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Research Article

Balance gains from a training program based on progressive sensory constraints for stroke survivors: a controlled randomized clinical trial

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HIGHLIGHTS
- Balance deficits in stroke can be attenuated through challenging training.
- Sensory manipulations led to higher balance gains in stroke.
- Exercises with sensory manipulation should be introduced into rehabilitation protocols.

ABBREVIATIONS

BBS	Berg Balance Scale
TB	Training block
TUG	Timed Up and Go

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BACKGROUND: Balance deficits in stroke survivors can be attenuated through appropriate training procedures.
AIM: In the current investigation, we aimed to compare gains in dynamic balance between a training protocol employing progressive visual and tactile/proprioceptive constraints against balance training under full sensory information in stroke survivors.
METHOD: Participants were randomly assigned to one of two groups for 12 balance training sessions, three sessions per week. In the constraint group (n=9), training was divided into four blocks of three sessions: full sensory information, visual constraint, tactile/proprioceptive constraint, and the combination of the latter two conditions. In the full sensory information group (n=10), participants trained under full vision supported on a rigid surface. At the end of each training block, evaluations were made through the Berg Balance Scale (BBS) and Timed Up and Go (TUG) tests. Analysis was made through Friedman, Wilcoxon matched-pairs and Mann-Whitney U tests.
RESULTS: Intra and intergroup analyses showed that training under sensory constraint led to higher performance gains than training under full sensory information both in the BBS postural (Δ = 21.20%, p = 0.02) and dynamic (Δ = 18.17%, p = 0.04) tasks. For TUG, analysis of proportional gains indicated significantly greater time reduction in the sensory constraint compared to the full group (Δ = 16.48%, p = 0.03).
CONCLUSION: Balance training under sensory constraint led to higher balance gains than training with availability of full sensory information.

KEYWORDS: Neurology | Rehabilitation | Sensory deprivation | Exercise

INTRODUCTION

Brain damage due to cerebral stroke is expected to impair body balance in most cases [1], resulting in a large proportion of falls over years following a cortical or subcortical infarction [2]. Post-stroke balance deficits have been manifested in greater amplitude [3-5] and velocity [6-7] of body sway in quiet standing, and in dynamic tasks requiring balance recovery [8-9]. An important component for body balance control affected by stroke is sensory feedback processing [10 (for a review)]. Stroke-related decreased balance stability has been found particularly in individuals with impaired ankle proprioception [11]. Further investigation has shown decreased postural stability mainly when visual information is suppressed [12-14] or made incoherent with body oscillation [15-18]. These results suggest that stroke survivors are vision-dependent for balance control, having a diminished capacity to use proprioceptive information signaling body sway.

A systematic review and meta-analysis has shown that balance deficits in a chronic stage of stroke can be attenuated employing therapeutic exercises, as indicated by clinical evaluations through the Berg Balance Scale (BBS) [19]. Of particular interest for rehabilitating neuromuscular dysfunctions provoked by stroke is the finding that more noticeable gains in stance stability seem to be achieved through practice of balance tasks under sensory constraints. Assessing a training program of five 1-hour sessions per week during four consecutive weeks, Bonan and colleagues [20] compared the effects of balance training under no vision versus full vision in stroke survivors, with balance evaluation made through a protocol involving sensory constraint. Results showed that the vision-constraint group achieved higher balance gains than the full vision group (see [21] for contradictory results). Further research compared the effects of balance training for stroke survivors under visual constraint against manipulation of tactile/proprioceptive information from the feet soles and ankles by training over a malleable surface [22]. Training sessions lasted 30 min., with 3 sessions per week for one month. Results showed that training balance under visual constraint induced higher gains in the ability to control static and dynamic balance than the group training over an unstable base with eyes open. Further results have suggested that multi-session training programs combining visual constraint with distortion of tactile and proprioceptive information from the feet soles led to additional gains of quiet [23] balance control in stroke survivors as compared to full sensory information training. Findings from the above-mentioned training protocols constraining sensory information in different ways relevant for balance control indicate that this procedure can increase performance gains from balance training in stroke survivors. However, an issue left untouched in previous research is understanding the effects of constraining progressively visual and tactile/proprioceptive information over a series of training sessions within a program oriented to body balance improvement in the chronic stage following a cerebral stroke. As previous results suggest that both separate constraints of visual and proprioceptive information during training can lead to increased balance gains, it is of applied interest to know the cumulative effects of different sensory constraints during a training program aiming to increase balance control in individuals who suffered a stroke.

In the present investigation, we conducted a randomized controlled trial aiming to evaluate performance gains from a training protocol based on a combined and progressive increment of sensory constraint, from full sensory information to a combination of sensory constraints through visual deprivation and distorted tactile/proprioceptive information from the feet soles/ankles, in comparison to a balance training in the condition of full visual information availability supported on a rigid surface. An original point of this study was the evaluation of the cumulative effects of each sensory constraint during the training program, assessing the potential balance gains regarding the previous condition with full sensory information or with another form of sensory constraint. We hypothesized that balance training in the regime of progressive sensory constraint leads to higher gains in functional tests requiring quiet and dynamic balance than regular full sensory information training.

