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The Effects of Adding External Mass and Localised Fatigue upon Static and Dynamic Balance

K. Abuzayan, H. Alabed, and S. Ali

***Abstract*—**The influence of physical (external added weight) and neurophysiological (fatigue) factors on static and dynamic balance in sport related activities was typified statically by the Romberg test (one foot flat, eyes open) and dynamically by jumping and hopping in both horizontal and vertical directions. Twenty healthy males were participated in this study. In Static condition, added weight increased body's inertia and therefore decreased body sway in AP direction though not significantly. Dynamically, added weight significantly increased body sway in both ML and AP 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 ML and AP 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.

***Keywords*—**Adding external mass, Dynamic balance, Localised fatigue, Static balance.

I. INTRODUCTION

BALANCE is defined as the ability to maintain the body's Centre of Mass (CoM) over its Base of Support (BoS) [1]. This occurred based a harmony between the CoM which is known as the balancing point of the body which in static standing circumstances means all torques are average to zero [2] and CoP which is defined as the point of application of force within the BoS that a subject applies to the support surface while attempting to stand still; Additionally, Hof *et al.* [3] introduced a novel method for estimating balance during movement (dynamic balance) such as hopping or jumping. The velocity of the CoM can influence balance behaviour. Hof *et al.* referred to it 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. the XCoM defined as the position of the vertical projection of the CoM plus a velocity correction factor which together should lie within the BoS [3].

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,[4]), fewer studies have investigated that in adult populations [5] and in these some have dealt with military manoeuvres [6]. Since jumping and single-leg hop stabilization tests are challenging and most closely mimic athletic performance [7] 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.* [8] 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 [9]. 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.

II. METHOD

A. 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),. 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. They were required to avoid strenuous exercise for at least 48 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

B. Instrumentation

Two force platforms were used the first 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.

K. Abuzayan is corresponding author at: Faculty of Physical Education and Sport Sciences, Tripoli University, Tripoli, Libya. (Tel.: +218918298924; fax: +21892) (E-mail address: kabuzayan@hotmail.com).

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.

Anthropometric measurements were made by the same person. Both sides of the limbs were measured. These values were essential to compute the Centre of Mass. Body mass and height were also measured. A total of 8 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*). They were also used to track the dynamic trajectories of the BoS during the events. The BoS was measured using additional feet markers.

C. Procedures

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

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 [10]

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).

D. Added Weight Protocol

A weighted vest was prepared for carrying the added loads. 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)].

E. 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 [11].

F. Data Collection

Activities and Testing Protocol:

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 (standardizing efforts).Only successful trials were used in this study.

To avoid bias, a Latin square was used to counterbalance the conditionswhich provide a unique order for administrating tests.

G. 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 [12]. 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.

A. 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.

III. RESULTS

B. Static Balance

1. Standing Balance Test (1-Foot Flat)

Typical graphical displays are given in (Fig. 1) for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in ML (ML) and AP (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.

