ORIGINAL ARTICLE

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

DG Sayenko[1], MI Alekhina[2], K Masani[1], AH Vette[3], H Obata[4], MR Popovic[1,3] and K Nakazawa[4,5]

[1]Rehabilitation Engineering Laboratory, Toronto Rehabilitation Institute, Ontario, Canada; [2]Perceptual Motor Behaviour Laboratory, Department of Exercise Sciences, University of Toronto, Ontario, Canada; [3]Institute of Biomaterials and Biomedical Engineering, University of Toronto, Ontario, Canada; [4]Department of Rehabilitation for Movement Functions, Research Institute of National Rehabilitation Center for Persons with Disabilities, Tokorozawa, Japan and [5]Department of Life Sciences, Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan

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) and (2) to determine whether standing static and dynamic stability during training-irrelevant tasks can be improved after the VBT.

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

Methods: Six participants with chronic motor and sensory incomplete SCI who were able to stand for at least 5 min without any form of assistive device performed the VBT, 3 days per week, for a total of 12 sessions. During the training, participants stood on a force platform and were instructed to shift their center of pressure in the 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 showed substantial improvements in the scores, which varied between 236 ± 94 and $130 \pm 14\%$ 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 $221 \pm 86\%$ of the pre-training values.

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

Introduction

The ultimate aim 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] In addition, 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 because of the task specificity of training.[14,15] In the SCI population, benefits of game-based exercises[16] and virtual reality[3] have been suggested for dynamic *sitting* balance. These studies have shown their potential for substantial improvements in sitting balance

Correspondence: Dr DG Sayenko, Rehabilitation Engineering Laboratory, Toronto Rehabilitation Institute, Lyndhurst Centre, 520 Sutherland Drive, Toronto, Ontario, Canada M4G 3V9.
E-mail: dimitry.sayenko@utoronto.ca

through the inclusion of functional approaches in the training.[3,16] 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[17] aimed at overcoming physiological problems, such as bladder infections,[17] spasticity,[18] blood pressure homeostasis,[19] and bone demineralization.[20] 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 after 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 impairment scale 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 to ensure stability of the participants' neurological condition; (2) ability to stand for at least 5 min 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, Taganrog, Russia). The Biodex Unweighing System (Biodex, Shirley, New York, 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 m in front of the force plate. The center of pressure (COP) position signal was used as an input to game-based exercises.

The training was performed 3 days per week for a total of 12 sessions. If a participant was not able to attend a

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).

Table 1 Characteristics of SCI participants

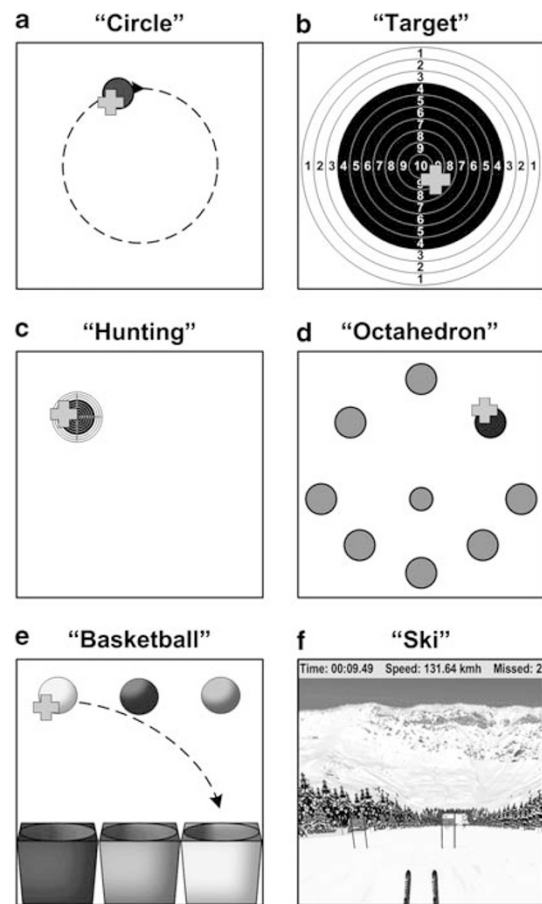| Participant	Age (years)	Sex	Height (cm)	Weight (kg)	Duration of injury (years)	Level	AIS	Assistive device
1	62	Male	173	65	3	C4	D	Walker
2	50	Male	175	68	4	C4	D	Walker
3	30	Male	180	77	11	T10	C	Wheelchair[a]
4	42	Female	164	62	23	T10	C	Wheelchair[a]
5	27	Male	179	78	6	T11	C	Wheelchair[a]
6	35	Male	178	75	8	T12	C	Wheelchair[a]

Abbreviations: AIS, American spinal injury association (ASIA) impairment scale; SCI, spinal cord injury.
[a]Participants used ankle foot orthoses and canes for walking.

scheduled session, the participant was asked to come to a replacement session. Each session lasted up to 60 min with a total standing time of at least 30 min.