METHODS

Participants

One hundred and one stroke survivors from the same public hospital database, following clinical evaluation and cerebral image analysis by neurologists, were considered as potential participants. Eligibility criteria for inclusion were the following: time range between 6 months and 3 years following stroke, hemiparesis, no neurologic or orthopedic diseases other than those resulting from stroke, ability to stand up and walk without any assistance, no damage to the cerebellum or brain stem. In agreement with the Declaration of Helsinki, participants provided informed consent according to the study protocol approved by the University of São Paulo (Brazil) ethics committee (protocol n. 01040212.7.0000.5391). This clinical trial was registered at https://clinicaltrials.gov/, identifier NCT01912794. This study follows the CONSORT recommendations to report parallel group randomized trials [24].

Pre-test assessments

As pre-test assessments, we measured BBS [19] and the Timed Up and Go (TUG) [25] tests. The BBS is based on 14 items, each graded on a 5-point scale, with a maximum score of 56 points. For analysis, BBS was separated into two subgroups of balance tasks, postural and dynamic [26]. The postural balance tasks included BBS items 2-3, 6-7, and 13-14 with a maximum score of 24 points, while the dynamic tasks were composed of the remaining tasks of BBS (items 1, 4-5, 8-12), with a maximum score of 32 points. An examiner specialist in BBS scoring rated online participants' performance. The TUG test evaluates functional mobility and dynamic balance by recording the time spent to complete the serial tasks of standing up from the seated position, walking forward for 3 m, turning 180°, walking back, and sitting on the same chair. This test was selected because it has been shown to be a good predictor of post-stroke falls [27], and thus related to dynamic balance. For evaluation, participants performed three trials of TUG, being asked to perform the test in the shortest time. Time was measured with a manual stopwatch by an experienced examiner. Evaluations were made individually in a quiet gym. At study admittance, we evaluated functional disability through the modified Rankin scale [28], spasticity through the modified Ashworth's scale [29], and different descriptive functional evaluations, including the Fugl-Meyer scale [30], and Mini-mental State Examination [31].

Experimental design and training protocols

In this controlled randomized clinical trial, participants were randomly assigned to one of two groups by using computer-generated random numbers, balancing for number of participants per group (made by the main researcher): sensory constraint (*n*=10) or full sensory information (*n*=10). The complete balance training program was developed over 12 sessions of 50 min. each, for 4 weeks, with the frequency of three sessions per week. For the constraint group, the training sessions were divided into four blocks of three sessions each. In the training block (TB) 1, balance tasks were practiced under full sensory information. In TB2, the constraint group practiced balance tasks keeping their eyes closed while supported on a rigid floor surface. In the TB3, they practiced balance tasks with their eyes open, while supported on a malleable high-density foam surface (9-cm thick). Thus, in the third training block participants of this group had the relationship between pressure on the feet soles and adequate ankle angle for body vertical orientation disrupted by surface malleability. In the final training block (TB4), participants practiced balance tasks under the most restrictive sensory condition given by the combination of eyes closed while supported on the malleable surface. Individuals in the full sensory information group practiced the balance tasks throughout the whole training program in the condition of full vision supported on a rigid floor surface. The sensory constraint and full sensory information groups practiced the same movements across the training program (see Figure 1, for a schematic representation of the study design). Intra- and inter-sessions, the tasks were selected and organized to have growing difficulty. Exercise categories were as it follows: In place, the tasks required (a) growing amplitude and speed of flexion-extension of the hip, knees and ankles to perform several free arm movements or for manipulation of objects (balls of different sizes and weights, rods); (b) decreasing support base area by keeping the two feet together, standing on the tip of the feet/heels or standing in unipedal support on the nonparetic leg; (c) from self-paced whole-body movements advancing into musically-paced rhythmic movements; and in displacement, (d) walking over progressively narrower surfaces with frequent direction change (crossing paths or stepping on ropes placed on the ground/malleable surface) and stepping over obstacles of different heights placed on the walking surface. Each exercise and respective variations were practiced for about 5 min. in training sessions, with number of trials varying across participants. This schedule resulted in about 10 series of different exercises per training session. The training sessions were provided in groups of 4-5 participants, with all of them receiving instructions from the same supervisor. After about 25 min. in each training session, participants had a sitting rest interval of about 2-3 min., and then another 25 min. of different exercises. Immediately after the end of each training block, we assessed functional tasks requiring postural or dynamic balance through the BBS and TUG tests. These evaluations were made with a minimum rest interval of 10 min. following the end of the third session within each training block.

