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Article

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Abstract In this study we examine the dynamic characteristics of the center of pressure (COP) profiles in quiet stance on various carpets through the framework of fractional Brownian motion. Four different carpets plus the force platform (which served as a control floor) were tested. Six healthy young subjects stood stationary in bare feet on each flooring condition under both eyes-open (EO) and eyes-closed (EC) conditions. A stabilogram diffusion analysis (SDA) was conducted in both anteroposterior and mediolateral directions to extract the dynamic features of the COP profiles. Two approximately linear regions (short- versus long-term regions) were found for all of the flooring conditions in the double logarithmic plot of the mean-square displacements versus time intervals, implying that a two-stage control scheme exists in regulating the posture. In general, a more compliant carpet was found to be associated with a shorter transitional time interval and a lower H_L value (Hurst coefficient in the long-term region) under the EO condition, but to be correlated with a higher H_S (Hurst coefficient in the short-term region) and a higher H_L under the EC condition. While the hard floor of the force platform significantly decreased H_L from the EO to the EC conditions, the alteration of visual environments did not substantially influence H_L for a compliant carpet.

Key words carpet, quiet stance, posture, center of pressure, fractional Brownian motion

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Carpets are one of the most widely used floor coverings in our daily life. It has been reported that the inappropriate application of carpets is a major environmental cause of detrimental outcomes such as accidental falls in the elderly at nursing homes [1]. Prolonged standing on an improper floor covering has also been found to intensify potential physical problems related to standing [2–4]. It is thus of great importance to understand the effect of floor coverings on human daily activities such as standing and walking.

A number of studies have been conducted to investigate the mechanical properties of carpets theoretically [5, 6] and experimentally [7–9]. To understand the interaction between carpets and humans, a few biomechanical and psychophysical studies [4, 10, 11] have also been carried

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Table 1 The parameters of the floor coverings tested in this study. The dimensions of the force platform were 40 × 60 cm and its stiffness modulus was adopted from the manual.

	Carpet A	Carpet B	Carpet C	Carpet D	Force platform
Manufacturing type	Tufted	Tufted	Tufted	Tufted	–
Construction	Cut pile	Cut pile	Cut pile	Loop pile	–
Surface material	Polyester	Wool	Wool	Polyester	Aluminum
Pile height (mm)	10.2	8.6	6.8	3.2	–
Carpet thickness (mm)	13.1	11.4	10.0	6.7	–
Stiffness (N mm^{-1})	87.8	115.3	160.0	578.1	4×10^5
Compliance (mm N^{-1})	0.0114	0.0087	0.0063	0.0017	0

out. The center of pressure (COP) profile, i.e. the position of the resultant ground reaction force, is normally used to reflect postural sway in quiet standing. Redfern et al. [4] examined the velocity and amplitude of postural sway on different carpets, and found that more compliant carpets increase the sway velocity and amplitude, particularly for the elderly, in dynamic visual environments. The present authors [11] studied the mean velocity and root-mean-square displacement of the COP profile, and meanwhile explored the correlations between postural sway and perceived standing comfort. They reported that more compliant floors were in general associated with faster sway velocity and smaller sway amplitude, and also provided greater perceived comfort, particularly in the ankles and feet. Although mean velocity and root-mean-square displacement are informative in describing the average features of a COP profile, no dynamic characteristics can be revealed in the spatial and temporal correlations between successive COP movements.

A stabilogram diffusion analysis (SDA) [12] has recently been applied to examine the dynamic characteristics of the COP profile under the framework of fractional Brownian motion. The COP profile was found to contain both stochastic and deterministic characteristics [13]; in other words, the COP changes its direction of motion with a predictable probability. A two-stage control scheme was proposed for the COP profile in quiet standing such that an open-loop control dominates over short time intervals while a closed-loop control rules over long time intervals [12]. These findings have been supported by the successive studies on investigating visual effects [14–17] or finger touch [18] in quiet standing. However, no flooring covering has been included in these previous studies.