Training protocols
In the 'circle' exercise (Figure 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 (Figure 1b), the participant was asked to keep the COP indicator in the center of a target as still as possible. In the 'hunting' exercise (Figure 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 s, the target would reappear in a different location. In the 'octahedron' exercise (Figure 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 s. In the 'basketball' exercise (Figure 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

(Figure 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's test were applied to the pooled data. We estimated the rate of learning for different exercises by performing a regression analysis
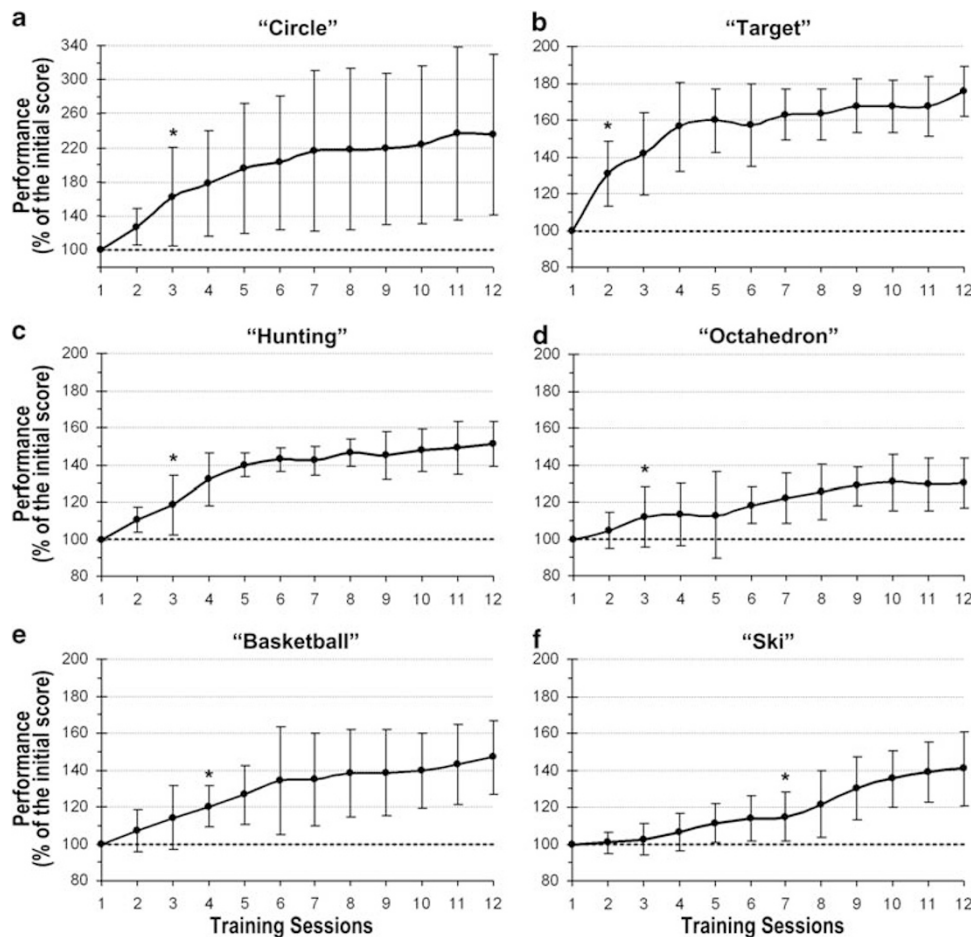
Figure 2 Pooled data showing the performance throughout the training period for all six exercises: (**a**) 'circle,' (**b**) 'target,' (**c**) 'hunting,' (**d**) 'octahedron,' (**e**) 'basketball,' and (**f**) 'ski.' Shown are the percentages of the initial score values obtained in the first session of the training (mean ± s.d.). 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 ($P < 0.05$).

