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Mechanical, Biomechanical and Psychophysical Study of Carpet Performance

Abstract This study investigated carpet performance by using mechanical, biomechanical and psychophysical methods. Four different carpets were tested in this study using a force platform which also served as a hard control floor. Compliance modulus was measured to characterize the mechanical property of carpets. Six college students stood barefoot on the force platform covered by a carpet sample under both eyes-open and eyes-closed conditions. The center of pressure recorded by the force platform was used to quantify the postural sway in quiet stance. Perceived comfort was evaluated in different body areas for each flooring condition. Visual environment was found to significantly influence postural sway in quiet standing, and more compliant carpets were observed in general to be associated with faster sway velocity and smaller sway area. Also, more compliant carpets provided better perceived comfort, in particular in ankles and feet.

Key words biomechanical, carpet, mechanical, psychophysical, quiet stance

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Carpets are one of the most widely used flooring coverings in both residential and work places. Besides decorating the environment, the application of carpets is also aimed to facilitate human activities, such as standing and walking by reducing impact and minimizing consequence of potential falls. It is not unexpected that standing on an inappropriate floor surface for a prolonged time can cause some physical problems. The American Podiatric Association reported in 1983 that foot or leg problems including discomfort, pain or orthopedic deformities occurred in 83 % of U.S. industrial workers [1]. Both inappropriate application of floors and constrained standing for a prolonged time have been identified as major factors causing these physical problems [2–4]. Floor condition has also been stated as a major environmental factor leading to accidental falls in the elderly [5]. Due to the deterioration of postural stability with aging, the elderly become less immune to falls, which can cause hip fractures and even accidental death [3]. Therefore, it is not a trivial issue to investigate the effect of floor coverings such as carpets on human standing and walking.

A number of studies have been conducted theoretically or experimentally to understand carpet performance from a mechanical point of view. Structural parameters, for example, were investigated through experiments to evaluate carpet physical properties [6] and carpet appearance loss [7]. Mathematical models were established to understand wear mechanism and to predict wear life of cut-pile [8] and loop-pile carpets [9]. To mimic human heel strike on carpets during walking, impact experiments were carried out to shed light on perceived walking comfort on car-

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pets [10, 11]. It is, however, essential to understand not only the mechanical properties of carpets, but also the biomechanical and psychophysical responses from humans so as to advance our knowledge of carpet performance.

Several biomechanical studies have been conducted to investigate the effects of floor coverings on standing with findings not in consensus yet. When asked to stand upright on a carpet, a person cannot be absolutely still, but rather sway voluntarily due to human body inertia. Center of pressure (COP) is usually examined to reflect postural sway of a person in quiet standing, which is the position of the resultant force applied on the floor and is usually collected using an instrument called force platform. Redfern and colleagues [3] compared postural sway on several carpets by examining mean velocity, root-mean-square and peak-to-peak of the COP profile and found that more compliant carpets were more likely to increase postural sway, particularly for the elderly in dynamic visual environment. Similar observations were reported from a study of mats [12], where stiffer mats caused smaller lateral COP shifts. However, Madeleine and colleagues [13] showed a contrasting finding that more compliant mats yielded smaller COP displacements in the mediolateral direction. In addition, Zhang and colleagues [4] demonstrated no significant effect of mat compliance on quiet standing in terms of the mean distance and standard deviation of the COP profile.

Psychophysical assessment of perceived comfort provides a subjective approach to revealing the appreciation of various floor conditions. Both carpets and mats were found to yield significantly more perceived comfort than a hard concrete floor, particularly in lower leg, ankle and foot [1, 14, 15]. Similar observations were found between carpets of various compliances [13]. Cham and Redfern [12], however, stated that mats with increased stiffness, increased elasticity and decreased energy absorption would offer higher perceived comfort. Whereas, Zhang and colleagues [4] again demonstrated no significant effect of mat compliance on the perceived comfort.

In existing literature on either postural sway or perceived comfort during quiet standing, there is no systematic investigation on carpets. Furthermore, no visual condition other than normal eyes-open was included in previous studies. Thus, this study aimed to investigate carpet performance from mechanical, biomechanical and psychophysical perspectives. Different visual environments were also tested to reveal the visual effect during quiet standing on different carpets. The secondary goal was to seek the correlations among carpet mechanical property, postural sway in quiet standing and psychophysical assessment of perceived comfort on different carpets.

