Thesis of PhD dissertation

The role of plantar mechanoreceptors in postural control

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1 Introduction

Keeping our balance is an essential requirement of our everyday functional movements and physical activity. Controlling and maintaining the balance of the human body is a complex process, which includes the harmonised functioning of the sensory information (visual, vestibular, and somatosensory systems), the musculoskeletal system and the central and peripheral nervous system. Although multiple sensory inputs are available to the central nervous system, it usually relies on a single type of information at a time for orientation by weighing the information based on their accuracy.

Since the changes in body position and the changes in plantar pressures during a quiet stance are related, the plantar cutaneous mechanoreceptors, due to their anatomical location, provide detailed information about the properties of the supporting surface and the position and movement of the body in relation to that.

Over the past few years, the focus of scientific research on balance has gradually shifted to the role of the somatosensory system (and, more specifically, the plantar cutaneous mechanoreceptors) in postural control. Numerous studies have confirmed the participation of the plantar cutaneous mechanoreceptors in the process of postural control and the beneficial effect of plantar mechanical stimulation on postural control; however, the exact mechanism of action of these stimulation methods has not been fully clarified. No data have been found in the relevant literature about the effect of manual plantar stimulation without joint mobilisation, as a sole mechanical stimulation, on postural stability, and about whether it has an effect on the sensitivity of the plantar mechanoreceptors, and the plantar tactile threshold.

The age-dependent changes of the somatosensory system have been confirmed by studies. No studies have been found whether plantar sensitivity can be influenced by mechanical stimulation in the elderly, and whether balance parameters can be improved by the manual stimulation of the sole in case of worsening sensory and motor functions.

2 Objectives

1. The purpose of our study was to confirm the role of the somatosensory system (and, more specifically, the plantar mechanoreceptors) in postural control in healthy young and elderly subjects. We assumed that the mechanical stimulation of the sole would result in improved balance parameters in both study groups, and that the effect of the mechanical stimulation would be evident in the absence of visual information in both groups, i.e., that the results of our study would support the theory of sensory re-weighing.
2. Our study was also aimed at exploring the changes that affect the balance parameters and the plantar sensitivity in the elderly, and we assumed that the study results regarding the sensory integration and tactile threshold of the elderly study group would support the age-dependent changes of the sensory systems.
3. In addition, we aimed at finding out what effects manual stimulation has on the plantar tactile sensitivity, and if a physiological change that would explain the positive changes in balance due to the stimulation can be demonstrated.

3 Methods

3.1 Participants

Fifty young, healthy volunteers [34 women, 16 men, mean age: 23 ± 2; mean weight: 67 ± 9.5 kg, mean height: 170 ± 7.1 cm, mean BMI: 22.81 ± 2.401 kg/m2 (mean ± Standard Error)] and fifty elderly, healthy volunteers [44 women, 6 men, mean age: 66±5; mean weight: 80 ± 16.56 kg, mean height: 163 ± 8.34 cm, mean BMI 29.85 ± 4.53 kg/m2 (mean ± Standard Error)] participated in the study. None of the participants suffered from any acute illness or had any diagnosed neurological or musculoskeletal disease, balance disorder or impairment, and none were taking medications with an effect on their balance. Each volunteer was informed about the purpose and the course of the study, in accordance with the ethical requirements of our institution.

3.2 Study methods

3.2.1 Assessment of static balance parameters

The horizontal excursion of the centre of gravity (COG) projected to a force platform was assessed by using the NeuroCom Basic Balance Master, the CTSIB programme. The CTSIB includes four test conditions: eyes open, firm surface; eyes open, foam surface; eyes closed, firm surface; and eyes closed, foam surface.

The static balance parameters were assessed during quiet stance, on a fixed force platform. The excursion of the COG was measured in both the anteroposterior (AP) and the mediolateral (ML) direction under each test condition. The excursion of the COG was recorded three times, for 10 seconds each, in every test condition. Our subjects stood barefoot on the force platform, first on a firm surface with eyes open and then eyes closed, and then on a foam surface (NeuroCom, 46 x 46 x 13 cm) with eyes open and then eyes closed. With the use of the foam surface, our purpose was to reduce the amount and accuracy of the tactile and pressure information from the external support.

For the balance test, our subjects assumed in a quiet, comfortable standing position on the platform, with their arms hanging loosely at the sides, facing forward. During the measurements without visual information, the subjects were asked to close their eyes. Their feet were positioned based on the signs of the NeuroCom platform; the distance between the midline of the heels ranged between 22 and 30 cm, depending on the height of the study subject.

3.2.2 Assessment of the plantar tactile sensory threshold

The plantar tactile threshold of our subjects was assessed using the SenseLab Aesthesiometer. Nylon monofilaments representing a specific nominal force were used to establish the minimum force with which the filament was pressed against the plantar skin and the study subject still felt it. The tactile threshold was determined before and immediately after the manual plantar stimulation. The assessment was performed in 6 regions of the sole – the heel, the lateral side of the midfoot, the first, the third and the fifth metatarsal head, and the hallux.