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]

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

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 (CIs) of the slopes were computed using the following equation:

$$CI = S \pm Z_{\alpha/2} \times (s.e./n^{1/2}), \qquad (2)$$

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, s.e. is the standard error of the measure, and n is the number of the training session. The desired width of the CI 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 s with the eyes open. After 2 min 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).[21–23]

During the dynamic stability test, the ability to voluntarily displace the COP to a maximum distance without losing balance was assessed.[24] 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 toward a target, which changed its color, hold this position, and then return the COP indicator to the center. The target was active for 7 s. The average amplitudes of the COP displacements were defined for each direction for the time interval from 3 to 6 s, 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 s.d.

Results

Exercise performance
Figure 2 shows 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' (Figure 2a) and 'target'
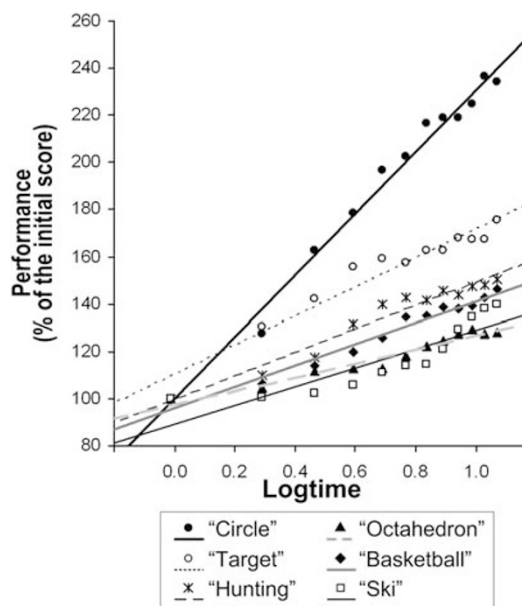
Figure 3 Regression curves representing the pool-average rate of learning for different exercises during the training period (logarithmic model). The abscissa indicates the log10 of the number of training session.

(Figure 2b): at the end of the training period, the average score reached 236 ± 94, and $176 \pm 14\%$ of the initial values, respectively. Somewhat similar yet lower performance was observed in the exercise 'hunting' (Figure 2c): the score on the 12th session reached $151 \pm 12\%$ of the initial value. A lower level of performance improvement occurred in exercises 'octahedron,' 'basketball,' and 'ski' (Figures 2d–f): the score on the 12th training session increased in comparison with the initial values, reaching 130 ± 14, 147 ± 20, and $141 \pm 20\%$, respectively.

The results of the regression analysis (Figure 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 (CI from 30.3 to 83.5) and 26.9 (CI 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 (CI from 17.2 to 25.9), 19.6 (CI from 13.1 to 26.1), and 17.2 (CI 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 (CI from 10.1 to 15.2).