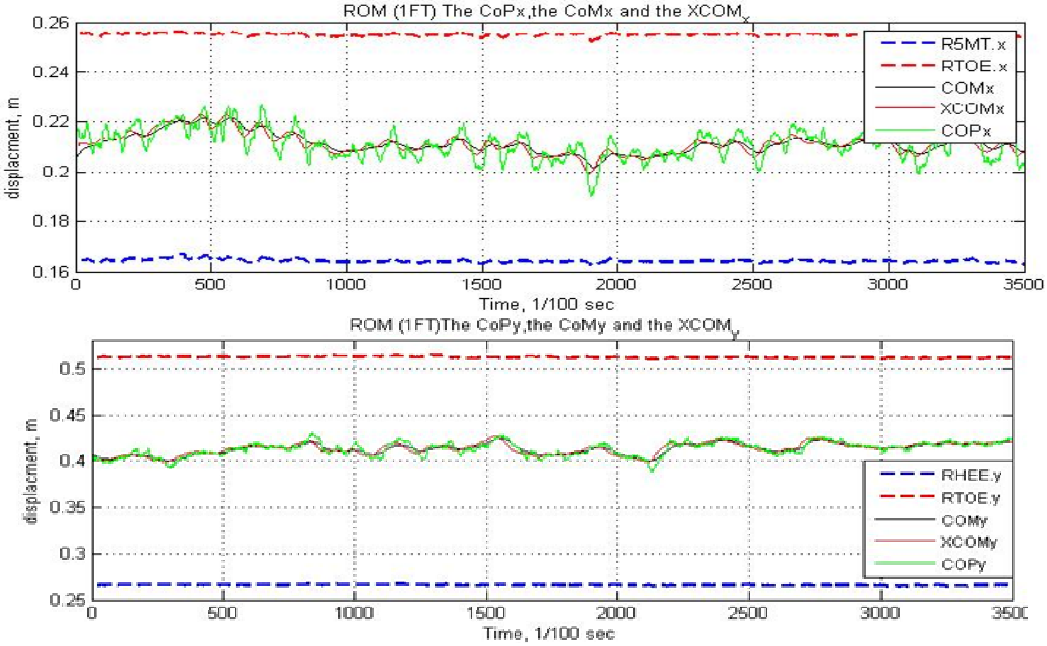

Fig. 1 The variables CoP, CoM and XCoM in the ML (x, upper) and the AP (y, lower) directions are illustrated for static balance (1-foot flat, eyes open). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BOS)

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. Otherwise, (for this slow movement) they are close together to represent stable circumstances.

The 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). Also, 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.

The 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). Also, the 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.

The 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 ($F_{(1,\ 19)} = 1.337$, $p > .05$). Also the 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.

A. Dynamic Balance:

2. Two Feet Horizontal Jump (Dynamic Balance)

Typical graphical displays are given in Fig.2 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in ML (x) and AP (y) directions during dynamic balance (2 feet horizontal jump). These variables were characterised by their range.

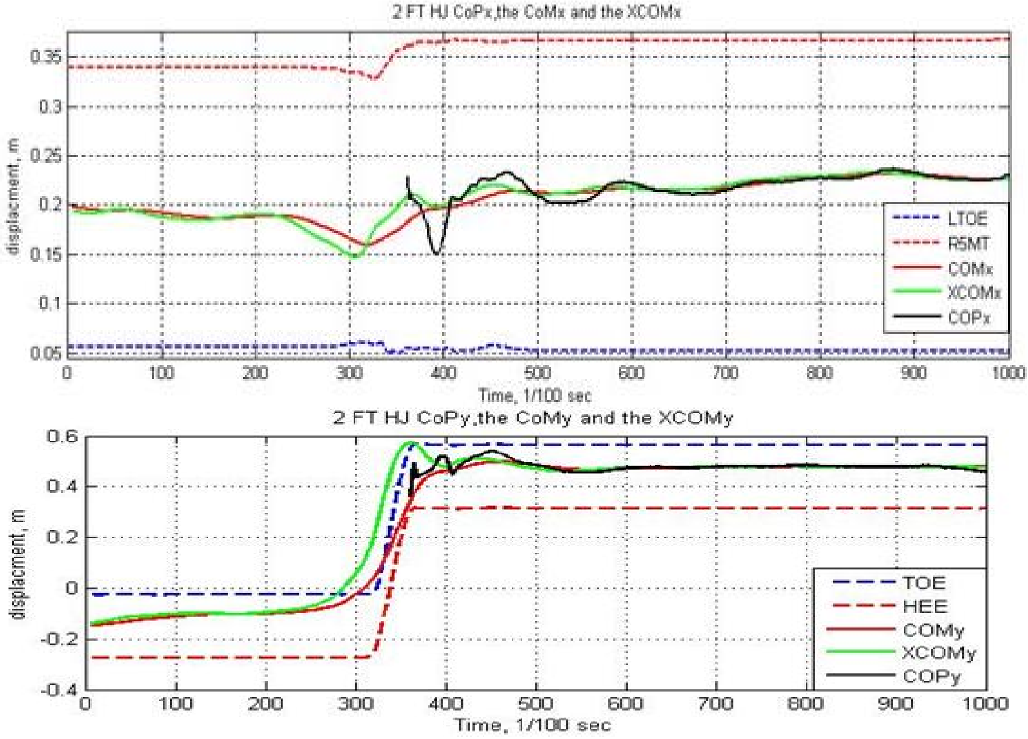

Fig. 2 The variables CoP, CoM and XCoM in the ML (x, upper) and the AP (y, lower) directions are illustrated for dynamic balance (2-feet flat horizontal jump). (Units = m) Dashed lines indicate the boundaries of the Base of Support (BOS)

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.

