2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Fractal Brownian Motion Assessment of the Center of Pressure Excursion During Impulse Phase on Standard Vertical Jump

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Abstract— **This study presents and applies fractal Brownian motion assessment of the center of pressure (COP) excursion during feet ground contact on standard vertical jump impulse phase with long and short countermovement (CM) in relation with lower limb muscle stretch-shortening cycle (SSC) comparing it with no CM and SSC. Fifty-four tests were performed by a group of six healthy male students of sports and physical education degree without previous injury, specific training, or fitness ability. Three repetitions were performed by each subject of a squat jump (SJ) without CM and SSC, countermovement jump (CMJ) with long CM and SSC, as well as drop jump (DJ) with short CM and SSC after depth jump from a 40 cm step. During trial tests ground reaction force and force moments were acquired with force platform and impulse phases were segmented for COP coordinates computation. Fractal Brownian motion analysis of COP excursion during impulse phases conduced to detection of differences between critical time and displacement as well as short and long-term diffusion coefficient (*Ds*, *Dl*) and Hurst index scale exponent (*Hs*, *Hl*), with *Ds*, *Dl* presenting statistical significative correlations -0.491, -0.559 and *Hs*, *Hl* non statistical significative correlations 0.266 and -0.424 with MVJ height (*ht*) at 5% significance for explaining underlying mechanisms on CM and SSC at MVJ.**

Clinical Relevance— **This work contributes with new method for the study expansion of the center of pressure excursion and stability during feet ground contact from orthostatic standing position to the impulse phase during standard maximum vertical jump as the most adequate method for assessment of lower limb muscle stretch-shortening cycle.**

I. Introduction

Contact control tasks such as standing, gait, running and jump require precise control of contact forces since ground reaction force acting at the feet center of pressure (COP) is, along with gravitational force acting at the center of mass (COM), responsible for the movement of the whole-body [1]. Nevertheless, COP considerably moves during feet ground contact [2], with this movement influencing COM-COP displacement analysis largely studied on orthostatic stability [3], gait [4] and running [5], but not on standard vertical jump.

Muscle stretch-shortening cycle (SSC) is a common form of muscle function corresponding to a muscle concentric action immediately preceded by an eccentric action to achieve more efficient submaximal activities and powerful maximal activities [6]. Despite muscle SSC is present in gait and running [7], its higher expression and analysis accessibility corresponds to maximum vertical jump (MVJ) with long and short countermovement (CM) and SSC in relation to no CM [8] and SSC with an open issue on COP excursion during impulse phase on each MVJ type, as well as on its contribution on long and short CM in comparison with no CM performance.

To assess the contribution of COP excursion during impulse phase on each MVJ type it was analyzed using fractal Brownian motion proposed by Collins and De Luca [9] as an extension of Brownian random walk with two underlaying mechanism on standing orthostatic oscillation, a transient regime associated to open chain control and stationary regime associated to closed chain control.

II. Materials and Methods

A. Experimental tests

A small sample of n=6 students of sports and physical education degree with (21.5 ± 1.4) years old, without previous injury, specific training or fitness ability was selected. Subjects were explained on tests to perform and signed free informed consent after approval of experimental procedures by the Institutional Review Board. Volunteers were weighted (76.7 ± 9.3) kg and their height measured (1.79 ± 0.06) m. After warming up, subjects performed each three SJ, CMJ and DJ out of a total of 54 experimental trials. During trial tests ground reaction forces and force moments were acquired with AMTI force plate BP2416-4000 CE and Mini Amp MAS-6 amplifier at 1000 Hz.

B. COP during impulse phase

Maximum vertical jump (MVJ) of SJ, CMJ and DJ trials were selected for each subject according to higher flight time with zero ground reaction forces (GRF) register. Impulse phase was segmented at each selected trial SJ, CMJ and DJ for each subject and *COPx*, *COPy* coordinates at transversal plane were obtained using equations (1) and (2) with *GRFx*, *GRFy* and *GRFz* the antero-posterior, medio-lateral and vertical components of GRF, *Zoff* a negative value corresponding to the vertical offset from the top plate to the origin of the force platform sensors system (–0.39851 m according to the

*Research supported by EACEA.