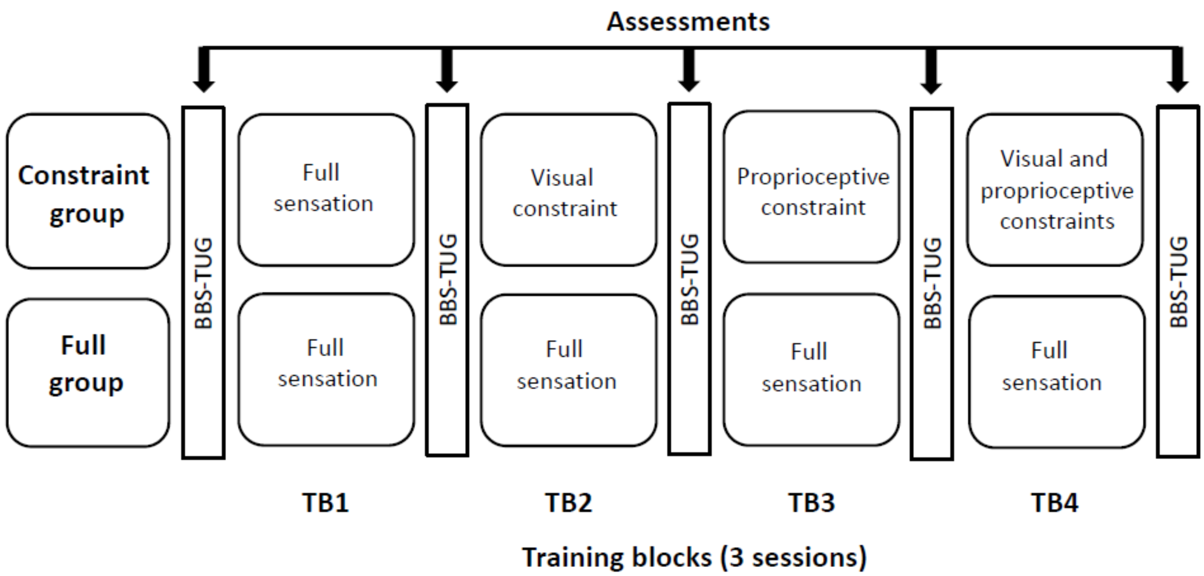

Figure 1. Representation of the study design, showing the sensory condition of training for the constraint and full groups across training blocks (TB) and times of assessment through the Berg Balance Scale (BB) and timed-up-and-go (TUG) test.

Analysis

The primary outcomes were results from the BBS score and the TUG completion time. Analysis was performed by one of the researchers, not blind for group composition. Due to lack of normal data distribution (Shapiro-Wilk test, $P < .05$), we used non-parametric tests. Analysis included data from the pre-test and the four training blocks. Evaluation of intragroup gains over training blocks was made through the Friedman ANOVA separately for each group. Pairwise post hoc comparisons were performed only between consecutive blocks through the Wilcoxon matched-pairs test, evaluating gains in a given block compared to the previous one. The intergroup comparisons for the pre-test and each training block were performed using the Mann-Whitney U test. Analysis from BBS was performed for the global score and separately for the postural and dynamic tasks. We also calculated the proportional gains from the whole training program (end of training block 4) between the two groups with reference to the pre-test using the Mann-Whitney U test. Effect sizes were calculated through Cohen's *d*[32]. The significance level was set at $p \leq .05$; significant differences are reported only.

RESULTS

Participants' selection

After screening, twenty individuals, men (n=12) and women (n=8), were selected[a]. The flowchart showing participants' selection and group allocation is presented in Figure 2. Participants had unilateral lesions at different sites in the right or left cerebral hemisphere. A detailed description of participants' demographic and neurologic characteristics separated by group is presented in Table 1. Between-group comparisons for demographic variables through the Mann-Whitney U test indicated that the full group was significantly older than the constraint group (Δ = 12 years), $p < .05$. Participants had mild to moderate functional disability (Rankin scale score < 3), and scores 1-2 in the modified Ashworth's spasticity scale. Results from descriptive functional evaluations are presented in Table 2. The two groups were not significantly different in these assessments. One participant of the constraint group dropped out during the training sessions. The other participants attended all training sessions, and none of them were excluded. Thus, the main analysis was conducted on 9 participants of the constraint group and 10 participants of the full group.

