Developing the Methods for the Study of Static and Dynamic Balance

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Developing the Methods for the Study of Static and Dynamic Balance

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Abstract**—**Static and dynamic balance are essential in daily and sports life. Many factors have been identified as influencing static balance control. Therefore, the aim of this study was to apply the (XCoM) method and other relevant variables (CoP, CoM, F_h, KE, P, Q, and, 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. 5 healthy male were participated in this study (Mean ± SD:- age 24.6 years ±4.5, height 177 cm ± 6.3, body mass 72.8 kg ± 6.6). Results found that 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.

Keywords**—**Centre of Mass, static balance, Dynamic balance, extrapolated Centre of Mass.

I. 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) this is defined as the ability to maintain the body's CoM over its BoS [1] and occurred when the CoM "the balancing point of the body which in static standing circumstances means all torques are average to zero" [2] and CoP "the point of application of force within the BoS that a subject applies to the support surface while attempting to stand still". Hof *et al*. [3] introduced a novel referred to it as the "extrapolated Centre of Mass" (XCoM) method for estimating dynamic balance such as hopping or jumping. The velocity of the CoM can influence balance behaviour. Hof *et al.* referred to it as the 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].

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. In addition to develop a suitable methods for studying static and dynamic balance in a sport context, apply the XCoM method to a range of sport activities such as hopping and jumping, and investigate which mechanical variables are most suited to investigate dynamic balance.

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II. METHOD

Few pilot experiments were made to examine the apparatus's functions such as testing the comprehensive synchronization between systems e.g. kinematic system (Vicon), kinetic system (kistler force platforms) and pressure mat (RS scan).

A. Participants

Participants in this study were 5 healthy male (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

B. 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).

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).

Anthropometric measurements were made while the participant stood barefoot with heels 15 cm apart and arms by sides. Foot angle, 15º, 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 (Fig. 1) of the subject's body. These locations were recorded by a Vicon motion capture system 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).

Fig. 1 The location of markers on the participant's body, following the 39-marker Plug-in-Gait protocol

Procedures

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.

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 in addition to spatial synchronization of forces and motion capture.

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 Fig 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

3) 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.

4) 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 [4]. From these data, the extrapolated Centre of Mass (XCoM), linear Kinetic Energy (KE), linear momentum (P), and frictional torque (Q).

Treating data from the output of analysis systems was complex. Microsoft Excel 2013 was used to process both force plate data (e.g. Forces and CoP) and the CoM data. Microsoft Office Excel 2013 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 2013 software.

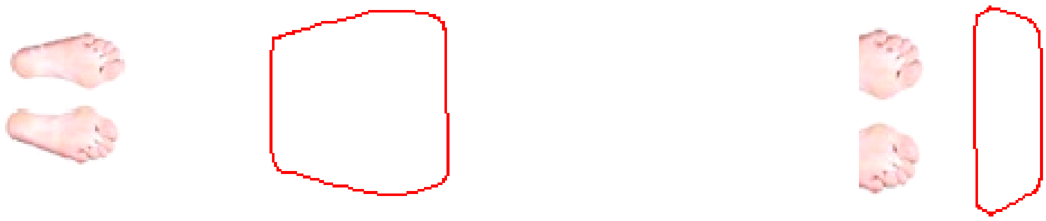
Statistical analysis

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.

5) Base of Support (BoS)

The Base of Support 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 [4[; [3] (Fig. 2). The BoS during static balance (two feet flat, eyes open) and during landing in dynamic balance (jumping on tiptoes).



The BoS during static balance (two feet flat, eyes open) and during landing in dynamic balance (jumping on tiptoes). Shows examples of the dynamic BoS at a single moment in time from standing and from tiptoe landing from a jump

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 7.8.0, R2009a).