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platform calibration report) and *Mx*, *My* the antero-posterior and medio-lateral GRF force moments,

$$COPx = -(My + Zoff \times GRFx) / GRFz \quad (1)$$

$$COPy = (Mx - Zoff \times GRFy) / GRFz. \quad (2)$$

According to the divergence of COP coordinates for lower *GRFz* amplitudes near zero, the initial 5 ms GRF register at the onset of the contact phase on DJ and immediately before the take-off on SJ, CMJ and DJ were discarded from analysis.

COP average plot Fig. 1 was obtained using the average of *COPx*, *COPy* coordinates as the origin (*COPavgx*, *COPavgy*) of the coordinate system and the radius *R* vs time was obtained as defined by equation (3) for the distance of the actual COP (*COPx*, *COPy*) to the average COP (*COPavgx*, *COPavgy*),

$$R = ((COPx - COPavgx)^2 + (COPy - COPavgy)^2)^{1/2}. \quad (3)$$

C. Fractal Brownian assessment of COP excursion

Fractal Brownian assessment of COP excursion corresponds to the extension of the equation (4) proposed by Einstein [10] for one dimensional Brownian movement to higher dimensions maintaining the linear relationship, with $<\Delta x^2>$ the mean square displacement, *D* the diffusion coefficient a measure of stochastic activity and Δt the time interval,

$$<\Delta x^2> = 2\, D\, \Delta t. \quad (4)$$

Applied extension of the classic Brownian motion to fractal Brownian motion, equation (5) was proposed by Mandelbrot and van Ness [11] with $0< H<1$ the Hurst index corresponding to the scale exponent and V_H a non-linear function of *H*,

$$<\Delta R^2> = 2\, D\, V_H\, \Delta t^{2H}. \quad (5)$$

H was determined by the slope of equation (6) corresponding to equation (5) at logarithmic scales,

$$\log <\Delta R^2> = 2\, H \log \Delta t + \log (2\, D\, V_H), \quad (6)$$

with H=0.5 corresponding to the classic Brownian motion and null correlation determined by equation (7),

$$C = 2\,(2^{2H-1}-1), \quad (7)$$

H>0.5 corresponding to C>0 a stochastic process positively correlated with persistent behavior maintaining movement direction and H<0.5 corresponding to C<0 a stochastic process negatively correlated with anti-persistent behavior and tendency for future inversion of past tendency.

D. Stabilogram diffusion of COP excursion

Mean square distances $<\Delta R^2>$ were calculated for each pair of COP points with increasing Δt time steps. Average square distances $<\Delta R^2>$ were plotted for each Δt time steps and linear regression lines were fitted to short- and long-term region segmented according to slope differences of $<\Delta R^2>$ *vs* Δt, determining short- and long-term diffusion coefficient *D*. Log-log graphs were plotted for mean square distances $<\Delta R^2>$ vs Δt time steps and linear regression lines were fitted to short- and long-term region, segmented according to slope differences, determining short- and long-term Hurst index scale exponent *H*.

E. Critical time and displacement

According to different slopes of short- and long-term diffusion of $<\Delta R^2>$ *vs* Δt, Fig. 2, intersection of fitted linear and logarithmic regression lines of short- and long-term regions were used to determine critical time t_c and critical displacement $<\Delta R^2_c>$ corresponding to the coordinates of the intersection points at the linear and log-log diagrams.

F. Statistical analysis

Critical time t_c and corresponding critical displacement $<\Delta R^2_c>$ as well as short- and long-term diffusion coefficient *D* and Hurst index scale exponent *H* were pared compared at different subject MVJ (SJ, CMJ and DJ) with IBM SPSS Statistics Version 25.

III. Results

A. Stabilograms and statokinesigrams

Fig. 1 presents representative example for one selected trial subject of stabilogram and corresponding statokinesigram during impulsive phase for each performed MVJ (SJ, CMJ, and DJ), whereas Fig.2 presents linear and corresponding log-log stabilogram diffusion.

