Running title:
Balance training in people with SCI

Positive effect of balance training with visual feedback on standing balance abilities in people with incomplete spinal cord injury

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Abstract

Objectives: (1) To evaluate the learning potential and performance improvements during standing balance training with visual feedback (VBT) in individuals with incomplete spinal cord injury (SCI); (2) To determine whether standing static and dynamic stability during training-irrelevant tasks can be improved following the VBT.

Setting: National Rehabilitation Center for Persons with Disabilities, Japan.

Methods: Six participants with chronic motor and sensory incomplete SCI who were able to stand for at least 5 minutes without any form of assistive device performed the VBT, three days per week, for a total of twelve sessions. During the training, participants stood on a force platform and were instructed to shift their centre of pressure in indicated directions as represented by a cursor on a monitor. The performance and the rate of learning were monitored throughout the training period. Before and after the program, static and dynamic stability was assessed.

Results: All participants demonstrated substantial improvements in the scores which varied between 236 ± 94 % and 130 ± 14 % of the initial values for different exercises. The balance performance during training-irrelevant tasks was significantly improved: for example, the area inside the stability zone after the training reached 221 ± 86 % of the pre-training values.

Conclusions: Postural control can be enhanced in individuals with incomplete SCI using VBT. All participants demonstrated substantial improvements during standing in both game performance and training-irrelevant tasks after the VBT.

Keywords: spinal cord injury; balance training; biofeedback; motor learning; plasticity

Introduction

The ultimate goal of individuals with spinal cord injury (SCI) is to maximize their independence in all aspects of life, given the limitations imposed by their injury.[1-3] Recovery of balance ability during standing is therefore one of the primary and essential aims of rehabilitative programs in individuals with incomplete SCI. These patients are obliged to develop and re-establish compensatory strategies to maintain balance, including activation of appropriate trunk, neck, and upper limbs muscles in response to internal and external postural disturbances. Conventional therapy in this population focuses on muscle strengthening and improving task-specific balance reactions[4]. Additionally, the importance of learning to use visual cues and sensory inputs from neurologically intact parts of the body has been emphasized to help maintain safe balance.[4, 5]

Recent advances in technology have resulted in the availability of visual feedback for the retraining of balance function in individuals with neurological disorders, including stroke,[6, 7] cerebellar ataxia,[7] cerebral palsy,[8] and Parkinson's disease.[7] Although further studies are needed to investigate a potential association between positive results obtained from laboratory force plate measures and clinical and functional outcomes,[6, 9] it has been shown that the main positive effect of such training on postural control can be attributed to sensorimotor integration[5, 10-13] as well as the coordination improvement due to the task-specificity of training.[14, 15] In the

SCI population, benefits of game-based exercises[24] and virtual reality[3] have been suggested for dynamic *sitting* balance. These studies have demonstrated their potential for substantial improvements in sitting balance through the inclusion of functional approaches in the training.[3,24] However, the effect of balance training with visual feedback during *standing* in the SCI population has not been reported well. It has been suggested that the standing posture has a number of therapeutic and functional benefits[16] aimed at overcoming physiological problems, such as bladder infections,[16] spasticity,[17] blood pressure homeostasis,[18] and bone demineralization.[19] We believe that regaining functionality during self-governed standing will decrease secondary complications and increase independence and, consequently improve the quality of life of individuals with SCI.

We hypothesized that balance training with visual feedback during standing can improve postural control in individuals with incomplete SCI. The purposes of our study were the following: (1) to evaluate the learning potential and performance improvements during the balance training and determine whether voluntary postural control during different tasks can be improved in individuals with incomplete SCI; (2) to determine whether static and dynamic stability during training-irrelevant tasks can be improved following the balance training; and (3) to suggest mechanisms that may be responsible for a potential improvement in postural control in individuals with incomplete SCI.

Materials and Methods

Participants

Six ambulatory participants with motor and sensory incomplete SCI participated in this study (Table 1). Information about each participant's characteristics was based on a self-reported American spinal injury association (ASIA) scale (AIS) classification, the neurological level of the injury, observed assistive device requirements, and the mobility status at the time when baseline measurements were recorded. The inclusion criteria were the following: (1) at least 12 months post-injury in order to ensure stability of the participants' neurological condition; (2) ability to stand for at least 5 minutes without any form of assistive device; and (3) ability to walk 10 m or more with or without the help of parallel sidebars. During the study, the participants did not participate in other rehabilitation or research interventions that might have influenced the outcomes of this study. Each participant gave written informed consent to the experimental procedure, which was approved by the local ethics committee in accordance with the declaration of Helsinki on the use of human subjects in experiments.

