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Perceptual Aspects of Postural Control: Does Pure Proprioceptive Training Exist?

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Abstract

As proprioceptive training is popular for injury prevention and rehabilitation, we evaluated its effect on balance parameters and assessed the frequency spectra of postural sway linked with the various sensory channels. We recorded the Center of Mass displacement of 30 healthy student research participants (mean age = 21.63; *SD* = 1.29 years) with a single force plate under eyes open (EO) and eyes closed (EC) positions while standing on either a firm or foam surface, both before and after an 8-week balance training intervention on a foam surface with EC. We subjected the data to frequency power spectral analysis to find any differences between the frequency bands, linked with various sensory data. On the foam surface in the EC condition, the sway path decreased significantly after proprioceptive training, but, on the firm surface in the EC condition, there was no change. On the foam surface in the EC condition, there was also a significant decrease in frequency power postproprioceptive training in the medium-to-low frequency band. While our data indicate better posttraining balance skills, improvements were task specific to the trained condition, with no transfer of the acquired skill, even to a similar, easier condition. As training improved the middle-low frequency band, linked with vestibular signals, this intervention is better described as balance than "proprioceptive" training.

Keywords

postural sway, frequency, balance training, transfer, vestibular

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Introduction

Postural control is considered to be a complex motor skill derived from the interaction of multiple sensorimotor processes (Horak & Macpherson, 1996). The two main functional goals of postural control are postural orientation and postural equilibrium. Postural orientation involves the active control of body alignment and tone with respect to gravity, support surface, visual environment, and internal references (Horak & Macpherson, 1996). Spatial orientation in postural control is based on the interpretation of convergent sensory information from somatosensory, vestibular, and visual systems (Horak, 2006). Postural stability or postural equilibrium, often referred to as *balance*, is the ability to control the body's Center of Mass (CoM) in relation to the base of support (BoS) during quiet standing and movement (Shumway-Cook & Woollacott, 2012). Over past decades, the effect of physical exercise on body balance has received increased attention, and it is now routine practice to incorporate balance exercises in preventive and even rehabilitative trainings by physiotherapists (PTs) and rehabilitation team members. Several training methods have been developed under different names, such as Core Stability, Neuromuscular, and Proprioceptive Training, in order to influence postural stability (Franco, Lopez, Lomas-Vega, Contreras, & Amat, 2012; Myer, Chu, Brent, & Hewett, 2008; Willardson, 2007).

In Core Stability Training, traditional resistance exercises have been modified to promote core stability. Such modifications have included (a) performing exercises on unstable, rather than stable, surfaces; (b) performing exercises while standing, rather than seated; (c) performing exercises with free weights, rather than machines; and (d) performing exercises unilaterally, rather than bilaterally (Willardson, 2007). The Neuromuscular Training protocol has been implemented with female athletes in order to target deficits in trunk and hip control. Five exercise phases have been utilized to facilitate progressions in the athletes' ability to control the trunk and improve "core stability" during dynamic activities. Targeted Neuromuscular Training at or near the onset of puberty may simultaneously improve lower extremity strength and power, reduce dangerous biomechanics related to anterior cruciate ligament injury risk, and improve single leg balance (Myer et al., 2008). Proprioceptive Training has become popular among athletes for injury prevention, and there is a growing body of scientific evidence about its effectiveness even in rehabilitation. Under the keywords, "Proprioceptive training," research papers mostly use training tools designed to promote instability (Franco et al., 2012). For example, ankle disc (unstable surface) training can positively affect the ankle muscles' motor performance in a unipedal balance task, most likely through improved strength and coordination, and possibly endurance; but how much of the observed improvement in motor performance is because of better ankle proprioception remains unclear (Ashton-Miller, Wojtys, Huston, & Fry-Welch, 2001).