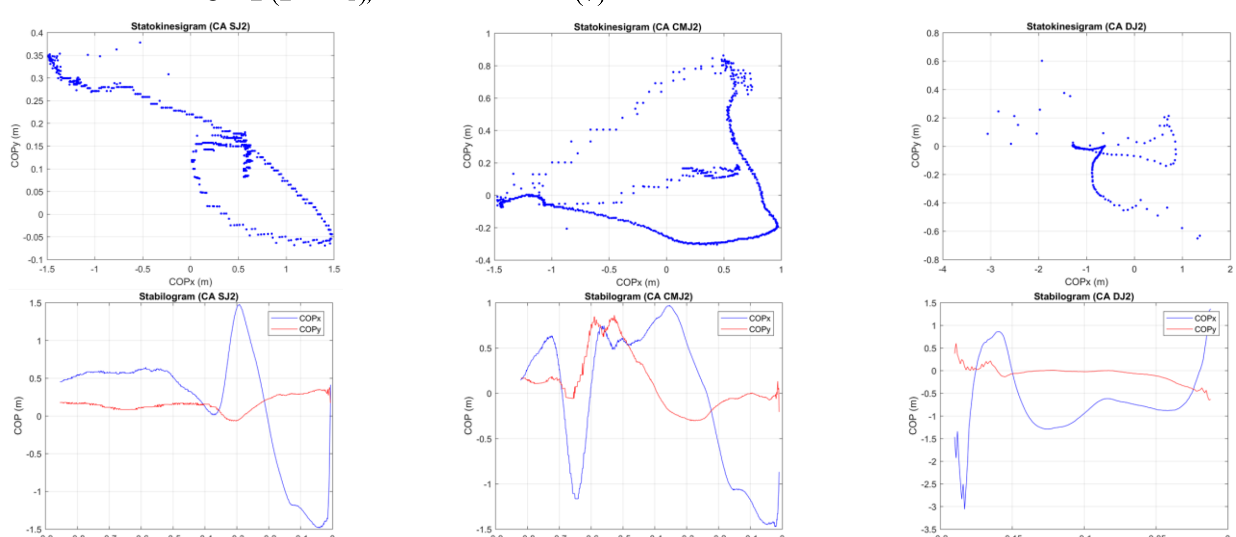

Figure 1. Stabilogram examples and corresponding statokinesigrams during impulsive phase for each MVJ (SJ, CMJ and DJ) of one selected trial subject.

