school children, *Hong Kong SAR*, accessed on 26/09/09 **http://w4.ub.uni-konstanz.de/cpa/article/viewFile/2245/2101**

Colby, S., Hintermeister, R. A., Torry, M. R., and Steadman, J. R. (1999). Lower limb stability with ACL impairment, *Journal of Orthopaedic and Sports Physical Therapy*, **29**, 444–451.

Corbeil, P., Simoneau, M., Rancourt, D., Tremblay, A., and Teasdale, N. (2001). Increased risk for falling associated with obesity: mathematical modelling of postural control. *IEEE, Transactions on Biomedical Engineering*. **9**, 126–136.

Corbeil, P., Blouin, J. S., Bégin, F., Nougier, V., and Teasdale, N. (2003). Perturbation of the postural control system induced by muscular fatigue. *Gait and Posture*, **18**, 92-100.

Crowe, A, P., Schiereck, R. W., de Boer, and Keessen, W. (1995). Characterization of human gait by means of body Centre of Mass oscillations derived from ground reaction forces, *IEEE, Engineering in Medicine and Biology Society*, **42**, 12–20.

Davis, K G., Sobeih, T. M. Succop, P., Jetter. W, Kotowski, S E., Bhattacharya, A. (2009). Impact of obesity on the postural balance of firefighters, *Journal Occupational Ergonomics*, **8**, 115-123.

De Wit, B., De Clercq, D., Aerts, P. (2000). Biomechanical analysis of the stance phase during barefoot and shod running, *Journal of Biomechanics*, **33**, 269-278.

Deitz, J. C., Richardson, P. R., Crowe, T. K., and Westcott, S. L. (1996). Performance of children with learning disabilities and motor delays on the pediatric clinical test of sensory interaction for balance (P-CTSIB), *Physics of Occupation and Therapy Podiatry,* **16,** 1–21.

Diener, H. C., Dichgans, J., Guschlbauer, B., and Bacher, M. (1986). Role of visual and static vestibular influences on dynamic posture control, *Human Neurobiology,* **5,** 105-113.

Dickin, D. C. (2007). Postural stability in altered and unaltered sensory environments following fatiguing exercise of lower extremity joints, *Scandinavian Journal of Medicine and Science in Sports,* **18,** 1-8.

Davidson, B. S., Madigan, M. L., Nussbaum, M. A. (2004). Effects of lumbar extensor fatigue and fatigue rate on postural sway, *European Journal of Applied Physiology.* **93,** 183-189.

Dorland's Illustrated Medical Dictionary (2003) 30th Edition. by Douglas M. Anderson W. B. Saunders, Philadelphia.

Eechaute, C., Vaes, P., Duquet, W. (2009) The chronic ankle instability scale: Clinimetric properties of a multidimensional, patient-assessed instrument, *Physical Therapy in Sport,* **9,** 57-66

Enoka, R. M. (1994). Neuromechanical basis of kinesiology. Second edition, Human kinetics, Champaign, IL.

Enoka, R. M., and Stuart, D. G. (1992). Neurobiology of muscle fatigue, *Journal Applied Physiology,* **72,** 1631–1648.

Era, P., and Heikkinen, E. (1985). postural sway during standing and unexpected disturbance of balance in random samples of men of different ages, *Journal of Gerontology*, **40**, 287-295.

Era, P., Konttinen, N., Mehto, P., Saarela, P., and Lyytinen, H. (1996). Postural stability and skilled performance. A study on top-level and naive rifle shooters, *Journal of Biomechanics*, **29**, 301-306.

Fregly, A. R., Oberman, A., Graybiel, A., and Mitchell, R. E. (1968). Thousand aviator study: no vestibular contributions to postural equilibrium functions, *Aero Medical*, **39**, 33–37.

Giagazoglou, P., Amiridis I. G., Zafeiridis, A., Thimara, M., Kouvelioti, V., and Kellis, E. (2009). Static balance control and lower limb strength in blind and sighted women, *European Journal of Applied Physiology*, **107**, 571–579.

Geldhof, E., Cardon, G., De Bourdeaudhuij, I., Danneels, L., Coorevits, P., Vanderstraeten, G., and De Clercq, D. (2006). Static and dynamic standing balance: test-retest reliability and reference values in 9 to 10 year old children, *European Journal of Pediatrics*, **165**, 779–786

Geurts, A., Nienhuis, B., and Mulder, T. (1993). Intra subject variability of selected force-platform parameters in the quantification of postural control, *Archives of Physical Medicine and Rehabilitation*, **74**, 1144-1150.

Gill, J. (1998). Postural stability measurements in amputee patients, Monash University. http://www.monash.edu.au/rehabtech/research/postural.htm,(accessed on 4th September 2006).

Goulding, A., Jones, I. E., Taylor, R.W., Piggot, J. M. and Taylor, D. (2003). Dynamic and static tests of balance and postural sway in boys: effects of previous wrist bone fractures and high adiposity, *Gait and Posture*, **17**, 136–141.

Gribble, P. A., Hertel, J., Denegar, C. R., and Buckley, W. E. (2004). The Effects of Fatigue and Chronic Ankle Instability on Dynamic Postural Control, *Journal of Athletic Training*, **39**, 321–329

Gribble, P. A., and Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control, *Archives of Physical Medicine and Rehabilitation*, **85**, 589-592.

Goldie, P. A., Bach, T. M., and Evans, O. M. (1989). Force platform measures for evaluating postural control: reliability and validity, *Archives of Physical Medicine and Rehabilitation*, **70**, 510–517.

Grimmer, K., Dansie, B., Milanese, S., Pirunsan, U., and Trott, P. (2002). Adolescent standing postural response to backpack loads: a randomized controlled experimental study, *BMC Musculoskeletal Disorders*, **3**, 1-10

Grimshaw, P., Lees A., Fowler, N., and Burden, B. (2006). *Sports and Exercise Biomechanics*, Instant notes, first edition, Taylor and Francis.

Guerraz, M., Hoffmann, J. S., Yarrow, K., Bronstein, A. M, Guerraz, M., Thilo, K. V., Bronstein, A. M., and Gresty, M. A. (2000). Influence of motion parallax on visually induced body sway, *Gait and Posture*, **41**, 3798-3804.

Gutierrez-Farewik, E. M., Bartonek, A., and Saraste, H. (2006). Comparison and evaluation of two common methods to measure center of mass displacement in three dimensions during gait, *Human Movement Science*, **25**, 238-256.

Hamill, J., and Knutzen, M. K. (2003). *Biomechanical basis of human movement*, second edition, Lippincott Williams and Wilkins.

Harringe, M. L., Halvorsen, K., Renstrom, P., Werner S. (*2008*). Postural control measured as the center of pressure excursion in young female gymnasts with low back pain or lower extremity injury, *Gait and Posture*, **28**, 38–45.