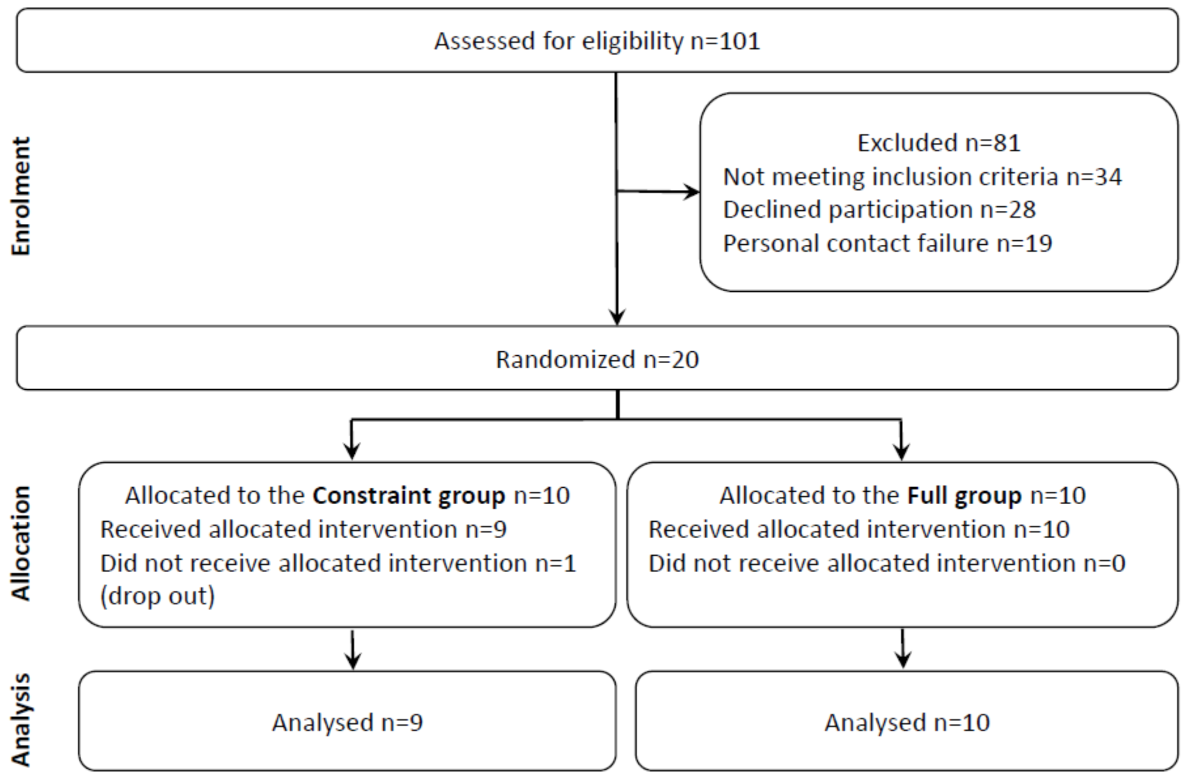

Figure 2. Flowchart showing participants' selection and allocation to the constraint and full groups.

[a] Estimation of required minimum sample size was based on Bayouk [23].

Table 1. Demographic and neurologic characteristics separated by group.

	Constraint group (*n*=9)	Full group (*n*=10)
Age (years)	56 (1.76)	68 (1.91)
Sex		
Men (*n*)	6	6
Women (*n*)	3	4
Cerebral lesion side		
Right (*n*)	3	6
Left (*n*)	6	4
Stroke time (months)	28.11 (8.73)	32.90 (7.88)
Lesioned areas (*n*)	Parietal (2) Frontal (1) Parietal and temporal (1) Temporal and frontal (2) Frontal, parietal and temporal (3)	Parietal (1) Occipital (2) Temporal and parietal (1) Frontal and parietal (2) Frontal, parietal and temporal (1) Frontal and basal ganglia (2) Temporal and occipital (1)

Means and standard errors.

Table 2. Median (range in parenthesis) from clinical evaluations at baseline separated by group.

	Groups	
	Constraint (*n* = 9)	Full (*n* = 10)
FMS: Sensibility (max. 12)	10 (8-12)	10 (7-12)
Motor (max. 34)	21 (5-34)	29 (12-32)
Balance (max. 14)	12 (8-13)	11 (9-12)
Total (max. 60)	53 (23-57)	48 (35-54)
MAE: hip aductors (max. 4)	1 (0-1)	1 (1-2)
Knee extensors (max. 4)	2 (1-2)	1 (0-2)
Knee flexors (max. 4)	2 (0-2)	1 (0-2)
Plantar flexors (max. 4)	1 (0-2)	1.5 (1-2)
MRS (max. 6)	2 (1-3)	1 (1-3)
MMSE (max. 30)	24 (18-28)	23 (18-29)

FMS: Fugl-Meyer scale; MAE: modified Ashworth scale; MRS: modified Rankin scale; MMSE: Mini Mental State Examination

Berg Balance Scale (BBS)

Intra-group between-block comparisons. Intragroup analysis of BBS for the constraint group showed a median gain of 9 points at the end of training program (median = 54) compared to pre-test (median = 45, 24% gain), with a significant effect of training block, Friedman ANOVA = 34.15, $p < .001$. Analysis showed a significant increase in the scores across the pre-test and the training blocks in both groups. The analysis between training blocks for the constraint group showed the following effects: TB1 > pre-test (Δ = 5.00, d = .78), TB2 > TB1 (Δ = 2.33, *d* = .55), TB3 > TB2 (Δ = 2.44, *d* = .75) (*p* values < 0.01). For the full group, no significant between-block differences were found (Figure 3).