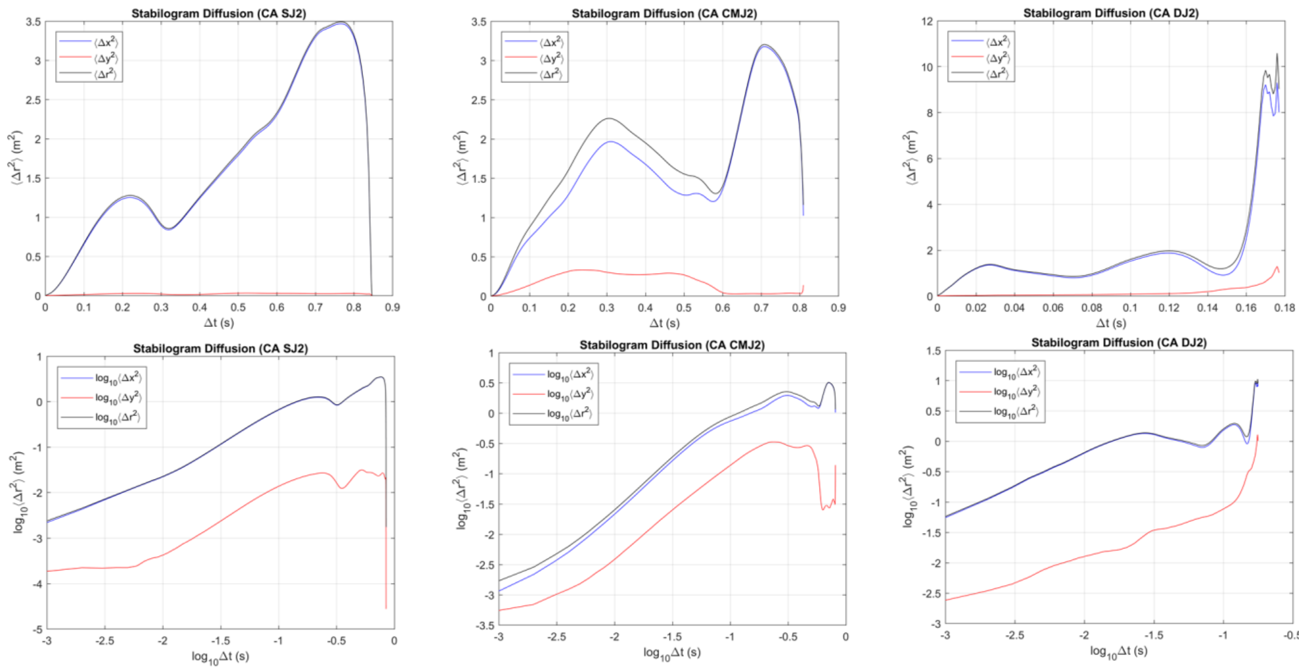

Figure 2. Stabilogram diffusion and corresponding log-log stabilogram diffusion during impulsive phase of one selected trial for each MVJ (SJ, CMJ and DJ).

B. Critical time and displacement

Critical time t_c presented on Levene test statistical significative different variances with higher value at CMJ than SJ and DJ ($p<0.05$), without statistical significative difference on variances ($p>0.05$) between SJ and DJ, Table 1. Critical displacement $<\Delta R^2_c>$ presented on Levene test similar variances at SJ, CMJ and DJ without statistical significative differences ($p>0.05$). Critical time t_c presented at CMJ higher mean value than SJ ($p>0.05$) both with higher mean value than DJ ($p<0.05$), Table 1. Critical displacement $<\Delta R^2_c>$ presented at CMJ higher mean value than SJ and DJ ($p<0.05$) without statistical significative difference between SJ and DJ ($p>0.05$).

C. Short- and long-term diffusion coefficient

Short-term diffusion coefficient D_s presented higher variance at DJ than CMJ and SJ, without statistical significative differences ($p>0.05$) on Levene test at DJ, CMJ and CMJ, SJ, and statistical significative differences ($p<0.05$) at SJ, DJ. Long-term diffusion coefficient D_l presented higher variance at DJ than CMJ and SJ without statistical significative differences ($p>0.05$) on Levene test at CMJ, SJ and statistical significative differences ($p<0.05$) at SJ, DJ and CMJ, DJ. Short- and long-term diffusion coefficient D_s and D_l presented at DJ higher mean value than SJ and CMJ ($p<0.05$) without statistical significative difference between SJ and CMJ ($p>0.05$), Table 1.

D. Short- and long-term Hurst index scale exponent

Short-term Hurst index scale exponent H_s presented higher variance at SJ than CMJ, both higher than DJ, all without statistical significative differences ($p>0.05$) on Levene test. Short-term Hurst index scale exponent H_s presented statistical significative difference ($p<0.05$) with higher mean value at SJ than CMJ and without statistical significative differences between DJ and CMJ, SJ ($p>0.05$), Table 1.

Long-term Hurst index scale exponent H_l presented higher variance at CMJ than DJ, both higher than SJ, all without statistical significative differences ($p>0.05$) on Levene test. Long-term Hurst index scale exponent H_l presented higher mean value at DJ than SJ and SJ higher value than CMJ both without statistical significative differences ($p>0.05$), and DJ presenting higher mean value than CMJ with statistical significative differences ($p<0.05$), Table 1.

E. Short- and long-term diffusion coefficient and Hurst index scale exponent

Short-term diffusion coefficient D_s presented at SJ and CMJ higher mean value than long-term diffusion coefficient D_l with statistical significative differences ($p<0.05$) and lower mean value of D_s than D_l at DJ without statistical significative differences ($p>0.05$). Short-term Hurst index scale exponent H_s presented at SJ and CMJ higher mean value than long-term Hurst index scale exponent H_l with statistical significative differences ($p<0.05$) and lower mean value of H_s than H_l at DJ without statistical significative differences ($p>0.05$).