Methods

Mechanical Experiment

In this study, four widely used yet different carpets were investigated in addition to the hard floor as a control of the force platform shown in Figure 1. Table 1 presents the structural and mechanical parameters of these five flooring conditions. All the carpets were purposely selected with the attempt to represent wide range of carpets used either at

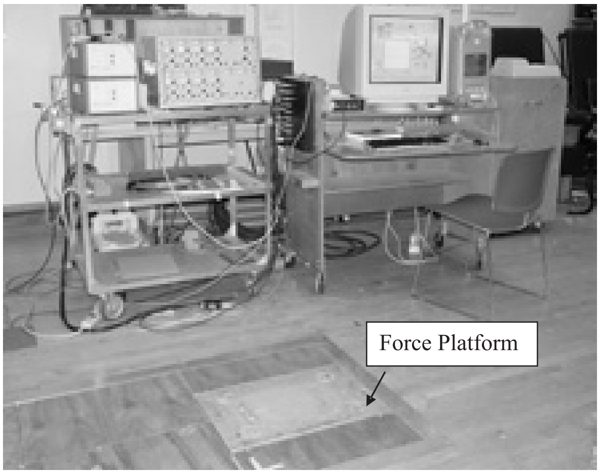

Figure 1 Experimental setup for the quiet standing test.

Table 1 Structural and mechanical properties of four carpets and the force platform.

	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 modulus (N/mm)	87.8	115.3	160.0	578.1	4×10^5
Compliance modulus (mm/N)	0.0114	0.0087	0.0063	0.0017	0

*The dimension of the force platform was 40 × 60 cm, and its stiffness modulus was adopted from the manual.

home or in workplaces, and their specifications are listed in Table 1. The structural parameters of the carpets were measured following the ASTM standards D418-93. Compression experiments were conducted on carpet samples (10 × 10 cm) by using an Instron tester model 4465 (Instron, Norwood, MA) at a crosshead speed of 5 mm/min [10]. Compressive modulus was calculated as the slope of the initial linear portion of the load-deformation curve. Although several other mechanical parameters besides modulus have been used to quantify the mechanical properties of floor coverings, including work lost, load decay and maximum deceleration, a relatively high correlation was found between the modulus and the other parameters in a study [12]. Therefore, only compressive modulus was measured in the present study to reflect the carpet compliance, which is defined as the reciprocal of the modulus (Table 1).

Biomechanical Experiment

Six college students (two male, four female) volunteered to participate in this study. The mean age was 22.1 years (range 20–28 years), mean weight 58.9 kg (range 45.2–66.9 kg), and mean height 166.7 cm (range 155–175 cm). All the participants reported no history of gait or postural disorders, neurological diseases and musculoskeletal pathologies that could influence normal posture. All the participants provided informed consent before experiment.

A Kistler® 9281B force platform (Kistler, Amherst, New York) was used to collect data of ground reaction forces and moments (Figure 1) in quiet standing test. A carpet sample, cut to the dimensions of the force platform 40 × 60 cm, was directly placed on the force platform. The participants stood barefoot as still as possible on a flooring condition with their arms comfortably at their sides. Two visual effects were examined including eyes-open (EO) and eyes-closed (EC) conditions. Under the EO condition, the participants were looking at a poster two meters away on a wall. Each subject completed the tests on two days with one visual condition tested on each day for about two hours. The sequence of visual presentation was randomized across the subjects. Within each testing day five floor conditions (four carpets plus the force platform) were randomly presented. Participants performed a block of ten trials on each flooring condition, and completed a total of 50 standing trials at each testing day. Each trial was collected for 15 seconds at the sampling rate of 100 Hz (we started collecting a trial about 5 seconds after the participant stood quietly on a floor to minimize the possible effect of unstable standing at the beginning of the trial). Enough rest time was provided to the participants to reduce potential fatigue.

Psychophysical Experiment

An 11-level linear scales rating method [13] was utilized to subjectively evaluate the comfort of carpets with score 0 to 10 representing most comfort to least comfort, respectively. The psychophysical assessment was conducted immediately after a participant completed a block of ten standing trials on one given flooring condition. Thus, participants evaluated each flooring condition once and conducted a total of five times of psychological assessment for five flooring conditions at each testing day. Participants were instructed to give a rating score evaluating the comfort levels in different parts of the body including lower back, hip, thigh, knee, shank, entire leg, ankle, forefoot, hindfoot, entire foot and whole body.