TABLE I
MEAN AND STANDARD DEVIATION OF THE RANGE OF EACH VARIABLE IN BOTH THE ML (ML) AND AP (AP) DIRECTIONS DURING DYNAMIC BALANCE (TWO FEET HORIZONTAL JUMP) FOR BASELINE, ADDED WEIGHT AND FATIGUE CONDITIONS

Variables	*Baseline*		*ed weightAdd*		*Fatigue*	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
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

- The Centre of Mass

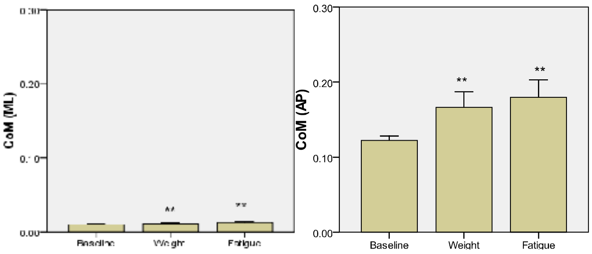

Fig. 3 The range of the (CoMML) and the (CoMAP) in dynamic balance (2-feet flat horizontal jump). (Units = m) (** indicates a significant difference from baseline at p < .01)

The 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). Also the 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.

- The extrapolated Centre of Mass

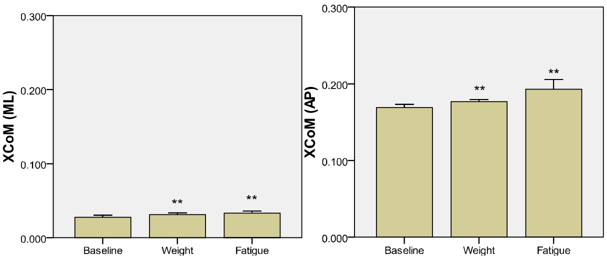

Fig. 4 The range of the (XCoMML) and the (XCoMAP) in dynamic balance (2-feet flat horizontal jump). (Units = m) (** indicates a significant difference from baseline at p < .01)

The $XCoM_{ML}$ 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). Also For the $XCoM_{AP}$ 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.

- The centre of pressure

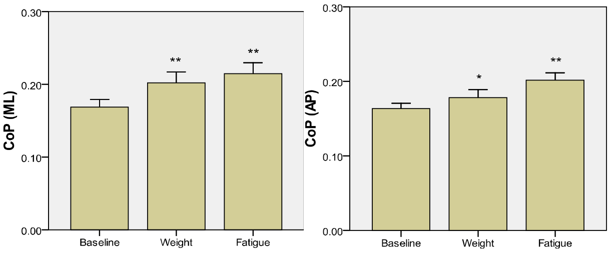

Fig. 5 The range of the (CoPML) and the (CoPAP) in dynamic balance (2-feet flat horizontal jump). (Units = m) (** indicates a significant difference from baseline at p < .01)

The 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). Also the 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.

3. Two Feet Vertical Jump (Dynamic Balance)

Typical graphical displays are given in Fig.6 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in ML (x) and AP (y) directions during dynamic balance (Two feet vertical jump). These variables were characterised by the range or peak values as appropriate for the data.