Hasan, S. S., Deborah, W. R., Szurkus, D. C., Ashmead, D. H., Peterson, S. W., and Shiavi, R. G. (1996). Simultaneous measurement of body Centre of Pressure and centre of gravity during upright stance. Part II: Amplitude and frequency data, *Gait and Posture*, **4**, 11-20.

Hasson, C. J., Van Emmerik, R. E. A., and Caldwell, G. E. (2008). Predicting dynamic postural instability using center of mass time-to-contact information, *Journal of Biomechanics*, **41**, 2121–2129.

Heller, M. F., Challis, J. H., and Sharkey, N. A. (2009). Changes in postural sway as a consequence of wearing a military backpack, *Gait and Posture*, **30**, 115–117.

Hennig, E. M., Byrne, N. M., Steele, J. R. and Hills, A. P. (2006). The biomechanics of restricted movement in adult obesity, the International Association for the Study of Obesity, *Obesity Reviews*, **7**, 13–24.

Hof, A. L., Gazendam, M. G. J. and Sinke, W. E. (2005). The condition for dynamic stability, *Journal of Biomechanics*, **38**, 1-8.

Hof, A. L. (2007). The equations of motion for a standing human reveal three mechanisms for balance, *Journal of Biomechanics*, **40**, 451-457.

Hof, A. L. (2008). The 'extrapolated center of mass' concept suggests a simple control of balance in walking, *Human Movement Science*, **27**, 112–125.

Horak, F. B. (1997). Clinical assessment of balance disorders, *Gait and Posture*, **6**, 76–84.

Hytönen, M. L., Pyykkö, I., Heikki, A., and Starck, J. (1993) Postural Control and Age, *Acta oto-laryngologica*, **113**, 119-122.

Iverson, B. D., Gossman, M. R., Shaddeau, S. A., and Turner, M. E. (1990). Balance performance, force production, and activity levels in non-institutionalized men 60 to 90 years of age, *Physical Therapy*, **70**, 348-355.

Jeffrey, M., and Schiffman, C. K. (2006). Effects of carried weight on random motion and traditional measures of postural sway, *Applied Ergonomics*, **37**, 607-614.

Jebb, S. A., and Moore, M. S. (1999). Contribution of a sedentary lifestyle and inactivity to the aetiology of overweight and obesity: current evidence and research issues, *Medicine and Science in Sports and Exercise*, **31**, 534– 541.

Jevsevar, S. D., Riley, P. O., Hodge, W. A., and Krebs, D. E. (1993). Knee kinematics and kinetics during locomotor activities of daily living in subjects with knee arthroplasty and in healthy control subjects, *Physical Therapy*, **73**, 229–239.

Johnson, R. P. (2000). The Effect of Load Position on Biomechanical and Physiological Measures during a Short Duration March, *Ergonomics Research Group*, 1-6. Kingston, Canada: RTO MP-056.

Karlsson, A., and Lanshammar, H. (1997). Analysis of postural sway strategies using an inverted pendulum model and force plate data, *Gait and Posture*, **5**, 198–203.

Karlsson, A., and Frykberg, G. (2000). Correlations between force plate measures for assessment of balance, *Clinical Biomechanics*, **15**, 365-369.

Kejonen, P. (2002). Body movements during postural stabilization. Measurements with a motion analysis system, PhD thesis, Department of Physical Medicine and Rehabilitation, University of Oulu. Finland.

Khasnis, A., and Gokula, R. M. (2003). Romberg tests, *Journal of Postgraduate Medicine*, **49**, 169-172.

Kinney LaPier, T. L., Liddle, S., and Bain, C. (1995). A comparison of static and dynamic standing balance in older men versus women. *Journal of Neurologic Physical Therapy*, **19**, 20-21.

Kingma, I., Toussaint, H. M., Commissaris, D. M., Hoozemans, M. J., and Ober, M. J. (1995). Optimizing the determination of the body center of mass, *Journal of Biomechanics*, **28**, 1137-1142.

Kirtley, C. (2006). *Clinical gait analysis, Theory and practice*, Churchill Livingstone, Elsevier Ltd.

Krebs, D. E., Wong, D., Jevsevar, D., Riley, P. O and Hodge, W. A. (1992). Trunk kinematics during locomotor activities, *Physical Therapy*, **72**, 505–514.

Kuo, A. D. (1995). An optimal control model for analyzing human postural balance, *IEEE, Transactions on Biomedical Engineering*, **42**, 87-101.

Latash, M. L. (1998). *Neurophysiological Basis of Movement*, Champaign, IL, Human Kinetics.

Latash, M. L., Ferreira, S. S., Wieczorek, S. A., and Duarte, M. (2003). Movement sway: changes in postural sway during voluntary shifts of the center of pressure, *Experimental Brain Research*, **150**, 314–324

Lebiedowska, M. K., Wente, T. M., and Dufour, M. (2009). The influence of foot position on body dynamics, *Journal of Biomechanics*, **42**, 762–766.

Ledin, T., Fransson P.A., and Magnusson M. (2004). Effects of postural disturbances with fatigued triceps sure muscles or with 20% additional body weight, *Gait and Posture*, **19**, 184–93.

Lee, D. N., and Lishman, J. R. (1975) Visual proprioceptive control of stance, Journal of Human Movement Studies, **1**, 87-95.

Levine, O. and Mizrahi, J. (1996). An iterative model for the estimation of the trajectory of the centre of gravity from bilateral reactive force measurements in standing sway, *Gait and Posture*, **4**, 89–99.

Lobb, B. (2004). Load carriage for fun: a survey of New Zealand trampers, their activities and injuries, *Applied Ergonomics*, **35**, 541–547.

Loram, I. D., Maganaris, C. N., and Lakie, M. (2007). The passive, human, calf muscles in relation to standing: the non-linear decrease from short range to long range stiffness, *The Journal of Physiology*, **584**, 661–675.

Lord, S.R. (2005) Vision, Balance and falls in the elderly, *Geriatric times*, **5**, 6.

Lucy, S. D., and Hayes, K. C. (1985). Postural sway profiles: normal subjects and subjects with cerebella ataxia, *Physiotherapy*, **37**, 140-148.

Maki, B.E. (1994). A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *Journal of Gerontology*, medical science, **49**, 72–84.

Maki, B. E., and McIlroy, W.E. (1997). The role of limb movements in maintaining upright stance: the "change-in-support" strategy, *Therapy*, **77**, 488–507.

Matrangola, S. L. (2008). A modeling investigating of obesity and balance, Master's Thesis, Virginia Polytechnic Institute and State University, USA.

Magnusson, M., Enbom, H., Johansson, R., and Pyykko, I. (1990) Significance of pressor input from the human feet in anterior-posterior postural control, The effect of hypothermia on vibration-induced body-sway, *Acta oto-laryngologica*, **110**, 182-188.