There is extensive evidence that these methods are beneficial in preventing injuries (Franco et al., 2012; Myer et al., 2008; Paterno, Myer, Ford, & Hewett, 2004), but a recent meta-analysis (Kümmel, Kramer, Giboin, & Gruber, 2016) found no general agreement regarding which terms best summarize training programs aiming to improve postural stability. According to Ashton-Miller et al. (2001), despite their widespread acceptance, current exercises aimed at "improving proprioception" lack empirical support for achieving that goal. Therefore, it is premature to conclude that such exercises improve true proprioception in terms of the accuracy of joint position sense or the threshold for detecting joint movement (Ashton-Miller et al., 2001). Proprioception is described as the acquisition of stimuli by peripheral receptors in addition to the conversion of mechanical stimuli to a neural signal that is transmitted along afferent pathways of the sensorimotor system (Lephart, Riemann, & Fu, 2000). Proprioception does not include central nervous system processing of the incoming afferent signal or control of efferent (outgoing) motor signals. However, this proprioceptive information is crucial for optimal motor performance (Mandelbaum et al., 2005). Therefore, further research is needed to test the hypothesis that such training improves joint proprioception.

It is possible to analyze the postural sway frequency spectra with fast Fourier transformation and then divide postural sway data recorded on a single force platform into various frequency bands linked with different sensory modalities. This division was first described by Oppenheim, Kohen-Raz, Alex, Kohen-Raz, and Azarya (1999), and then revised in our own earlier works (Nagy et al., 2004, 2007). In this study, we used this method to evaluate the specific effect of a "proprioceptive" training module on balance parameters measured by the single force platform, focusing on power frequency analysis, in healthy young students. We also revealed the frequency band that was most sensitive to postural changes induced by the training program. For this purpose, we sought to exclude the role of visual input using eyes closed (EC) training and to increase the postural requirements and the amount of incoming proprioceptive signal information using an unstable surface as the BoS. This allowed us to clarify whether the increased proprioceptive stimuli during training actually improved proprioceptive information processing, as reflected through postural sway data. We hypothesized that if training with tools designed to promote instability was pure proprioceptive training, postural sway changes induced by the training would be characteristic of the frequency band linked with proprioceptive stimuli.

Method

Participants

In total, 30 healthy female PT students (mean age = 21.63; *SD* = 1.29 years; mean height = 1.672, *SD* = 0.0575 m; mean mass = 61.9, *SD* = 7.54 kg; mean body mass index [BMI] = 22.15, *SD* = 2.65) volunteered for the study. All participants gave their written informed consent prior to participation.

The measurements and the training used complied with the current laws of our country, in line with the Helsinki declaration, and the protocol was approved by the local institutional Ethics Committee.

Measurement Procedures

We measured static postural stability during standing on a single force platform (Neurocom Basic Balance Master®, Neurocom International Inc., Clackamas, OR, USA) in standing position, recording the Center of Pressure (CoP) displacement. The static balance parameters were measured by the single force platform before and after an 8-week "proprioceptive" training module (sessions were two times per week and focused on standing balance exercises on an unstable foam surface—Airex balance pad—with EC). The CoP displacement was quantified in quiet standing, the arms hanging freely on both sides. The participants stood barefoot on the platform with the feet positioned side by side according to the force plate indicator signs, under two visual conditions (eyes open, EO, and EC) and two surface conditions (firm and foam). The examiner supervised the closed position of the eyes; opening the eyes during the measurement was an exclusion criterion. We preferred the EC measurements and training instead of being blindfolded considering the different psychological effects of these two situations. Using a blindfold is a kind of constraint, which may create a feeling of uncertainty during balance measurement and may result in a negative compensatory balance strategy, the fixing or stiffening strategy, which we wanted to avoid during testing and training periods.

Measurements were repeated three times (duration 10 seconds) in each condition, and the sway path was calculated in both anteroposterior (AP) and mediolateral (ML) directions.

Data were further analyzed by fast Fourier transformation in various frequency bands (low: 0–0.1 Hz; medium–low: 0.1–0.5 Hz; medium–high: 0.5–1 Hz; and high: 1–3 Hz), based partly on Oppenheim et al. (1999), and partly on our earlier research. Focusing on the perceptual aspect of postural control and the sensory modalities utilized in balance tasks, the low frequency band is thought to be linked with the visual sense, the middle-low band with the vestibular sense, and the middle-high with proprioceptive sensory information. The high frequency band is connected to central nervous system activity (Nagy et al., 2004, 2007; Oppenheim et al., 1999).

