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Nonlinear dynamics analysis of the human balance control subjected to physical and sensory perturbations

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Postural control after applying perturbation involves neural and muscular efforts to limit the center of mass (CoM) motion. Linear dynamical approaches may not unveil all complexities of body efforts. This study was aimed at determining two nonlinear dynamics parameters (fractal dimension (FD) and largest Lyapunov exponent (LLE)) in addition to the linear standing metrics of balance in perturbed stance. Sixteen healthy young males were subjected to sudden rotations of the standing platform. The vision and cognition during the standing were also interfered. Motion capturing was used to measure the lower limb joints and the CoM displacements. The CoM path length as a linear parameter was increased by elimination of vision ($p<0.01$) and adding a cognitive load ($p<0.01$). The CoM nonlinear metric FD was decreased due to the cognitive loads ($p<0.001$). The visual interference increased the FD of all joints when the task included the cognitive loads ($p<0.01$). The slightly positive LLE values showed weakly-chaotic behavior of the whole body. The local joint rotations indicated higher LLEs. Results indicated weakly chaotic response of the whole body. Increase in the task difficulty by adding sensory interference had difference effects on parameters. Linear and nonlinear metrics of the perturbed stance showed that a combination of them may properly represent the body behavior.

Key words: postural control, nonlinear dynamics, perturbation, vision, cognitive

INTRODUCTION

Postural control is a multi-sensory task that simultaneously involves central nervous system (CNS), musculoskeletal system and sensory organs (Peterka 2003). A routine decision of the CNS in response to a perturbation is changing the body position by postural adjustment to confine center of mass (CoM) movements within the base of support (Federolf et al. 2013, Oba et al. 2015, Runge et al. 1999). Evaluation of the CoM excursion gained several attentions as a proper index for the whole body efforts due to its simple and reliable measurement (Abe et al. 2010). Several researchers have considered linear dynamics in analyzing the CoM excursion (Dingenen et al. 2013, Federolf et al. 2013). Although these techniques have appropriately indicated the overall difficulty, ability or deficiency of the standing tasks, they may not be sensitive enough to analyze the systemic dynamics of the human balance control (Han et al. 2005, Liu et al. 2015). But applying the nonlinear dynamics methods in the study of balance may unveil more details on the stability and its complexity (Sasaki et al. 2001). The nonlinearity in the balance control originates from various sources like the delays in sensory systems, nonlinear muscular stiffness, etc. (Blaszczyk et al. 2014, Chagdes et al. 2012) which forces the CNS to be involved and instantaneously control the body after the application of perturbations (Reynard and Terrier 2014). Obviously, the stance in the perturbed cases requires more neural and muscular efforts compared with quiet standing (Creath et al. 2005). The later, however, has been subjected to a wide range of nonlinear analyses from assuring its chaotic nature (Buzzi et al. 2003, Collins et al. 1995, Hausdorff et al. 2001, Yamada 1995) to developing a discriminative metric for the sensory interference (Ladislao and Fioretti 2007, Negahban et al. 2013), muscular frailty or aging (Blaszczyk and Klonowski 2001, Han et al. 2005), locomotive diseases (Pascolo et al. 2006), and also in environmental changes (Murata and Iwase 1998, Negahban et al. 2013).

A good index of the chaotic systems may be the largest Lyapunov exponent (LLE) which is widely-used for examination of biological data. The LLE assesses the convergence or divergence of a time series trajectory relative to a reference one. Many researchers (Ladislao and Fioretti 2007, Murata and Iwase 1998, Pascolo et al. 2006, Safi et al. 2015, Yamada 1995) found the LLE positive or slightly above zero and concluded that the postural sway is chaotic and the better standing conditions e.g. youth, health, open eyes, fixed support, etc. owns lower LLE values. In addition to the LLE, other researchers used

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fractal dimensions (FD) as a reliable nonlinear parameter to show the complexity and chaotic behavior of a time series (Doyle et al. 2005, Duarte and Zatsiorsky 2000). An increase in the FD may indicate a higher tendency for postural instability (Blaszczyk and Klonowski 2001, Doyle et al. 2005).