The aim of the present study is to apply the SDA to extract the stochastic parameters of the COP profile and compare them among various carpets. Two visual conditions are tested: eyes open (EO) and eyes closed (EC). We hypothesize that similar two-stage control schemes should exist in the COP profile for various flooring conditions, and that the stochastic parameters should be capable of differentiating between the dynamic features of postural sway on different carpets.

Methods and Materials

Experimental Methods

The experimental procedure has been reported in our previous paper [11]. In summary, six college students (two male, four female) volunteered to participate in this study and provided informed consent before the experiment. The subjects were 22.1 ± 2.9 years old, 1.67 ± 0.08 m tall, and weighed 58.9 ± 8.9 kg. All of the participants reported no history of gait or postural disorders, neurological diseases or musculoskeletal pathologies that could influence normal posture.

Four different carpets were investigated and the hard floor of the force platform served as a control. All of the carpets were purposely selected to represent a wide range of carpets used either at home or in workplaces. Table 1 presents the structural and mechanical parameters of these five flooring conditions (more details can be found in our previous paper [11]). The compliance (i.e. the reciprocal of the compressive stiffness) of the flooring conditions decreases in sequence from carpet A, to B, to C, to D, to the force platform floor.

A Kistler® 9281B force platform (Kistler, Amherst, New York) was used to collect the ground reaction forces and moments data during a subject's quiet standing, from which the COP profile was calculated. A carpet sample was placed directly on the force platform so that a carpeted floor (carpet plus the force platform) was tested for each carpet. The participants stood barefoot as still as possible on the carpeted floor with their arms comfortably at their sides. Two visual conditions, EO and EC, were tested. Under the EO condition, the participants were looking straight at a poster that was about 2 m away hanging on a wall. Each subject completed the tests over two days with one visual condition tested on each day. The sequence of visual presentation was randomized across the subjects. On each testing day, the five flooring conditions (four carpeted floors plus the force platform only) were randomly presented. Participants performed a block of 10 trials on each flooring condition and completed a total of 50 standing trials on each testing day. During each trial, data was collected for 15 s at a sampling rate of 100 Hz. Enough rest time was provided between trials to minimize potential fatigue.

SDA

Fractional Brownian motion was introduced by Mandelbrot and van Ness [19] in 1968 to extend the classical Brownian motion to a generalized family of Gaussian stochastic processes. From the statistical mechanics point of view, one can predict the activity of a fractional Brownian motion in terms of probability, but not the outcome of each individual random event. This model, therefore, does not examine real-time and real displacements. Rather, it explores averaged displacements over time intervals. The relationship between the mean-square displacement $\langle \Delta d^2 \rangle$, for example, of the COP profile in this study and time interval Δt can be expressed as [20]

$$\langle \Delta d^2 \rangle \sim \Delta t^{2H} \quad (1)$$

where H is the Hurst exponent. Whereas the mean-square displacement $\langle \Delta d^2 \rangle$ itself can be determined by the expression [12]

$$\langle \Delta d^2 \rangle = \frac{1}{N-m} \sum_{i=1}^{N-m} (\Delta d_i)^2 \quad (2)$$

where m is the span of a segment pair in a COP over a given Δt, Δd_i is the displacement between the segment pair of the COP at point i and $i + m$, respectively, and $N - m$ is the number of the paired COPs available for this Δt. For details of the SDA, the interested reader can refer to the seminal study by Collins and De Luca [12].