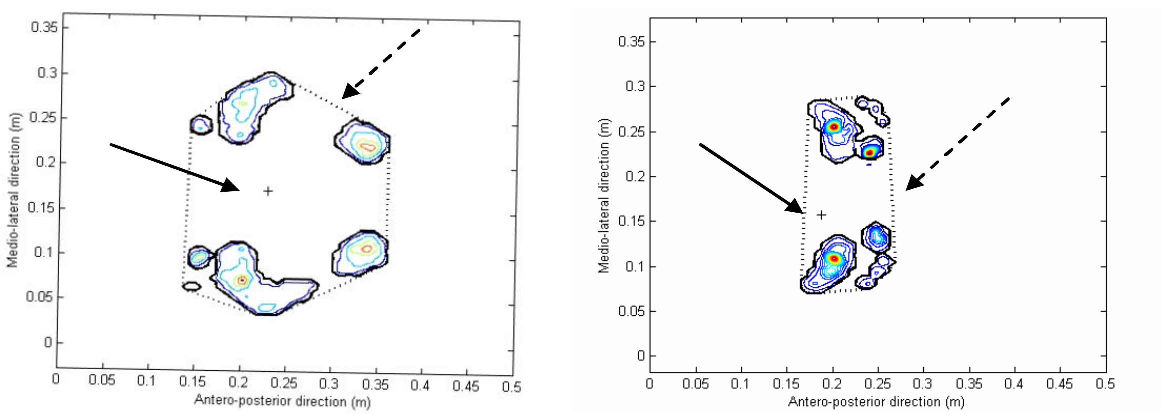


Fig. 3 The functional BoS during standing (two feet flat, eyes open) and during tiptoe landing from a jump (two feet). The cross sign represents the location of the CoP at that moment in time (the solid arrow indicates the CoP) and (the dotted arrow indicates the BoS)

This method has provided a new term that can be called the functional base of support, indicating that during dynamic activities not necessarily the entire available BoS is used to maintain balance. The functional BoS (dotted line, Fig. 3) is the outer area used to maintain one's balance at any moment in time. Therefore, the method of measuring the functional BoS is a more detailed representation of the BoS than the ordinary method, which can be determined dynamically from a pressure mat instead of using a fixed shape, which is previously been used.

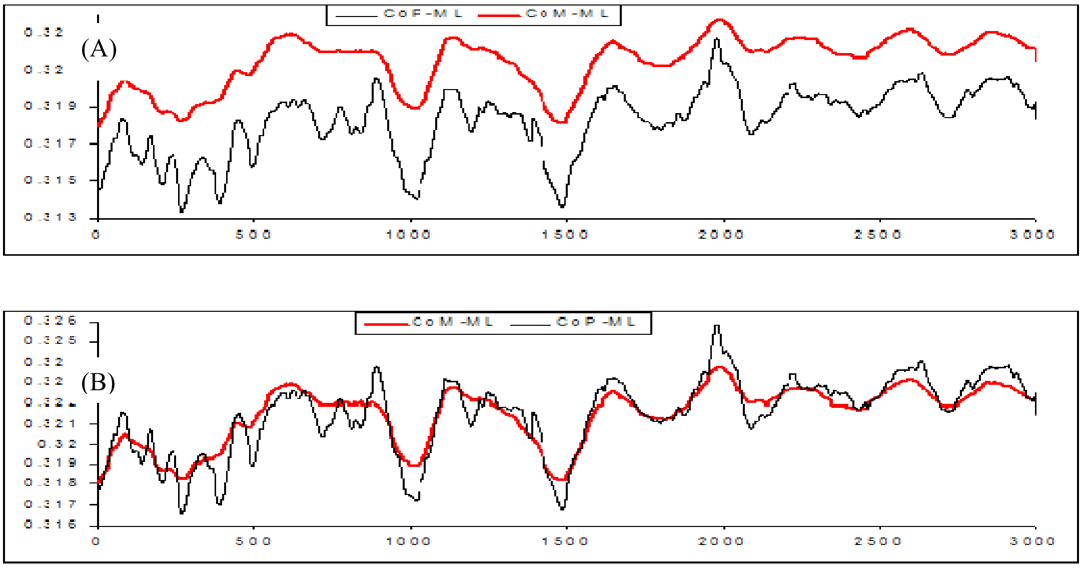
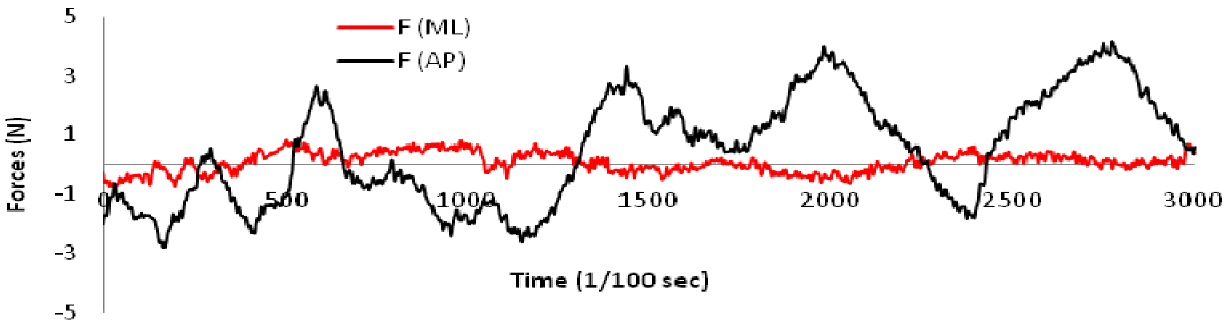