Postural stability
In Figure 4, the pooled data of RDIST (Figure 4a), MVELO (Figure 4b), and AREA-CE (Figure 4c) are depicted for the performance before and after the balance training. The results show 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 $221 \pm 86\%$ of the pre-training values (Figure 5; Table 2).
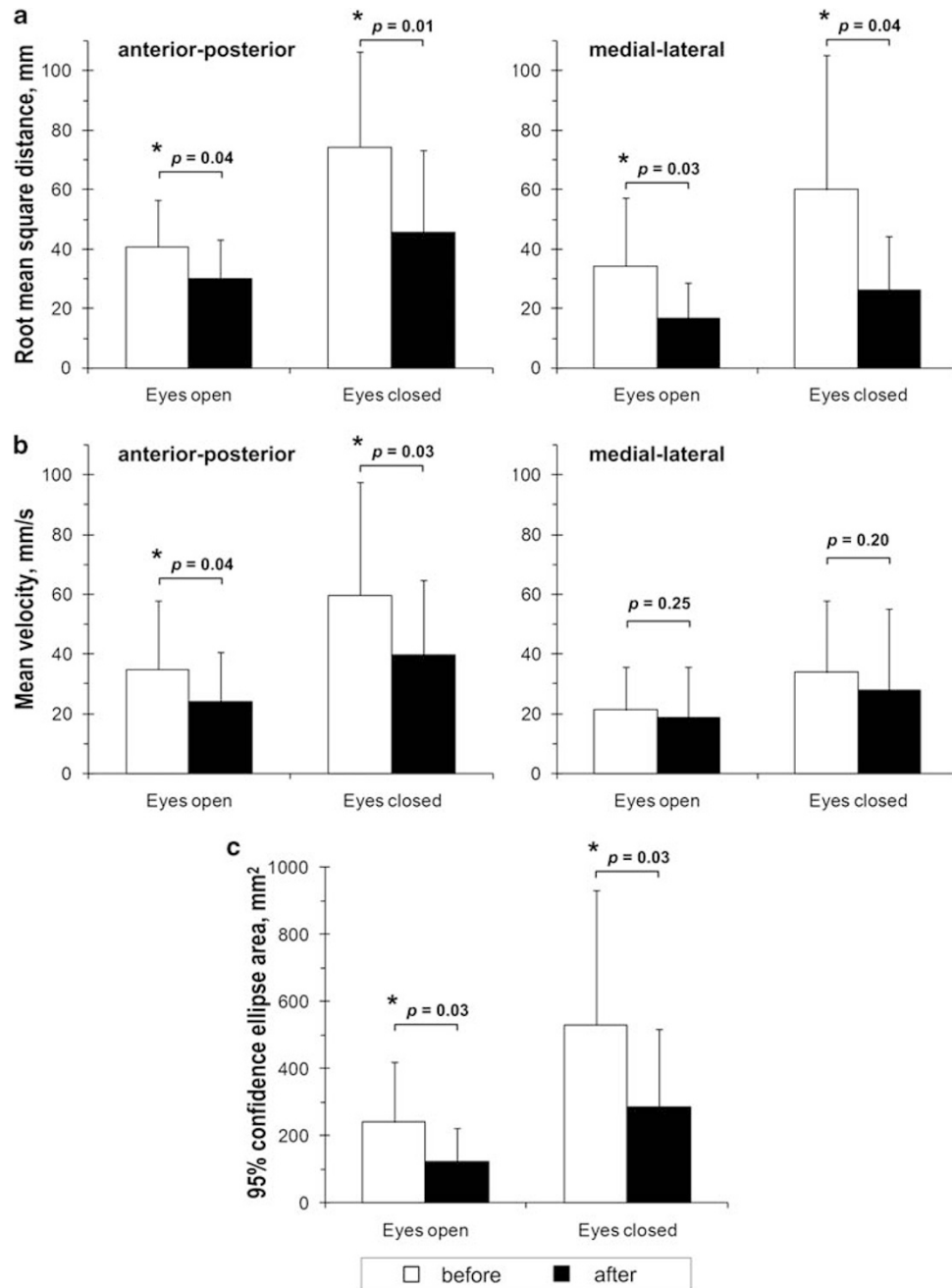
Figure 4 Test of static stability. Pooled data showing (**a**) the root mean square distance (RDIST), (**b**) the mean velocity (MVELO), and (**c**) the 95% confidence ellipse area (AREA-CE) of the COP fluctuation during standing with eyes open and eyes closed before (white columns) and after (black columns) the balance training (mean ± s.d.). 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 ($P < 0.05$).

Discussion

In this study, two main results were found. First, after the balance training with visual feedback, all participants showed 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' and 'target'), a given stereotyped pattern of movement had to be generated, requiring a high precision of movement performance. For the second type ('basketball' and 'ski'), the participants apparently applied a general strategy of voluntary postural control that included attention, decision making, and performance of the task with

Table 2 Average values of the RDIST, MVELO, AREA-CE, and AREA-SZ after the balance training (mean ± s.d.)

Measure	Condition	Anterior–posterior (% of initial values)	Medial–lateral (% of initial values)
RDIST	EO	75 ± 17	61 ± 35
	EC	60 ± 25	38 ± 30
MVELO	EO	73 ± 20	85 ± 30
	EC	66 ± 25	79 ± 34
AREA-CE	EO	52 ± 32	
	EC	46 ± 25	
AREA-SZ	EO	221 ± 86	