The Hurst exponent H designates the correlation between the past and future movements of the COP. It can be any real number between 0 and 1. When $H = 0.5$, the COP profile is a pure random walk (a classical Brownian motion) such that the future COP movement is independent of its past movement. When $H > 0.5$, COP movements are positively correlated, i.e. a direction that the COP moved in the last step will be most likely continued in the next step. This feature is known as persistence. A higher H in this context yields a higher level of persistence, with the totally deterministic feature attained at $H = 1$, so that a COP that moves away from the geometric mean of the COP is to continue this trend and lead to a larger sway range. Conversely, when $H < 0.5$, COP movements are negatively correlated, i.e. a direction that the COP moved in the last step will be expected to alter in the next step. This feature is termed as anti-persistence. A lower H in this context yields a higher level of anti-persistence with the totally deterministic feature attained at $H = 0$. The COP that moves away from the geometric mean of the COP is expected to reverse and result in a smaller sway area. In summary, the value of H, if not equal to 0.5, denotes the level of stochastic and deterministic characteristics in the COP profile.

Before extracting stochastic parameters, raw COP profiles were filtered by the second-order Butterworth low-pass algorithm with the cutoff frequency 3 Hz determined by Jackson's algorithm [21]. Figure 1(a) shows a representative COP trajectory from a subject standing on a carpet for 15 s. Figure 1(b) presents the breakdown of the COP trajectory in the mediolateral (ML) and anteroposterior (AP) directions. The SDA analysis was conducted for both the ML and AP directions accordingly. Figure 1(c) displays the resultant double logarithmic plot of the mean-square displacements versus time intervals in the ML direction (see the details below). Two approximately linear portions were observed in this plot such that the slope of one portion was noticeably different from that of the other portion. Similar trends were also observed in the AP direction.

When conducting the SDA analysis with each subject, we first generated the double logarithmic plot of the mean-square displacements versus time intervals for each trial, and then averaged 10 such plots into an ensemble for each flooring condition under each visual condition. This resulting ensemble-averaged double logarithmic plot was then used to determine the transitional time interval and calculate the Hurst coefficient [12]. The algorithm proposed by Rougier [22] was applied to determine the transitional time interval. The straight broken line in Figure 1(c) denotes a pure random walk with $H = 0.5$, and passes through the resultant double logarithmic plot at the shortest time interval, which was equal to the reciprocal of the sampling rate. The distance between a COP logarithmic plot and the straight dotted line was calculated for each time interval, and the transitional time interval T was determined when this distance reached the maximum value. The resultant COP logarithmic plot was then divided into two approximately linear portions: the portion before the transitional time interval T was called a short-term region, while the portion after the transitional time interval T was called a long-term region. The linear slope was calculated for each region using the least-squares algorithm, and the Hurst exponent in each region was calculated as one-half of the slope (see Equation (1)).

A customized MatLab (Mathworks, Natick, MA) program was used to calculate the COP stochastic parameters. A two-way (flooring × visual) analysis of variance (ANOVA)