Fig. 4 (A) and (B) An example (standing, two feet flat, eyes open) of the inaccuracy in spatial synchronization between kinetic and kinematic coordinate systems, shown through systematic shift between CoP and CoM in ML direction (A, top graph). This can be corrected for static balance measurements by re-trending the CoP data (B, bottom graph) (units = m)

III. Results

Ground reaction force (GRF) Typical graphical displays are given in Fig. 5 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**

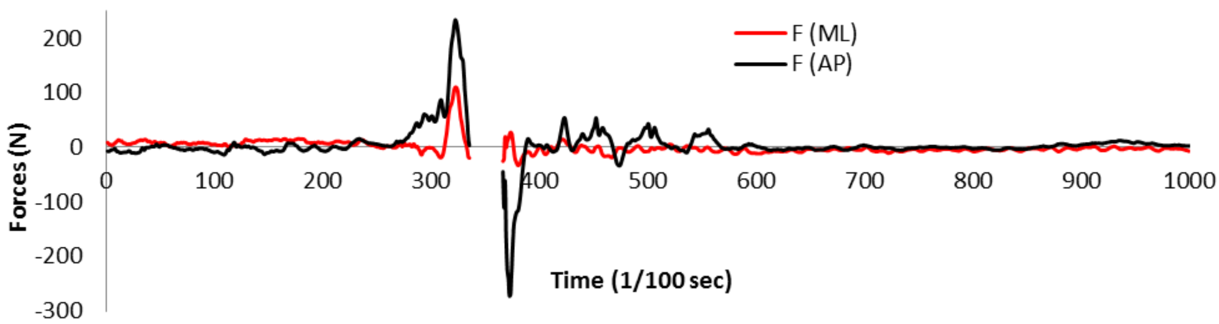


Fig. 5 Illustrates the F_{ML} and F_{AP} in two conditions: static balance (2-feet flat eyes open) and dynamic balance (Jumping on tip toes). (Units = N)

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 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 1and 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 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) 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 II 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 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.