Experimental setup and procedure

The training and the data collection were performed with the force plate analysis system "Stabilan-01" (Rhythm, Russia). The Biodex

Unweighing System (Biodex, USA) was used in combination with a harness to prevent falls during standing. During the training, participants stood on the force plate and were instructed to look at the monitor, placed at eye level, approximately 1.5 meters in front of the force plate. The center of pressure (COP) position signal was utilized as an input to game-based exercises.

The training was performed three days per week for a total of twelve sessions. If a participant was not able to attend a scheduled session, the participant was asked to come to a replacement session. Each session lasted up to 60 minutes with a total standing time of at least 30 minutes.

Training protocols

In the “Circle” exercise (Fig. 1a), a target moved around the center of the screen. The participant was instructed to track the target and hold the COP indicator over it. In the “Target” exercise (Fig. 1b), the participant was asked to keep the COP indicator in the center of a target as still as possible. In the “Hunting” exercise (Fig. 1c), a target appeared on the screen in random locations. Once the COP indicator was held “still” within the boundaries of the target for 3 seconds, the target would reappear in a different location. In the “Octahedron” exercise (Fig. 1d), eight targets were presented at 45-degree angles from one another around the center. The participant was asked to move the COP indicator to each target, and hold the position for 5 seconds. In the “Basketball” exercise (Fig. 1e), three targets (balls) of different color appeared on the top of the screen. The participant was asked to “capture” the target, and “drag” it into the basket of the matching color. In the “Ski” exercise (Fig. 1f), the participant was asked to simulate downhill skiing.

The duration of each exercise varied from 1 to 2 min. The score was calculated based on the accumulated time that the COP indicator was over the targets or/and based on the number of successful trials. The exercises were presented in random order. Once a consistent score in each exercise was attained by the participants, the difficulty level of the exercise was increased. The initial difficulty of the exercises was adjusted to each participant based on their performance during the familiarization session. During each training session, an equal number of rounds of each exercise was presented to the participant.

Exercise performance

During the training period, the level of the performance and the rate of learning were monitored. The performance for each exercise was expressed as a percentage of the initial score on the first session. A one-way ANOVA with repeated measures ($\alpha = 0.05$) and a subsequent Dunnet test were applied to the pooled data. We estimated the rate of learning for different exercises by performing a regression analysis using a logarithmic model in which the rate of learning was proportional to the logarithm of the learning time. The model was described using the following equation:[7]

$$y = a + b * \log_{10} * d, \qquad (1)$$

where y is the expected performance on the day of the training *d*; and *a* and *b* are the regression coefficients, describing the initial level of performance and slope, respectively. To compare the rate of learning across exercises, confidence intervals (C.I.) of the slopes were computed using the following equation:

$$C.I. = S \pm Z_{\alpha/2} * (SE/n^{1/2}), \qquad (2)$$

where S is a value of the slope; α is a significance level; *Z* is a z-score for a two-tailed distribution equal to 1.96; SE is the standard error of the measure; *n* is the number of the training session. The desired width of the confidence interval was 95%.

Postural stability assessment

Before and after the training period, two different aspects of balance were evaluated: *static* and *dynamic stability*.

During the static stability test, the participant was instructed to stand on the force plate as still as possible for 60 seconds with the eyes open.

After 2 minutes of rest, the task was repeated with the eyes closed. The fluctuations of the COP were analyzed with root mean square distance (RDIST), the 95% confidence ellipse area (AREA-CE), and the mean velocity (MVELO). [20-22]

During the dynamic stability test, the ability to voluntarily displace the COP to a maximum distance without losing balance was assessed.[23] Eight targets were presented on the screen at 45-degree angles from one another around the center. The participant was instructed to shift the COP indicator as far as possible towards a target which changed its color, hold this position, and then return the COP indicator to the center. The target was active for 7 seconds. The average amplitudes of the COP displacements were defined for each direction for the time interval from 3 to 6 seconds, and were then used as vertices of an octagon. The area of this octagon was defined as the stability zone (AREA-SZ) and was calculated using the following formula:

$$S = \frac{1}{2}\sum_{i=0}^{n-1}(x_i y_{i+1} - x_{i+1} y_i) \qquad (3)$$

where x is the anterior-posterior position of COP and y is the medial-lateral position of COP.