The nonlinear dynamics methods were often applied on the excursion of the center of pressure (CoP) which may not properly represent the mechanisms of the lower limb joints. Liu and others (2015) used a coordinated LLE (square-root of the sum of squared differences between the segmental LLEs) to better show the details of nonlinear dynamics of the standing strategies under translational perturbation. They reticulated some qualitative classes of standing to the stepping or winging mechanisms, and, concluded that the perturbed stance could make the balance features more obvious (Liu et al. 2015). Therefore, the goal of the present study is to assess the LLE and FD of the CoM excursion and the lower limb joints to analyze first the chaotic nature of the whole body and its local contributors in standing stability of young healthy subjects after applying rotational perturbations. The vision and cognition during standing were also interfered to assess their roles in standing. It was hypothesized that an increase in the task difficulty by removing the vision and adding cognitive loads increases the body efforts to compensate the produced instability. This paper also examined the discriminative ability of the linear and non-linear metrics in different physical and sensory conditions of balance.

METHODS

Subjects

Sixteen healthy young males (aged 27.1±2.9 years; height 176±5 cm; weight 74.3±9.4 kg) among the university students volunteered to participate in the test. None of them had a history of sensory or muscular diseases. They were informed the test conditions by reading a brief explanation about the test in addition to the verbal explanations and finally signed the consent form. The protocol of the test was prepared based on the declaration of Helsinki which approved by the local ethics committee of medical experiments.

Procedure

The participants stood barefoot on a motorized platform with a single plane of motion (in the sagittal plane). Subjects' postural reactions were provoked by unexpected abrupt inclinations of the support surface. They were asked to put their feet equal to the shoulders' width and fold arms across the chest. Each subject underwent rotational perturbations of the standing platform (10 degrees in 150 ms) both in toes-down (TD) and toes-up (TU) direction for five trials. Rotation of standing platform was previously used by other researches (Blaszczyk et al. 1993, Vlutters et al. 2015). Furthermore, visual feedback in open eyes conditions (EO) were interfered by closing the eyes (EC). A cognitive load (CL) was imposed to the subject by asking an arithmetic question (two-digit numbers subtraction) in addition to the no-cognitive load (NC). Each subject, therefore, has had forty trials (5 trials×2 direction×2 vision×2 cognitive levels). In other words, the eight physical and sensory perturbations were tested five times to assure the reliability. The trials were tested in a fully-randomized order by asking the subject to randomly sort an unknown set of trial numbers. Participants were free to move after applying the perturbation to keep their balance. The unsuccessful (including separated soles, unfolded arms or stepping) or wrongly-responded trials were repeated.