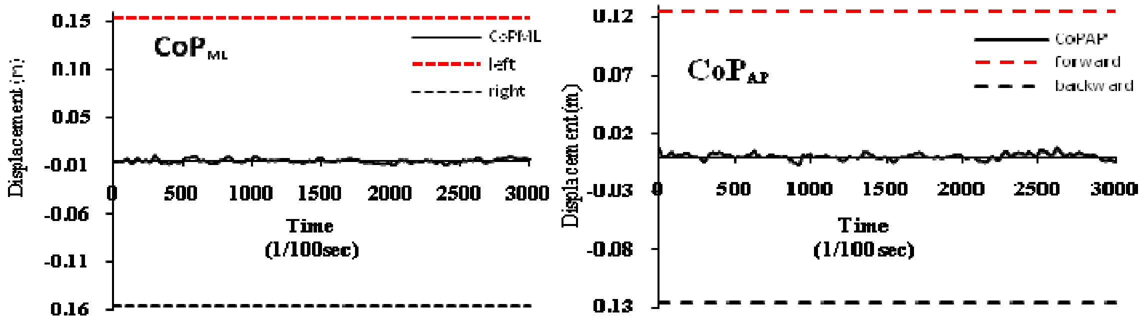
TABLE I
MEAN OF RMS OF 3 TRIALS (N = 5) OF FORCES IN BOTH MEDIO-LATERAL (ML) AND ANTERIOR-POSTERIOR (AP) DIRECTIONS FOR STATIC BALANCE (2-FEET FLAT EYES OPEN) AND THE MEAN OF PEAKS OF F_{ML} AND F_{AP} FOR DYNAMIC BALANCE (JUMPING ON TIP

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**

- Centre of Pressure (CoP)

Typical graphs Fig. 6 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**

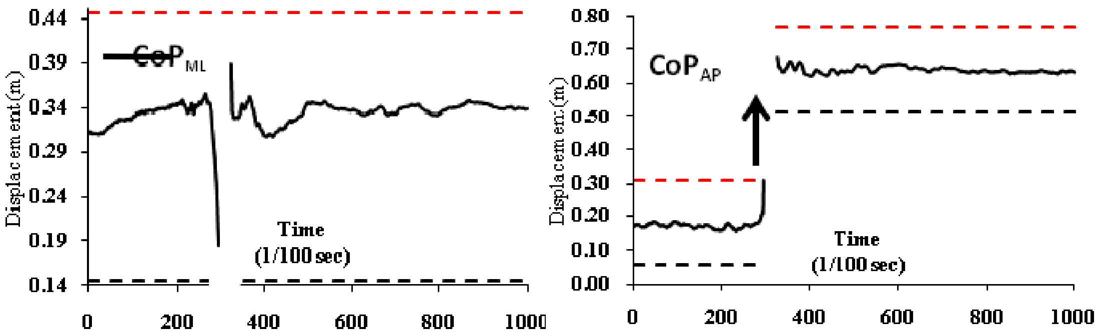


Fig. 6 Illustrates the variables COP_{ML} and COP_{AP} in both in both static balance (2-feet flat eyes open) and dynamic balance (jumping on tip toes) and the functional BoS (dotted line). (Units= m)

The absolute CoP values depend on where the feet are placed on the force platform. The vertical arrow in the dynamic CoP_{AP} (Fig. 6) 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

TABLE II

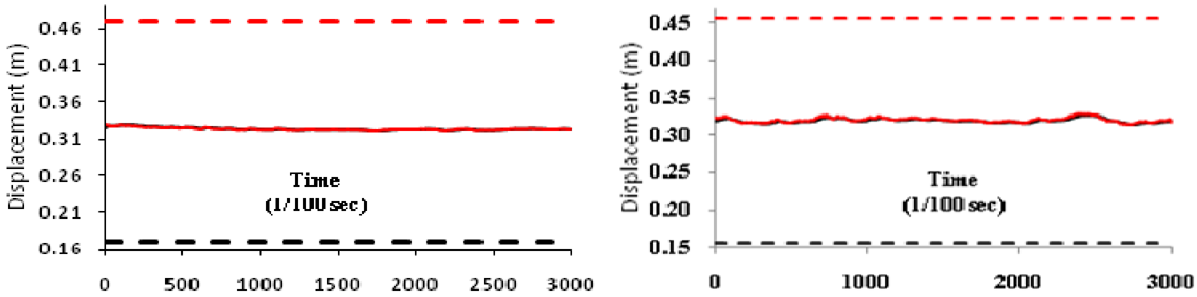
MEAN OF RMS 3 TRIALS (N = 5) OF THE COP IN BOTH MEDIO-LATERAL (ML) AND ANTERIOR-POSTERIOR (AP) DIRECTIONS FOR STATIC BALANCE (2-FEET FLAT EYES OPEN) AND THE MEAN OF RANGE OF COP_{ML} AND COP_{AP} FOR DYNAMIC BALANCE (JUMPING ON TIP TOES). (UNITS = M)