For each measure, comparisons between values before and after the training were performed using a paired *t*-test. The level of significance was set at alpha = 0.05 for all analyses. The results for the pooled data are presented as mean values and standard deviations (SD).

Results

Exercise performance

Figure 2 demonstrates the pooled data of the participants' performance throughout the training period in all exercises as a percentage of the initial scores values obtained on the first day of the training. The most prominent performance was revealed in the exercises “Circle” (Fig. 2a) and “Target” (Fig. 2b): at the end of the training period, the average score reached 236 ± 94 %, and 176 ± 14 % of the initial values, respectively. Somewhat similar yet lower performance was observed in the exercise “Hunting” (Fig. 2c): the score on the twelfth session reached 151 ± 12 % of the initial value. A lower level of performance improvement occurred in exercises “Octahedron”, “Basketball”, and “Ski” (Fig. 2d-f): the score on the twelfth training session increased in comparison with the initial values, reaching 130 ± 14 %, 147 ± 20 %, and 141 ± 20 %, respectively.

The results of the regression analysis (Fig. 3) revealed that the most significant changes in the learning rate occurred in the exercises “Circle” and “Target”: the slope of the regression curves in the logarithmic model reached 56.9 (C.I. from 30.3 to 83.5) and 26.9 (C.I. from 23.0 to 30.8), respectively. Lower learning rates occurred in the exercises “Hunting”, “Basketball” and “Ski”, where the slope of the regression curve reached 21.5 (C.I. from 17.2 to 25.9), 19.6 (C.I. from 13.1 to 26.1) and 17.2 (C.I. from 12.5 to 21.9), respectively. Finally, the slowest learning rate took place in the exercise “Octahedron”, where the slope of the regression curve reached 12.7 (C.I. from 10.1 to 15.2).

Postural stability

In Figure 4, the pooled data of RDIST (Fig. 4a), MVELO (Fig. 4b) and AREA-CE (Fig. 4c) are depicted for the performance, before and after the balance training. The results demonstrate that all measures except MVELO of the medial-lateral COP fluctuation were significantly decreased after the balance training (Table 2).

During the test of dynamic stability, AREA-SZ was significantly increased after the training period, reaching 221 ± 86 % of the pre-training values (Fig. 5, Table 2).

Discussion

In the present study, two main results were found: First, after the balance training with visual feedback, all participants demonstrated substantial improvement in the scores of each exercise, though the achieved performance and rate of learning varied across different exercises. Second, the balance performance during both static and dynamic assessment was significantly improved after the training.

Improved balance function

Two types of supervised learning conditions were implemented during the balance training.[7] For the first type (“Circle”, “Target”), a given stereotyped pattern of movement had to be generated, requiring a high precision of movement performance. For the second type (“Basketball”, “Ski”), the participants apparently applied a general strategy of voluntary postural control that included attention, decision-making, and performance of the task with different movement patterns. Additionally, mixed conditions (“Hunting”, “Octahedron”) were used during the training. Our analysis revealed that the most successful improvement was achieved in exercises of the first type that presented the same movement pattern again and again, whereas less progress was obtained in exercises with different movement patterns. The lowest performance and learning rate during the exercise “Octahedron” might be explained by a greater muscle activity during this exercise; thus, the improvement of muscle performance occurred with a lower increment than enhancement in postural synergies and strategies.

Evidence from human studies has shown that goal-oriented and task-specific training improves impaired function after central and peripheral nervous system disorders or lesions.[14, 15, 24] Presumably, an increase in cortical control of muscles after incomplete SCI might allow functional recovery through the development of alternative movement strategies.[25] As a result, the motor programs for balance control strategies, provided by *task-specific* training, appeared to be effective and could affect the final outcome of the participants in our study.

