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Neuroadaptive Balance Training to Reduce Fall Risk in the Elderly

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Abstract: *Falls among older adults are often associated with age-related decline in sensorimotor integration and postural control. Perturbation-based balance training (PBT) is increasingly recognised for its role in enhancing stability through targeted motor adaptations. This study examines the functional effects of a two-week PBT intervention on balance and fall risk in elderly individuals (aged 75–92), using Tinetti, TUG, and Romberg assessments. Significant post-intervention improvements in the experimental group suggest that PBT may facilitate sensorimotor recalibration and promote neuroadaptive balance strategies. While neurophysiological mechanisms were not directly assessed, the observed functional gains point to enhanced central integration of proprioceptive feedback and motor planning. These findings underscore the potential of task-specific, reactive balance training as a neurorehabilitation strategy for fall prevention in geriatric cohorts. Despite the absence of neurophysiological instrumentation, the improvements suggest underlying cortical and subcortical adaptations that warrant further investigation. Future studies should incorporate wearable sensors, electromyography, or neuroimaging modalities to characterise neuroplastic modifications and assess the retention of motor learning. These additions could help optimise intervention design and better personalise fall prevention strategies for older adults.*

Keywords: *neuroplasticity; perturbation training; fall prevention; elderly; sensorimotor control; balance.*

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1. Introduction

Falls occur annually in approximately 30% of adults aged over 65 years (Ganz & Latham, 2020). In addition to personal suffering, falls and the resulting injuries represent a significant public health concern due to their association with an increased risk of disability, hospitalisation, institutionalisation, and subsequent mortality. In Europe, the total number of deaths has steadily increased since 1990. The Global Burden of Disease study reported nearly 17 million years of life lost due to falls in 2017 (James et al., 2020; Haagsma et al., 2020). The associated social and economic consequences are significant, and in high-income countries, approximately 1% of healthcare costs are related to falls (O'Mahony et al., 2015).

The incidence of falls is higher among older adults living in care homes or during hospitalisation (Shao et al., 2023; Özen, Ceyhan, & Şimşek, 2023; Long et al., 2022). This disparity implies that context-specific risk factors may exist, necessitating differentiated prevention strategies.

While falls pose an injury risk to all individuals, older adults are particularly susceptible. This heightened vulnerability is attributed to physical, sensory, and cognitive changes linked to aging, as well as environments that are not designed for older individuals (Tsujishita, Nagamatsu, & Sanada, 2022; Lin et al., 2022).

Major biomechanical perturbations during walking, such as slips or loss of balance, are responsible for the majority of falls among the elderly living in the community (Crenshaw et al., 2017).

Interventions aimed at reducing potential falls in older adults and those with pathological balance impairments have received considerable attention in the literature, with recent studies focusing on the topic (Cameron et al., 2018; Fan, 2020).

Current research supports the effectiveness of physical exercise in fall prevention, with training that induces body imbalances being one of the most effective methods (Fan, 2020; Sibley et al., 2021).

Balance training that disrupts overall body stability has shown promising outcomes in reducing the risk of falls during daily activities among older adults, while also demonstrating clinical feasibility (Rosenblatt, Marone, & Grabiner, 2013; Pai et al., 2014; Lurie et al., 2022).

The aim of Perturbation Balance Training (PBT) is to specifically improve the ability to restore postural stability in situations where balance deficits occur, such as when falls result from slipping or tripping. PBT must meet two key criteria: first, it must involve unexpected external perturbations that trigger a motor response, and second, these disturbances should be intense enough to cause a loss of body stability, simulating a fall. Another essential characteristic of this training is that it applies imbalances during daily activities, like walking or transitional movements (such as sitting to standing), which frequently represent contexts in which older adults are prone to falling (Robinovitch, 2018; van Schooten et al., 2018; Yang et al., 2018).

Postural destabilisation exercises can be manually induced by the physiotherapist (Mansfield et al., 2018; Marigold et al., 2005) or through devices such as treadmills (Gerards et al., 2023; Steib et al., 2017), stability platforms (Ribeiro de Souza et al., 2023; Mansfield et al., 2010), or customised sliding/displacement walkways (Okubo et al., 2019).