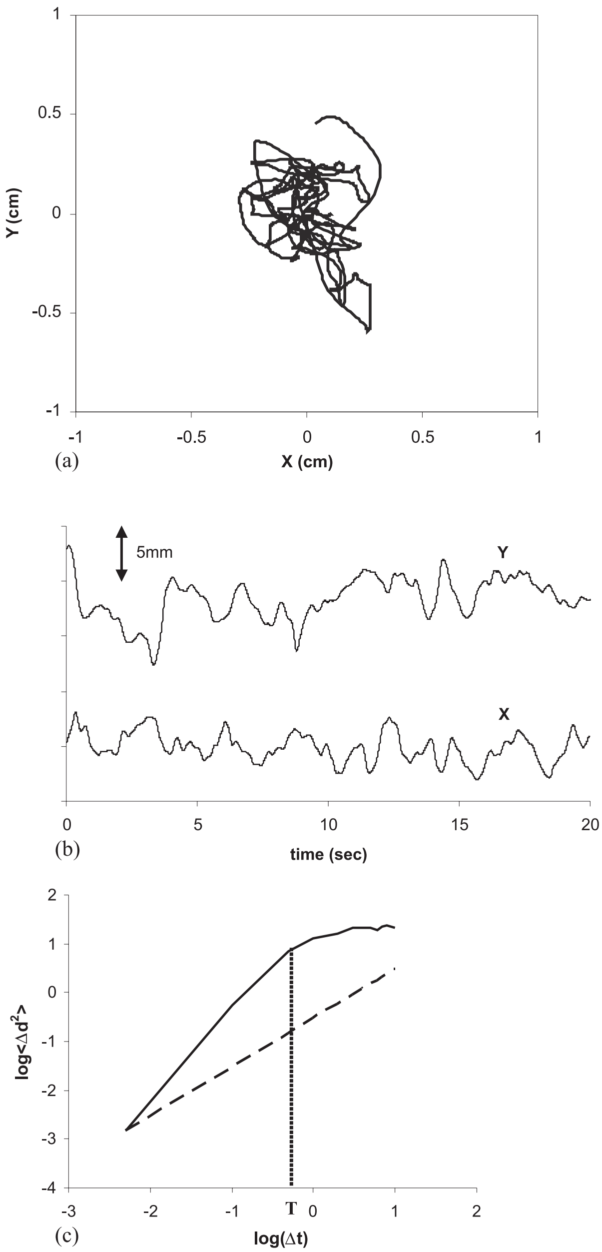

Figure 1 (a) A representative trajectory of the COP profile from a subject standing on a carpet over 15 seconds. Axes *x* and *y* denote the ML and AP directions, respectively. (b) The displacement of the COP along the *x*-axis (ML) and *y*-axis (AP). (c) A resultant double logarithmic plot of mean-square displacements versus time intervals for the COP profile in the ML direction.

with repeated measures on both factors was performed in SAS (SAS, Cary, North Carolina) to investigate the effects of flooring and visual conditions on the stochastic parameters. A one-way (flooring) ANOVA with repeated measures followed by *post-hoc* Tukey's multiple comparisons was conducted, when necessary, under each visual condition to examine the difference in flooring conditions. The Pearson's correlation coefficients were calculated between the floor compliance and the COP stochastic parameters. The level of significance was set at $p < 0.05$ for all of the statistical evaluations.

Results

Figure 2 presents the transitional time interval *T*, the Hurst coefficient in the short-term region H_S and the Hurst coefficient in the long-term region H_L for the AP and ML directions. As H_S was greater than 0.5 and H_L was less than 0.5, persistence and anti-persistence were thus expected to modulate the posture in the short- and long-term regions, respectively. In the AP direction, there was a marginally significant flooring effect ($p = 0.11$) for the transitional time interval *T* (Figure 2(a)). Secondary one-way ANOVA analyses showed that there was a marginally significant flooring effect for *T* under the EC condition ($p = 0.07$). Tukey's multiple comparisons indicated that carpet A yielded a shorter *T* than carpet C ($p = 0.11$) under the EC condition. There was a significant visual effect ($p < 0.05$) for H_L (Figure 2(e)) such that H_L was significantly lower under the EC condition than under the EO condition. Specifically, only carpet D ($p < 0.05$) and the force platform floor ($p < 0.01$) were found to significantly reduce H_L when moving from the EO to the EC condition. There was also a trend for the interaction between the flooring and visual conditions for H_L ($p = 0.15$). Secondary one-way ANOVA analyses showed that there was a marginally significant flooring effect under the EC condition ($p = 0.08$), in which carpet A generated higher H_L than carpet E ($p = 0.17$) and the force platform floor ($p = 0.16$).