Training Procedure

Participants took part in an 8-week balance training intervention led by a PT two times per week, for 60 minutes each. After 10 minutes of general mobilizing exercises, that is the warming-up period, exercises were combinations of lower extremity strength and flexibility closed kinetic chain weight-bearing exercises, static (holding a position), and dynamic (creating perturbations) balance exercises. The focus has been put on the trunk and hip control, asymmetric upper and lower extremity exercises, and self-generated trunk perturbations, that is, exercises generally accepted as balance training exercises. Our training protocol was based on the literature defining the exercises suitable for improving proprioception and balance (Franco et al., 2012; Willardson, 2007). To narrow and specify the perceptual aspects of our program, we focused on limiting visual sensory information throughout training by having participants keep their EC for as long as possible. We intentionally used no blindfold to avoid any external constraint on the postural control; thus, even though we instructed participants to keep their EC, they had the option to open their eyes. We supposed that providing this option of free eye opening in situations when they were losing balance gave participants enough confidence to avoid relying on an eye-fixation strategy that would cause them to stiffen the body by voluntary overt muscle cocontractions and freezing. These stiffening strategies lead to inadequate acquisition of needed sensory information for planning and executing dynamic and interactive movements (Young & Williams, 2015), and they interfere with selective balance reactions. During training, we also maximized proprioceptive sensory information through ongoing perturbations and challenges to the somatosensory and vestibular system associated with having participants stand on the unstable foam surface (Airex Balance Pad) rather than on a firm surface.

Data Analysis

All data were subjected to one-way analysis of variance (ANOVA; Statistica 8.0 Software) in order to compare the effects of the training on sway path and the frequency power in the various frequency bands under different visual conditions and BoS. The post hoc test was the Fisher's least significant difference multiple comparisons test. We adopted $p < .05$ as the level of probability for all statistical analyses of the data.

Results

The lack of visual information available to participants differentially affected balance parameters in accordance with what different BoS participants experienced. The one-way ANOVA, $F(7, 232) = 11.80186$, mean squared error $(\text{MSE}) = 1.59$, $p < .001$, demonstrated statistically significant differences between conditions (Table 1). The sway path (see Table 2) when participants stood on the foam surface was significantly larger with EC than with EO before and after the "proprioceptive" training, in both ML and AP directions, ($p < .001$; see Figure 1). However, these sway path effects from a lack of visual information were not evident when participants were engaged in quiet standing on the firm surface (see Figure 2).

Table 1. Summary of the Analysis of Variance Results.

Variable	SS effect	*df* effect	MS effect	*SS* error	*df* error	*MS* error	*F*	*p*
Sway path	131.5277	7	18.78967	369.3658	232	1.592094	11.80186	.000000
Low frequency	1,010,809	15	67,387.25	1,291,620	464	2,783.664	24.20811	.000000
Medium–low frequency	329,765	15	21,984.35	181,025	464	390.141	56.34983	.000000
Medium–high frequency	9,734	15	648.94	13,853	464	29.855	21.73604	.000000
High frequency	799	15	53.28	2,165	464	4.665	11.42081	.000000

df = degree of freedom; MS = Mean Squares; SS = Sum of Squares.

Table 2. Summary of the Sway Path Descriptive Data.

N	Visual condition	Time	Direction	Surface	Mean	*SD*	*SE*
30	EO	Before	ML	Foam	5.94900	2.219954	0.405306
30	EO	Before	ML	Firm	2.15167	0.717664	0.131027
30	EO	Before	AP	Foam	7.44533	2.520145	0.460113
30	EO	Before	AP	Firm	3.59133	1.334003	0.243554
30	EO	After	ML	Foam	5.50733	2.208135	0.403149
30	EO	After	ML	Firm	1.71833	0.819647	0.149646
30	EO	After	AP	Foam	6.82300	2.446962	0.446752
30	EO	After	AP	Firm	2.63833	1.414679	0.258284
30	EC	Before	ML	Foam	13.75667	6.570776	1.199654
30	EC	Before	ML	Firm	1.68967	0.685729	0.125196
30	EC	Before	AP	Foam	18.08933	5.866328	1.071040
30	EC	Before	AP	Firm	3.43033	1.829617	0.334041
30	EC	After	ML	Foam	10.97567	3.957497	0.722537
30	EC	After	ML	Firm	1.74200	0.957098	0.174741
30	EC	After	AP	Foam	13.92600	3.683895	0.672584
30	EC	After	AP	Firm	3.08767	1.742196	0.318080