PBT requires additional safety measures compared to traditional balance training. For example, safety harnesses are commonly used when applying high-intensity external perturbations. However, when less intense external disturbances are used by the physiotherapist, training can be performed without extra safety equipment. Despite this, both the therapist and the patient need to be aware of their physical thresholds, and having a second therapist present to assist with stability is recommended (McCrum et al., 2022).

A study comparing three types of interventions (perturbation training, conventional balance training, and no training) applied to older adults concluded that perturbation training reduced the likelihood of falls, improved balance confidence, and increased the quality of life for the participating cohort (Arghavani, Zolaktaf, & Lenjannejadian, 2020).

In recent years, interest has grown in understanding the neural substrates of balance recovery, particularly the contributions of cortical and subcortical structures involved in processing perturbations. Functional neuroimaging studies suggest that reactive balance tasks activate regions such as the supplementary motor area, cerebellum, and basal ganglia, highlighting the brain's adaptive neuroplastic response to external destabilisation. These findings support the integration of perturbation-based training within neurorehabilitation frameworks for aging populations (McCrum et. al., 2022).

This study aimed to evaluate the impact of Perturbation Balance Training (PBT) on improving balance and reducing falls in older adults who have experienced balance disorders in the past six months. The hypothesis was that the group undergoing PBT would show greater improvements in balance and functional performance compared to the control group receiving conventional physiotherapeutic interventions.

2. Review of the Specialised Literature

A systematic review on the incidence and risk factors of falls among older adults residing in nursing homes highlighted that the cumulative incidence of falls was 43% (Shao et al., 2023).

In the specialised literature, there is evidence supporting the effectiveness of perturbation balance training (PBT) in significantly reducing the risk of falls in healthy older adults living in the community, individuals with Parkinson's disease, and those who have had a stroke (Pigman et al., 2019; McCrum et al., 2022). It has also been found that PBT improves the ability to recover balance following disturbances in frail older adults in institutions (Aviles et al., 2019).

In addition to improving balance and reducing the incidence of falls, body imbalance-based balance training can significantly reduce the fear of falling (Paquette et al., 2015). Research conducted so far has shown that the frequency of this type of training has varied from a single session (Pai et al., 2014) up to 3 sessions per week, for 8 weeks (Unger et al., 2021). For example, one study demonstrated a 50% reduction in the incidence of falls in the daily lives of older adults living in the community, after a single training session (which involved repeated exposure to 24 slips), and these results were maintained after a 12-month follow-up period (Pai et al., 2014).

Beyond physical outcomes, recent theoretical models suggest that perturbation-based interventions engage neurocognitive systems responsible for sensorimotor coordination, error detection, and motor planning. Functional connectivity analyses have shown increased activation in the cerebellum and sensorimotor cortex following repeated exposure to balance disturbances, implying adaptive neuroplastic changes. Moreover, PBT is increasingly studied in relation to cognitive-motor interference, revealing its potential to enhance executive control during postural tasks, which is critical for fall prevention in dual-task scenarios commonly encountered in real life.

3. Materials and Methods

To analyse the effectiveness of the training program based on the induction of body imbalances (PBT), two groups of participants aged between 75 and 92 years were constituted. The intervention group (n = 31, mean age = 83.48 years) underwent perturbation-based balance training, while the control group (n = 31, mean age = 80.74 years) received standard group physiotherapy. The study was conducted in May 2024; all participants who were included in the study expressed their agreement in writing through informed consent, to participate in the research; they have been informed about the objectives, potential risks and benefits of participating in this program as well as the possibility to withdraw from it at any time. They were also informed that the collected data would remain confidential, anonymised, and would be used only for research purposes.

Inclusion criteria comprised individuals aged over 65 years with a documented history of falls attributable to balance impairments within the past six months, and who had not recently completed any other balance-focused exercise programme. The exclusion criteria included acute neurological disorders, uncorrected visual disturbances, recurrent dizziness of unknown aetiology, significant cognitive deficit, and lower limb amputations. Subjects in the study group performed perturbation training for two weeks, one session per day, and the duration of one session was ~30–40 minutes.

The two-week implementation period was selected based on evidence from the specialised literature, which has observed improvements in the endurance of adults living in the community even after a single complete training session (Pai et al., 2014). Additionally, a study with a total of four training sessions also showed positive effects on endurance of seniors in the community, although these effects were not sustained in the long term (Nørgaard et al., 2024).