Abbreviations: AREA-CE, 95% confidence ellipse area; AREA-SZ, area inside the stability zone; MVELO, mean velocity; RDIST, root mean square distance.
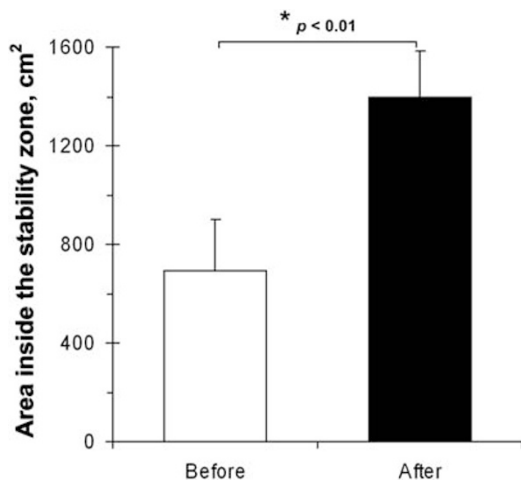
Figure 5 Test of dynamic stability. Average values of the area inside the stability zone before (white column) and after (black column) the balance training (mean ± s.d.). Asterisks indicate statistically significant difference between the value before and after the training ($P < 0.05$).

different movement patterns. In addition, mixed conditions ('hunting' and '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.[14–16] 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, seemed 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 earlier shown 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.[21–23] The increased AREA-SZ on the other hand has been related to an enhancement of muscle strength.[24] Consequently, we can also assume a *non-specific* effect of the training on the postural control mechanisms after 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 remain largely intact and still partially interconnected by unlesioned fibers.[25] Although any of the adaptive reorganizations might contribute to the exhibited improvement, we turn our attention toward the main function 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 because of 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 the strength and endurance of muscles participating in control of posture, especially in participants with minimal function before the training.[24,32,33] 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.[24,34–36] 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

(for example 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. In addition, muscle strength and aerobic capacity have to be measured in important postural muscles.

Conclusion

As the first report in this field, we showed 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.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

References

1 Anneken V, Hanssen-Doose A, Hirschfeld S, Scheuer T, Thietje R. Influence of physical exercise on quality of life in individuals with spinal cord injury. *Spinal Cord* 2009; **48**: 393–399.

2 Fernhall B, Heffernan K, Jae SY, Hedrick B. Health implications of physical activity in individuals with spinal cord injury: a literature review. *J Health Hum Serv Adm* 2008; **30**: 468–502.

3 Kizony R, Raz L, Katz N, Weingarden H, Weiss PL. Video-capture virtual reality system for patients with paraplegic spinal cord injury. *J Rehabil Res Dev* 2005; **42**: 595–608.

4 Bromley I. *Tetraplegia and Paraplegia: A Guide for Physiotherapists*, 6th edn Churchill Livingstone: Edinburgh, New York, 2006.

5 Partridge CJ. *Neurological Physiotherapy: Bases of Evidence for Practice: Treatment and Management of Patients Described by Specialist Clinicians*. Whurr: London, 2002.

6 Barclay-Goddard R, Stevenson T, Poluha W, Moffatt ME, Taback SP. Force platform feedback for standing balance training after stroke. *Cochrane Database Syst Rev* 2004; **4**: CD004129.

7 Ioffe ME, Ustinova KI, Chernikova LA, Kulikov MA. Supervised learning of postural tasks in patients with poststroke hemiparesis, Parkinson's disease or cerebellar ataxia. *Exp Brain Res* 2006; **168**: 384–394.

8 Woollacott M, Shumway-Cook A, Hutchinson S, Ciol M, Price R, Kartin D. Effect of balance training on muscle activity used in recovery of stability in children with cerebral palsy: a pilot study. *Dev Med Child Neurol* 2005; **47**: 455–461.

9 Van Peppen RP, Kortsmit M, Lindeman E, Kwakkel G. Effects of visual feedback therapy on postural control in bilateral standing after stroke: a systematic review. *J Rehabil Med* 2006; **38**: 3–9.

10 Mulder T, Hulstyn W. Sensory feedback therapy and theoretical knowledge of motor control and learning. *Am J Phys Med* 1984; **63**: 226–244.

11 Nichols DS. Balance retraining after stroke using force platform biofeedback. *Phys Ther* 1997; **77**: 553–558.

12 Oie KS, Kiemel T, Jeka JJ. Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture. *Brain Res Cogn Brain Res* 2002; **14**: 164–176.

13 Walker C, Brouwer BJ, Culham EG. Use of visual feedback in retraining balance following acute stroke. *Phys Ther* 2000; **80**: 886–895.

14 Kwakkel G. Impact of intensity of practice after stroke: issues for consideration. *Disabil Rehabil* 2006; **28**: 823–830.

15 Richards CL, Malouin F, Bravo G, Dumas F, Wood-Dauphinee S. The role of technology in task-oriented training in persons with subacute stroke: a randomized controlled trial. *Neurorehabil Neural Repair* 2004; **18**: 199–211.