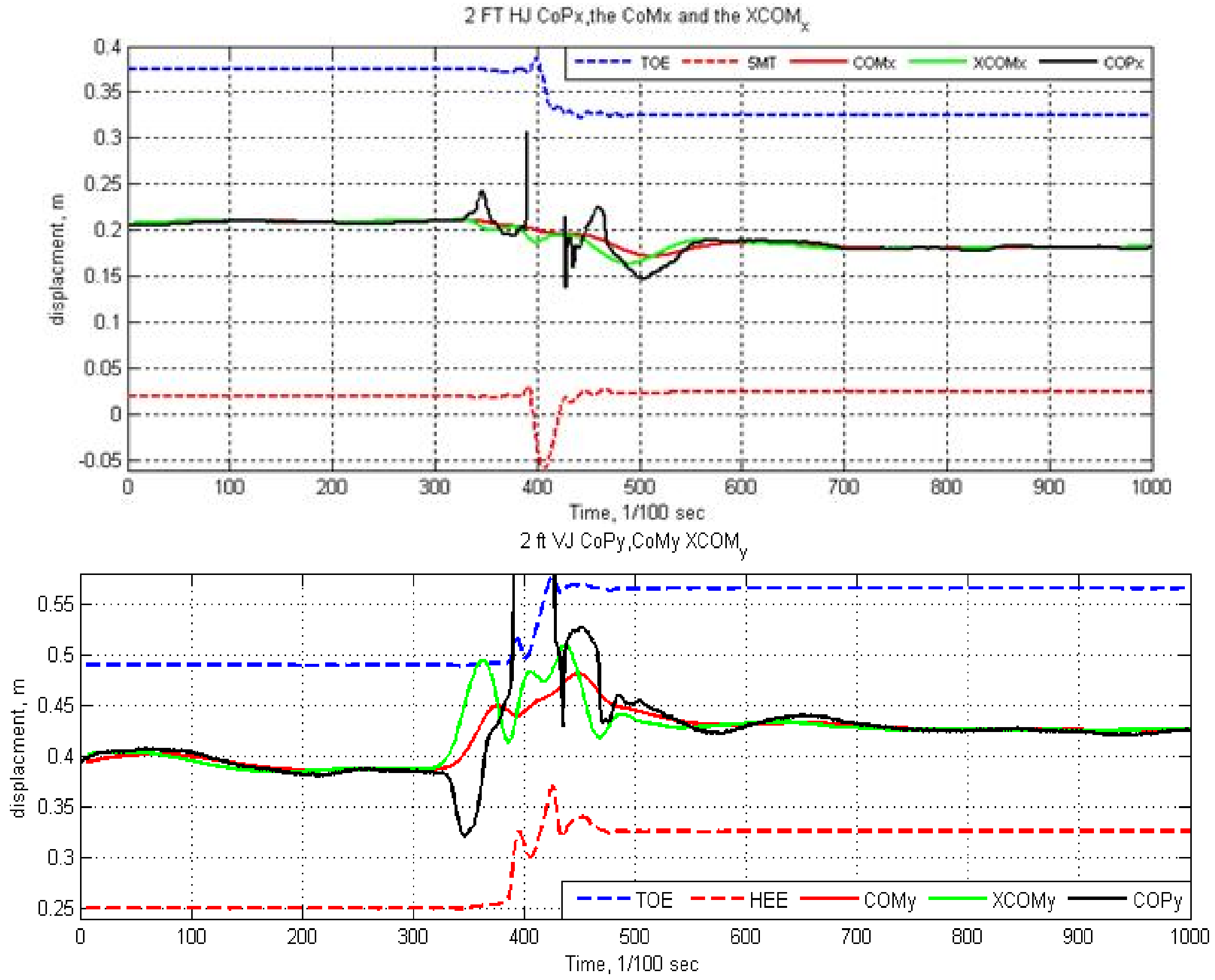

Fig. 6 The variables CoM, XCoM and CoP in the ML(x, upper) and the AP (y, lower) directions are illustrated for dynamic balance (2-feet flat vertical jump). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BoS)

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.

TABLE II
MEAN AND STANDARD DEVIATION OF THE RANGE OF EACH VARIABLE IN BOTH THE ML AND AP (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

- The Centre of Mass

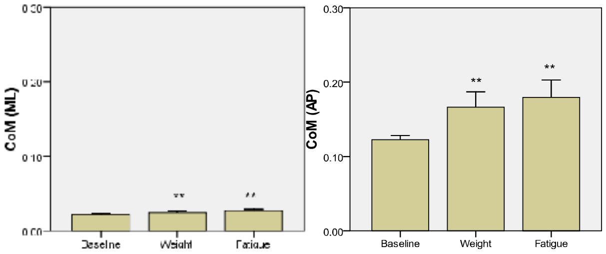

Fig. 7 The range of the (CoM_{ML}) and the (CoM_{AP}) in dynamic balance (2-feet flat vertical jump). (Units = m) (** indicates a significant difference from baseline at p < .01)

The 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 ($F_{(1, 19)} = 18.855$, $p < .01$). Also the 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.