Data Analysis

The COP parameters examined in this study consisted of the mean velocity (VEL) and root-mean-square (RMS). Both parameters were highly reliable and extensively used in studies of postural sway in quiet stance [3, 16, 17]. Before calculating these two COP parameters, raw COP data were filtered by a second order Butterworth low-pass filtering logarithm with the cutoff frequency of 5 Hz determined by Jackson's logarithm [18].

The COP parameters were then calculated as

$$VEL = \frac{1}{T}\sum_{i=1}^{N-1}\sqrt{(X_{i+1}-X_i)^2+(Y_{i+1}-Y_i)^2} \tag{1}$$

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left((X_i-\bar{X})^2+(Y_i-\bar{Y})^2\right)} \tag{2}$$

where (X_i, Y_i) are the coordinates of the COP at point i, N is the total number of points, T is the test duration and $(\bar{X}, \bar{Y})$ are the average coordinates of the COP calculated as

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N}X_i, \quad \bar{Y} = \frac{1}{N}\sum_{i=1}^{N}Y_i \tag{3}$$

Both VEL and RMS were calculated for each trial, and ensemble average of VEL and RMS was computed across ten trials for a flooring condition per participant. By definition, a higher VEL represented a quicker postural sway, and a lower RMS denoted a smaller sway range.

A two-way (2 visual × 5 flooring condition) analysis of variance (ANOVA) with repeated measures was used to test the effect of visual and flooring conditions on the COP parameters. A one-way ANOVA with repeated measures was conducted to examine the effect of flooring conditions under each visual condition, and Tukey's post-hoc multiple comparisons was implemented when necessary. When analyzing the psychophysical rating scores, Friedman's two-way nonparametric ANOVA by ranks was applied in each

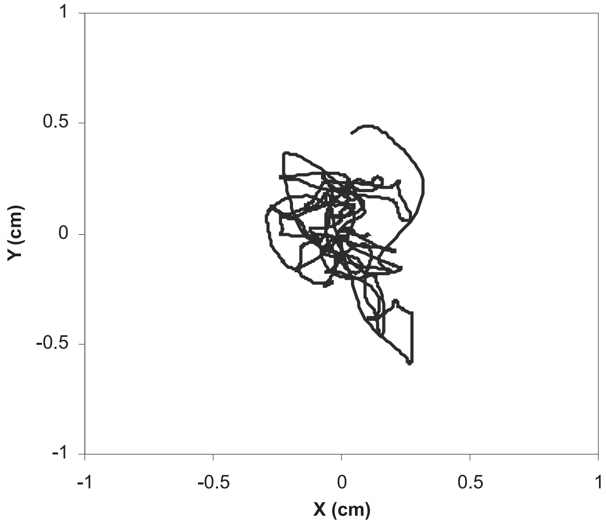

Figure 2 A representative trajectory of the COP from a subject standing on a carpet over 15 seconds. Axes *x* and *y* denote the mediolateral (side to side) and anteroposterior (forward and backward), respectively.

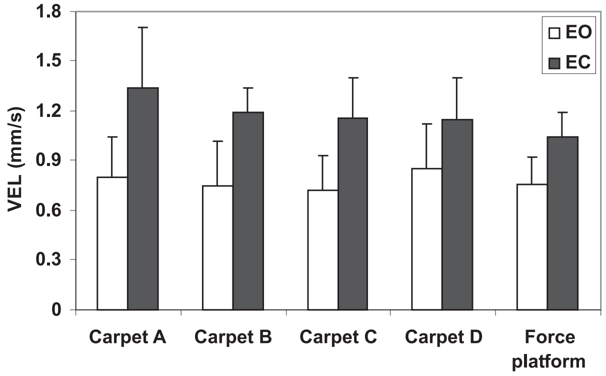

Figure 3 Mean and standard deviation of the COP mean velocity (VEL).

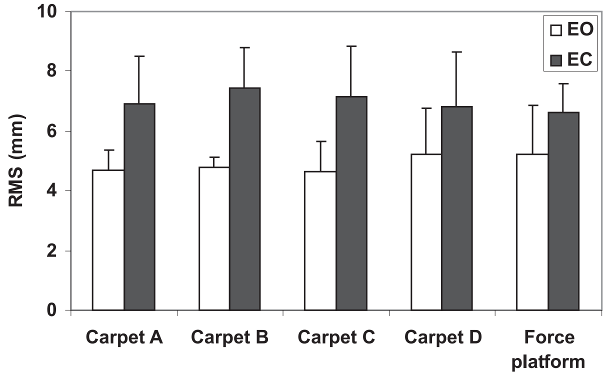

Figure 4 Mean and standard deviation of the COP root-mean-square (RMS).

visual condition to investigate comfort difference among the flooring conditions for each rated body part. Person's correlation coefficients were analyzed between the compliance modulus and COP parameters, and Spearman's rank correlation coefficients were calculated for (1) compliance modulus versus psychophysical ratings, and (2) COP parameters versus psychophysical ratings.