In the ML direction, there was a significant flooring and visual interaction ($p < 0.05$) for the transitional time interval *T* (Figure 2(b)). Secondary one-way ANOVA analyses indicated that there was a marginally significant flooring effect on *T* under the EO condition ($p = 0.11$) and a significant flooring effect under the EC condition ($p < 0.05$). Tukey's multiple comparisons revealed that carpet D yielded longer *T* than carpet B ($p = 0.17$) under the EO condition, while carpet C generated significantly longer *T* than carpet A and D ($p < 0.05$) under the EC condition. There was a marginally significant flooring and visual interaction ($p = 0.07$) on H_S (Figure 2(d)). Secondary one-way ANONA analyses indicated that there was a marginally significant flooring effect on H_S under the EC condition ($p = 0.09$), in which carpet B yielded lower H_S than carpet A ($p = 0.08$) and carpet D ($p = 0.14$). The visual effect on H_L (Figure 2(f)) was found to be marginally significant ($p = 0.11$). Specifi-

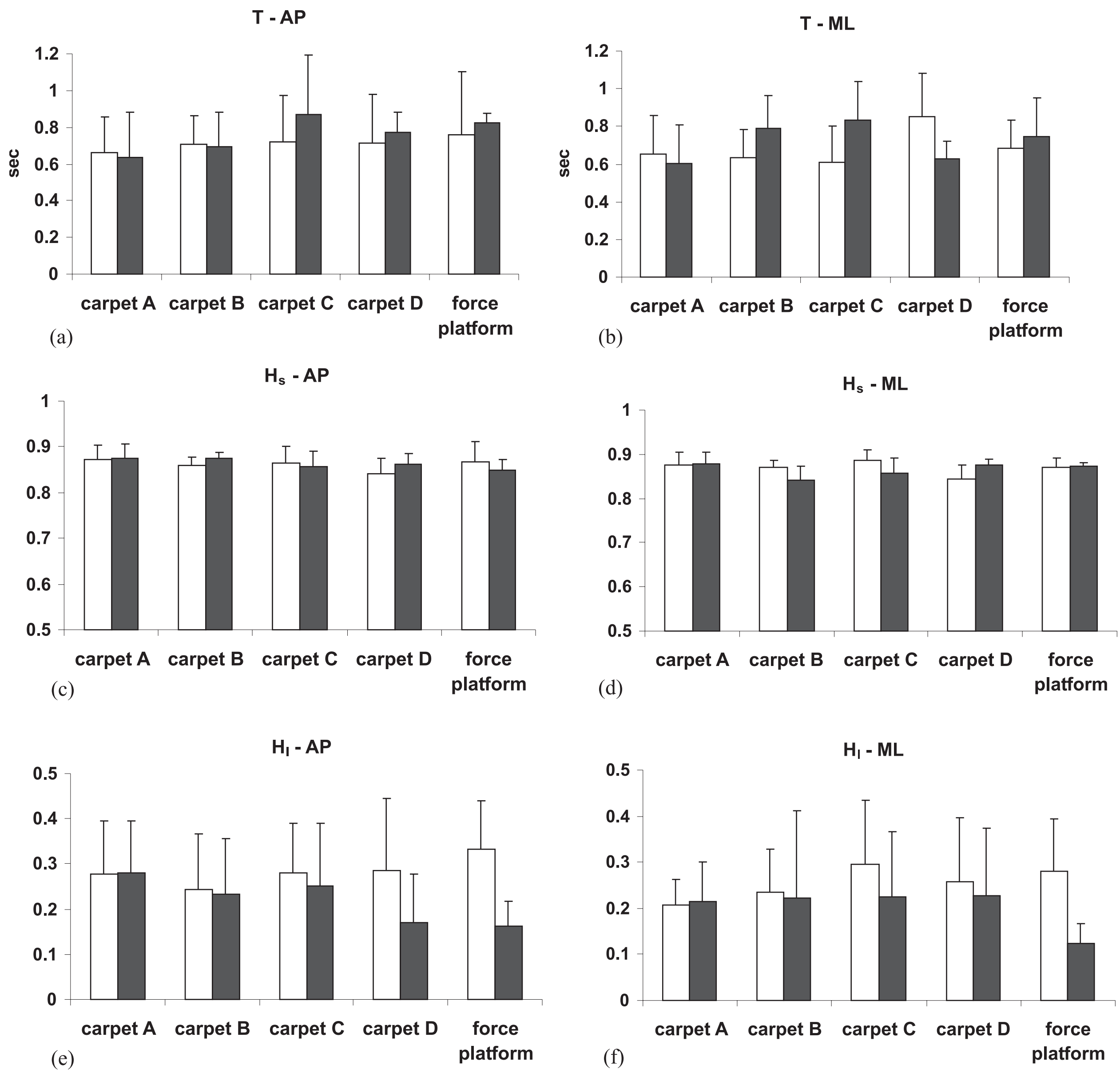

Figure 2 Mean and standard deviation of the stochastic parameters extracted from the COP profiles: (a) transition time interval T in the AP direction; (b) transition time interval T in the ML direction; (c) Hurst exponent H_S in the AP direction; (d) Hurst exponent H_S in the ML direction; (e) Hurst exponent H_L in the AP direction; (f) Hurst exponent H_L in the ML direction. □ Here denotes the EO condition and ■ denotes the EC condition.

cally, the force platform floor was found to decrease H_L from the EO to the EC conditions ($p = 0.10$).

Significant correlation between the flooring compliance and the stochastic parameters was found only in the AP direction (Figure 3). Under the EO condition, the flooring compliance was negatively correlated with T ($r = -0.87$, $p = 0.06$, Figure 3(a)). In contrast, under the EC condition, the flooring compliance was positively correlated with both H_S ($r = 0.86$, $p = 0.06$, Figure 3(b)) and H_L ($r = 0.95$, $p < 0.05$, Figure 3(c)). The correlation between the floor-