3.3 Stimulation of the plantar mechanoreceptors

3.3.1 Stimulating surface

To assess the immediate effect of a stimulating surface, a special, thin layer with rubber spikes (spike density: 5 spikes/cm^2, height of one spike: 7 mm, diameter: 2 mm), placed over the platform or the foam on the platform, was used during the assessment of the static balance parameters. Our study subjects did not report any unpleasant or uncomfortable feelings during the use of the spiked layer. The excursion of the COG was measured with the spiked layer in place both on the firm and the foam surface, with the eyes open and closed. Three measurements were performed under each condition, and each measurement lasted for 10 minutes.

3.3.2 Manual stimulation

The manual technique used for the stimulation consisted of static and gliding-squeezing grips and rubs on the plantar surface of the feet, especially in the region of the heel and the metatarsal heads, that is, on the supporting points of the feet. The plantar stimulation was applied for 10 minutes, both soles were stimulated simultaneously, with the subject in a comfortable sitting position and with the feet supported. After the stimulation, the subject was standing quietly for 20 seconds before the balance test to avoid the negative effects of the sudden standing-up on the study results. The static balance parameters were measured before and after manual stimulation. The values measured before the stimulation were considered the baseline data, and these served as control data during the study.

3.4 Statistical analysis

3.4.1 Plantar tactile threshold

Since the nominal pressing force corresponding to the diameter of the monofilaments is a discrete number, the median of the minimum nominal force measured in each plantar region was determined and considered as the plantar tactile threshold of our subjects. The Statistica 8 software and the Wilcoxon signed ranks test were used to compare the tactile sensory threshold of the young and elderly groups with the normal plantar tactile threshold (0.21 g), and to compare the plantar tactile threshold measured before and after the manual stimulation.

3.4.2 Sway path

The sway path that quantifies the excursion of the COG was calculated under each sensory condition from the position of the COG recorded by the force platform every hundredth second. The sway path was calculated in both the ML (x) and the AP (y) direction based on the following formulae (1 and 2), where *n* is the number of subjects, *i* is the numbering, s_y is the excursion length of the COG in the AP direction and s_x is that in the lateral, i.e. the ML direction:

$$s_x = \sum_{i=1}^{n-1} \sqrt{(x_{i+1} - x_i)^2} \quad (1)$$

$$s_y = \sum_{i=1}^{n-1} \sqrt{(y_{i+1} - y_i)^2} \quad (2)$$

Variance analysis with the Statistica software was performed on the resulting data to compare the different stimulation types and the test conditions as independent variables. The sway data on firm and foam surfaces were analysed with two-way ANOVA to confirm the main effects, and to demonstrate the interactions between the two visual factors (eyes open and closed) and the three stimulation factors (baseline data – without stimulation, manual stimulation, and spiked layer). The Newmann-Keuls test was used for a post hoc comparison. A significance level of $p < 0.05$ was accepted during data analysis.

4 Results

4.1 The effect of the 10-minute manual stimulation and the stimulating surface on balance parameters in case of the firm and the foam surfaces in the young study group

During the baseline measurements, the main effect of the visual information was observed on both surfaces and in both directions (AP p <0.001; ML p <0.001), i.e., the sway path was significantly increased in the absence of visual information. These changes were not present in either the AP or the ML direction in the case of the firm surface after manual stimulation, and in the ML direction, when the spiked layer was used. According to our results, a significant interaction was confirmed between the stimulation and the visual information both in the AP (p <0.001) and the ML (p <0.001) directions on firm surface, i.e., the effect of mechanical stimulation prevailed in the absence of visual information. On the foam surface, however, the analysis did not confirm an interaction between the stimulation and the visual information.

When assessing postural stability on firm surface, with the eyes closed, we observed the main effect of the manual plantar stimulation in both the AP ($p < 0.001$) and the ML ($p < 0.001$) directions, i.e., the sway path was significantly decreased, compared with the data of the baseline measurement.

An additional main effect of the stimulation was that the use of the spiked layer decreased the sway path significantly in both the AP ($p < 0.001$) and the ML (p < 0,001) directions, when visual information was not available. This effect was more significant in the ML direction, the effect of the spiked layer compensated for the absence of visual information. On foam surface, the spiked layer did not have an effect on the sway path. In the presence of visual information, none of the stimulations we used led to a change in the sway path, either in the AP or in the ML direction.

4.2 The effect of the 10-minute manual stimulation and the stimulating surface on balance parameters in case of the firm and the foam surfaces in the elderly study group

When assessing postural stability on firm surface, without stimulation, the main effect of the visual information was confirmed; closing the eyes increased the sway path significantly in the AP direction ($p<0.004$), although this significant increase was not evident after manual stimulation, i.e., the plantar stimulation partially made up for the missing visual information.