Results

A representative trajectory of the COP from a subject standing on a carpet over 15 seconds is displayed in Figure 2. Mean and standard deviation of the ensemble average of VEL and RMS are shown in Figures 3 and 4, respectively. Participants generated significantly higher VEL ($p < 0.001$) and RMS ($p = 0.015$) values in the EC condition than in the EO condition. Also, there was a significant floor effect ($p < 0.001$) on the VEL results. Specifically, the VEL for carpet A was significantly higher than that for the force platform in the EC condition ($p < 0.05$, Table 2). Meanwhile, no significant interaction between visual and flooring conditions was found in either VEL or RMS data.

Psychophysical rating scores of perceived comfort are presented in Tables 3 and 4 for the EO and EC conditions, respectively. There was a significant floor effect in the EC condition, where carpet A yielded significantly lower comfort rating scores compared to the force platform hard floor on the whole body as well as individual parts including the ankle, forefoot, hindfoot and entire foot, respectively ($p < 0.05$). The results of multiple comparisons are presented in Table 2, revealing the difference in comfort ratings among the flooring conditions in the EC condition. It is worth noting that the force platform hard floor consistently yielded the most perceived discomfort among all the flooring conditions regardless of the visual environment.

Compliance modulus of the flooring conditions was found to significantly correlate with the RMS in the EO condition, but with negative correlation ($r = -0.87$, $p < 0.05$), but positively correlated with the VEL in the EC condition ($r = 0.90$, $p < 0.05$), respectively. Regardless of the visual conditions, there was a complete agreement between the compliance modulus and perceived firmness of the flooring conditions ($r = -1.0$, $p < 0.01$). Significant correlation between compliance modulus and rating scores was

Table 2 Results of Tukey's post-hoc multiple comparisons in the EC condition.

	Carpet A	Carpet B	Carpet C	Carpet D	Force platform
COP VEL	a	a b	a b	a b	b
Ankle comfort	a	a b	a b	a b	b
Forefoot comfort	a	a b	a b	a b	b
Hindfoot comfort	a	a b	a b	a b	b
Entire foot comfort	a	a b	a b	b	b
Whole body comfort	a	a b	a b	a b	b

The flooring conditions with the same symbol (a or b) indicate no significant difference at $p < 0.05$ level.

Table 3 Mean and standard deviation of psychophysical assessments of floor firmness and comfort levels in different body areas for the EO condition.

	Carpet A	Carpet B	Carpet C	Carpet D	Force platform
Floor firmness	4.2 (2.5)	5.0 (2.8)	7.0 (1.6)	8.8 (1.3)	10.0 (1.4)
Back	2.6 (2.2)	2.5 (3.8)	3.4 (2.1)	1.8 (1.0)	4.8 (2.1)
Hip	2.0 (1.9)	3.0 (3.5)	2.8 (2.6)	1.5 (0.6)	3.8 (2.9)
Thigh	2.6 (1.5)	3.5 (3.1)	3.8 (3.2)	2.8 (1.0)	4.3 (3.0)
Knee	3.6 (1.8)	4.5 (2.6)	4.4 (1.7)	3.5 (0.6)	4.8 (2.9)
Shank	3.6 (2.3)	3.5 (3.1)	4.2 (2.8)	3.5 (2.4)	4.5 (3.1)
Entire leg	3.2 (1.9)	4.0 (3.2)	4.0 (2.7)	3.0 (1.4)	4.0 (3.7)
Ankle	3.8 (1.9)	3.5 (2.1)	3.6 (2.1)	4.8 (3.1)	4.0 (2.9)
Forefoot	3.2 (2.3)	3.8 (2.8)	4.2 (2.0)	4.5 (3.9)	4.5 (2.5)
Hindfoot	4.0 (2.7)	3.8 (2.6)	3.2 (1.6)	4.3 (4.0)	4.5 (2.5)
Entire foot	3.4 (2.6)	3.8 (2.8)	3.2 (2.4)	4.3 (4.0)	4.5 (2.5)
Whole body	3.0 (1.9)	4.3 (2.8)	4.0 (2.2)	4.0 (2.2)	4.8 (3.0)

Table 4 Mean and standard deviation of psychophysical assessments of floor firmness and comfort levels in different body areas for the EC condition.