Between-group comparisons. Between-group comparisons per block indicated significantly higher scores for the constraint than for the full group in the TB2 (Δ = 4.11, *d* = .95, $p < .05$), TB3 (Δ = 5.76, *d* = 1.41, $p < .005$), and TB4 (Δ = 5.72, *d* = 1.51, $p = .001$). Between-group comparisons of proportional change at the end of the training program indicated significantly higher values for the constraint group (Δ = 18.17%, *d* = .93, $p = 0.04$).

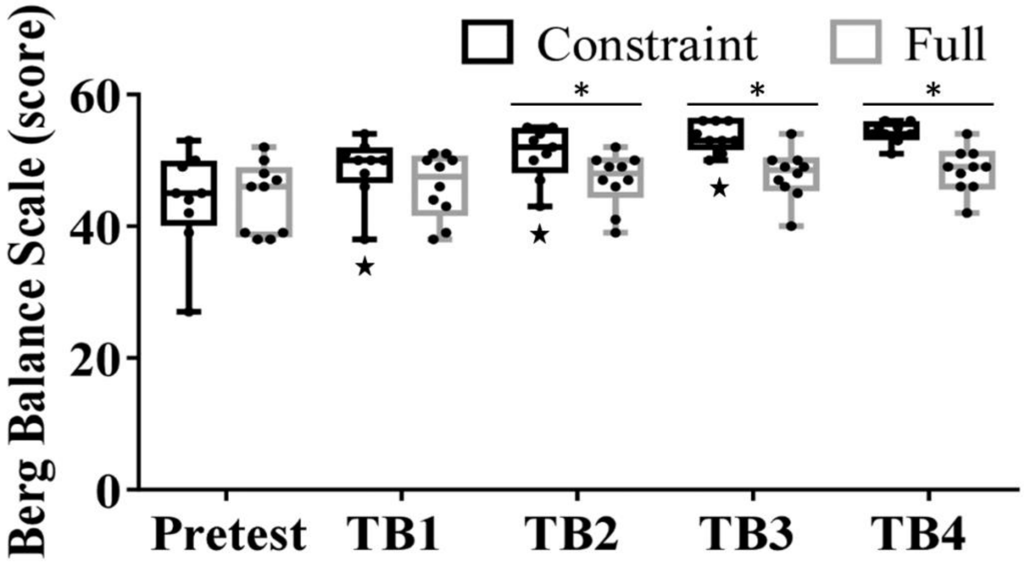

Figure 3. Comparison of median and individual values (first and third quartiles indicated by box limits) of the global Berg Balance Scale scores (maximum 56) between the constraint and full groups in the pre-test and after each training block: TB1, full sensory information; TB2, visual constraint; TB3, proprioceptive constraint; and TB4, association between visual and proprioceptive constraints; asterisks indicate significant difference between groups, and black stars indicate intragroup differences to the preceding block or pre-test.

Postural BBS tasks

Intra-group between-block comparisons. For the separate analysis of the set of BBS postural tasks, results for the constraint group showed a median gain of 4 points at the end of training (median = 23) as compared to pre-test (median = 19, 21% gain), with a significant effect of training block, Friedman ANOVA = 32.25, $p < .001$ (Figure 4A). Pairwise comparisons between consecutive blocks showed the following significant differences across the training blocks: TB1 > pre-test ($\Delta = 2.11$, $d = .69$), TB2 > TB1 ($\Delta = .67$, $d = .30$), TB3 > TB2 ($\Delta = 1.56$, $d = .88$) (p values < .05). Analysis of the full group indicated a gain of 1 point at the end of training program (end median = 21, pre-test median = 20, 9% gain), with no significant differences across blocks, Friedman ANOVA = 8.20, $p = .08$.

Between-group comparisons. Pairwise comparisons between groups per training block indicated significantly higher scores for the constraint than the full group at the end of TB3 ($\Delta = 2.58$, $d = 1.14$, $p < .005$), and TB4 ($\Delta = 2.38$, $d = 1.14$, $p < .01$). Between-group comparisons of proportional change at the end of the training program indicated significantly higher values for the constraint than the full group ($\Delta = 21.20\%$, $d = .94$, $p = 0.02$).

Dynamic BBS tasks

Intra-group between-block comparisons. Analysis of BBS dynamic tasks for the constraint group indicated a median gain of 6 points at the end of training (median = 32) as compared to pre-test (median = 26, 19% gain), with a significant effect of training block, Friedman ANOVA = 30.74, $p < .001$ (Figure 4B). Pairwise comparisons between consecutive blocks showed the following significant differences across the training blocks: TB1 > pre-test ($\Delta = 3.11$, $d = .84$), TB2 > TB1 ($\Delta = 1.56$, $d = .67$) (p values < .05). For the full group, results indicated a median gain of 2.5 points at the end of the training program (median = 28.5) as compared to the pre-test (median = 26, 10% gain), with a significant effect of training block, Friedman ANOVA = 20.00, $p < .001$. Pairwise comparisons between consecutive training blocks showed significantly higher scores in the TB1 than in the pre-test ($\Delta = 1.50$, $d = .54$, $p < .05$).