SUBJECT	STATIC (RMS)		DYNAMIC (RANGE)			
			Take-off		LANDING	
	CoP_{ML} (m)	CoP_{AP} (m)	CoP_{ML} (m)	CoP_{AP} (m)	CoP_{ML}(m)	COP_{AP} (M)
SUBJECT 1	0.008	0.014	0.293	0.153	0.064	0.048
SUBJECT 2	0.009	0.013	0.295	0.154	0.065	0.056
SUBJECT 3	0.009	0.013	0.290	0.157	0.066	0.055
SUBJECT 4	0.01	0.014	0.297	0.161	0.063	0.049
SUBJECT 5	0.01	0.014	0.292	0.151	0.064	0.058
GRAND MEAN	0.009	0.014	0.293	0.155	0.064	0.053
SD	0.001	0.001	0.003	0.004	0.001	0.004

- **Centre of Mass (CoM) and the extrapolated Centre of Mass (XCoM)**

Typical graphs Fig. 7 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**

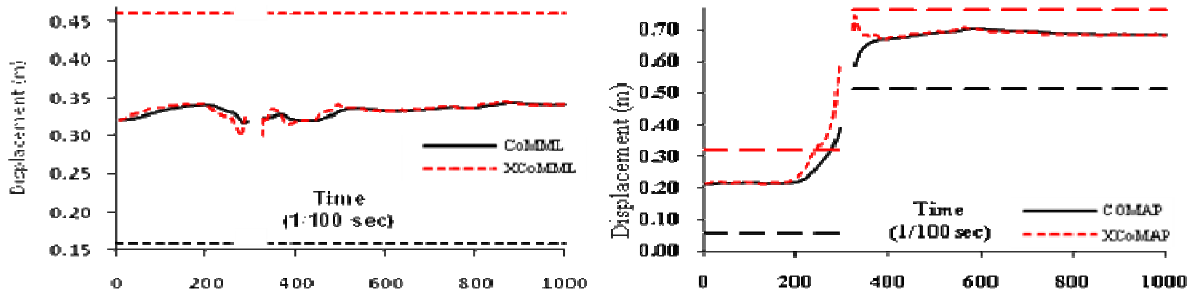


Fig. 7 Illustrates the variables CoM and the XCoM in both directions: in static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes) and the extreme Base of Support (dotted line). (Units= m).

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 III) 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 III
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	0.007	0.023	0.052	0.037	0.057
SUBJECT 2	0.009	0.011	0.024	0.050	0.039	0.056
SUBJECT 3	0.007	0.008	0.024	0.053	0.036	0.058
SUBJECT 4	0.008	0.010	0.025	0.054	0.034	0.055
SUBJECT 5	0.008	0.009	0.025	0.051	0.038	0.057
GRAND MEAN	**0.008**	**0.009**	**0.024**	**0.052**	**0.037**	**0.057**
SD	**0.001**	**0.001**	**0.001**	**0.002**	**0.002**	**0.056**

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 4) 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 IV) 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.