McGinnis, P. M. (2005) *Biomechanics of Sport and Exercise*, Library of Congress-Cataloging-in-Publication-Data fourth edition, Human kinetics.

McGraw, B., McClenaghan, B. A., Williams, H. G., Dickerson, J., and Ward, D S. (2000). Gait and postural stability in obese and non-obese prepubertal boys, *Archives of Physical Medicine and Rehabilitation*, **81**, 484–489.

Miller, R. G., Kent-Braun, J. A., Sharma, K. R. and Weiner, M. W. (1995). Mechanisms of human muscle fatigue: quantitating the contribution of metabolic factors and activation impairment, *Advances in Experimental Medicine and Biology*, **384**, 195–210.

Moraes, R., and Patla A.E. (2005). Stability requirements determine the preferred alternate foot placement choice during human locomotion. Department of Kinesiology, University of Waterloo, Canada, *Gait and Posture*, **21**, S39

Morasso, P. G., Spada, G., and Capra, R. (1999). Computing the CoM from the CoP in postural sway movement, *Human Movement Science*, **18**, 759–767.

Nardone, A., Tarantola, J., Giordano, A., and Schieppati, M. (1997). Fatigue effects on body balance, *Electroencephalography and Clinical Neurophysiology*, **105**, 309-320.

Nashner, L. M., and McCollum, G. (1985).The organization of human postural movements: A formal basis and experimental synthesis. Behaviour and Brain Science. **8**, 135-172.

Oates, A. R. (2007). Control of Dynamic Stability during Gait Termination on a Slippery Surface, Ph.D. thesis, University Waterloo, Canada.

Ochsendorf, D. T., Mattacola, C. G., and Arnold, B. L. (2000). Effect of orthotics on postural sway after fatigue of the plantar flexors and dorsiflexors, *Journal of Athletic Training*, 35, 26–30.

Ödkvist, T. L. (1993). Effects of Increased Inertial Load in Dynamic and Randomized Perturbed, *Acta oto-laryngologica*, 249-252.

Oliveira, L. F., Vieira T. M. M., Macedo A. R., Simpson, D. M., and Nadal, J. (2009). Postural sway changes during pregnancy: A descriptive study using stabilometry, *European Journal of Obstetrics and Gynecology and Reproductive Biology*, **147**, 25-28.

Orendurff, M. S., Segal, A. D., Klute, G. K., Berge, J. S., Rohr, E. S., and Kadel, N. J. (2004). The effect of walking speed on center of mass displacement, *Journal of Rehabilitation Research and Development*, **41**, 829–834

Otten, E. (1999). Balancing on a narrow ridge; biomechanics and control, Philosophical Transaction, *The Royal Society*, **354**, 869-875.

Pai, Y. C., Naughton, B. J., and Chang, R. W. (1992). Control of dynamic transfer during sit-to-stand among young and elderly individuals, In *Posture and Gait*: Control mechanisms (Edited by Woollacott, M. and Horak, F.), **2**, pp. 301-304, University of Oregon, Eugene, OR.

Pai, Y. C., and Patton, J. (1997). Center of mass velocity-position predictions for balance control, *Journal of Biomechanics*, **30**, 347-354.

Pai, Y. C. (2003). Movement termination and stability in standing, *Journal of Exercise and Sport Science Reviews*, **31**, pp. 19-25.

Palumbo, N., George, B., Johnson, A., and Cade, D. (2001). The effects of backpack load carrying on dynamic balance as measured by limits of stability, *Work*, **16**, 123-129.

Patla, A. E., Prentice, S. D., Robinson, C., and Neufeld, J. (1991). Visual control of locomotion: strategies for changing direction and for going over obstacles. *Journal of Experimental Psychology*, 17, 603–634.

Paulus, W. M., Straube, A., and Brandt, T. (1984). Visual stabilization of posture: Physiological stimulus characteristics and clinical aspects, Brain, *journal of Neurology*, **107**, 1143-1163.

Qu, X., and Nussbaum, M. A. (2009). Effects of external loads on balance control during upright stance: Experimental results and model-based predictions, *Gait and Posture*, **29**, 23–30.

Ramsdell, K. M., Mattacola, C. G., Uhl, T. L., McCroy, J. L., and Malone, T. R. (2001). Effects of two ankle fatigue models on the duration of postural stability dysfunction, *Journal of Athletic Training*, **40**, 191–194.

Ramstrand, N., Thuesen, A. H., Nielsen, D. B., and Rusaw, D. (2010). Effects of an unstable shoe construction on balance in women aged over 50 years, *Clinical Biomechanics*, In Press, Corrected Proof, *Available online 21 February 2010.*

Reevesa, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos V and Maganaris C. N. (2008). Influence of light handrail use on the biomechanics of stair negotiation in old age, *Gait and Posture*, **28**, 327–336.

Redfern, M. S., Moore, P. L., and Yarsky, C. M. (1997). The Influence of Flooring on Standing Balance among Older Persons, *Journal of Human Factors*, **39**, 445-455.

Reimer, R. C., and Wikstrom, E. A. (2010). Functional fatigue of the hip and ankle musculature cause similar alterations in single leg stance postural control, *Journal of Science and Medicine in Sport*, **13**, 161–166.

Ribas, S. I., and Guirro, E. (2007). Analysis of plantar pressure and postural balance during different phases of pregnancy, *Revista Brasileira de Fisioterapia*, **11**, 391-396.

Riemann, B. L., Caggiano, N. A., and Lephart, S M. (1999). Examination of a clinical method of assessing postural control during a functional performance task, Journal of Sport Rehabilitation, **8**, 171–183.

Roland N. J., Smith C. A., Miller I. W., Jones A. S., and Lesser T. H. (1995). A simple technique to measure body sways in normal subjects and patients with dizziness, *The Journal of Laryngology and Otology*, 109, 189-192.

Ross, S. E, Guskiewicz, K. M., and Yu, B. (2005). Time to stabilization differences in functionally unstable and stable ankles, *Journal of Athletic Training*, 40, 298–304.

Rothwell, J. (1994). *Control of human voluntary movement*, second edition, Chapman and Hall, London.

Santos, B. R., Delisle, A., Lariviere, C., Plamondon, A., and Imbeau, D. (2008). Reliability of Centre of Pressure summary measures of postural steadiness in healthy young adults, *Gait and Posture*, 27, 408–415.

Sato, K, Heise, G. D., and Liu, K. (2008). Differences in dynamic stabilization between volleyball and rugby players, ISBS Conference 2008, July 14-18, 2008, Seoul, Korea.

Schieppati, M., Nardone A., and Schmid, M. (2003). Neck muscle fatigue affects postural control in man, *Neuroscience*, 121, 277–85.

Schiffman, J. M., Bensel, C. K., Hasselquist, L, Norton, K., and Piscitelle, L. (2005). The effects of soldiers' loads on postural sway, U.S. Army Natick Soldier Center, Natick, MA, 01760, USA.