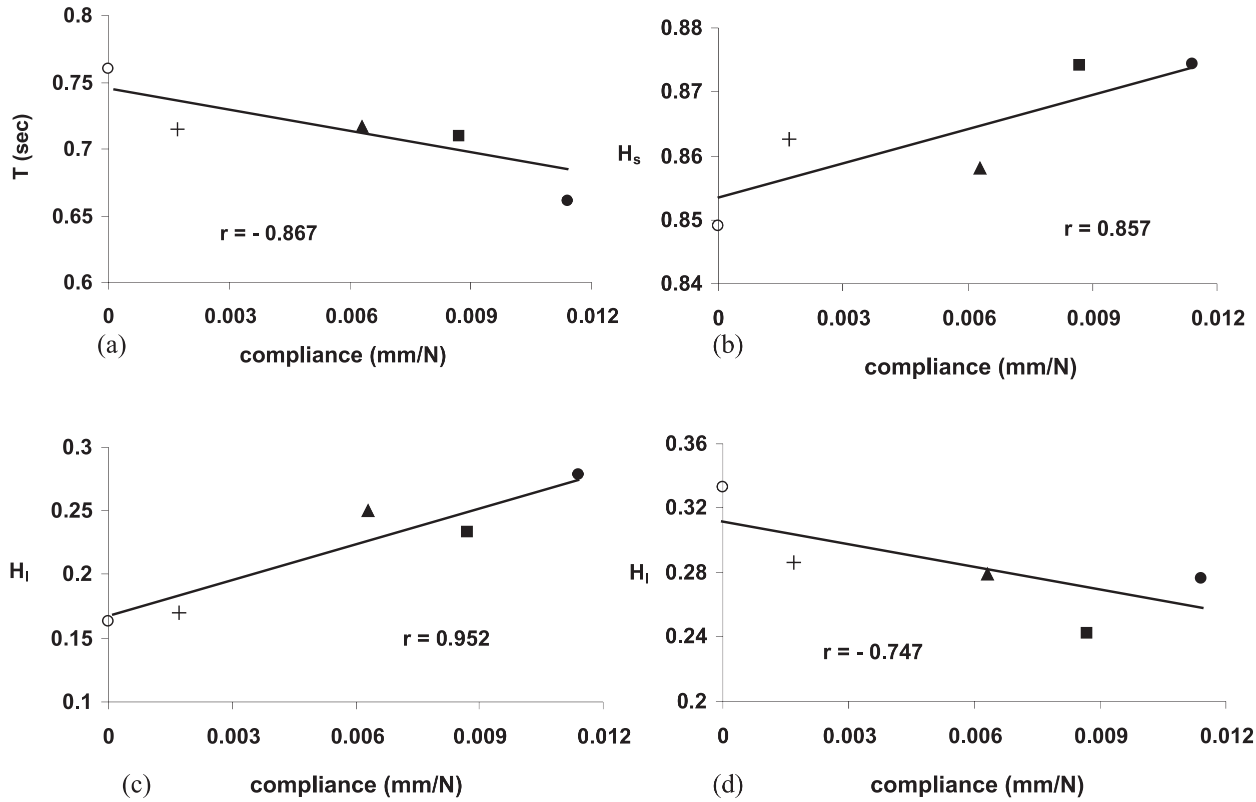

Figure 3 Correlation between the flooring compliance and the stochastic parameters in the AP direction: (a) correlation between the compliance and T under the EO condition; (b) correlation between the compliance and H_S under the EC condition; (c) correlation between the compliance and H_L under the EC condition; (d) correlation between the compliance and H_L under the EO condition. Here ● denotes carpet A, ■ denotes carpet B, ▲ denotes carpet C, + denotes carpet D and ○ denotes the force platform.

ing condition and H_L under the EO condition is shown in Figure 3(d) ($r = -0.75$, $p = 0.15$) for a comparison of the visual effect on H_L.

Discussion

The aim of the present study was to extract the dynamic features of the COP profile from standing on different flooring conditions through the technique of fractional Brownian motion. A two-stage control scheme (the persistence regulates posture over short time intervals and the anti-persistence rules over long time intervals for all of the flooring conditions in this study) is in agreement with the previous findings reported for the hard floor of the force platform [12, 14, 16–18]. A floor covering such as carpet therefore may not alter the dynamic nature of the persistence versus anti-persistence for the COP profile in quiet standing. However, stochastic parameters such as the transitional time interval and the Hurst coefficient can be appreciably influenced by different flooring conditions under various visual environments.

Transitional time intervals in the present study ranged from 0.6 to 0.8 s, which are comparable with those reported by Collins and De Luca [12, 14] but higher than values reported elsewhere [15–18]. Collins and De Luca [12] proposed that a sensory threshold corresponding to the transitional time interval exists in the central nervous system such that the central nervous system collects afferent information continually before reaching the threshold, and regulates posture after the transitional time interval. This interpretation is, however, still up for debate [23, 24]. Liebovitch and Yang [25] applied a model of the fractional Brownian motion with long relaxation time to numerically simulate biological time series and stated that the persistence is due to inertial movement of the particle while the anti-persistence lies in the naturally bounded biological systems.