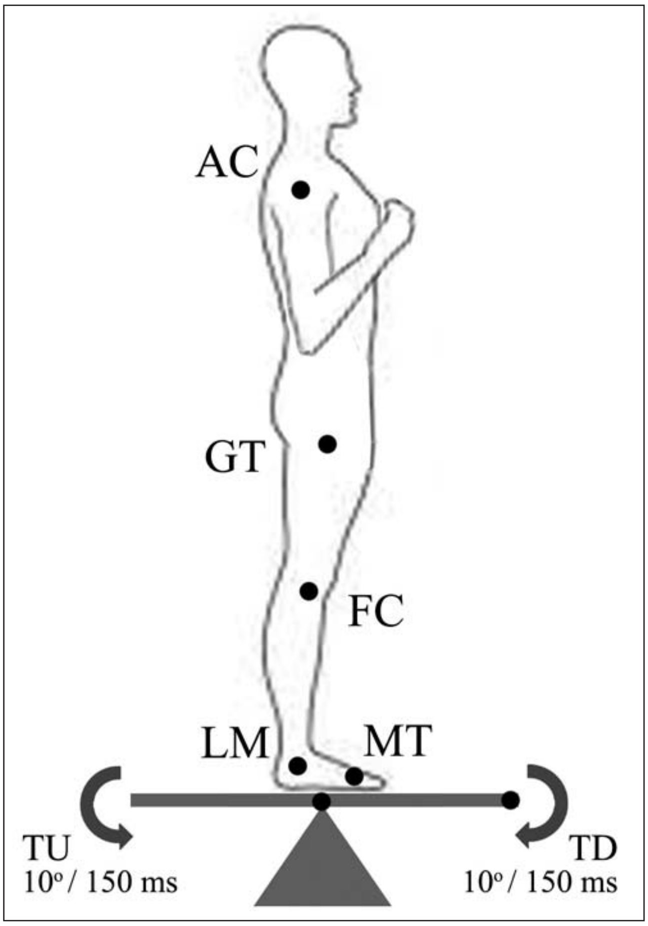

Fig. 1. Schematic representation of the perturbation set-up and the markers location, AC: acromion; GT: greater trochanter; FC: lateral femoral condyle; LM: lateral malleolus; MT: fifth metatarsal.

Measurement

Kinematic data were captured by a high-speed camera (Casio® EX-ZR20, Tokyo, Japan) in the sagittal plane to record the in-plane movements (120 frame/s) of five active LED markers attached on the right external malleolus, fifth metatarsal, lateral femoral condyle, greater trochanter and acromion. The aim of the motion capture was to achieve the ankle, knee and hip joint rotations and then to calculate the CoM position as functions of time. Fig. 1 schematically shows the set-up and marker locations. Reliability of the 2D in-plane data acquisition has already been investigated (Fonda et al. 2014). The intra-class correlation coefficients of mean, range, maximum and root mean square of the lower limb joint angles and the CoM excursion were calculated. It was found that the kinematic extracted data are fairly – (0.46) to excellently-reliable (0.98). Two other markers were attached to the platform (rotation shaft and right end (see Fig. 1) to obtain the perturbation onset time. A customized image processing code was used to extract the kinematic data of the markers.

Data analysis

The CoM movement was routinely calculated based on the weighted displacement of the body segments' center of mass relative to the total body weight. It was assumed that the CoM diverges from the reference trajectory as:

$$\left|\delta Z(t)\right| \approx e^{\lambda t}\left|\delta Z_0\right|, \tag{1}$$

where $|\delta Z_0|$ is the initial separation which diverges to $|\delta Z(t)|$ by time. The power λ denotes the Lyapunov exponent which its negative value assures the convergence of the trajectory or the stability (Wolf et al. 1985). Two different criteria were considered to find the LLE for the kinematic parameters based on the input time series. The first criterion presumed the separation from the initial position that the CoM stayed just before the perturbation over the total time range (TT). The second criterion assumed the time series from the initial to the first alternate stable posture (ASP). The first ASP here was defined as the earliest posture that the CoM is remained constant for at least 0.2 s. This time range was inspired from the literature (Collins et al. 1995, Goldberg et al. 2012). The LLE was calculated based on the equation:

$$\mathrm{LLE} = \lim_{t\to\infty} \lim_{\left|\delta Z_0\right|\to 0} \frac{1}{t} \log \frac{\left|\delta Z(t)\right|}{\left|\delta Z_0\right|}, \tag{2}$$

for time series ($Z(t)$) of the kinematic parameters. Furthermore, the FD for the kinematic indices was determined based on the Higuchi dimension as:

$$\mathrm{FD} = \frac{\mathrm{d}\log\big(L(k)\big)}{\mathrm{d}\log(k)}, \tag{3}$$

where $L(k)$ is the path length when the measuring stick length was k. The symbol d denotes the differentials. Traditional linear parameters included the path length (PL, sum of iterative displacement between the points on the parameter time series curve), range (R, the difference between maximum and minimum) and root mean square (RMS) of the kinematic indices.

Statistical analysis

The three linear and the FD nonlinear metrics of perturbed standing were subjected to linear mixed models analysis of variance in eight levels (2 direction×2 vision×2 cognitive condition). The linear mixed model ANOVA on the LLE has considered an additional 2-level effect of the criteria in its calculation. The alpha band was set to 0.05.