Each PBT session included a 3-5 minute warm-up (breathing exercises involving the upper limbs, warming up the ankles with toe-heel rolling exercises, walking in place for 1 minute), 15-20 minutes of exercise with the induction of body imbalances by the therapist and a 5-10 minute recovery period after the effort. The exercise protocol took place in the gymnasium of the "St. Parascheva" retirement home, and the participants worked individually with the physiotherapist, who constantly supervised them during the exercises. To reduce anxiety levels, the participants were informed from the initial assessment about the disturbances that would be applied during the exercises. In addition, two or three demonstrations were carried out before the actual training. For example, during the exercise of moving forward on the mats, while walking, the therapist applied six external perturbations (2 from the side by pushing at the level of the right shoulder, respectively left shoulder, 2 thrusts at the sternal level, and 2 thrusts at the thoraco-dorsal level). The participants were also informed that the purpose of applying these intentional body imbalances was to practice strategies for regaining balance (through the action of stepping) after the therapist's intervention produces this instability. Through the exercises, possible fall risk situations in everyday life were simulated, and effective motor responses were trained so that a possible fall could be avoided.

Postural perturbations were introduced once the participants were able to perform the tasks requested by the therapist easily and without losing balance. Each session included approximately 60 balance perturbations (6 perturbations per exercise). The six perturbations involved push or pull (on the trunk - anterior/posterior, shoulders - from the side/front-back) applied by the physiotherapist during the exercises.

The voluntary tasks during which the perturbations were applied were: walking forward/backward with legs in tandem, shifting weight from one leg to the other for two minutes, alternate step on a step sitting on a mat, walking on mats 5 cm thick, walking on a straight line of 3 m (marked on the ground with black non-slip tape) simultaneously with alternating turning of the head to the right and left, walking forward respecting the marking on the route - description of the number 8, walking on a route with obstacles, walking on the electric treadmill.

Although the intervention primarily targeted physical balance, its design indirectly engaged neural circuits involved in sensorimotor integration, anticipatory postural control, and reactive stepping. Recent research suggests that perturbation training may induce neuroadaptive modifications in the supplementary motor area, cerebellum, and basal ganglia, reducing postural response latency and interlimb coordination (McCrum et al., 2022; Steib et al., 2017). Functional neuroimaging in older adults has demonstrated increased activity in the dorsolateral prefrontal cortex and superior parietal lobule following balance training involving unexpected perturbations (Papegaaij et al., 2014). These adaptive mechanisms may underlie the observed behavioural improvements.

The subjects in the control group performed a group physiotherapy program (1 therapist per 6 participants) aimed at osteoarthritis, with the same frequency, the same duration of the recovery session, respectively, ~30-40 minutes a day, for two weeks.

The tests used to monitor the effects of the intervention were the Timed Up and Go test ("Get up and go"), the Tinetti scale to evaluate the risk of falling, but also the quality of walking, and the Romberg test to assess balance. The tests were applied before the implementation of the recovery protocols and at their completion.

The Tinetti scale consists of two components: the balance test and the walking test. It evaluates actions such as sitting unsupported, rising from sitting, sitting from standing, standing unsupported, standing with eyes closed, turning 360°, and lumbar flexion. Each action is rated based on the individual's ability to perform the task using either 2 (0 and 1) or 3 levels (0, 1, and 2). The test also examines key elements of walking (step initiation, step length, step continuity, deviation of the walking path, trunk movement), all at the subject's own pace. The total score (maximum of 28 points) reflects the presence or absence of a fall risk (Uysal, Cetisli-Korkmaz, & Cavlak, 2020; Scura & Munakomi, 2022).

The Timed Up and Go (TUG) test was used to assess an elderly patient's ability to walk 3 meters; if an older adult takes more than 12 seconds to complete the TUG, they are considered at risk of falling (Chen & Chou, 2024; Reis et al., 2024).

The Romberg test was used to assess static balance in the standing position, with the feet placed together and the arms held alongside the body. The test is considered positive if the patient falls or is unable to maintain balance with their eyes closed (Forbes, Munakomi, & Cronovich, 2023; Gallamini et al., 2021).

Although no neurophysiological tools (e.g., EEG, EMG, or fNIRS) were utilised in this study, the protocol was specifically designed to challenge postural reflex circuits and facilitate adaptive motor learning. Findings from related studies employing surface EMG suggest increased activation of reactive muscle synergies following perturbation exposure, reinforcing the role of spinal and supraspinal adaptation (Mansfield et al., 2015). Future studies should consider incorporating neurophysiological assessments to objectively quantify cortical and neuromuscular engagement.