AP = anteroposterior; EC = eyes closed; EO = eyes opened; ML = mediolateral.

As for the effect of our training, on the foam surface, the sway path in the EC condition in both AP ($p < .001$) and ML ($p = .00033$) directions decreased significantly after the "proprioceptive" training; but, interestingly, there was no change induced by the exercises when participants stood on the firm surface

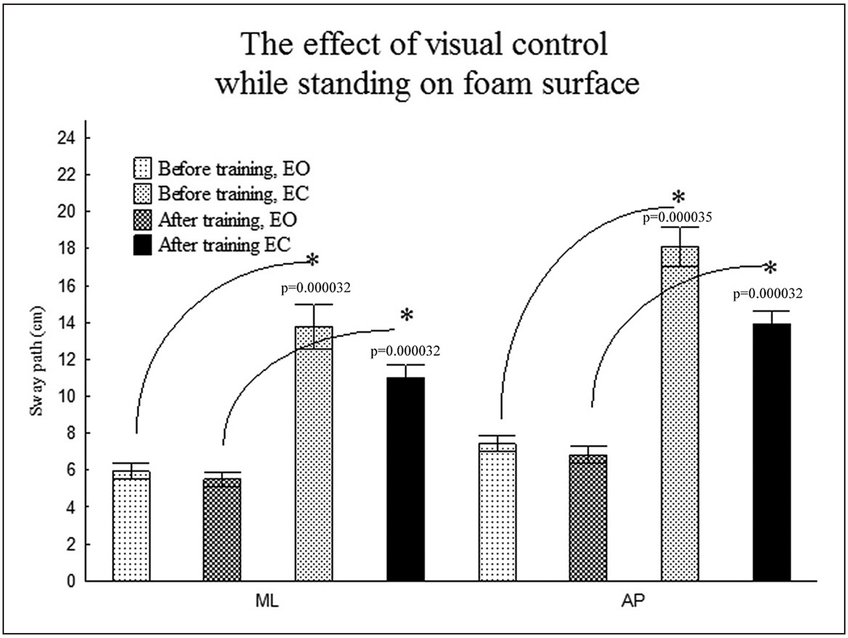

Figure 1. The effect of visual control while standing on foam surface. Statistically significant differences ($p < .05$) are marked with asterisk (*) showing the effect of training or the effect of vision respectively.

without visual control (see Figure 3). On the firm surface, the only significant change was a decrease in sway path with visual control in the AP direction after the training ($p = .0038$; see Figure 4).

Concerning the frequency power data, the one-way ANOVA, $F(15, 464) = 56.35$, $\text{MSE} = 390.14$, $p < .001$, demonstrated statistically significant differences (see Table 1). In addition, the frequency analysis and the post hoc comparisons revealed a more delicate change as the effect of our training. Specifically, there was a significant decrease in frequency power after the training, on the foam surface, in the medium–low frequency band (between 0.1 and 0.5 Hz) without visual input in the AP direction ($p = .000015$); in the ML direction, the decrease was not significant ($p = .081$; see Table 3, Figure 5). As regards the other analyzed frequency bands, especially the medium–high frequency band, the post hoc comparison revealed no similar decrease.