TABLE I. MVJ HEIGHT, COP CRITICAL TIME AND DISPLACEMENT, SHORT AND LONG TERM DIFFUSION AND HURST INDEX SCALE EXPONENT

Parameter	**COP excursion on impulse phase**		
	SJ	***CMJ***	***DJ***
ht (m)	0.332 ± 0.045	0.364 ± 0.042	0.274 ± 0.016
t_c (s)	0.216 ± 0.026	0.328 ± 0.149	0.039 ± 0.016
$<\Delta R^2_c>$ (m²/s)	1.173 ± 0.494	1.996 ± 0.654	1.200 ± 0.313
D_s (m²/s)	3.047 ± 1.065	4.035 ± 2.941	17.786 ± 6.188
D_l (m²/s)	1.856 ± 1.271	1.073 ± 2.148	21.929 ± 8.833
H_s	0.634 ± 0.092	0.557 ± 0.085	0.516 ± 0.055
H_l	0.464 ± 0.133	0.138 ± 0.382	0.607 ± 0.195

IV. DISCUSSION

A. Short- and long-term diffusion coefficient

According to the ability of diffusion coefficient for quantification of COP stochastic activity and postural instability with higher diffusion coefficient associated to higher stochastic activity and postural instability, DJ presented higher variance and mean value of short- and long-term diffusion coefficient D_s and D_l than SJ and CMJ with similar values at SJ and CMJ, thus pointing to higher stochastic activity and postural instability at DJ than SJ and CMJ, with similar stochastic activity and postural instability at SJ and CMJ. SJ and CMJ presented higher mean values of D_s short-term diffusion coefficient than D_l long-term diffusion coefficient point to short-term open loop control and higher stochastic activity than at long-term closed loop control. On the contrary DJ presented lower mean value of D_s than D_l without statistical significative differences ($p>0.05$) with and open issue on the mechanisms acting on short- and long-term at DJ. Impulse phase starts on SJ and CMJ from feet ground contact position and end with take-off, while DJ presents an impact of the feet with the ground at reception, ending with take-off. This is particularly important since reception and take-off events at impulse phase respectively present at start/end lower amplitude values of vertical ground reaction forces *GRFz*, with impact at antero-posterior and medio-lateral, *COPx* and *COPy* stability, despite impulse phase time segmentation has been performed to reduce COP instability. Also, antero-posterior *COPx* presented higher diffusion coefficient than medio-lateral *COPy* pointing to higher instability at antero-posterior direction than at medio-lateral direction.

B. Short- and long-term Hurst index scale exponent

Short-term Hurst index scale exponent H_s presented average value higher than 0.5 with statistical significative differences at SJ ($p<0.05$) and without statistical significative differences at CMJ and DJ ($p>0.05$) corresponding to stochastic process positively correlated and persistent behavior maintaining movement direction. Long-term Hurst index scale exponent H_l presented average value lower than 0.5 at SJ, CMJ and higher value than 0.5 at DJ, all without statistical significative differences ($p>0.05$) pointing to stochastic process negatively correlated with anti-persistent behavior and tendency for future inversion of past tendency at SJ, CMJ and to stochastic process positively correlated and persistent behavior maintaining movement direction at DJ on long-term regime.

C. Critical time and displacement

Critical point coordinates, critical time t_c and displacement $<\Delta R^2_c>$, determine the transition between short- and long-term regime associated to open and closed loop control. This transition occurred at lower critical time on DJ than SJ with statistical significative difference ($p<0.05$), both lower than CMJ without statistical significative difference ($p>0.05$). Critical displacement $<\Delta R^2_c>$ presented at SJ and DJ similar values without statistical significative differences ($p>0.05$) both lower than CMJ with statistical significative differences ($p<0.05$).

V. CONCLUSION

Expansion of COP excursion analysis from balance at orthostatic position to dynamic conditions assessing COP fractal Brownian motion during impulse phase on standard maximum vertical jump as proven to be executable and useful determining differences on critical time, mean square distances, and short- and long-term diffusion coefficient as well as Hurst index scale exponent of COP excursion during impulse phases at different MVJ. Applied method for determining critical point coordinates assumes determinant role on detection of transition between short- and long-term regime. This way instant feedback on COP excursion at short- and long-term regime can be provided to the performers in relation with attained performance based on MVJ height at different standard MVJ. Fractal Brownian motion analysis thus presents as a key stochastic metric of persistent and anti-persistent behaviour with advantage in relation to classic COP for detection of short- and long-term instability based on antero-posterior and medio-lateral GRF, complementing MVJ exclusive assessment based on vertical GRF, with application on daily leaving, recreational activities, and sports. According to attained differences on COP diffusion at impulse phase of different analysed MVJ the contribution of this factor can be pointed as one of the several factors determining achieved differences on MVJ and corresponding SSC performance.

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