Shimba, T. (1984). An estimation of centre of gravity from force platform data, *Journal of Biomechanics*, 17, 53–60.

Shambes, G. (1976) Static postural control in children, American Journal of Physical Medicine and Rehabilitation, 55, 221-252.

Simoneau, M., Bégin, F., and Teasdale, N. (2006). The effects of moderate fatigue on dynamic balance control and attentional demands, *Journal of Neuroengineering and Rehabilitation.* 3, 1-9.

Singh, T., and Koh M. (2009). Effects of backpack load position on spatiotemporal parameters and trunk forward lean, *Gait and Posture*, 29, 49–53

Sundstrup, E., Jakobsen M. D., Andersen, J. L., Randers, M. B., Petersen, J., Suetta, C., Aagaard, P., Krustrup, P. (2010) Muscle function and postural balance in lifelong trained male footballers compared with sedentary elderly men and youngsters, *Scandinavian Journal of Medicine and Science in Sports*, **20**, 90-97.

Talbott, N. R. (2005). The Effect of the Weight, Location and Type of Backpack on Posture and Postural Stability of Children, unpublished Ph.D. thesis, Department of Environmental Health of the College of Medicine, Occupational Safety and Ergonomics, Division of Research and Advanced Studies of the University of Cincinnati, USA.

Usui, N., Maekawa, K., and Hirasawa, Y. (1995). Development of the upright postural sway of children, *Developmental Medicine and Child Neurology*, 37, 985–996.

van Asseldonk, E. H. F., Carpenter, M. G., van der Helm F. C. T., and van der Kooij, H. (2007). Use of Induced Acceleration to Quantify the stabilization Effect of External and Internal Forces on Postural Responses, IEEE, *Transactions on Biomedical Engineering*, 54, 2284-2295.

Vaes, P., Duquet, W., and Van Gheluwe, B. (2002) Peroneal Reaction Times and Eversion Motor Response in Healthy and Unstable Ankles, *Journal of Athletic Training*, 37, 475–480.

Vanrenterghem, J., Lees, A., Lenoir, M., Aerts, P., and De Clercq, D. (2004) Performing the vertical jump: Movement adaptations for submaximal jumping Human Movement Science, *Human Movement Science*, **22**, 713-727

Vollestad, N. K., Sejersted, O.M., Bahr, R., Woods, J. J. and Bigland- Ritchie, B. (1988). Motor drive and metabolic responses during repeated submaximal contractions in man, *Journal of Applied Physiology*, **64**, 1421–1427.

Vollestad, N. K. (1997). Measurement of human muscle fatigue, *Journal of Neuroscience Methods*, **74**, 219–227.

Wallace, C., Reiber, G. E., LeMaster, J., Smith, D. G., Sullivan, K., Hayes, S., and Vath, C. (2002). Incidence of falls, risk factors for falls, and fall related fractures in individuals with diabetes and a prior foot ulcer, *Diabetes Care*, **25**, 1983–1986.

WHO (2010) World Health Organization http://www.who.int/violence_injury_prevention/other_injury/falls/en/index.htm Accessed on 31/03/2010.

Wikipedia (2010) http://en.wikipedia.org/wiki/Vestibular_system. Accessed on 31/03/2010.

Wikstrom, E. A., Powers, M. E., and Tillman, M. D. (2004). Dynamic stabilization time after isokinetic and functional fatigue, *Journal Athletic Training*, **39**, 247–253.

Wikstrom, E. A., Tillman, M. D., Smith, A. N., and Borsa, P. A. (2005). A new force-plate technology measure of dynamic postural stability: The Dynamic Postural Stability Index, *Journal of Athletic Training*, **40**, 305–309.

Winter, D. A. (1987). Sagittal plane balance and posture in human walking, IEEE, *Engineering in Medicine and Biology Magazine*, 6, 8–11.

Winter, D. A. (1990). *Biomechanics and motor control of human movement*, Second Edition, Wiley-Inter science. John Wiley and Sons Inc. New York. USA.

Winter, D. A. (1995). *A.B.C (anatomy, biomechanics and control) of balance during standing and walking*, Waterloo Biomechanics, University of Waterloo.

Winter, D. A., Prince, F., Frank, J. S., Powell, C. and Zabjek, K. F. (1996). Unified theory regarding A/P and M/L balance in quiet stance, *Journal of Neurophysiology*, 75, 2334-2343.

Winter, D. A., Prince, F., and Patla, A. (1997). Validity of the inverted pendulum model of balance in quiet standing, *Gait and Posture*, 5, 153-154.

Winter, D.A., Patla, A. E., Prince, F., and Ishac, M. (1998). Stiffness control of balance in quiet standing, *Journal of Neurophysiology*, 80, 1211-1221.

Woollacott, M., Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research, *Gait and Posture*, 16, 1-14.

Wrisley, D. M., and Whitney, S. L. (2004). The effect of foot position on the modified clinical test of sensory interaction and balance, *Archives of Physical Medicine and Rehabilitation*, 85, 335–338.

Zatsiorsky, M. V., and King, D. L. (1998). An algorithm for determining gravity line location from posturographic recordings, *Journal of Biomechanics*, 31, 161–164.

Zatsiorsky, M. V. (2002). *Kinetics of Human Motion*, Champaign, IL: Human Kinetics.

Chapter (8) Appendices

Appendix 1. Form of consent

EC3

LIVERPOOL JOHN MOORES UNIVERSITY

FORM OF CONSENT TO TAKE PART AS A SUBJECT IN A MAJOR PROCEDURE OR RESEARCH PROJECT

Title of project/procedure:

Physical and neurophysiological factors influencing dynamic balance.

I, ... agree to take part in

(Subject's full name)* the above named project/procedure, the details of which have been fully explained to me and described in writing.

Signed .... Date:...

(Subject)

I, KHALED JEBRIL ABUZAYAN.. certify that the details of this **(Investigator's full name)***

Project/procedure have been fully explained and described in writing to the subject named above and have been understood by him/her.

Signed .... Date ....

(Investigator)

I, ... certify that the details of this **(Witness' full name)**

Project/procedure have been fully explained and described in writing to the subject named above and have been understood by him/her.

Signed.. **Date**..

(Witness)

NB The witness must be an independent third party.

* Please print in block capitals

Appendix 2. Participant Information Sheet

Volunteers should be informed before the start of the procedure or experiment or interview about the procedure using a participant information sheet.

This should begin by stating clearly:

- the name and academic location of the experiment
- the nature, purpose of the project/study
- description of the participant's involvement in terms understandable to the participant
- the right to withdraw from the project/study at any time without prejudice to access to services which are already being provided or may subsequently be provided to the participant

Please find attached a suggested style participant information sheet.