Discussion

The main finding of this study was a decreased sway path on the foam surface after the “proprioceptive” training without visual information. This finding

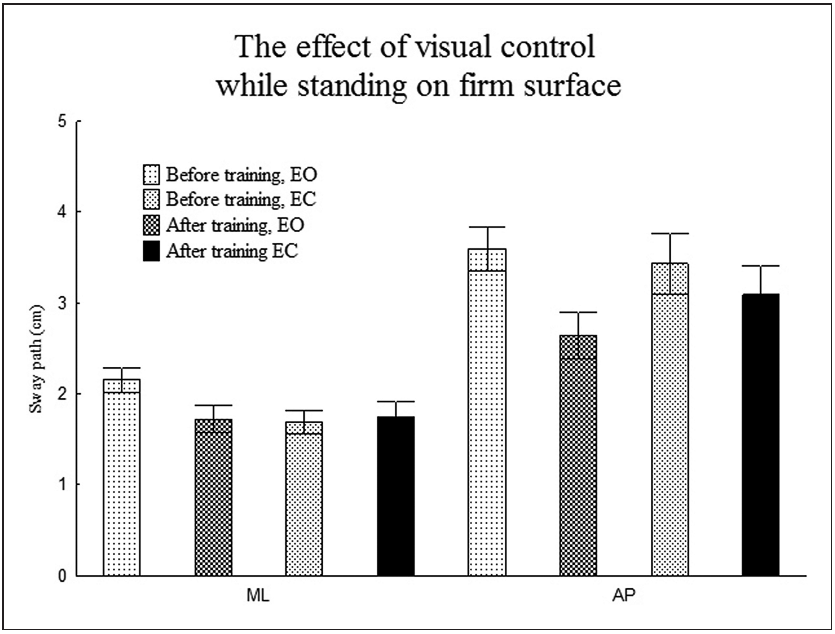

Figure 2. The effect of visual control while standing on firm surface. Statistically significant differences ($p < .05$) are marked with asterisk (*) showing the effect of training or the effect of vision respectively.

indicated a better balance performance in the condition that mirrored the training situation. Interestingly, these improvements were not seen in the other EC condition, that is, while standing on a firm surface, which was considered to be an easier balance task. Therefore, we concluded that these training-related improvements were task specific to the unstable, balance-inducing, foam surface and EC condition, and were not transferred to the easier EO condition. It is also interesting to note that when standing on a firm surface, the presence or absence of visual information did not influence the sway path at all, possibly because these participants (young PT students) had sufficiently good body awareness that the firm surface made the task too easy for errors to be evident, essentially meaning that there was a ‘‘ceiling effect’’ on this task for our participant group, making it a poor dependent measure for skilled participants.

A critical issue in rehabilitation is how training transfers either to a new task or to a new environment (Shumway-Cook & Woollacott, 2012). Researchers have determined that the amount of transfer depends on the similarity between the two tasks or the two environments (T. D. Lee, 1988; Schmidt, Young, Swinnen, & Shappiro, 1989). A critical aspect in both appears to be whether the neural processing demands in the two situations are similar. In our investigation, standing on the firm surface with EC meant totally different sensory