For the statistical analysis of the data obtained from the initial and final tests in the two groups, we used SPSS (Statistical Package for the Social Sciences), a widely used statistical analysis software in research, and applied the following tests: paired t-test and independent t-test.

The Paired t-test was used to compare the initial results with the final results, post-intervention, within the same group, and was applied to both groups (comparing balance, gait, and fall risk results obtained from the Romberg test, the Tinetti scale, and the Timed Up and Go (TUG) test).

The Independent t-test was applied to compare the means between the two groups (which received different treatments: the experimental group and the control group) at the final moment (post-intervention), to determine whether the interventions produced statistically significant differences in the obtained results.

4. Findings

At baseline, both groups recorded low and medium scores in the Tinetti tests (mean score: 20.75 out of a maximum of 28) and TUG (average score - 7.96 seconds out of 12 seconds/participant) and in the Romberg test 43 participants out of 62 had a positive Romberg test (24 participants in the study group and 19 participants in the control group)

Low scores on these tests are common in the elderly who often experience balance disorders and consequently, an increased risk of falling as they age (Johnson et al., 2020).

Regarding the evaluation with the Tinetti scale, the activities that obtained the lowest scores were those of orthostatism with closed eyes, 360° turning, sternal bending, deviation of the walking path, and swinging the trunk.

Table 1. Initial and final Tinetti evaluation for the study and control group

Tinetti_Initial	Study group	31	21.1613	1.39276	P 0,096
	Control group	31	21.8387	1.71458	
Tinetti_Final	Study group	31	25.0645	1.26321	P 0,000
	Control group	31	23.4194	1.43235	

According to Table 1, following the application of the perturbation-based training and the group physiotherapy program, at the final test with the Tinetti scale (Table 1), improvements were observed compared to the score obtained initially in both groups; more important changes were obtained in the study group, with scores increasing by 2 to 5 points, while in the control group the final score increased by only 1–2 points. These differences were statistically significant ($p < 0.001$). The activities that obtained the highest scores were the 360° turn, the deviation of the walking route, and the continuity of the steps.

These improvements align with previous findings indicating that perturbation-based interventions facilitate adaptations in postural control strategies, potentially through enhanced sensorimotor integration and anticipatory cortical mechanisms (Papegaaij et al., 2014; McCrum et al., 2022).

Further improvements were observed in the TUG test (Table 2), where participants in the intervention group completed the course up to 2 seconds faster than at baseline ($p < 0.001$). In contrast, only 13 participants in the control group showed a reduction of 1 second in completion time.

Given that TUG assesses both dynamic balance and executive control during locomotion, the improved performance may reflect enhanced motor planning and accelerated neuromuscular responses, mechanisms supported by increased cortical excitability and reduced reaction latency after balance training (Mansfield et al., 2015; Steib et al., 2017).

Table 2. Initial and final testing TUG study group and the control group

TUG_ Initial	Study group	31	16.9355	1.09348	P 0,731
	Control group	31	17.0323	1.11007	
TUG_ Final	Study group	31	14.8065	.90992	P 0,000
	Control group	31	16.3871	1.47597	

At the final Romberg testing (Table 3), it was noted that in the case of the study group, if at the beginning there were 24 subjects with Romberg positive and 7 subjects with Romberg negative, at the final testing, there were 20 subjects with Romberg negative and only 11 subjects with Romberg positive. In contrast, the control group showed no clinically significant change: at baseline, 19 participants had a positive Romberg and 12 a negative one; at the final test, 15 were positive and 16 negative.

Table 3. Initial and final testing Romberg study group and the control group

Romberg_Initial	Study group	31	1.2258	.42502	P 0,174
	Control group	31	1.3871	.49514	
Romberg_Final	Study group	31	1.6452	.48637	P 0,311
	Control group	31	1.5161	.50800	

Romberg test outcome depends on the integration of visual, vestibular, and proprioceptive inputs. The notable improvement in the experimental group may indicate a recalibration of proprioceptive feedback pathways and possibly cerebellar-mediated balance adjustments, as discussed in neurorehabilitation frameworks for elderly adults (Papegaaij et al., 2014; Aviles et al., 2019).