RESULTS

Table I presents the mean and standard deviation of the PL, R and RMS of the lower limb joint angles and the CoM position. The RMS of the kinematic data were insensitive to the changes in the physical test condition and the sensory interference. The CoM path length was more dependent on the test conditions. Both the visual and cognitive interference increased the path length of the CoM. The knee rotations were increased by addition of the cognitive loads. The ankle and the hip joints were not affected by changes in the sensory feedback. The joints and the CoM reacted similarly in response to the toes-down and up perturbations. The p-values of the statistical analyses were mentioned in Table I. The range of the kinematic parameter was merely sensitive in the CoM to the visual and cognitive changes. Addition of an arithmetic question and closing the eyes resulted in wider ranges of the CoM.

Fig. 2 illustrates the largest Lyapunov exponent (LLE) for rotations of the three lower limb joints and the CoM excursion. The ankle's LLE was more dependent on the test conditions. While the subjects did not use the visual feedback, addition of an attentional dual task considerably decreased ($p<0.01$) the LLE no matter what the perturbation direction or the calculation criterion was. The direction of the perturbation was effective for the knee merely in the cases of simultaneous existence of visual and cognitive interference. The knee rotated more in the TU direction ($p<0.05$). The visual interference had no effect on the stability in terms of the LLE nonlinear parameter. Furthermore, the consideration of the shorter time series i.e. up to the first alternate stable posture did not influence on the LLE values in all kinematic indices of standing.

Fig. 3 also depicts the fractal dimension (FD) of the joint reactions and the CoM movements against the physical, visual and cognitive disturbances. In general, no significant difference was observed between the directions for all four kinematic data. The ankle and knee revealed similar nonlinear behavior between the normal i.e. EO+NC cases and the sensory interfered ones. The ankle disclosed higher FD in closed eyes conditions by adding a cognitive load ($p<0.01$). But in opened eyes conditions, addition of a cognitive load decreased the FD ($p<0.01$). The normal cases in the hip and the CoM were, however, significantly different from the CL cases. Besides, the visual and cognitive roles were statistically highlighted ($p<0.01$) when one of them is interfered.

DISCUSSION

The present study investigated the reaction of the human body in terms of the CoM excursion and the lower limb joints to a bi-directional rotational perturbation. It was assumed that the component contributors in the lower extremities play a nonlinear role in standing in addition to the collective parameters like the CoM. Both the linear and nonlinear behaviors of the component and collective stance parameters were analyzed to investigate their discriminative characters in response to the physical and sensory perturbations.

Linear dynamics

The most differentiating parameters among the linear metrics was the path length, specifically for the CoM. The CoM was calculated based of the motions of the lower limb joints in response to the physical perturbations and represented the body sway. The more PL value meant the higher consumption of energy to compensate the overall body motion during the balance. It may result in lower control on the postural balance (Casteran et al. 2016). Although the physical changes in the standing platform did not affect the path length of the CoM movement, addition of an arithmetic cognitive task or closing the eyes considerably increased the PL. It implied that while the CNS is interfered by a dual task or missed the visual feedback motions of the body increased linearly and it consumes more energy in comparison with the normal cases. Since the data of this study were only included the successful trials of keeping the balance, higher PL required higher endeavors of the body to retain the stability. Therefore, visual or cognitive interference may reduce the stability.

Table I. Means ±SD of the linear parameters for the CoM and the lower limb joints in eight different test conditions. Abbreviations are Nr=normal, EC=eyes closed, CL=cognitive load, TD=toes-down, TU=toes-up, PL=path length, R=range, RMS=root mean square