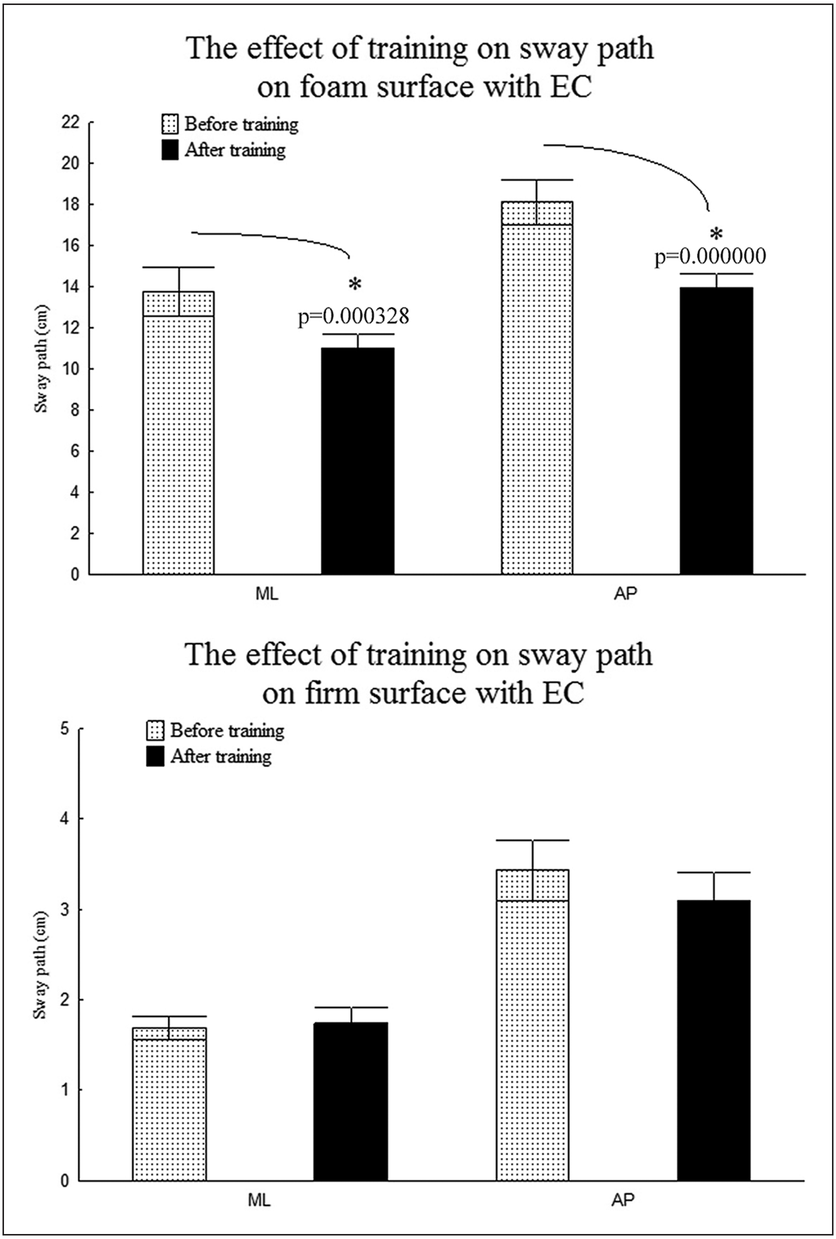

Figure 3. The effect of training on sway path on firm and foam surface with EC. Statistically significant differences ($p < .05$) are marked with asterisk (*) showing the effect of training or the effect of vision respectively.

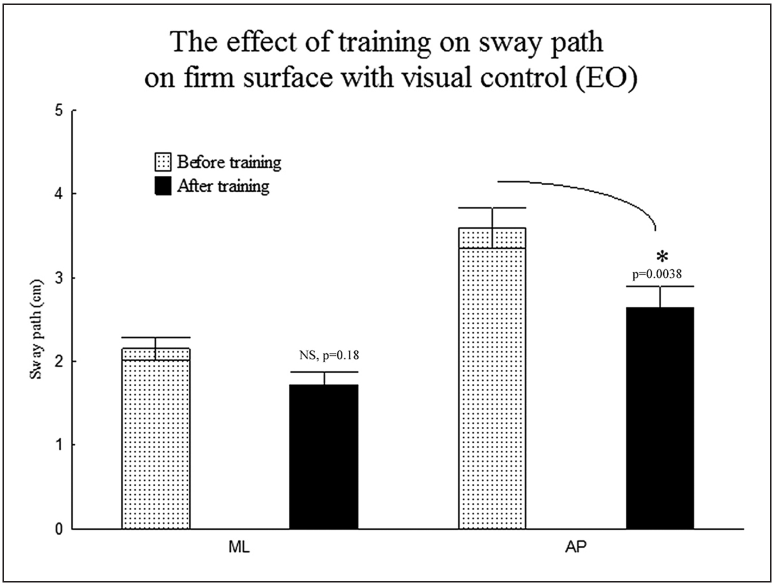

Figure 4. The effect of training on sway path on firm surface with visual control (EO). Statistically significant differences ($p < .05$) are marked with asterisk (*) showing the effect of training or the effect of vision respectively.