16 Betker AL, Desai A, Nett C, Kapadia N, Szturm T. Game-based exercises for dynamic short-sitting balance rehabilitation of people with chronic spinal cord and traumatic brain injuries. *Phys Ther* 2007; **87**: 1389–1398.

17 Walter JS, Sola PG, Sacks J, Lucero Y, Langbein E, Weaver F. Indications for a home standing program for individuals with spinal cord injury. *J Spinal Cord Med* 1999; **22**: 152–158.

18 Agarwal S, Triolo RJ, Kobetic R, Miller M, Bieri C, Kukke S et al. Long-term user perceptions of an implanted neuroprosthesis for exercise, standing, and transfers after spinal cord injury. *J Rehabil Res Dev* 2003; **40**: 241–252.

19 Harkema SJ, Ferreira CK, van den Brand RJ, Krassioukov AV. Improvements in orthostatic instability with stand locomotor training in individuals with spinal cord injury. *J Neurotrauma* 2008; **25**: 1467–1475.

20 Biering-Sorensen F, Hansen B, Lee BS. Non-pharmacological treatment and prevention of bone loss after spinal cord injury: a systematic review. *Spinal Cord* 2009; **47**: 508–518.

21 Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng* 1996; **43**: 956–966.

22 Hufschmidt A, Dichgans J, Mauritz KH, Hufschmidt M. Some methods and parameters of body sway quantification and their neurological applications. *Arch Psychiatr Nervenkr* 1980; **228**: 135–150.

23 Maki BE, Holliday PJ, Fernie GR. Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. *J Am Geriatr Soc* 1990; **38**: 1–9.

24 Melzer I, Benjuya N, Kaplanski J, Alexander N. Association between ankle muscle strength and limit of stability in older adults. *Age Ageing* 2009; **38**: 119–123.

25 Raineteau O, Schwab ME. Plasticity of motor systems after incomplete spinal cord injury. *Nat Rev Neurosci* 2001; **2**: 263–273.

26 Cheng PT, Wang CM, Chung CY, Chen CL. Effects of visual feedback rhythmic weight-shift training on hemiplegic stroke patients. *Clin Rehabil* 2004; **18**: 747–753.

27 Dault MC, de Haart M, Geurts AC, Arts IM, Nienhuis B. Effects of visual center of pressure feedback on postural control in young and elderly healthy adults and in stroke patients. *Hum Mov Sci* 2003; **22**: 221–236.

28 Edgerton VR, Tillakaratne NJ, Bigbee AJ, de Leon RD, Roy RR. Plasticity of the spinal neural circuitry after injury. *Annu Rev Neurosci* 2004; **27**: 145–167.

29 Harkema SJ. Neural plasticity after human spinal cord injury: application of locomotor training to the rehabilitation of walking. *Neuroscientist* 2001; **7**: 455–468.

30 Dietz V, Harkema SJ. Locomotor activity in spinal cord-injured persons. *J Appl Physiol* 2004; **96**: 1954–1960.

31 Oddsson LIE, Boissy P, Melzer I. How to improve gait and balance function in elderly individuals—compliance with principles of training. *Eur Rev Aging Phys Act* 2007; **4**: 15–23.

32 Messier SP, Royer TD, Craven TE, O'Toole ML, Burns R, Ettinger Jr WH. Long-term exercise and its effect on balance in older, osteoarthritic adults: results from the Fitness, Arthritis, and Seniors Trial (FAST). *J Am Geriatr Soc* 2000; **48**: 131–138.

33 Moxley Scarborough D, Krebs DE, Harris BA. Quadriceps muscle strength and dynamic stability in elderly persons. *Gait Posture* 1999; **10**: 10–20.

34 Judge JO, Whipple RH, Wolfson LI. Effects of resistive and balance exercises on isokinetic strength in older persons. *J Am Geriatr Soc* 1994; **42**: 937–946.

35 Wolfson L, Whipple R, Judge J, Amerman P, Derby C, King M. Training balance and strength in the elderly to improve function. *J Am Geriatr Soc* 1993; **41**: 341–343.

36 Wolfson L, Whipple R, Derby C, Judge J, King M, Amerman P *et al*. Balance and strength training in older adults: intervention gains and Tai Chi maintenance. *J Am Geriatr Soc* 1996; **44**: 498–506.