On foam surface, the main effect of the visual information was confirmed in both directions and under all stimulation conditions, i.e., the sway path was significantly increased after closing the eyes. After manual stimulation, with the eyes closed, the main effect of the plantar manual stimulation can be observed in both the AP ($p < 0.032$) and the ML ($p < 0.014$) directions, i.e., the sway path was significantly decreased, compared with the baseline data.

The stimulating spiked layer did not prove to be effective, and it did not decrease the excursion on either surface. In the presence of visual information, none of the stimulations used led to a significant change in the sway path, either in the AP or in the ML direction.

4.3 Plantar tactile sensitivity in the young and the elderly study groups, and its change after manual stimulation

By comparing the nominal pressing force that quantifies the plantar tactile sensory threshold between the two groups, it was confirmed that the plantar sensitivity of the healthy elderly subjects with an intact somatosensory system was significantly lower than that of the young subjects in every studied plantar region, i.e., the measured minimum pressing force still felt by the elderly subjects is significantly higher, the sensory threshold of the mechanoreceptors in the skin of the sole is increased.

In the young study group, the manual stimulation significantly decreased the nominal pressing force still felt in every studied region of the sole (first metatarsal head p <0.002; hallux p <0.002; third metatarsal head p <0.000; fifth metatarsal head p <0.011; lateral p <0.000; heel p <0.001), i.e., a decrease in the tactile sensory threshold and an increase in plantar sensitivity were confirmed.

In the elderly study group, the tactile sensory threshold was significantly decreased in three studied regions of the sole following the manual stimulation (first metatarsal head p <0.018; hallux p <0.026; fifth metatarsal head p <0.041), whereas the decrease in the other three regions was not significant. According to our results, the stimulation partially increased the tactile sensitivity of the sole.

5 Discussion and conclusions

Our study confirmed that a 10-minute manual stimulation of the sole increased the significance of the pressure information coming from the supporting surface during postural control thus facilitating stability. According to our results, the manual stimulation of the sole improved postural control in the absence of visual information, and therefore, the 10-minute manual stimulation of the plantar mechanoreceptors can compensate for the missing visual information and for the interfering nature of the inaccurate mechanical information coming from the foam supporting surface. In our study, the decrease in the sway path under the eyes closed condition and following manual stimulation confirms the adaptation mechanism of the central nervous system, when it used the information from the facilitated plantar mechanoreceptors as an alternative sensory input to maintain postural stability and orientation.

In the case of our elderly subjects, unlike in the young subjects, the efficacy of manual stimulation was observed mainly when assessed on foam surface. The manual stimulation of the sole, when assessed with the eyes closed and on foam surface, significantly decreased the sway path in both directions. We think that this result supports the aging of the vestibular system in the case of our elderly subjects, since they could utilize the effect of manual stimulation the most under the condition in which only the information from the vestibular system was available to them.

Our results, therefore, showed a significant interaction between the manual stimulation and the visual condition also in the elderly group, confirmed the possibility of influencing postural stability, and supported the presence of sensory re-weighing also in the elderly, despite the fact that, as a result of age-dependent changes, the sensory information was inaccurate or reduced.

Based on our results, in young subjects, a spiked layer could contribute to the improvement of the static balance parameters on a firm supporting surface. As opposed to manual stimulation, however, the spiked surface was found to be inefficient on foam surface or in the elderly. Short and less intense impact could not compensate in the young subjects for the foam surface property of reducing pressure impulses. For our elderly subjects, the somatosensory information provided by the stimulating surface was inefficient because of the short acting time, which may be related to the age-dependent reduced peripheral sensitivity.

In our young subjects, a low tactile threshold was measured at baseline, which significantly decreased in all studied regions after mechanical stimulation. Our results, therefore, confirmed our hypothesis that manual stimulation exerts its positive effect on postural control by increasing plantar sensitivity through the increasing somatosensory afferentation.

In the elderly study group, an increased tactile threshold was found in all studied regions at the baseline measurement. The stimulation resulted in a decreased sensory threshold in each studied region, and a statistically significant reduction was observed in three out of the six regions (first metatarsal head, hallux, and fifth metatarsal head).

Our research has confirmed the age-dependent change of the somatosensory system. The plantar sensitivity in the elderly group was significantly lower than the values characteristic to the young subjects. Our results support that manual stimulation enabled the pressure information from the supporting surface to be utilized to a greater extent by increasing plantar sensitivity. This effect was most evident under sensory conditions in which the information received and transmitted by the other sensory organs was absent or inaccurate.

Manual stimulation is a simple procedure that is available to every physiotherapist. Although further investigation is required to find out how long the sensitivity-increasing effect of the stimulation lasts, it can be stated that it may be a suitable additional tool for the improvement of postural control and for the prevention of falls.

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