information processing (utilizing mainly the proprioceptive inputs) from standing on the unstable surface with EC (reweighing sensory inputs and primarily utilizing the vestibular information, for which our study provided further evidence as discussed later). Recent advances in neuroscience research suggest that alterations in the human brain occur in response to intense motor-skill learning (Doyon & Benali, 2005). This "experience-dependent plasticity" refers to changes that occur in the brain (morphologic and molecular) as a result of experience (Pascual-Leone, Amedi, Fregni, & Merabet, 2005). Experience-dependent plasticity underlies the acquisition of skilled behavior in healthy humans. In addition, increasing evidence indicates that plasticity in the primary motor cortex plays an important role in skill acquisition (Muellbacher, Ziemann, Boroojerdi, Cohen, & Hallett, 2001). Therefore, we can describe the above mentioned improvements as a specific learned skill that improved with practice in one training situation (unstable BoS, EC) but did not transfer to another one; in this case, the easier situation of standing on firm, stable surface with EC. As our easier, transfer condition was not practiced during training and had a different underlying neural processing and different perceptual background, this study found that these specific skills could not be transferred even to a situation that was supposedly easier. Thus, physiotherapeutic interventions of this kind should be task specific as well. In addition, although the

Table 3. Summary of the Medium-to-Low Frequency Descriptive Data.

Frequency band	*N*	Visual condition	Time	Direction	Surface	Mean	*SD*	*SE*
Medium–low	30	EO	Before	ML	Foam	35.47687	17.23377	3.146442
Medium–low	30	EO	Before	ML	Firm	11.26153	5.21874	0.952807
Medium–low	30	EO	Before	AP	Foam	48.36327	19.98087	3.647991
Medium–low	30	EO	Before	AP	Firm	23.68655	10.38600	1.896215
Medium–low	30	EO	After	ML	Foam	30.60575	16.01847	2.924559
Medium–low	30	EO	After	ML	Firm	11.27698	4.99837	0.912573
Medium–low	30	EO	After	AP	Foam	37.93450	15.84122	2.892198
Medium–low	30	EO	After	AP	Firm	19.53495	11.33437	2.069363
Medium–low	30	EC	Before	ML	Foam	72.53062	41.15894	7.514559
Medium–low	30	EC	Before	ML	Firm	8.92702	4.99631	0.912198
Medium–low	30	EC	Before	AP	Foam	96.73798	37.22928	6.797106
Medium–low	30	EC	Before	AP	Firm	21.34519	13.69049	2.499530
Medium–low	30	EC	After	ML	Foam	63.61306	24.11712	4.403164
Medium–low	30	EC	After	ML	Firm	9.76114	5.88353	1.074180
Medium–low	30	EC	After	AP	Foam	74.40225	26.70657	4.875930
Medium–low	30	EC	After	AP	Firm	19.61618	11.31181	2.065244

AP = anteroposterior; EC = eyes closed; EO = eyes open; ML = mediolateral.

results of the sway path comparisons suggest improved balance ability from training, the association of these improvements with vestibular rather than only proprioceptive information processing leaves questionable the inference that improvements resulted from proprioceptive processing gains.

A second important finding of our study, deriving from frequency spectra analysis, was a significant decrease in posttraining frequency power on the foam surface, in the medium-to-low frequency band, (between 0.1 and 0.5 Hz) without visual input. Based on these findings, we rejected our hypothesis, that if training with tools designed to promote instability was pure proprioceptive training, postural sway changes induced by the training would be characteristic of the frequency band linked with proprioceptive stimuli. The medium-to-low frequency band (0.1–0.50 Hz) is thought to be sensitive to vestibular stress and disturbances (Nagy et al., 2004; Oppenheim et al., 1999). Because our training better improved sensory processing associated with this medium-to-low frequency band and there were no significant changes in the frequency band linked with proprioceptive stimuli, we provide important evidence that practicing balance exercises on an unstable base of support (in this study, on the Airex balance pad) with EC most influences vestibular information processing