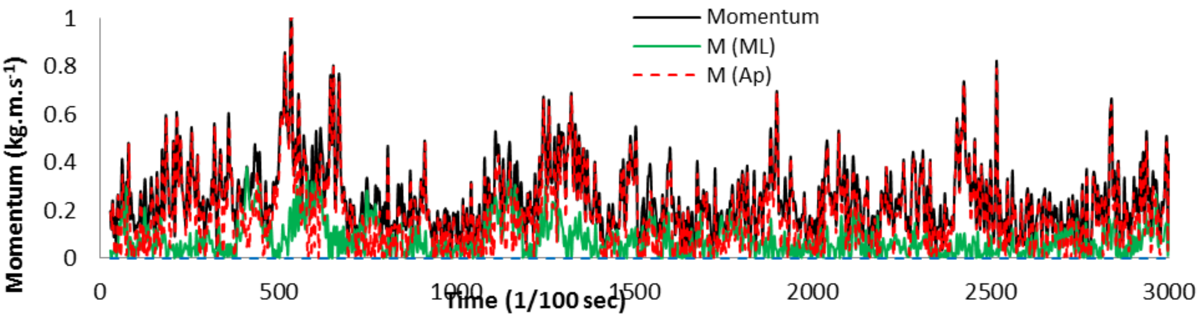
TABLE IV
MEAN OF RMS OF 3 TRIALS (N = 5) OF THE COM_{AP} AND THE $XCOM_{AP}$ IN THE ANTERIOR-POSTERIOR (AP) DIRECTION FOR STATIC BALANCE (2-FEET FLAT EYES OPEN), AND THE MEAN OF RANGE OF COM_{AP} AND THE $XCOM_{AP}$ FOR DYNAMIC BALANCE (JUMPING ON TIP TOES). (UNITS = M) *NOTE: THE LANDING LOCATIONS ARE VARIED FROM TAKE-OFF

SUBJECT	STATIC (RMS)		DYNAMIC (RANGE)			
			Take off		LANDING	
	CoM_{AP}	$XCoM_{AP}$	CoM_{AP}	$XCoM_{AP}$	CoM_{AP}	$XCOM_{AP}$
SUBJECT 1	0.007	0.012	0.227	0.524	0.143	**0.156**
SUBJECT 2	0.008	0.014	0.228	0.535	0.145	**0.159**
SUBJECT 3	0.007	0.013	0.230	0.560	0.148	**0.158**
SUBJECT 4	0.01	0.016	0.233	0.551	0.147	**0.157**
SUBJECT 5	0.009	0.014	0.230	0.544	0.146	**0.157**
GRAND MEAN	**0.008**	**0.014**	**0.229**	**0.543**	**0.146**	**0.157**
SD	**0.001**	**0.001**	**0.002**	**0.014**	**0.002**	**0.001**

- **Momentum (P)**

Typical graphs Fig. 8 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**

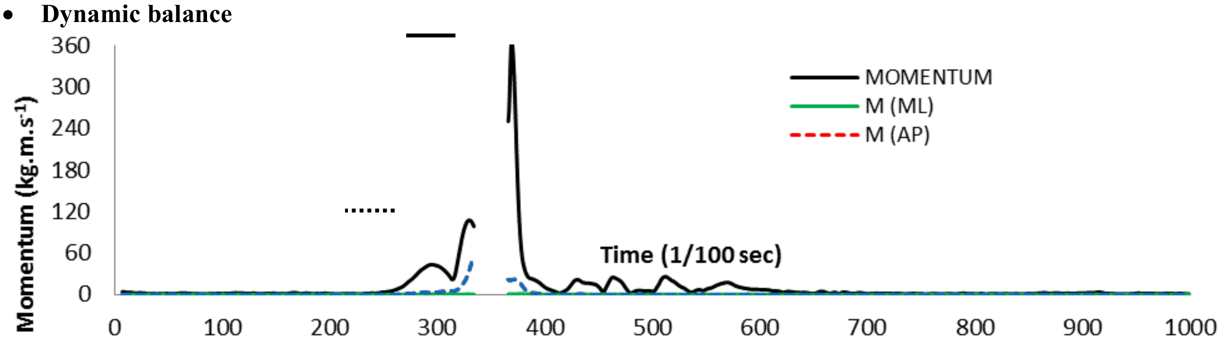


Fig. 8 Illustrates the P_{total} and the P_{ML-AP} in both static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes). (Units= $kg.m.s^{-1}$)