Between-group comparisons. Comparisons between the two groups per training block indicated significantly higher values for the constraint group in TB2 ($\Delta = 3.00$, $d = 1.27$, $p = .01$), TB3 ($\Delta = 3.18$, $d = 1.35$, $p = .005$), and TB4 ($\Delta = 3.24$, $d = 1.56$, $p < .001$). Between-group comparisons of proportional change at the end of the training program indicated no significant differences ($\Delta = 13.93\%$, $d = .76$, $p = 0.11$).

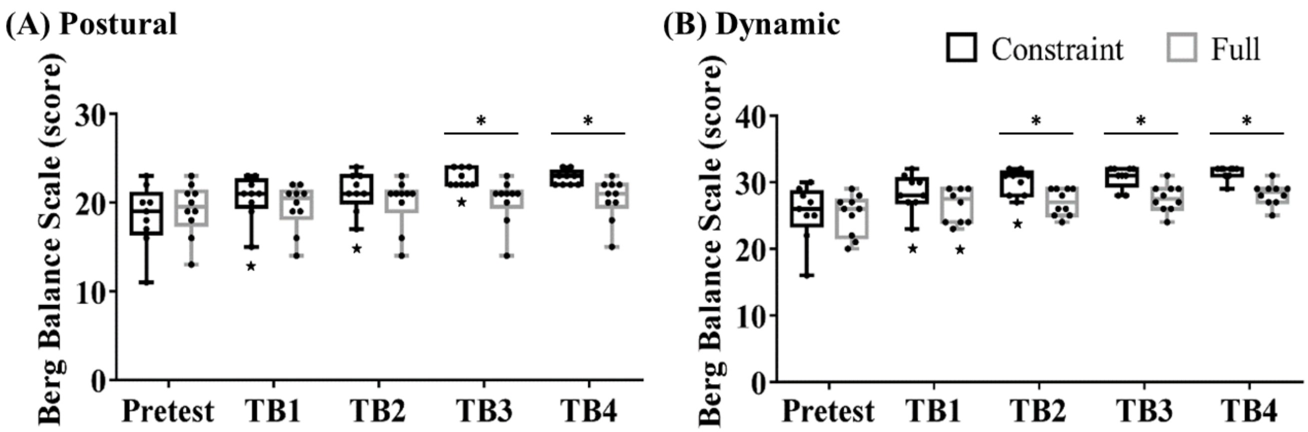

Figure 4. Comparison of median and individual values (first and third quartiles indicated by box limits) of Berg Balance Scale scores between the constraint and full groups in the pre-test and after each training block (TB1-TB4) separately for the (A) postural (maximum score: 24) and (B) dynamic (maximum score: 32) balance tasks; asterisks indicate significant difference between groups, and black stars indicate intragroup differences to the preceding block or pre-test.

Timed Up and Go (TUG)

Intra-group between-block comparisons. Intragroup analysis of the TUG test for the constraint group showed a median time reduction of 6 s at the end of training (median = 11 s) compared to the pre-test (median = 17 s, 35% reduction), with a significant effect of training block, Friedman ANOVA = 30.67, $p < .001$. Pairwise between-block comparisons indicated decreasing completion times between several adjacent training blocks, as it follows: TB1 < pre-test (Δ = 4.00 s, *d* = .48), TB2 < TB1 (Δ = 1.78 s, *d* = .30), and TB4 < TB3 (Δ = 1.89 s, *d* = 1.35) (*p* values < .05) (Figure 5). For the full group, results indicated a median time reduction at the end of training of 4 s (median =13 s) as compared to pre-test (median = 17 s, end, 17% reduction), with a significant effect of training block, Friedman ANOVA = 17.63, $p < .005$. Pairwise between-block comparisons showed that the time to complete the test was significantly shorter in TB4 than in TB3 (Δ = 1.30 s, *d* = .30).

Between-group comparisons. Between-group comparisons per block indicated no significant differences across the training blocks ($p > .05$). Between-group comparisons of proportional change at the end of the training program indicated significantly greater time reduction in the constraint than in the full group (Δ = 16.48%, *d* = 1.04, *p* = 0.03).