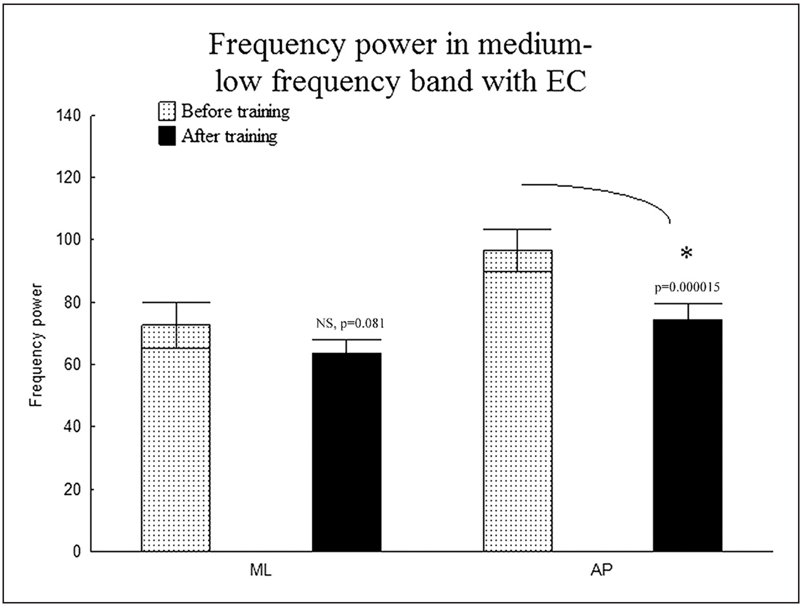

Figure 5. Frequency power in medium-to-low frequency band with EC. Statistically significant differences ($p < .05$) are marked with asterisk (*) showing the effect of training or the effect of vision respectively.

in postural control. Thus, it is more correct to entitle these training exercises as balance or Neuromuscular Training than as "proprioceptive" training. This conclusion is in line with assertions from Ashton-Miller et al. (2001) that these rehabilitative balance exercises improve balance performance at specific balance tasks and lead to improved balance rather than proprioceptive performance (Ashton-Miller et al., 2001).

The shift in utilizing sensory information processing so that training is in accordance with subsequent environmental and task expectations for postural control is gaining popularity in theory and research. In the central perceptual processing of the incoming sensory signals, sensory reweighing is a well-known phenomenon. We proposed in an earlier paper studying the effect of plantar mechanical stimulation on postural control that mechanical stimulation of the plantar sole would provide an efficient activation of plantar mechanoreceptors so as to compensate for the lack of vision on the firm surface, as well as for the lack of visual input and inaccurate somatosensory information on the foam surface (Preszner-Domjan et al., 2012), possibly representing further evidence of sensory reweighing. Previous investigations have shown that visual input plays a significant role in balance control (Brandt, Paulus, & Straube, 1986; D. L. Lee & Lishman, 1977). However, when visual information is unavailable, but the somatosensory and vestibular information are available and accurate, the individual must rely primarily on the somatosensory input, and only secondarily on the vestibular input. In this study, as neither visual nor proper somatosensory inputs were available during training sessions (standing on special foam surface causing extra perturbations, EC), only vestibular information was available for the postural control. Thus, training on an unstable surface with EC led to improved vestibular postural control because of sensory reweighing (adapting the postural control to the specific task requirements). This type of state-dependent learning may explain the failure to transfer the improved balance skills into an easier situation (standing on firm surface with EC) when somatosensory signals were again available and again the most important sources of information.

A limitation of this study is a relatively low number of participants, and our restricted participant sample of PT students with good body awareness. As noted, there was a resultant ''ceiling effect'' on one part of our measurements. Further investigations are necessary to support these results in different and larger populations. Although the results of these sway path comparisons would suggest improved balance ability from training, the association of these improvements with various frequency bands should be further clarified, and there is a need for better understanding of the sensory contribution. Because of the complex nature of balance, when practitioners organize balance training, they must take into account the interactions between the individual, the task, and the environment. Exercises must be task specific and problem oriented to achieve optimal, real therapeutic and functional benefit.

Declaration of Conflicting Interests

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