At the same time, both static and dynamic stability tests did not correspond directly to the motor tasks engaged throughout the training period. Nonetheless, both static and dynamic stability tests (including eyes-closed condition during the static test) revealed a significant improvement of postural control after the training period in all participants. It has been previously demonstrated that during static postural stability test, RDIST and AREA-CE can be related to the effectiveness of, or the stability achieved by, the postural control system; and MVELO has been related to the amount of regulatory activity associated with this level of stability.[20-22] The increased AREA-SZ on the other hand has been related to an enhancement of muscle strength.[23] Consequently, we can assume also a *non-specific* effect of the training on the postural control mechanisms following our balance training program.

Potential mechanisms

The central nervous system of individuals with incomplete SCI is susceptible to substantial reorganization as cortical, subcortical and much of the local spinal cord circuitry remains largely intact and still partially interconnected by unlesioned fibres.[25] Although any of the adaptive reorganizations might contribute to the exhibited improvement, we turn our attention towards the main role of supraspinal reorganization (plasticity) as the mechanism most likely associated with cognitive processes – namely, the formation of internal models and learning of limits.

It has been suggested in studies with stroke survivors that, by giving the participants additional visual information, they became more aware of the body's displacements and orientation in space,[13] were able to integrate somatosensory and visual information in relation to stance and movements,[26] recalibrate deficient proprioceptive information,[13, 27] and compensate the sensorimotor deficit.[10] We hypothesize that, in individuals with SCI, mechanisms of balance improvement due to altered sensorimotor integration and more extensive processing of residual proprioceptive and cutaneous sensory information also seem feasible.[25, 28-30]

Our training program provided a progressive challenge and overload to the postural control system throughout the training period.[31] We assume that such activity per se could improve strength and endurance of muscles participating in control of posture, especially in participants with minimal function prior to the training.[23, 32, 33] Furthermore, our balance training program included exercises that closely mimicked reaching in standing tasks, thereby providing muscle activation associated with functional challenge of maintaining balance.[23, 34-36] We therefore suggest that the improved function during dynamic tasks might be at least partially attributed to enhancements of the muscle properties.

Study limitations and future directions

Further studies in a larger group of individuals with SCI are required to confirm our observations. Ideally, these studies would include a control group and clinical information (e.g., lower extremity motor score) as well as measures of activity limitation and participation restriction to determine the clinical impact and functional consequences of balance training with visual feedback. Additionally, muscle strength and aerobic capacity have to be measured in key postural muscles.

Conclusion

As the first report in this field, we demonstrated that individuals with chronic incomplete SCI show improvements in upright static and dynamic postural control after balance training with visual feedback during standing. Although our observations have to be confirmed in further studies, we assume that balance training with visual feedback opens up a possibility to supplement routine rehabilitative interventions in individuals with incomplete SCI. The main positive effect of the balance training on postural control may be associated with the improvement of existing and the development of new motor strategies, sensorimotor integration, and a direct effect of the training on the muscles’ functional properties.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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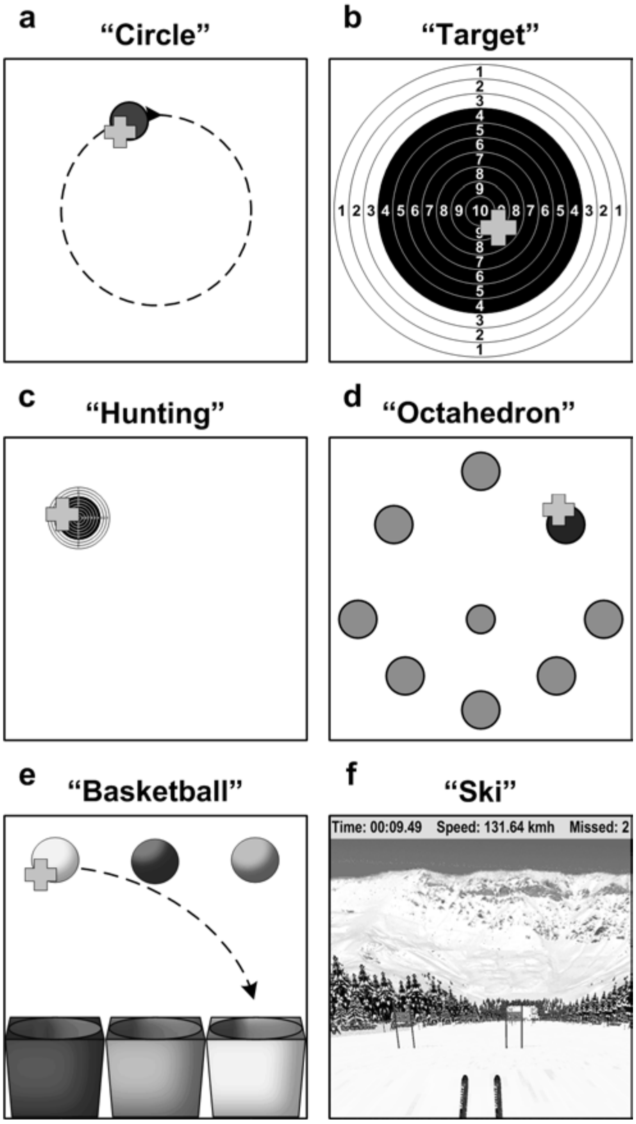