		Nr		EC		CL		EC + CL	
		TD	TU	TD	TU	TD	TU	TD	TU
PL	CoM	4.1±0.8^{a,c**}	4.5±1.1^{b**}	4.9±0.8^{c**}	5.2±1.2	5.4±1.1^{a**}	5.9±1.6^{b**}	5.3±1.5	5.6±0.7
	Ankle	16.6±4.8	16.8±5.0	15.4±5.1	16.9±4.1	18.1±4.3	20.2±5.6	18.5±8.0	17.8±6.7
	Knee	15.9±5.4^{a*}	16.5±5.6	17.2±6.2	16.7±2.3	21.5±7.9^{a*}	19.5±4.5	19.7±5.2	18.1±3.7
	Hip	16.9±6.5	18.5±6.6	17.0±6.4	19.2±4.4	20.8±8.3	21.7±5.7	19.4±6.4	21.1±4.9
R	CoM	2.8±0.6^{a,c**}	3.0±0.8^{b,d**}	3.7±0.8^{c**}	3.7±1.0^{d**}	3.8±0.9^{a**}	4.1±1.0^{b**}	4.0±0.9	4.2±0.6
	Ankle	7.0±1.6	6.7±2.0	7.9±2.0	7.2±1.7	6.7±1.5	6.7±1.9	7.7±2.0	6.9±1.4
	Knee	6.8±2.3	5.9±1.9	8.4±3.2	6.7±1.9	6.4±2.5	5.9±1.2	7.6±2.3	6.6±1.8
	Hip	6.2±2.9	7.3±2.0	8.9±6.3	8.9±4.5	6.3±3.8	7.9±2.9	7.4±5.3	8.8±3.5
RMS	CoM	1.9±0.5	1.9±0.7	2.6±0.5	2.8±0.9	2.2±0.8	2.2±0.8	2.3±1.0	2.5±0.6
	Ankle	10.1±4.8	3.6±2.0	10.4±4.9	4.5±1.5	9.5±5.0	3.3±1.9	9.3±4.5	4.4±2.2
	Knee	17.2±5.1	14.6±5.0	18.1±5.2	15.2±4.7	16.1±5.9	14.1±5.5	17.7±4.8	15.4±4.7
	Hip	6.5±3.6	7.2±4.0	7.9±5.4	7.7±5.5	6.4±4.6	7.1±3.9	7.5±5.8	8.1±3.5

a, b, c and d significant differences between the marked pairs. ** denotes $p<0.01$, * denotes $p<0.05$.

From a component point of view, the knee was the only joint that has made a significant difference increase in the PL by loadings the cognitive tasks. No significant changes existed for the ankle and hip joints by changing the test conditions. The majority of the previous works reported the path length of the center of pressure which has increased by elimination of the visual feedback (Collins et al. 1995, Corbeil et al. 2003, Melzer and Oddsson 2016, Sullivan et al. 2009). Also, a directional measure of CoM length showed a significant difference between opened and closed eye conditions in healthy young persons (Blaszczyk 2016). Adding a cognitive dual task increased the body endeavors required to maintain the CoM in the allowed region. It may be reflected in the PL parameter as previously occurred for the children (Schmid et al. 2007).

The CoM range of variation also revealed roughly the same results with the path length. The collective linear parameter were sensitive against the changes in the sensory information in standing. None of the lower limb joints' range, however, reacted against the sensory or physical perturbations. Hence, the range of variations could not disclose the joint strategies in keeping the balance as a linear dynamics metric. The RMS values were also insensitive to all changes even for the CoM excursion. This parameter was improper to investigate the effects of the visual, cognitive and physical changes.

Nonlinear dynamics

The nonlinear dynamics developed two metrics i.e. the fractal dimension and the largest Lyapunov exponent. The later was calculated once for the total time series and then for the time series up to the first time that the body has found an alternate stable posture. There was no significant difference between the considered criteria for the LLE calculation in the perturbed stance. The LLE results were all positive but with near-zero values which implied a weakly-chaotic nature for the body reactions to the rotational perturbations. Such a behavior was identified for the quiet standing when the parameter of nonlinear analysis was the CoP (Ladislao and Fioretti 2007, Lamoth and van Heuvelen 2012, Pascolo et al. 2006, Yamada 1995). Application of nonlinear