Participant Information Sheet

Name of experimenter: **Khaled Jebril Abuzayan**________________

Supervisor: **Professor Adrian Lees**____________________

Title of study/project:

Physical and neurophysiological factors influencing dynamic balance.

Purpose of study: To investigate the characteristics of dynamic balance in sport related activities, with specific reference to the influence of body mass changes and muscular fatigue.

Procedures and Participants Role: You will be asked to perform a series of activities which involve static and dynamic balance. Static balance activities will include standing still on 1 foot. Dynamic balance activities will include hopping and jumping taking off from one surface (e.g. on an elevated plat form 20 cm) and landing on to another (e.g. ground). You will be required to wear a body suit so that reflective markers can be placed on. These markers will be recorded by a motion analysis system in the laboratory. At the same time ground reaction forces will be recorded from force platforms. Several trails of each activity will be performed both with eyes open and eyes closed. The session is expected to take about 2 hours. You will be given the opportunity to stretch, warm up and practice the activities demonstrated to your before data collection.

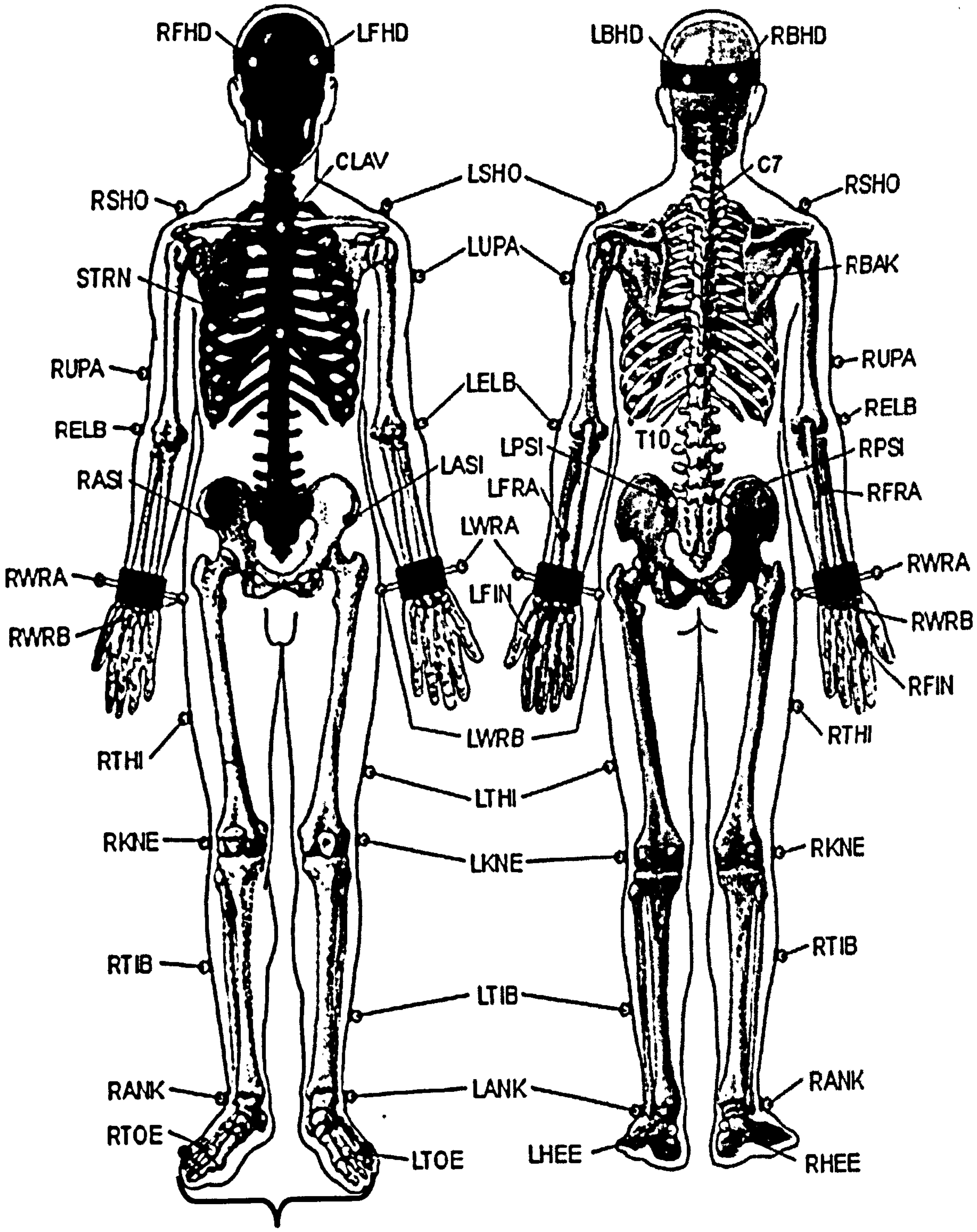
In study (3) you will be required to wear a weighted jacket (max 15 kg) which will not be uncomfortable. Testing procedures will be the same as those outlined above.

In study (3) you will additionally be required to undertake a fatigue exercise of the ankle joint muscles (repeated plantar-flexion of both ankles). Testing procedures will be the same as those outlined above.

Please Note:

All participants have the right to withdraw from the project/study at any time without prejudice to access of services which are already being provided or may subsequently be provided to the participant.

Appendix 3. The plug-in gait markers set



The additional fifth metatarsal markers

PLUGIN GAIT MARKER SET

Upper Body

Head Markers

LFHD Located approximately over the left temple

RFHD Located approximately over the right temple

LBHD Placed on the back of the head, roughly in a horizontal plane of the front head markers

RBHD Placed on the back of the head, roughly in a horizontal plane of the front head markers

Torso Markers

C7 7th placed on the 7th cervical vertebrae

T10 placed on the 10th thoracic vertebrae

CLAV Clavicle Jugular Notch where the clavicles meet the sternum

STRN Sternum Xiphoid process of the Sternum

RBAK Right Back Placed in the middle of the right scapula.

Arm Markers

LSHO Placed on the Acromio-clavicular joint

LUPA Placed on the upper arm between the elbow and shoulder markers.