Unlike the particle in the classical Brownian motion, the COP profile that reflects ground reaction forces and moments is related to the mass of the human body. As inertia always tends to keep the particle moving in the same direction, a persistent correlation can be expected in short time intervals in the COP profile. When the time interval is larger than the relaxation time of the inertial movement, the anti-persistence emerges due to the bounded nature of the biological system in which the COP cannot exceed a certain region without loss of balance. The damping functions of different carpets obviously affect the inertial part of the COP over short time intervals, and may also generate a cumulative effect on the anti-persistence in the COP profile over long time intervals, although they cannot alter the nature of the process. Thus, a similar two-stage control scheme in postural regulation was observed for all of the flooring conditions in this study.

The flooring differences illustrated by the stochastic parameters T and H_L imply that the dynamic features of carpets can be differentiated by SDA under the framework of fractional Brownian motion. The marginally negative correlation between the floor compliance and H_L under the EO condition and the significantly positive correlation between these two in the EC condition suggest that the stochastic features of the COP profile for a given flooring condition can be influenced by visual environments. Mechanically, the damping or impact force of an object is proportional to the velocity of the object; that is, a higher damping force is associated with a faster velocity. The compliance of the flooring conditions used in this study has been reported as significantly correlated with the mean velocity of the COP under the EC condition, but that correlation was not significant under the EO condition [11]. Thus, we speculate that the flooring differences in terms of the stochastic parameters may not be due to the damping difference under the EO condition, but under the EC condition the damping function of flooring conditions may play an important role in determining the dynamic features of the COP profile.