Figure 1 Interface examples of the game-based exercises: (**a**) “Circle”; (**b**) “Target”; (**c**) “Hunting”; (**d**) “Octahedron”; (**e**) “Basketball”; and (**f**) “Ski”. Arrows depict directions for the COP indicator translation (were not shown during the exercises).

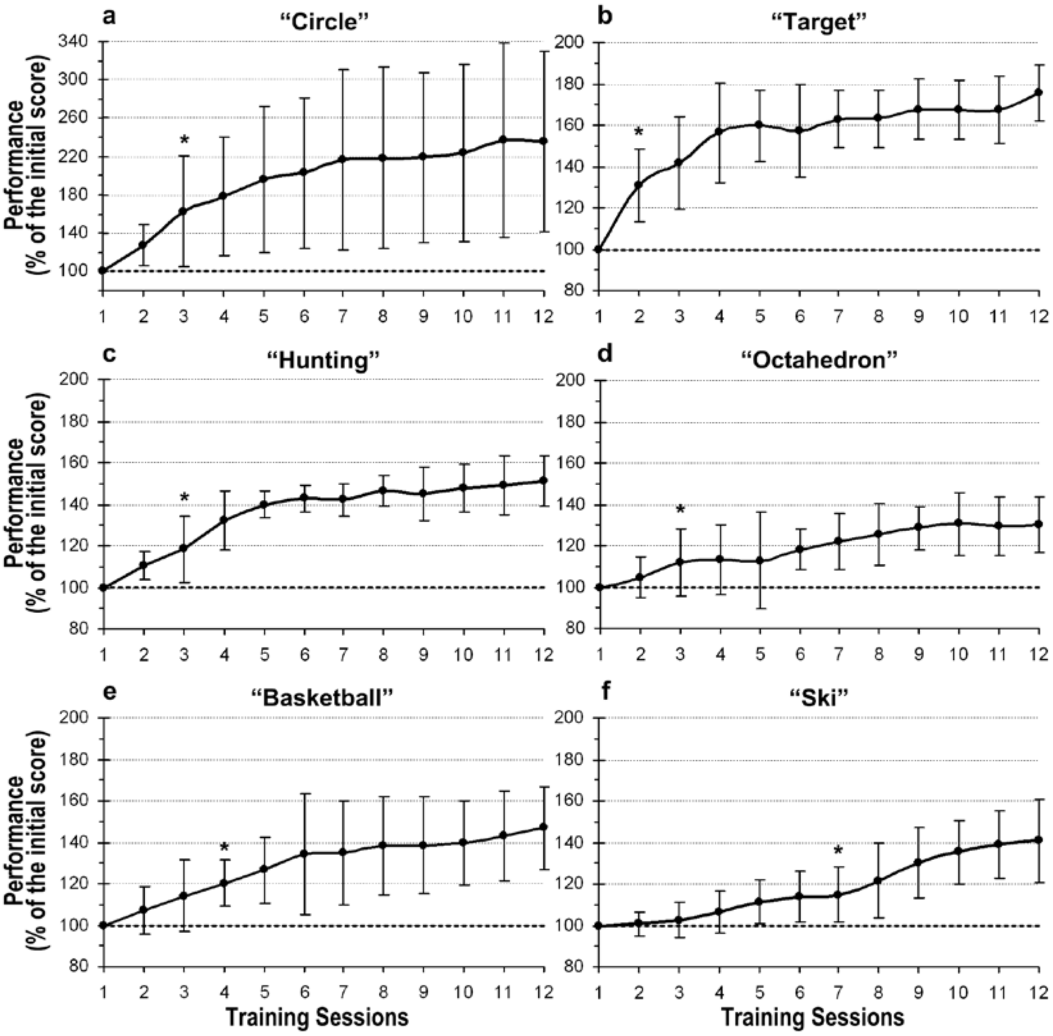

Figure 2 Pooled data showing the performance throughout the training period for all six exercises: (**a**) "Circle, (**b**) "Target", (**c**) "Hunting", (**d**) "Octahedron", (**e**) "Basketball", and (**f**) "Ski". Shown are