- The Extrapolated Centre of Mass

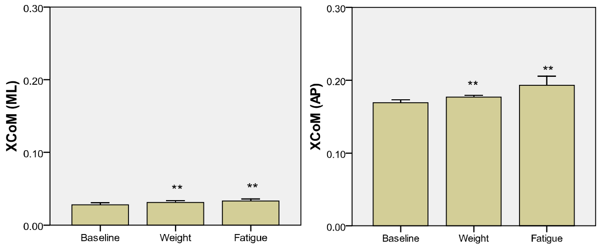

Fig. 8 The range of the ($XCoM_{ML}$) and the ($XCoM_{AP}$) in dynamic balance (2-feet flat vertical jump). (Units = m) (** indicates a significant difference from baseline at p < .01)

The $XCoM_{ML}$ 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 ($F_{(1, 19)} = 19.138$, $p > .05$). Also the $XCoM_{AP}$ 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.

- The Centre of Pressure

The 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 ($F_{(1, 19)} = 32.527$, $p > .01$). Also the 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

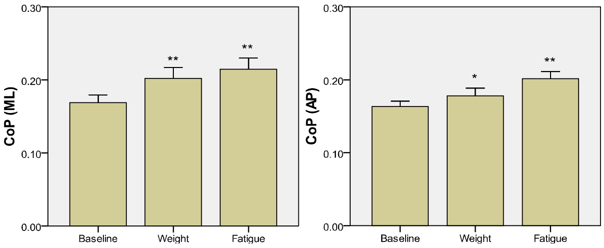

Fig. 9 The range of the (CoP_{ML}) and the (CoP_{AP}) in dynamic balance (2-feet flat vertical jump). (Units = m) (** indicates a significant difference from baseline at p < .01)

2. One Foot Horizontal Hop (Dynamic Balance)

Typical graphical displays are given in Fig. 10 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in ML (x) and AP (y) directions during dynamic balance (One foot horizontal hop). These variables were characterised by their range or peak values as appropriate for the data.