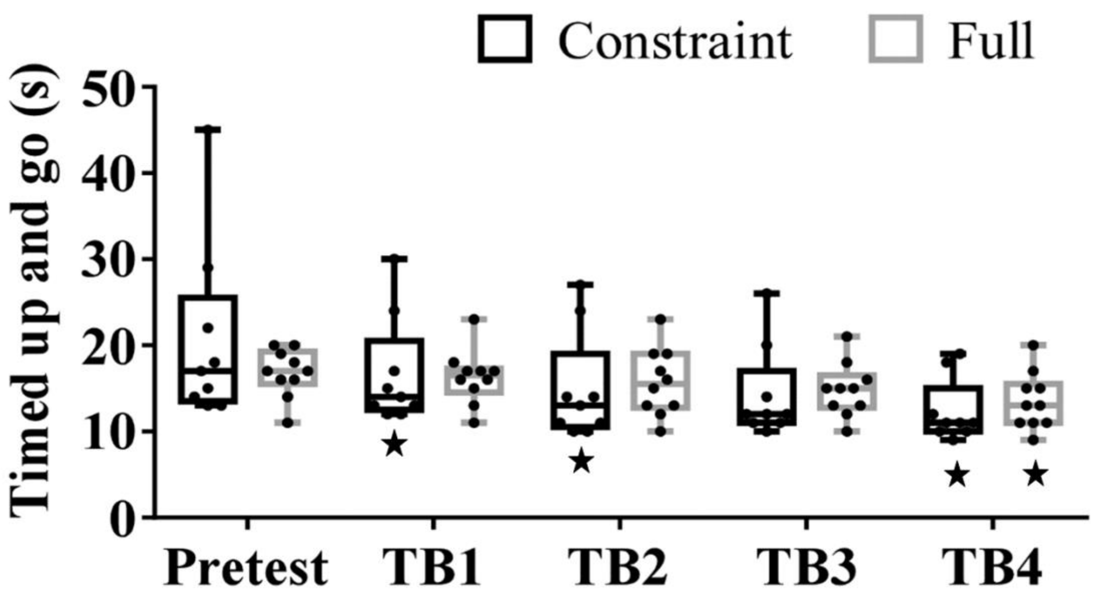

Figure 5. Comparison of median and individual times (first and third quartiles indicated by box limits) achieved in the Timed Up and Go test between the constraint and full groups in the pre-test and after each training block (TB1-TB4); black stars indicate intragroup differences to the preceding block or pre-test.

DISCUSSION

In this controlled randomized trial, we evaluated gains from balance training under combined and progressive sensory constraints on performance of clinical tests requiring postural/dynamic balance and mobility, having as control training with full sensory information. Results showed incremental gains in consecutive blocks in the global score of BBS scores when training under visual constraint, and further gains in the third training block when tactile/proprioceptive information was constrained. In contrast, training with full sensory information led to gains in consecutive blocks only when comparing the first training block and the pre-test evaluation. The higher performance of the sensory constraint than the full sensory information group was observed in all training blocks with separate or combined sensory constraint. Analysis of TUG indicated more noticeable gains between consecutive training blocks for the sensory constraint compared to the full group, with significantly lower performance times between consecutive training blocks in most comparisons, including combined (TB4) and tactile/proprioceptive (TB3) manipulations, with a proportional higher improvement of the constraint compared to the full group. There were no falls or adverse events experienced during the balance training or testing.

A point worth noticing in our results is that constraint of different sources of sensory information relevant for balance control across training blocks were shown to magnify training-related balance gains. Previous investigations have suggested that vision deprivation is more effective than distorting tactile/proprioceptive information during balance training for stroke rehabilitation [22]. Further results indicated that combining manipulation of visual and tactile/proprioceptive information during the whole balance training program can lead to superior results than regular sensory unrestricted training [23]. Our results add to the previous findings by showing gains in both postural and dynamic tasks of BBS over three-session training blocks, while individuals training the same movements under full vision achieved limited gains only. Then, we showed that a few training sessions under either visual or proprioceptive sensory constraint are able to lead to cumulative balance gains in different task categories. These results supported our hypothesis of superior performance gains when training body balance in the regime of progressively constrained sensory information.

Considering the relevance of visual and proprioceptive information for balance control, a relevant question to be discussed is what could explain the superior gains from training under sensory constraint. Previous studies have suggested that stroke leads to a reorganization of intersensory integration, resulting in greater dependence on vision compared to proprioceptive inputs when standing [15-16,20]. Increased dependence on vision for balance control in individuals with chronic stroke may be associated with impoverished ankle proprioception [11], a source of sensory feedback particularly important for balance control [33-34]. This sensory deficit can be thought to lead the sensorimotor system to increase the use of vision for balance control as a reliable source of feedback for control of postural stability [35-36]. When vision is suppressed during training, the available sensory sources (tact from the feet soles, ankle proprioception, and vestibular signals) are conceived to be upweighted in the sensorimotor system responsible for body balance control. This enforced use of nonvisual feedback sources during balance training can be thought to lead to a sensorimotor reorganization, promoting a more regular use of tactile/proprioceptive feedback when full vision is restored.