the percentages of the initial score values obtained in the first session of the training (mean ± SD). Asterisks indicate the first session of the training for which the performance was significantly different from the performance during the initial session of the training (*P* < 0.05).

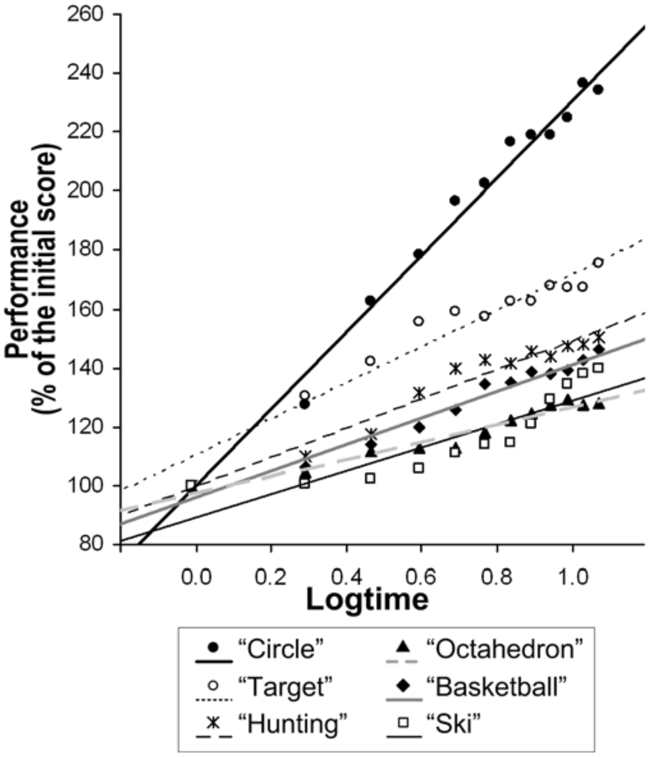

Figure 3 Regression curves representing the pool-average rate of learning for different exercises during the training period (logarithmic model). The abscissa indicates the log10 of the number of training session.