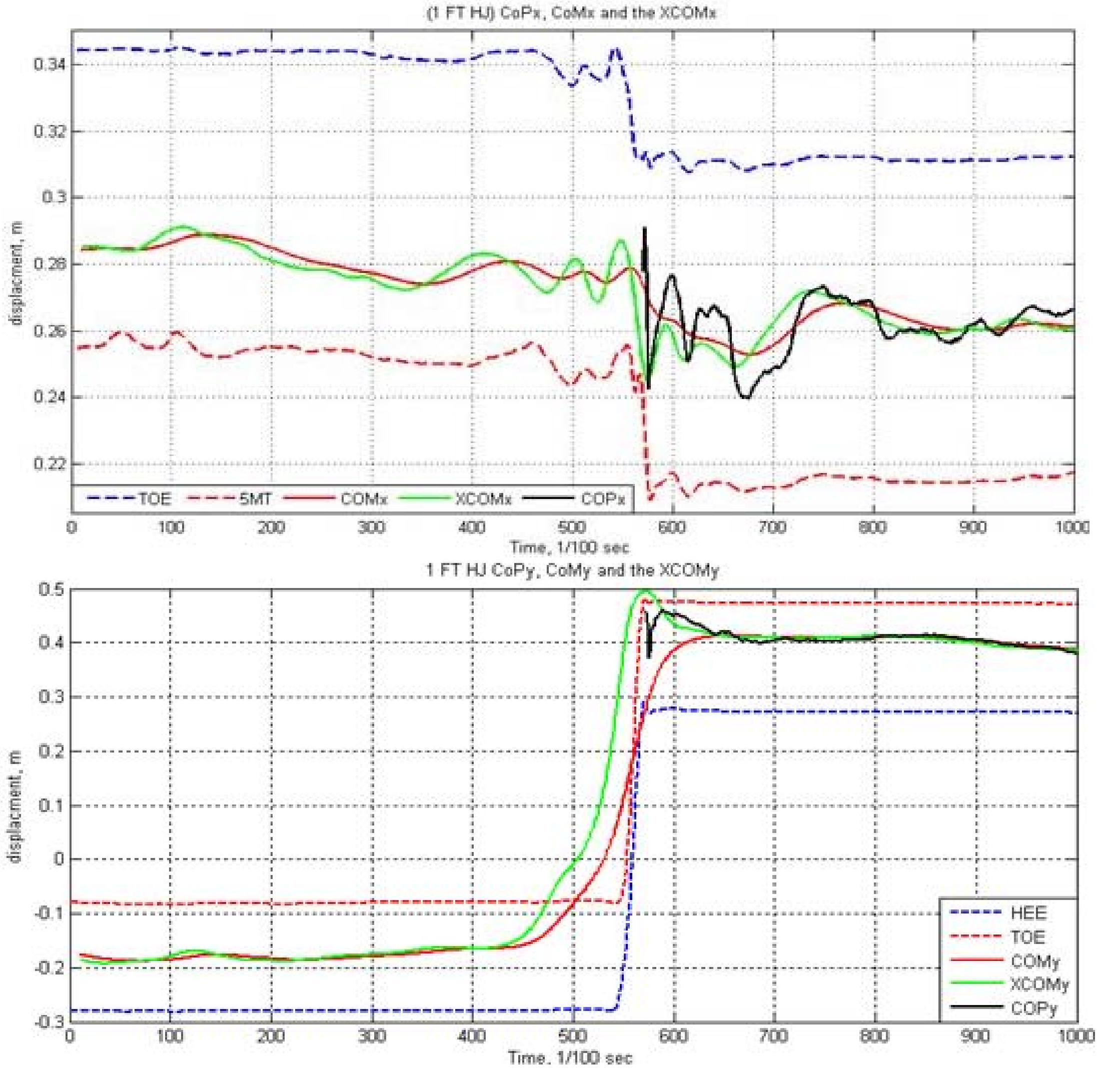

Fig. 10 Illustrates the variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for dynamic balance (1-foot flat horizontal hop). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BoS)

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.

TABLE III
Mean and Standard Deviation of Each Variable in Both the ML (ml) and AP (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**
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

- The Centre of Mass

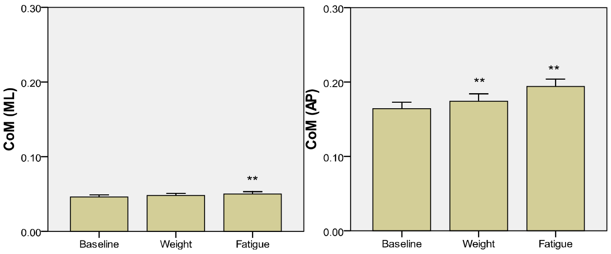

Fig. 11 The range of the (CoM$_{ML}$) and the (CoM$_{AP}$) in dynamic balance (One foot horizontal hop). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

The 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, $p > .05$). Also the 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.

- The Extrapolated Centre of Mass

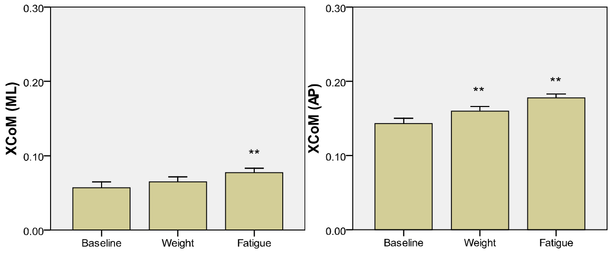

Fig. 12 The range of the (XCoM$_{ML}$) and the (XCoM$_{AP}$) in dynamic balance (One foot horizontal hop). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

The 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, $p < .05$). Also the 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.

- The Centre of Pressure

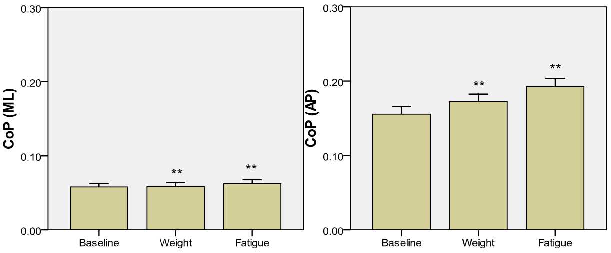

Fig. 13 The range of the (CoP$_{ML}$) and (CoP$_{AP}$) in dynamic balance (1-feet horizontal hop). (Units = m) (** indicates a significant difference from baseline at $p < .01$)

The 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, $p > .01$). Also the 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.