	Carpet A	Carpet B	Carpet C	Carpet D	Force platform
Floor firmness	3.5 (1.4)	4.8 (2.5)	6.0 (2.3)	8.6 (2.1)	9.2 (1.8)
Back	1.8 (1.7)	2.8 (4.1)	2.7 (2.3)	2.4 (2.7)	3.8 (3.0)
Hip	2.1 (1.7)	2.6 (4.2)	1.8 (1.7)	1.8 (1.3)	3.8 (3.5)
Thigh	3.0 (2.4)	3.4 (3.8)	2.5 (1.2)	2.6 (1.8)	3.8 (2.6)
Knee	3.3 (1.8)	4.0 (3.1)	3.2 (1.9)	3.8 (1.6)	4.2 (2.0)
Shank	2.2 (1.2)	4.8 (3.4)	3.0 (1.5)	3.2 (1.6)	4.4 (2.6)
Entire leg	2.5 (1.5)	3.8 (3.7)	3.0 (1.9)	3.2 (1.8)	4.4 (3.0)
Ankle	2.3 (1.8)	4.8 (3.3)	3.3 (2.7)	5.6 (3.2)	4.6 (2.1)
Forefoot	1.5 (1.4)	4.0 (3.2)	3.2 (1.9)	4.6 (3.3)	4.0 (2.7)
Hindfoot	2.2 (1.0)	4.2 (3.6)	3.3 (2.7)	4.2 (3.6)	4.0 (2.2)
Entire foot	1.7 (1.0)	4.2 (3.3)	3.3 (2.3)	4.6 (3.3)	4.2 (2.4)
Whole body	2.5 (1.0)	4.2 (3.7)	3.5 (1.5)	4.2 (2.5)	4.4 (2.3)

also found in forefoot ($r = -0.98$, $p < 0.01$) in the EO condition and on whole body ($r = -0.90$, $p < 0.05$) in the EC condition. In addition, significant correlation between the COP parameters (VEL and RMS) and the psychophysical ratings is presented in Figure 5. The VEL was significantly correlated with the ratings on entire leg ($r = -0.90$, $p < 0.05$) in the EO condition, and correlated with ratings on whole body ($r = -0.90$, $p < 0.05$) in the EC condition. The

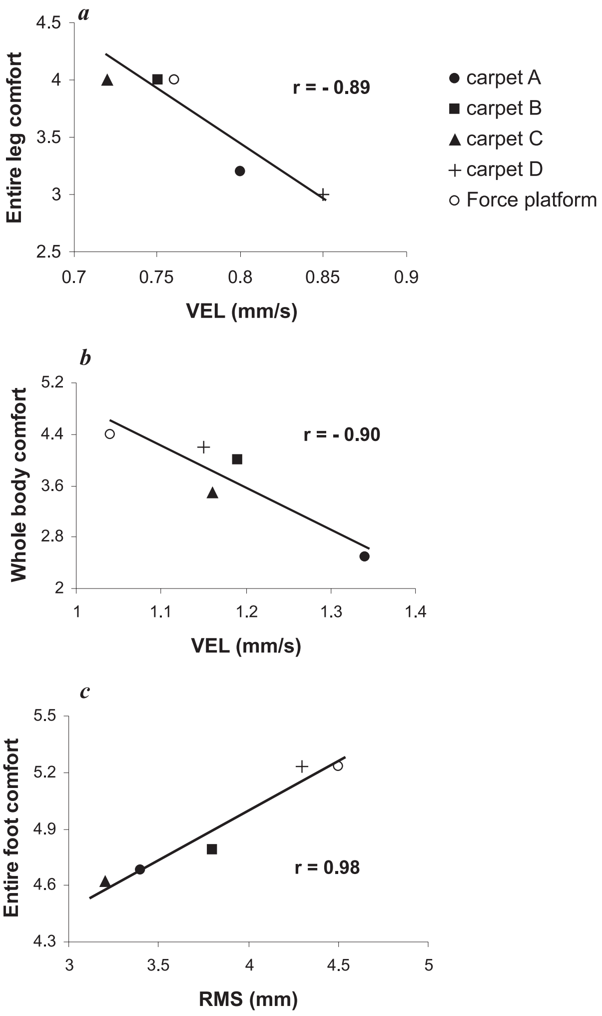

Figure 5 Correlation between the COP parameters and psychophysical ratings. (a) Correlation between the VEL and the rating scores in entire leg comfort in the EO condition; (b) correlation between the VEL and the rating scores in whole body comfort in the EC condition; (c) correlation between the RMS and the rating scores in entire foot in the EO condition.