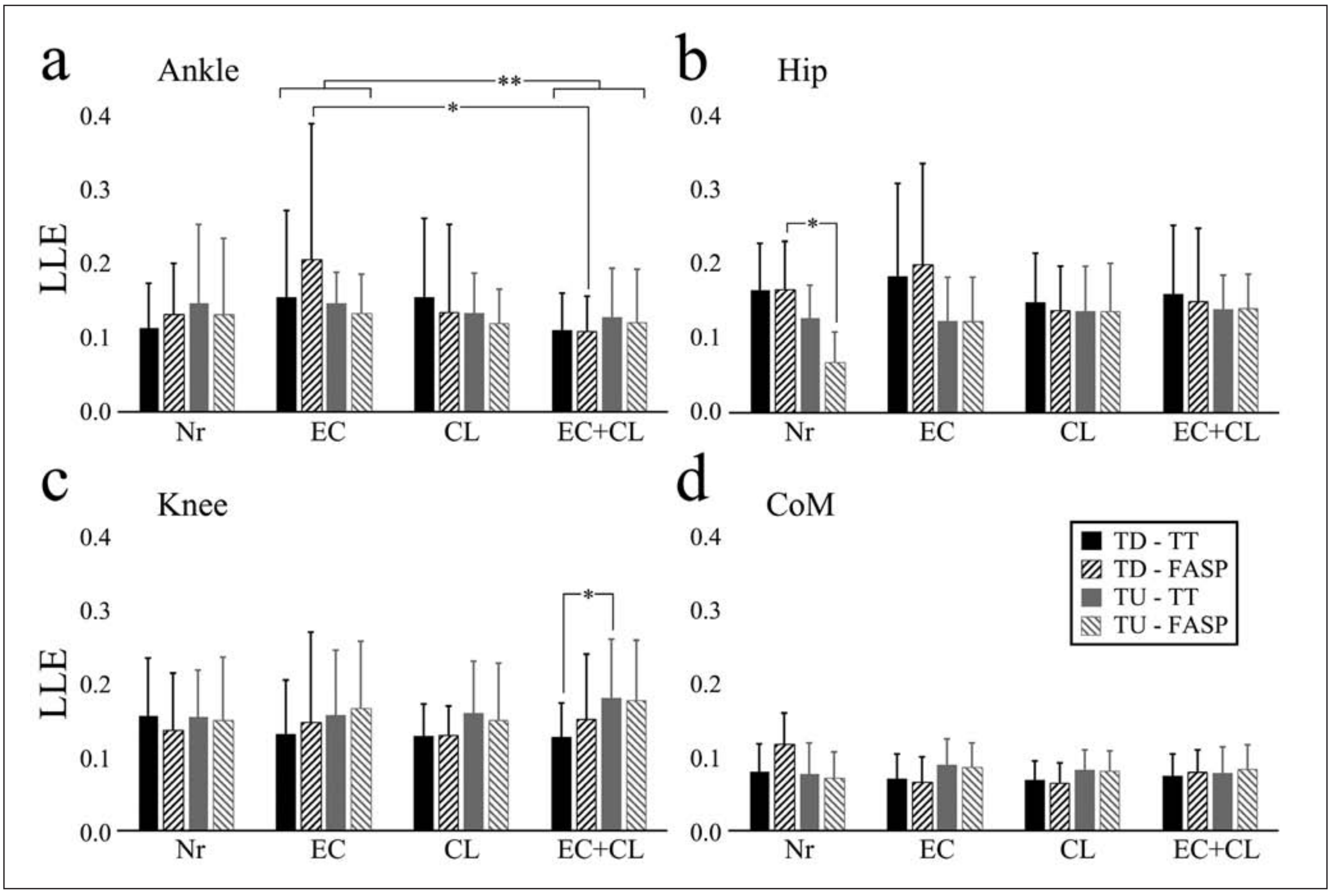

Fig. 2. Largest Lyapunov exponent (LLE) of three lower limb joints and the CoM for different test conditions. The filled bars denote the LLE for total time series (TT) and the hashed bars depict the LLE for zero to the first alternate stable posture (FASP) time series. The single asterisk difference means $p<0.05$ and the double $p<0.01$. Abbreviations are Nr=normal, EC=eyes closed, CL=cognitive load, TD=toes-down, TU=toes-up.