3.One Foot Flat Vertical Hop (Dynamic)

Typical graphical displays are given in Fig. 14 for the Centre of Pressure (CoP), Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM) in ML (x) and AP (y) directions during dynamic balance (One foot vertical hop). These variables were characterised by the range or peak values as appropriate for the data.

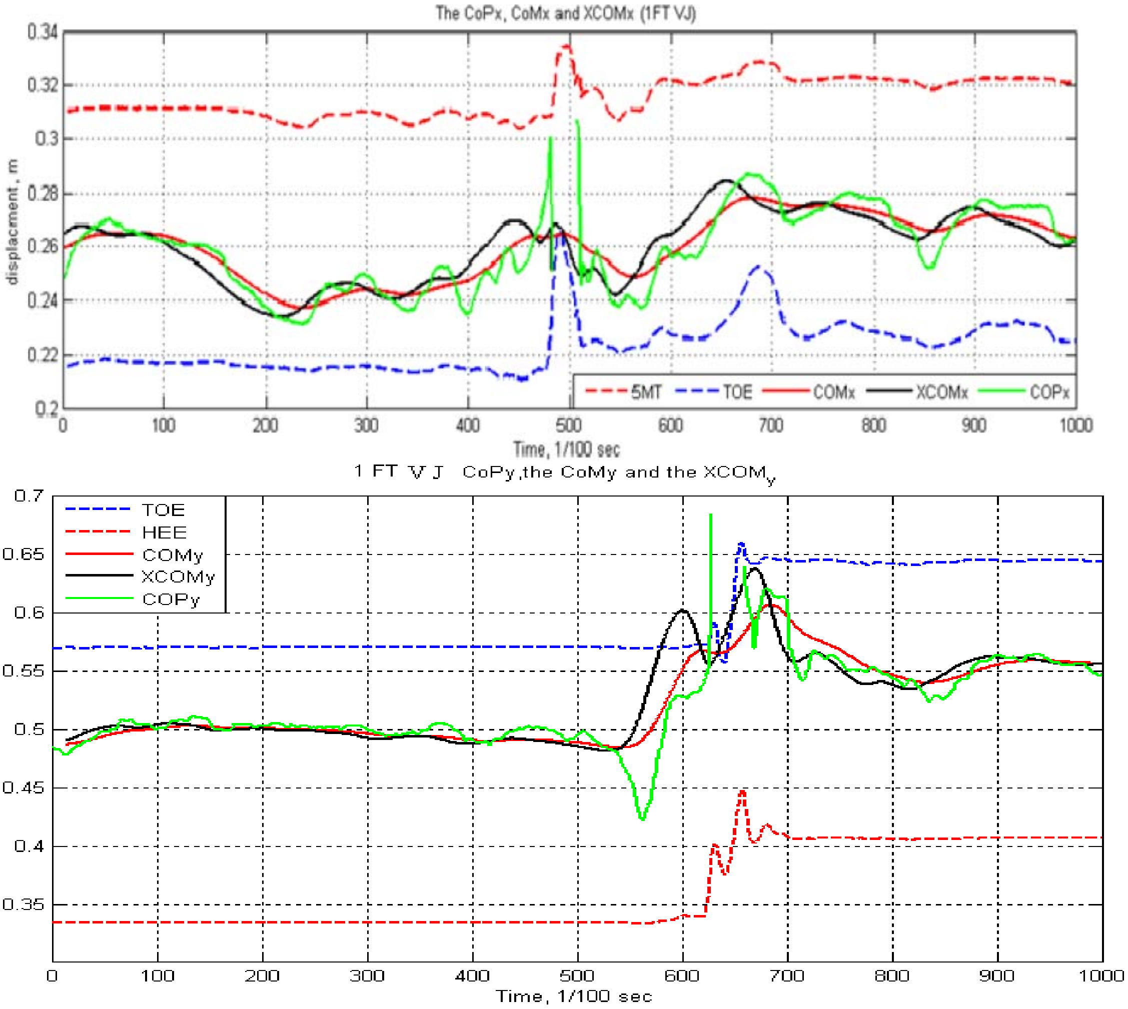

Fig. 14 Illustrates the variables CoP, CoM and XCoM in the ML (x) and the AP (y) directions are illustrated for dynamic balance (1-foot flat vertical hop). (Units = m). Dashed lines indicate the boundaries of the Base of Support (BoS)

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.