RMS was significantly correlated with the ratings on entire foot ($r = 0.98$, $p < 0.01$) in the EO condition.

Discussion

The significantly higher VEL and RMS values in the EC condition than those in the EO condition demonstrated that people swayed at a higher speed and with a greater magnitude when no visual clue was available in quiet standing. Since humans rely on visual, somatosensory and vestibular information to regulate postural control, it was, thus, not unexpected that less sensory information available due to visual loss would lead to more postural sway. This trend has been reported to be more apparent for the elderly than for young adults [17]. Flooring conditions, however, contributed, to a certain extent, somatosensory clues to help regulate postural control. In contrast to no significance found among the flooring conditions in the EO condition, significantly higher VEL value from carpet A than that from the force platform in the EC condition suggested that the differentiation of carpet performance could be conditional or dependent; a situation like visual loss would amplify biomechanical responses such as postural sway for the same carpets.

Two significant correlations, the RMS decreases with carpet compliance in the EO condition and the VEL increases with the compliance in the EC condition, demonstrated that more compliant carpets may yield more restricted sway in the normal visual condition, but lead to faster sway with vision loss. On the other hand, more compliant floors may generate conflicting proprioceptive clues on ankles and feet [3]. This may be compensated by the visual aid in the normal visual condition, but may yield more postural sway when visual clues are not available.

The significant influence of carpets on perceived comfort only observed in the EC condition again implied that other more drastic visual environments other than the normal eyes-open may help augment the difference in carpet performance. The consistent observations of the highest discomfort from the force platform hard floor regardless of visual conditions, as well as the much better comfort ratings for carpet A than those for the hard floor agreed well with previous findings on carpets or mats [1, 13–15]. The significant discomfort felt on ankle, foot and whole body further demonstrated that carpets appear to have more effects on the lower extremities than on the upper extremities and trunk in quiet standing [1, 12]. In addition, the complete agreement between the perceived firmness and compliance of carpets irrespective of visual conditions indicated the usefulness of carpet compliance, and also the verification of the psychophysical assessment used in this study.

One of the primary purposes of this study was to investigate the correlation between the COP parameters and the perceived comfort ratings in quiet standing. The significant correlations of perceived comfort on leg and whole body with higher VEL and lower RMS values suggested that comfort in standing may be related to a fast yet smaller sway, which is in contrast to the findings in mats [12]. A faster but smaller sway may help relieve pressure applied on plantar foot and meanwhile reduce the possibility of the COP moving beyond base of support, which can yield a step or fall. In addition, postural sway with high velocity on compliant carpets may help reduce venous pressure and facilitate blood flow in lower extremities and feet [19]. This can reduce potential fatigue in quiet standing and, thus, improve perceived comfort.

The present study intended to provide insight into carpet performance through the combination of mechanical, biomechanical and psychophysical approaches. It did, however, not aim to provide a firm guideline in manufacturing or selecting carpets, although this will be the ultimate goal. One limitation of this study was the small number of participants involved in the biomechanical and psychophysical assessment of human responses on different carpets. More participants would increase the reliability of the data and may provide more insight into the issues. Also, trial duration in this study was relatively short compared to other studies [1, 3, 4, 12, 13, 20]. Increase of trial duration would allow us to study the longer-term effect of carpets on human responses in quiet standing.

Conclusions

The combination of mechanical, biomechanical and psychophysical approaches provided multiple perspectives of carpet performance. Compressive compliance, that is the reciprocal of the stiffness, was capable of characterizing mechanical property of carpets. In quiet standing, visual environment significantly influenced the postural sway on any of the flooring conditions, and more compliant carpets were found in general to be associated with faster sway velocity yet smaller sway range. Also, more compliant carpets provided better perceived comfort compared to a hard floor, in particular on the parts of ankles and feet. The correlation between the postural sway parameters and the perceived comfort rating may imply that a comfortable quiet standing leads to a faster but smaller sway.

Acknowledgements

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