Should be placed asymmetrically with **RUPA**

LELB Placed on lateral epicondyle approximating elbow joint axis

LFRA Placed on the lower arm between the wrist and elbow markers. Should be placed asymmetrically with **RFRA**

LWRA Left wrist marker A Left wrist bar thumb side

LWRB Left wrist marker B Left wrist bar pinkie side

The wrist markers are placed at the ends of a bar attached symmetrically with a wristband
LFIN placed on the dorsum of the hand just below the head of the second metacarpal

Lower Body

Pelvis

LASI placed directly over the left anterior superior iliac spine

RASI Placed directly over the right anterior superior iliac spine

LPSI placed directly over the left posterior superior iliac spine

RPSI Placed directly over the right posterior superior iliac spine

Leg Markers

LKNE Placed on the lateral epicondyle of the left knee

LTHI Place the marker over the lower lateral 1/3 surface of the thigh,

LANK Placed on the lateral mal

Foot Markers

LTOE Placed over the second metatarsal head

LHEE Placed on the calcaneous

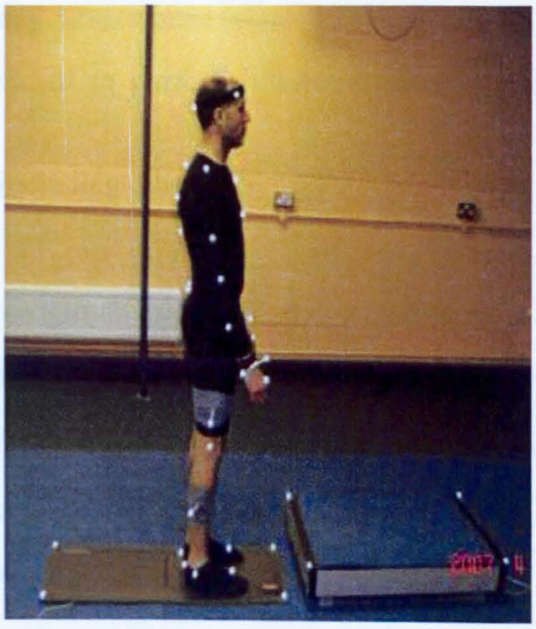
L5MT Placed on the 5th the *mid tarsal* joint, Should be placed asymmetrically with **R5MT**

Appendix 4. Participant Questionnaire

Participant Questionnaire

Liverpool John Moores University
Research Institute for
Sport and Exercise Sciences

Physical and physiological factors influencing dynamic balance



Personal Details & Medical and Lifestyle Assessment questionnaires

Please Read Carefully

The main purpose of this questionnaire is to find out about your health status and lifestyle habits. Information that you provide will be treated as highly confidential and used only to determine your suitability to participate safely and effectively in this study.

Please note: This questionnaire is an important part of the study. We request that you answer all questions as accurately and as honestly as possible. Most questions can be answered by either placing a circle around the appropriate response, a tick in the box provided, or a short written response

1) Personal information:

Home: ______________________________

Mobile: ______________________________

Email: ______________________________

2) Personal Medical History Assessment (circle answer)

Have you ever been instructed to perform **physical activity** only recommended by a doctor? Yes No

If yes, please give details, including dates ______________________________

1. Do you have reduced **eye sight** or had an eye operation? Yes No

If yes, is that because

It is hard to read a textbook up close ☐

It is hard to see clear in the distance (short sightedness) ☐

You are colour blind ☐

Other than the previous ☐

Do you wear glasses for this? Yes No

If yes, is there a difference in the level of correction for both eyes? Yes No

2. Do you have reduced **hearing** ability? Yes No

If yes, has this been diagnosed by your doctor? Yes No

3. Do you sometimes lose your **balance** due to Dizziness Yes No

Stumbling over an object Yes No

Walking up/down stairs, pavement, sloping ground... Yes No

Unexpected obstacle Yes No

Other than the previous Yes No

If you sometimes lose your balance, has this ever led to a fall?

(even without injury)? Yes No

4. Do you ever lose consciousness? Yes No

5. Have you ever been severely breathless as a result of low/moderate level exercise? Yes No

6. Do you suffer from high or low blood pressure? Yes No

If yes, which one? Low High

7. Have you ever been told your blood cholesterol is too high? Yes No

If yes, please state your cholesterol level (if known) ____________________

8. Do you suffer from diabetes? Yes No

If yes, how is it controlled (please tick)

a) Dietary means ☐ b) Insulin injection ☐

c) Oral medication ☐ c) Uncontrolled ☐

9. Do you suffer from asthma, or any respiratory disorders? Yes No

Please give details of condition and any medication taken including inhaler ____

____

____

Is the breathing condition made worse by exercise? Yes No

If yes, what level of exercise (please circle) low moderate strenuous

10. Do you have any musculo-skeletal problems? Yes No

If so, please give details of condition ______________________________

11. Do you suffer from any of the following: -

HIV/AIDS Yes No

Hepatitis B or C Yes No

Or any other disease transmitted by blood Yes No

Haemophiliac Yes No

Chronic's disease Yes No

Thyroid Problems Yes No

Adrenal Problems Yes No

Pituitary Problems Yes No

12. Are you currently taking prescribed medication? Yes No

If yes, give name and dosage ________________________________

3) Physical Activity Assessment

1. Considering a typical 7-day period (week), how many times do you do the following kinds of exercise for during your free time (write on each line the appropriate number). Please also indicate which activity (circle or add to the list).

Times per Week Duration (to the nearest 5mins)

a) **Strenuous Exercise**

(Heart beats rapidly)

(e.g. running, jogging, hockey, football, soccer, ________ ________

Squash, basketball, cross country skiing, judo,

Roller skating, vigorous swimming, vigorous longer distance *cycling)*

b) **Moderate Exercise**

(Not Exhausting)

(e.g. fast walking, baseball, tennis, easy cycling, ________ ________

volleyball, badminton, easy swimming,

alpine skiing, popular and folk dancing)

c) **Mild Exercise**

(Minimal Effort)

(e.g. yoga, archery, fishing from river bed, ________ ________

bowling, horseshoes, golf, easy walk)

2. Considering a typical 7-day period (week), during your leisure time, how often do you engage in regular activity long enough to work up a sweat with your heart beating rapidly?

Often ☐ Sometimes ☐ Never/Rarely ☐

3. Are you currently engaged in moderate or intense training? Yes No

If yes, please detail training schedule including type of activity, intensity, number of sessions per week and duration of each session

____

____

____

If no, have you previously engaged in moderate or intense training? Yes No

If yes, please give details of your schedule:

Intensity	**Number of times per week**	**Duration of each session (to nearest 5 minutes)**
________	____________	________________

What year did you start training? ______________________________

How long ago did you stop training? ____________________________

25. Please detail any further information you would like to tell us ______________

____

Participant signature: ______________________________

Thank you for completing this questionnaire
Once complete please return to :-

Khaled Abuzayan,
Movement Function Research Laboratory
Research Institute for Sport and Exercise Sciences,
Liverpool John Moores University, Henry Cotton Campus,
15-21 Webster Street,
Liverpool,L3 2ET

Tel : 07825698575 E-mail : K.Abuzayan@2006.ljmu.ac.uk

Appendix 5. Borg's scale

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Appendix 6. A Matlab script and functions that were modified or written by the author (the highlighted parts were modified or written by the author)

Note. The bold line in the highlighted section is an example of a function written by the author and given in details overleaf.