Our findings of increased postural and dynamic balance gains from balance training on a malleable surface in TB3 are consistent with previous findings in neurotypical young [37-38], older [39-40], and neurologic [41] individuals. As standing on a malleable surface provokes increased body sway [8], a possible interpretation is that further use of information from the vestibular apparatus was required for balance stabilization during training on foam. This situation might favor reactivation of regular integration of vestibular information with visual input for head stabilization in space, leading to improved balance control. Additionally, a possible mechanism supporting balance improvement by training on a malleable surface is attenuation of reflex excitability while increasing cortical participation in balance control. Supporting evidence for this proposition was provided by Hoffman and Koceja [42] by showing that body support on an unstable support base leads to a reduced H-reflex gains in the lower limbs. Further results showed that diminished H reflex excitability can be retained by regular balance training on a malleable surface [43-44]. Reduced reflex excitability has been conceptualized to be due to suppression of Ia-afferent excitation to the alpha-motoneurons, attenuating excessive joint oscillations due to automatic spinal circuits, with resulting postural stabilization [45]. Furthermore, diminished participation of peripheral circuits has been shown to be associated with increased control by the cerebral cortex [45-46]. Further results have evidenced that standing on a malleable surface lead to reduced intracortical inhibition, an effect particularly true for older individuals [47]. These results support the interpretation that balance gains specifically from distorting sensory information from the lower limbs and feet soles by training on a malleable surface are due to some extent to diminished participation of poorly controlled peripheral reflexes and increased participation of cortically-mediated balance regulation.

Particularly for the BBS, in the fourth training block there was diminished room for improvement, due to the ceiling effect, compared to the previous blocks. In this regard, it should be noted that the large dispersion of results mainly across participants of the constraint group was considerably reduced over the training blocks. This observation includes an outlier of the constraint group at the pre-test evaluation contrasting to rather similar scores within this group in the last evaluation made after TB4, with scores for all participants being at or near the maximum score in the BBS test. This result means that the sensory constraint training was effective to improve balance control of all participants of the constraint group in different tasks comprised by BBS to a performance level equivalent to a neurotypical individual (cf. [48]). Our finding of better performance in the combined constraint of vision and proprioception (TB4) than in the single manipulation of proprioceptive information in the preceding training block (TB3) in the TUG test suggests that association of sensory constraints can produce higher mobility gains, supposedly due to improved dynamic balance control, than constraining single sensory sources as we did in the previous training blocks (TB3 and TB4). Detection of further gains in TB4 in the TUG test was favored by inexistence of a ceiling measurement, as it is based on completion time.

Although this preliminary investigation on the effect of a specific sequence and combination of sensory constraints on training-related balance gains lacks control groups receiving the whole training under a constant sensory constraint, we speculate a potential advantage of our sequential strategy leading to augmented balance improvement over training blocks. Preceding results have shown that suppression of vision in dynamic balance control initially leads to increased challenge to maintain center of mass on the support base, as indicated by greater amplitudes of feet center of pressure displacement and magnitude of muscular activation of the lower limbs [49], and delayed stability recovery following balance perturbations [50]. On the other hand, Schmidt et al. [49] showed exponential adaptation over a few minutes when performing a dynamic balance task under visual constraint, with muscular activation and center of pressure sway becoming progressively more similar to values observed in performance under full vision. In the context of a balance training program, we conjecture that performing voluntary movements under visual or proprioceptive constraints leads to sensorimotor adaptation as well, hypothetically making a sensory constraint progressively less challenging to balance control as the training program is developed. From this perspective, manipulation of different sensory sources during balance training and their combination may demand further attentional resources [51-52] and cortical activation [53-54] important for motor learning, leading to increased body balance. An additional point to be considered as a potential benefit of constraining different sources of sensory information during training is diminished reliance on feedback-based and increased use of anticipatory-based balance control. Given that anticipating the consequences of self-produced movements is required for stable dynamic balance [55-56], constraining different sources of sensory feedback during training can be thought to increase the preeminence of anticipatory over feedback control. Such an increased participation of anticipatory processes might favor balance control in different dynamic tasks by developing a newly learned internal model, with the challenge imposed by diverse sensory constraints leading to generalization to untrained self-produced movements and postures [57]. In this case, sensory feedback would be used only to correct small errors in predicting the consequences of voluntary movements to body balance (cf. [50]).

This study has limitations to be considered in the interpretation of results. There is an age difference between the groups, with younger participants in the constraint group, which may have affected the training effects. The limited number of participants lead to increased risk of bias due to individual differences of responsiveness to the tested balance training protocols. Achievement of the ceiling score in BBS postural and dynamic balance tasks by several participants may have prevented detection of further performance improvements over training blocks. To corroborate our conjecture that constraining different sensory sources and their combination over balance training sessions is potentially more beneficial than maintaining a constant sensory constraint, results from our procedures should be compared against results of whole training programs manipulating a single sensory constraint or their combination from the outset in further investigation. Our study lacked a follow-up evaluation to test for persistence of the documented gains immediately after the training sessions and the whole program.

CONCLUSION

As the main conclusion, our results showed that the protocol of body balance training based on a combination of visual and proprioceptive constraints for stroke survivors led to greater performance gains in postural and dynamic balance tasks over the training blocks in comparison with a conventional balance training receiving full (unconstrained) sensory information. As a relevant clinical application, our findings indicate the efficacy of constraining different sources of sensory feedback and their combination during balance training to achieve improved rehabilitation of body balance in chronic stroke survivors. As individual data indicated, this effect was consistent across participants, which suggests its potential to induce balance improvements also in those individuals who had their balance more extensively affected by the cerebral infarction.

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