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 Fig. 8) 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 Fig. 8) 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 V 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 V
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 5 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 asindividuals 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).

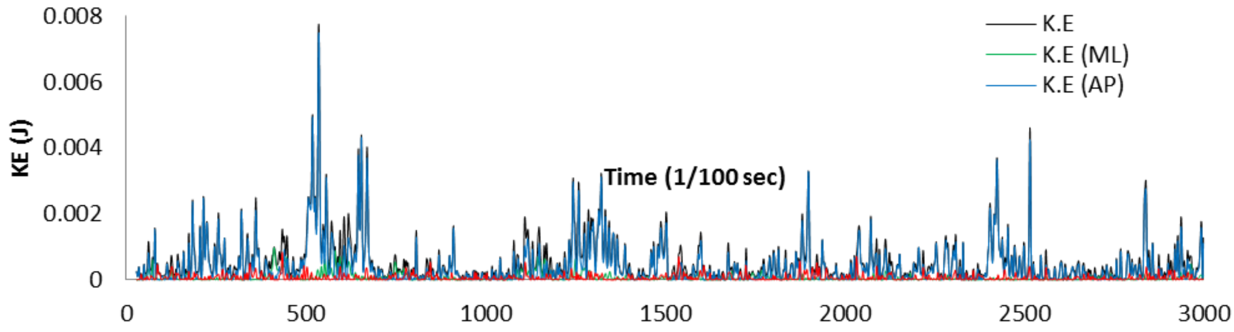
TABLE VI
MEAN OF RANGE OF PEAKS OF 3 TRIALS (N = 5) OF THE OF THE P_{TOTAL}, P_{ML} P_{AP} AND P_V DIRECTIONS FOR DYNAMIC BALANCE (JUMPING ON TIP TOES) VARIABLE = PEAK. (UNITS= KG.M.S^{-1})

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**

- **kinetic Energy (KE)**

Typical graphs Fig. 9 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**

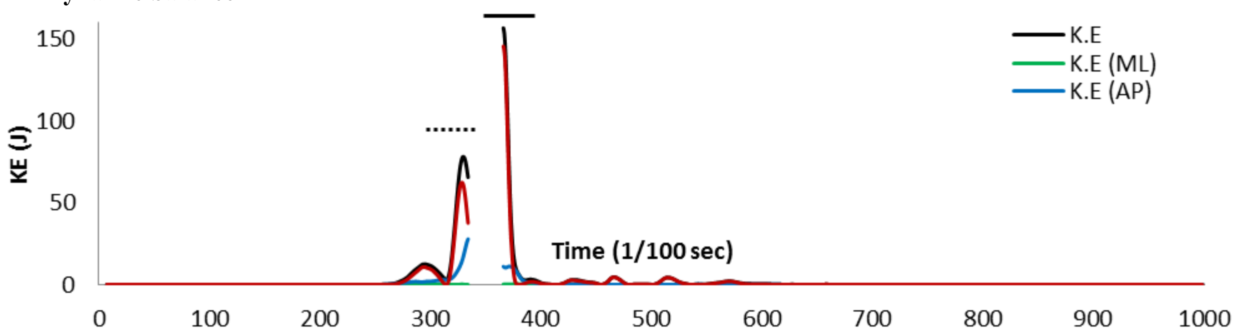


Fig. 9 Illustrates the KE_{total}, KE_{ML} and KE_{AP} in both static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes). (Units= J)

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 and show that the KE_{total} is greater than the KE_{ML} and KE_{V} and nearly equals the P_{AP} for the static activities as individuals apply momentum in AP direction.