dynamics on the CoM displacement in perturbed stance also showed weak chaotic responses of the body in different physical and sensory conditions. The LLE for the CoM was not dependent on the vision and cognitive conditions. Previous works developed different results. Some researchers uttered that the elimination of visual feedback decreased the stability by increasing the LLE values (e.g. Donker et al. 2007). Unlikely, other researchers like Huisinga and others (2012) found a decrease in the LLE values for EC conditions meaning a decrease in the standing instability. Such a discrepancy in the LLE values of standing was also existed for cognitive interference (Donker et al. 2007, Negahban et al. 2013). The cognitive loads in this study, however, has significantly affected the ankle LLEs but merely when the eyes were closed. Addition of the cognitive interference with closed eyes reduced the local instability of the ankle joint. But this effect has not changed the whole body stability. The hip and knee joints were also not influenced by physical or sensory perturbations. Sensitivity of the ankle to the cognitive loads may be due to the vicinity of this joint to the perturbation location. The ankle has reacted to the rotational perturbations sooner than the others and cognitive involvement may more affect the ankle joint. It should be noted that the blindfold cases intensified this effect so that it becomes statistically significant.

Fractal dimension of the kinematic parameters showed more dependency on the sensory interference. Once the eyes were closed, application of an arithmetic cognitive load aimed at withdrawing the attention from the postural control affected the standing by reducing the regularity in the time-series of the stance parameters. Similarly, when a cognitive load was imposed to the subjects, elimination of the visual feedback increased the FD. The lone cognitive loads also affected the hip and the CoM variations but the closed eyes without cognitive dual task had no significant effect on the FD. The CoM as a collective parameter of standing showed higher regularity (FD<1.14) than the component joint values. Fractal dimension of the knee was higher among the joints (maximally=1.49) but their differences were only significant in interactions with the cognitively loaded cases (CL). The FD equal to 1 implies a smooth variation of a time series data refrain from any chaotic behavior. In contrast, the fully chaotic behavior necessitates the FD to be equal to 2 (Blaszczyk and Klonowski 2001). Han and others (2005) found the Renyi fractal dimension of the CoP of healthy subjects approximately equal to 1.2 for a 20-s quiet standing task. The literature (Blaszczyk and Klonowski 2001, Duarte and Zatsiorsky 2000, Han et al. 2005) found different values for the fractal dimension of standing ranged from 1.2 to 1.65 for both the CoM and CoP excursion. The CoP, in general,