Function of Summary of Landing Balance

```
% jvsDataSummaryLandingBalance

% Script to process landing balance data from c3d files based on COP
data and COM data

% Required:

%   Structure AllDerivatives from jvsDataAnalysisLandingBalance.m

%   jvfSPSSSubjectListing.m

%   save4spss.m, uigetVariable.fig, uigetVariable.m (in Matlab root
folder)

clear all; clc

% (1) Load Matfile

myDir = uigetdir;

cd(myDir); % change directory

myFile = uigetfile ('*.mat','Load the matfile');

load(myFile)

% (2) Get summary data for all files in structure

[mySubjectList,SubjectNames] = jvfSPSSSubjectListing(AllDerivatives);

fprintf('done 1\n')

 [SI,SINames] = jvflandingSI(AllDerivatives);

fprintf('done 2\n')

 [TTS,TTSNames] = jvflandingTTS(AllDerivatives);

fprintf('done 3\n')

 [COPrange,jvfrange_COP_LandingNames] =
jvfrangeCOP_FP1_Landing1(AllDerivatives);

%fprintf('done 4\n')

 [CoMrange,jvfrangeXCOMNames] = jvfrangeCOM(AllDerivatives);

fprintf('done 5\n')
```

```
[XCOMrange,jvfrangeXCOM_LandingNames] =
jvfrangeXCOM_Landing1(AllDerivatives);

fprintf('done 6\n')

 [maxQ, kgbmaxQ_LandingNames] = kgbmaxQ_Landing (AllDerivatives);

fprintf('done 7\n')

 [minQ,kgbminQ_Landing1Names] = kgbminQ_Landing (AllDerivatives);

fprintf('done 8\n')

[minF,kgbminF_LandingNames] = kgbminF_Landing (AllDerivatives);

fprintf('done 9\n')

[maxF,kgbmaxF_LandingNames] = kgbmaxF_Landing (AllDerivatives);

fprintf('done 10\n')

% (3) Compile dat file for SPSS from summary data

Compile data array and varname cell array

myData = [SI TTS COPrange CoMrange XCOMrange maxQ minQ minF maxF];

myVarnames = [SubjectNames jvflandingSI jvflandingTTS
jvfrange_COP_Landing Names jvfrangeCOM_Landing1 jvfrange_COP_Landing
kgbmaxQ_LandingNames kgbminQ_LandingNames kgbminF_LandingNames
kgbmaxF_LandingNames]';

Save to SPSS file

save4spss(myData,myVarnames)
```

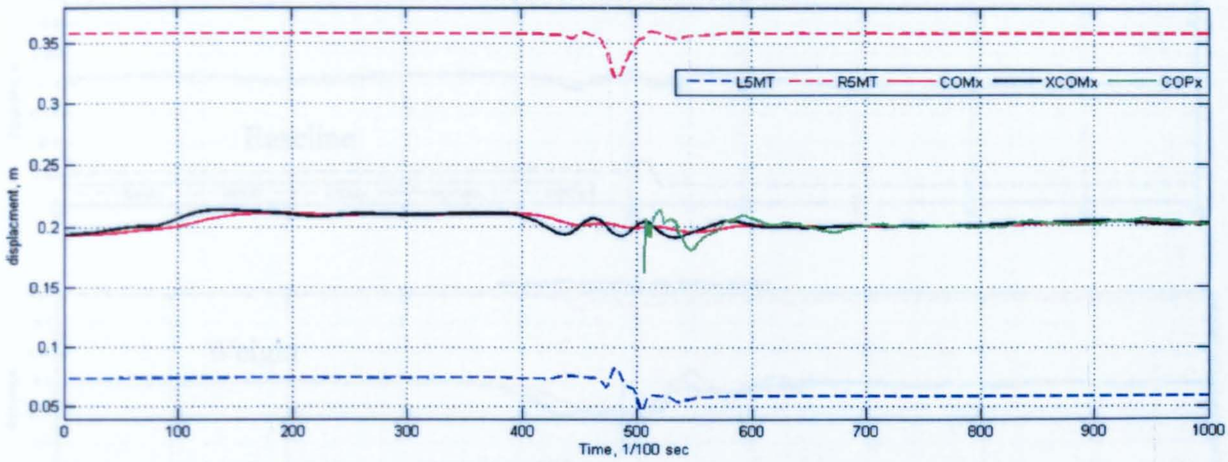
An example of a *Matlab function* written by the author.

Function (kgbmaxQ) for calculating the maximum of the Q variable.

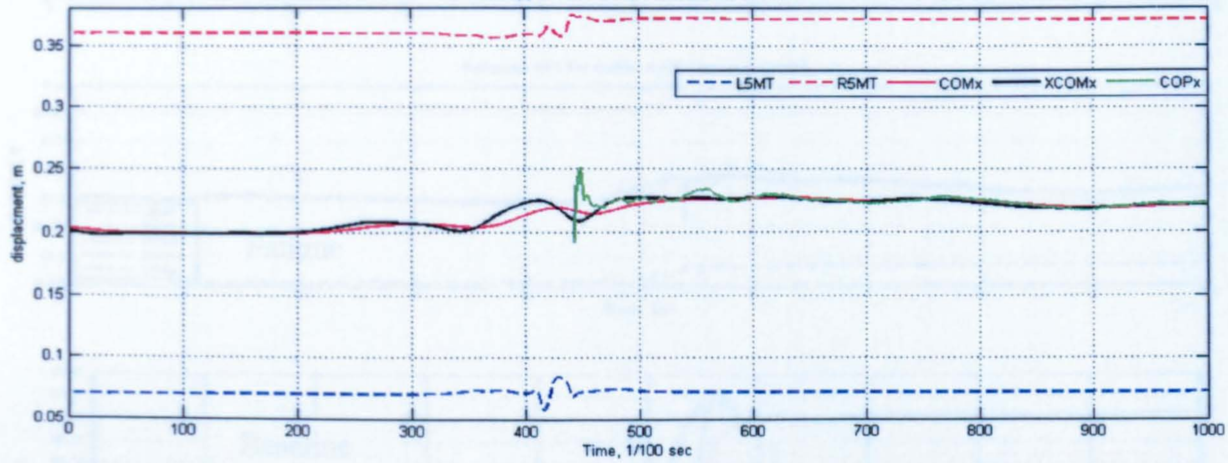
```
function [xy,varnames] = kgbmaxQ(S)
% [xyz] = jvfstdForces_FP1(S)
% Function to walk through mat-file compiled through
jvsDataAnalysisLanding.m
% It calculates the standard deviation of the Force data of Force
Platform 1 calculating
% the behaviour of balancing during period after landing + 1 second
until landing + 3 seconds
% to compare to the behaviour of balancing during standing.
% INPUT:
%   S = array of structures according to jvsDataAnalysisLanding.m.
% OUTPUT:
%   xyz = standard deviations of forces in x, y and z of FP1
%   varnames = cell array with variable names
xy = zeros(numel(S),2);     %initiate output array
% Generate output array
 for k=1:numel(S)
    if strcmp(S(k).Timing.Status,'reject') % If file was rejected, all
values NaN.
        xy(k,:) = NaN(1,2);
        else
        %%% Extract the relevant fields from the structure:
        [x,y] = deal(S(k).Q.x,S(k).Q.y);
        myTiming = S(k).Timing;
            % Reduce data to selected time interval
        if strmatch(myTiming.Status, 'edited','exact')
          myStart = ceil(myTiming.Landing + myTiming.AnalogFrameRate*1);
% calculate videoframerate timing start
          myEnd = ceil(myTiming.Landing + myTiming.AnalogFrameRate*3);
% calculate videoframerate timing end
          [x,y] = deal(x(myStart:myEnd),y(myStart:myEnd));
        end
            %%% Remove NANs from the time series:
            i = any(isnan([x y ]),2);      %indices of nan
            x(i) = [];
            y(i) = [];
            %%% Compute std values:
            xy(k,:) = max([x y]);
   end
end
% Generate cell array with variable names
varnames = {'maxQx' 'maxQy'};
```