Further the central nervous system usually modulates posture based on the afferent input from the visual, somatosensory and vestibular systems. The somatosensory information is obtained directly from the mechanoreceptors in the feet and the muscle receptors around the ankle muscles in quiet standing. Compliant floor coverings have been speculated to generate conflicting somatosensory input in quiet standing [3, 4]. In the EO condition, from the threshold perspective in the nervous system, this conflicting somatosensory information may intensify the response from the central nervous system such that it takes a shorter period to reach the threshold and, hence, results in a higher level of anti-persistent sway over long time intervals. On the other hand, under the EC condition, postural control relies heavily on the somatosensory and vestibular systems. The compensation from these two sensory systems may not be strong enough for a significant increase of anti-persistence to be observed in either hard carpet D or the force platform hard floor. However, for compliant carpets, the aforementioned appreciable influence of damping functions may, to some extent, be offset by the conflicting somatosensory information generated from those carpets. Thus, insignificant change of stochastic parameters is expected for compliant carpets from the EO to the EC condition.

Compliant carpets naturally alter the interface between the supporting surface and the feet by increasing the contact area and decreasing the foot pressure [26]. This provides greater perceived standing comfort, especially in the ankle and feet [11], and may thus reduce potential fatigue and facilitate better standing. The finding that the unaffected dynamic features of posture for compliant carpets under various visual conditions could suggest that compliant carpets may not be as beneficial as relatively firm carpets in regulating posture in the absence of the visual input. This dynamic feature should be taken into account when making decisions regarding floor covering. In nursing homes, for instance, an excessively compliant floor covering may not help the elderly to maintain their balance when encountering a visual confliction or interference. A firmer floor covering may be a better option, as in accordance with the findings of Redfern et al. [4]. However, a more general guideline in the application of carpets cannot be obtained until more extensive studies on floor coverings are conducted.

The aim of the present study was to explore carpet performance from the perspective of the dynamic characteristics of posture profiles under various visual conditions. Although the four different carpets and one force platform used to manipulate different flooring conditions may defer in some ways besides compliance, previous studies on postural control and flooring [4, 27] have demonstrated that flooring compliance is an important characteristic in representing the mechanical properties of the flooring and is highly correlated with postural sway. Thus, the differences in dynamic features of quiet standing on four carpets and the force platform in this study should be accounted for mainly by the different flooring compliances. One limitation of this study is the small number of participants, which may be responsible for the marginal flooring significances observed in this study. An increase in the number of participants would definitely raise the statistical reliability and provide more insight into the issues studied. Also, trial duration in this study is relatively short compared with other studies [12, 14–18]. Longer trial duration would increase the reliability of SDA. In addition, more visual environments such as dynamic visual situations should be studied, as these visual conditions can be detrimental in postural control in the elderly and people with postural disorders.

Conclusions

Analysis of the posture profile in quiet stance on carpets through the framework of fractional Brownian motion has shown that differences in the dynamic feature of posture can be revealed for different flooring conditions. A floor covering such as carpet does not alter the dynamic structure of the persistence versus anti-persistence for a COP profile in quiet standing. Different flooring conditions can appreciably influence the stochastic parameters such as the transitional time interval and the Hurst coefficient under various visual environments. More compliant carpets tend to generate a higher level of anti-persistence in posture over long time intervals than the hard floor under the EO condition, but a lower level of anti-persistence under the EC condition. The insignificant change of anti-persistence for compliant carpets between these two visual conditions implies that compliant carpets may not be as beneficial as relatively firm carpets in regulating posture under a visual confliction or interference.

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