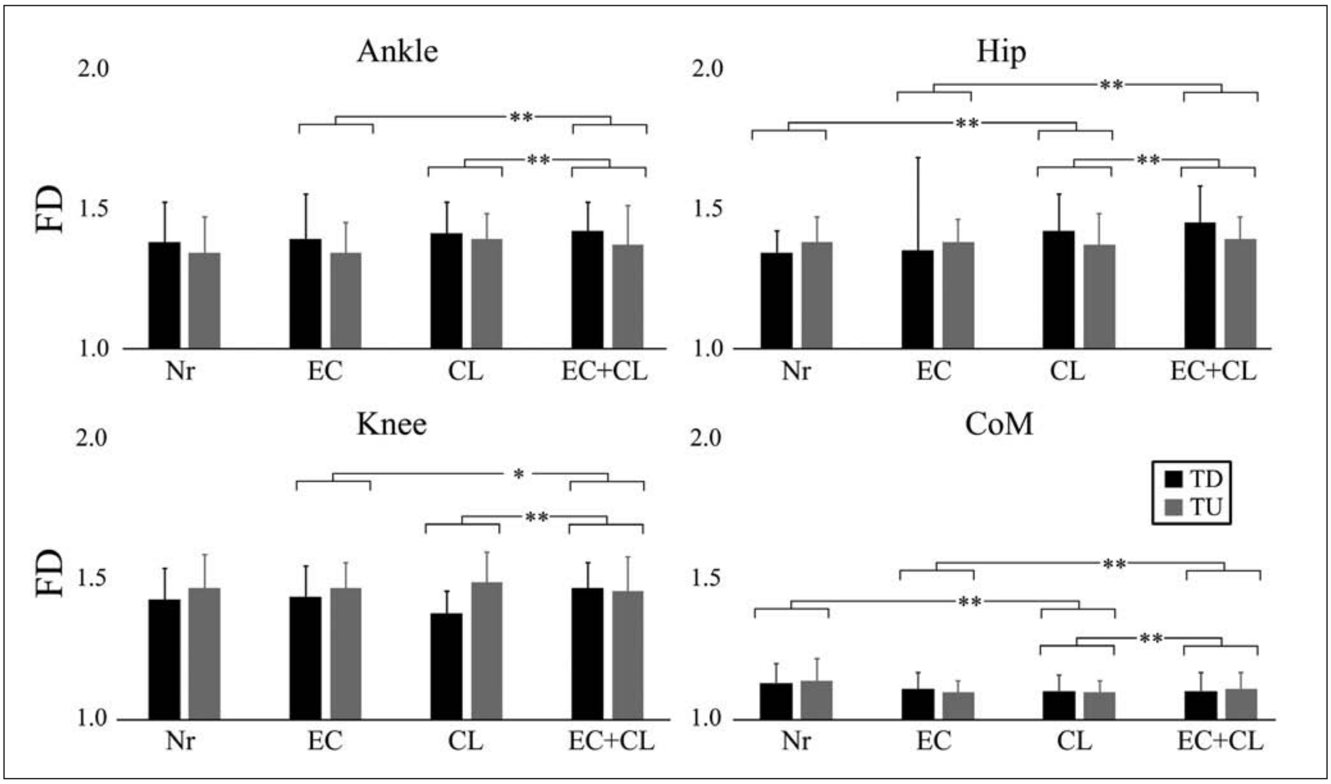

Fig. 3. Fractal dimension (FD) of the test cases for four kinematic parameters of standing. The single asterisk difference means $p<0.05$ and the double $p<0.01$. Abbreviations are Nr=normal, EC=eyes closed, CL=cognitive load, TD=toes-down, TU=toes-up.

induced higher FD than the CoM. Blaszczyk and Klonowski (2001) compared the FD for these indices and calculated the CoP's fractal dimension 0.18 greater than that of the CoM. Another reason for the diversity in the range of FD outputs (roughly in the same conditions of the tasks and subjects) may be due to the duration of the standing. The longer tasks of standing (20 or 30 min) caused greater fractal dimensions which may be originated from the muscle fatigue or other internal perturbations. Although the use of fractal dimension is theoretically applicable for infinite time series, Duarte and Zatsiorsky (2000) stated that the nonlinear dynamics method could discover valuable details of the human standing from early seconds to several minutes. Considerations of the joint kinematic parameters either in linear or nonlinear accounts suggests that the collective parameters like the CoM or CoP may disregard the role of the component parameters. A separate look at the joints may unveil the details of the postural adjustment patterns in response to different perturbations.

Direction of physical perturbation neither affected the LLE nor the FD. The linear parameters also were independent from the toes-down or -up directions. It implies that the body reacted similarly against the rotational perturbation. Providing the stability was not different in forward or backward inclinations of the standing platform. Also the lower limb musculature may reveal different patterns of recruitment (Henry et al. 1998, Horak and Nashner 1986, Runge et al. 1999), but the overall endeavors of the body in response to the perturbations was the same in both directions. Further investigations like the frequency analysis or phase plane mapping may be needed to better disclose the local efforts of the multi-segmented body in keeping the balance.

The presented study was encountered with some limitations. More importantly, the total time for all data was two seconds. In contrast to the quiet standing tests whose total sampling time are longer, the perturbed standing studies cannot consider extended times due to the nature of immediate reactions against the perturbation. Consideration of further times may reduce the effect of perturbations and add some confronting errors.

CONCLUSIONS

Movement of the CoM after applying a perturbation revealed a weakly chaotic behavior to seek an alternate stable posture. Two nonlinear parameters of fractal dimension and largest Lyapunov exponents confirmed the complexity of postural balance among the healthy subjects. Direction of rotational perturbations did not affect the overall response of the body in postural balance. However, the task difficulty i.e. presence of vision and then cognitive interference affected the regularity of the time-series of collective and component kinematic parameters. A Combination of linear and nonlinear metrics could properly interpret the behavior of the human neuromuscular system in response to physical and sensory perturbations.

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