TABLE IV
MEAN AND STANDARD DEVIATION OF RANGE OF THE VARIABLES IN BOTH THE ML (ML) AND AP (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

- The Centre of Mass

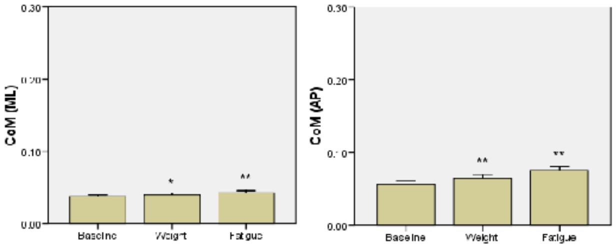

Fig. 15 The range of the (CoM$_{ML}$) and (the CoM$_{AP}$) in dynamic balance (1-feet vertical hop). (Units = m) (** indicates a significant difference from baseline at p < .01)

The 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). 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.

- The Centre of Mass

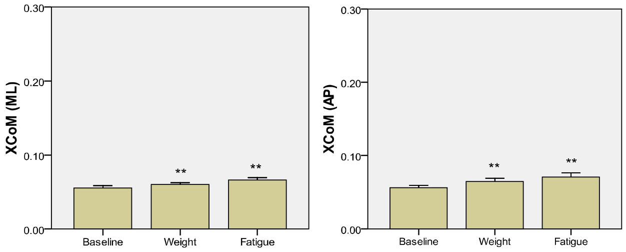

Fig. 16 The range of the (XCoM$_{ML}$) and (XCoM$_{AP}$) in dynamic balance (1-feet vertical hop). (Units = m) (** indicates a significant difference from baseline at p < .01)

The 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). 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.

- The Centre of Pressure

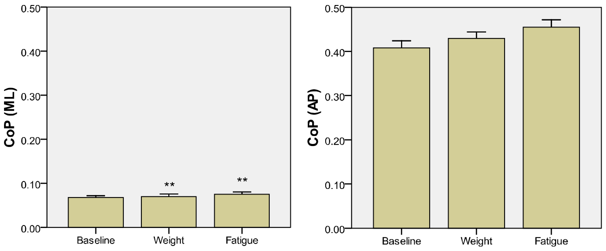

Fig. 17 The range of the CoP$_{ML}$ and CoP$_{AP}$ in dynamic balance (1-feet vertical hop). (Units = m) (** indicates a significant difference from baseline at p < .01)

The CoP$_{\mathbf{ML}}$ 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). For the variable CoP$_{\mathbf{AP}}$ 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.

IV. 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 ([11]; n=18, [12]; n= 12, [13]; n=17, [13]; 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, others recommended using 10%, 15% or 20% of total body weight (BW)[14]; [4]; [13]), most of which indicate significant changes. The lack of an effect on postural stability when carrying lighter loads has been reported by others [15] 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 [16]; [17]; [18]; [19] 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 [20]. 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.

4. Statically

In the static balance test (one foot flat, eyes open), the present findings are in agreement with previous results [21]. 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 [22]. This mechanically is due to increase of inertia and therefore postural balance may well be preserved [21]. 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 [23]. 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 ML and AP 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 [8]. The results agreed with other studies which found an increase in body sway oscillations during static balance tests in the fatigued state [24]; [25]. 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.

5. 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, 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%. 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 and CoP 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 AP direction during the landing phase (Figures: 2, 6,10 and14). The translation of the CoM considerably increases its velocity which is important considering the feasible movement for the control of one's balance [26]. 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 [26] 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.

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.

In summary, This investigation of study 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 [27]. 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.

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