Appendix 7. Effect of trials (1, 2, and 3) 2FTF_HJ

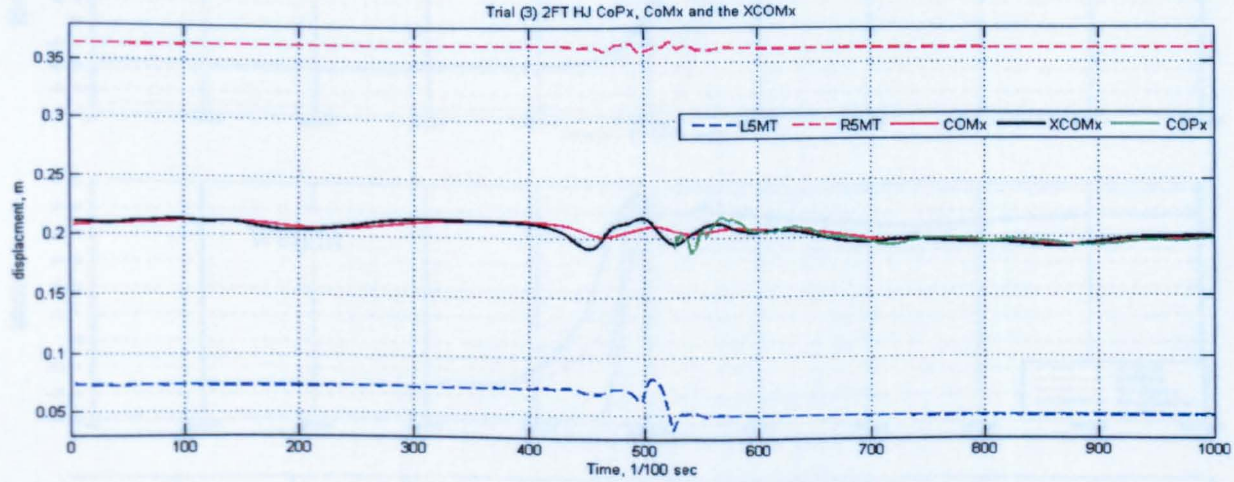
Trial (1) 2FT HJ CoPx, CoMx and the XCOMx



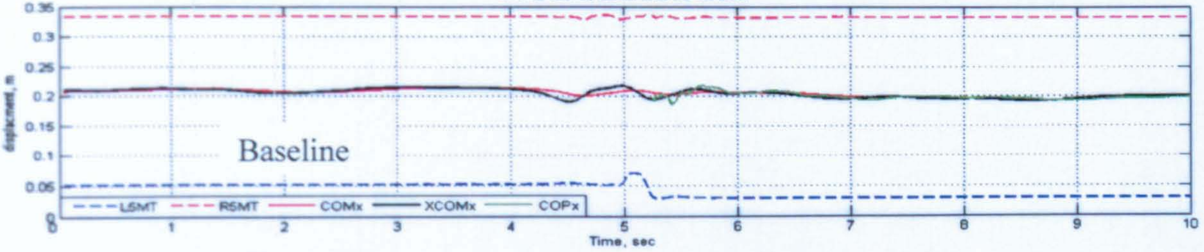
Trial (2) 2FT HJ CoPx, CoMx and the XCOMx

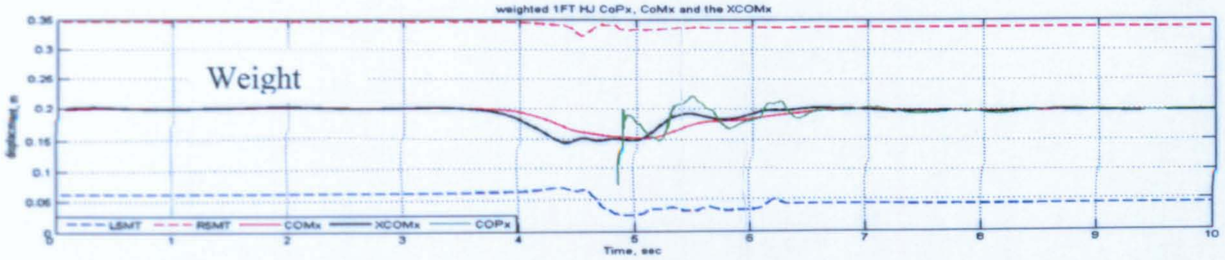


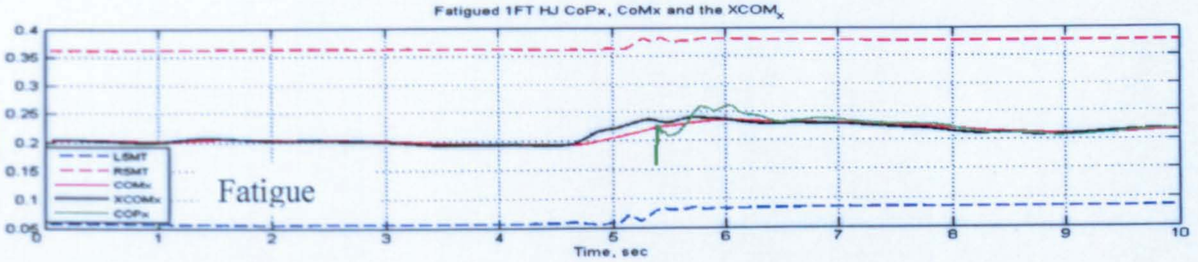
Trial (3) 2FT HJ CoPx, CoMx and the XCOMx



Appendix 8. Effect of condition (baseline, weight, and fatigue) 2FTF_HJ


1FT HJ CoPx, CoMx and the XCOMx


weighted 1FT HJ CoPx, CoMx and the XCOMx


Fatigued 1FT HJ CoPx, CoMx and the XCOM$_x$