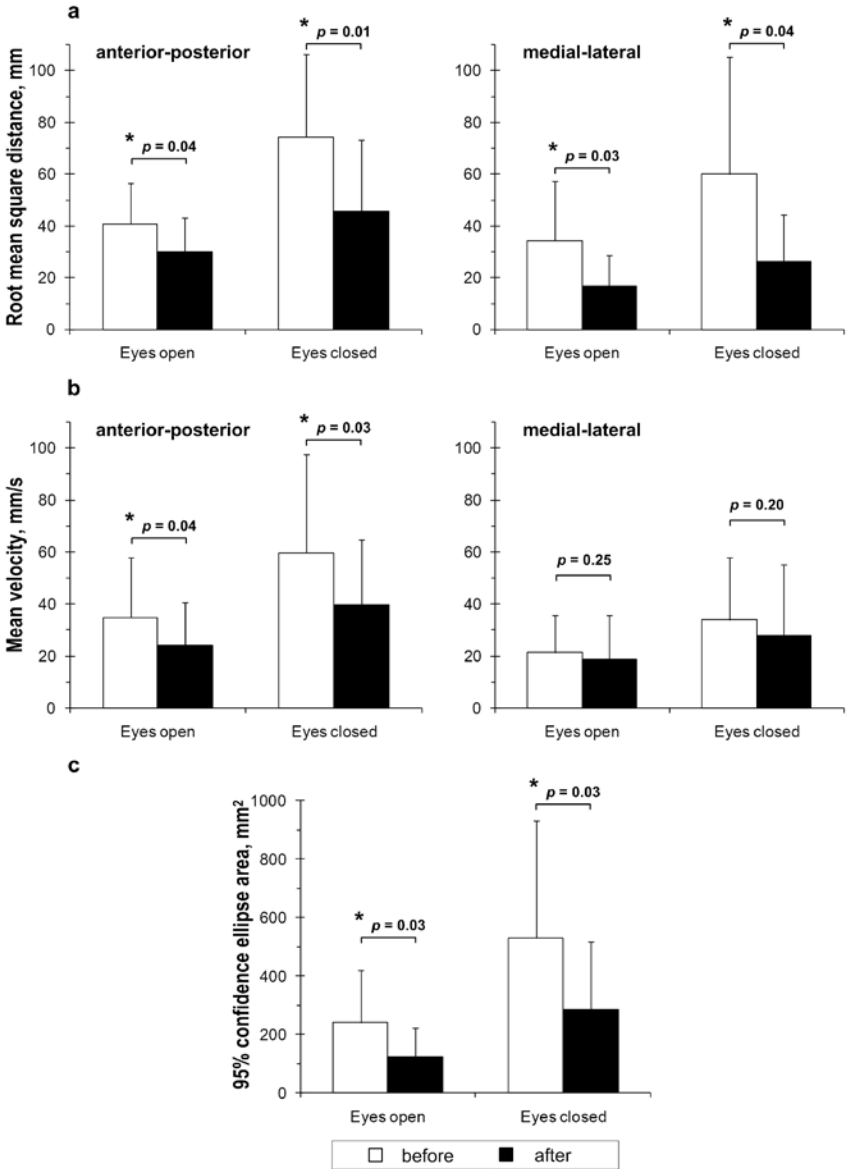

Figure 4 Test of static stability. Pooled data showing (**a**) the root mean square distance (RDIST), (**b**) the mean velocity (MVELO), and (**c**) the 95% confidence ellipse area (AREA-CE) of the COP fluctuation during standing with eyes open and eyes closed before (white columns) and after (black columns) the balance training (mean ± SD). RDIST (**a**) and MVELO (**b**) during anterior-posterior and medial-lateral fluctuations of the COP are shown on the left and right panels, respectively. Asterisks indicate statistically significant differences between the values before and after the training ($P < 0.05$).

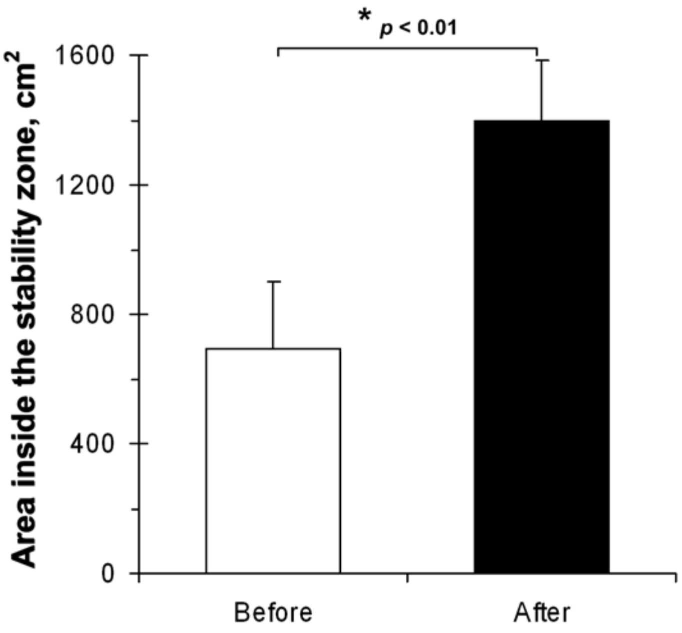

Figure 5 Test of dynamic stability. Average values of the area inside the stability zone before (white column) and after (black column) the balance training (mean ± SD). Asterisks indicate statistically significant difference between the value before and after the training ($P < 0.05$).