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 VII 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 VII
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	0.0080	0.0010	0.0075	**0.0008**
SUBJECT 2	0.0079	0.0011	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	**0.098×10^{-3}**	**0.085×10^{-3}**	**0.179×10^{-3}**	**0.051×10^{-3}**

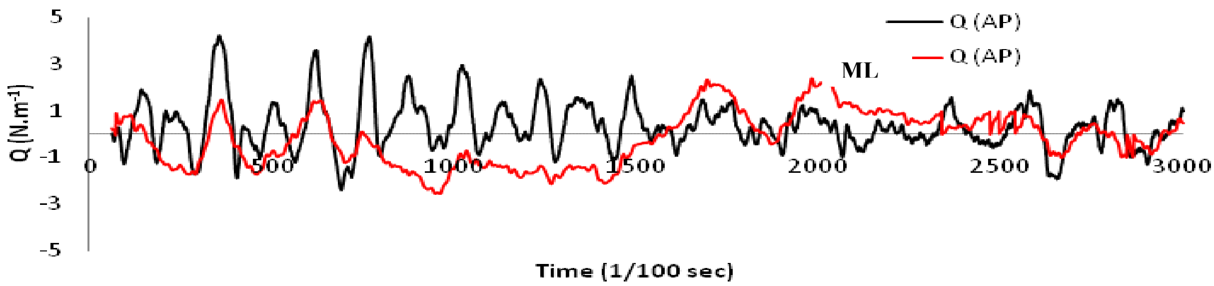
TABLE VIII
MEAN OF RANGE OF PEAKS OF 3 TRIALS (N = 5) OF THE KE_{TOTAL} AND ITS COMPONENTS (KE_{ML}, KE_{AP} AND KE_V) IN ML, AP AND V DIRECTIONS. DYNAMIC BALANCE (JUMPING ON TIP TOES). (UNITS= J)

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**

- **The Friction Torque *(Q)***

Typical graphs Fig. 10 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**

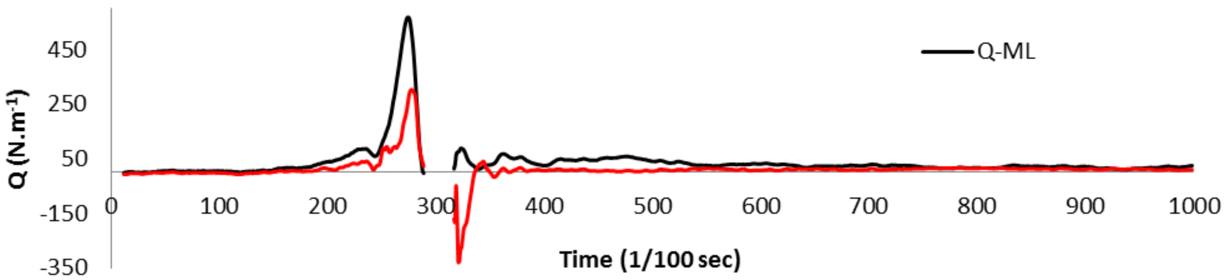


Fig. 10 Illustrates the Q_{ML} and Q_{AP} in both static balance (2-feet flat eyes open) and dynamic balance (jumping on 2 feet tiptoes) (Units=N.m)

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 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 9) show that they are similar during take-off phase while Q_{AP} is greater than the Q_{ML} during landing.

TABLE IX
MEAN OF RMS OF 3 TRIALS (N = 5) OF QML AND THE QAP 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)			
	Q_{ML}	Q_{AP}	**Take-off**		LANDING	
			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

IV. 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. [6] n = 8, [7]; n =6, [8]; 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 [Fig. 4 (A) and (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 [5].

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. 4 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 [3] 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 destabilization 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.

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