5. Discussions

Previous studies implementing this type of therapeutic approach have shown positive effects of PBT in improving balance in the elderly. There is evidence to suggest that PBT can reduce falls in everyday life by up to 40-50% (Okubo, Schoene, & Lord, 2017; Mansfield et al., 2015; Devasahayam et al., 2022).

The results obtained following the application of the two therapeutic methods showed significant improvements in balance in the study group (at the final test there were only 11 subjects with a positive Romberg and the other 20 obtained a negative Romberg) Additionally, the values of the Tinetti Scale showed an increase in scores by 2 -5 points, and a reduction of up to 2 seconds in TUG performance time. In contrast, outcomes in the control group were largely unchanged, with final scores either maintained or showing only minor, non-significant improvements.

Furthermore, the statistical analysis revealed that the P values obtained from the T-test were below 0.05, indicating that the differences between the two participant groups are statistically significant.

These results highlight the fact that balance training based on balance perturbations has beneficial effects in improving balance and reducing the risk of falls in the elderly.

We hypothesised that the study group would demonstrate significant improvements over the control group, which was confirmed by the statistical results presented; the scores on the Tinetti, TUG, and Romberg tests improved in the study group, with statistically significant differences observed between the groups of analysed participants.

Beyond these statistical differences, the neurofunctional implications of PBT are particularly relevant. Studies using fMRI and EEG have demonstrated that reactive balance tasks lead to increased activation in the cerebellum, supplementary motor area, and parietal cortex, regions involved in anticipatory and compensatory postural control (Papegaaij et al., 2014). This suggests that the improvements observed in our study may be mediated by enhanced integration of proprioceptive input and sensorimotor feedback loops.

Additionally, perturbation training has been associated with improved dual-task performance in elderly individuals, indicating a possible cognitive benefit through improved executive control during motor challenges (Weerdesteyn et al., 2006; Silsupadol et al., 2006). While our study did not directly assess cognitive outcomes, such effects could support a broader neurocognitive rehabilitation role for PBT.

A review of the literature on the impact of perturbation-based balance training concluded that balance, lower limb strength, and quality of life were improved using this method in the elderly (Bhagwat & Deodhe, 2023). A study conducted in Iran involving 60 elderly individuals with a history of at least one fall in the past 6 months found that perturbation training not only reduced the risk of falling but also enhanced self-confidence in basic activities and improved overall quality of life (Arghavani, Zolaktaf, & Lenjannejadian, 2020).

Research comparing the effects of body imbalance training, hip stabilisation exercises, and fall risk in older adults suggests that combining perturbation training with strength exercises can provide additional benefits (Rogers et al., 2021).

A study conducted in Denmark from March 2021 to November 2022 shows that 140 seniors aged over 65 participated in four sessions (20 minutes long each) of either perturbation-based balance training (intervention group) or regular treadmill walking (control group). Research concluded that perturbation training improved (short-term) reaction time and walking speed among elderly individuals in communities (Nørgaard et al., 2024). The fact that the results obtained were not maintained in the long term (the follow-up period was 6 months and 1 year) suggests that the number of sessions performed, the frequency, and the period of implementation are very important in the success of this method.

Also in the literature, we find studies that include perturbation training interventions with longer implementation periods (over 4 weeks) in the elderly, people in the community, and in patients with Parkinson disease that have shown physical improvements, cognitive, and psycho-social (Shen & Mak, 2015; Steib et al., 2017).

Some authors suggest that exercises focused on inducing body imbalances should be considered as part of a multicomponent training program, rather than a standalone intervention. An exercise programme that includes mobility, strength, balance, and coordination components has been demonstrated to be the most effective in enhancing overall physical and cognitive functioning in older adults (Casas-Herrero et al., 2022; Giné-Garriga et al., 2014; Schoene et al., 2014).

The inclusion of perturbation-based exercises in multi-component training programs could decrease the risk of falls in seniors with special attention to dosage and implementation period (Grabiner et al., 2014; Nørgaard et al., 2021).

Balance training based on perturbations appears to be a promising approach for fall prevention in older adults. This task-specific balance training, which involves repeated exposure to sudden disturbances, could represent a paradigm shift that may improve the effectiveness of fall prevention interventions, even with a relatively small number of training sessions. We believe that future research should include maintenance training sessions, since the optimal number of sessions, intensity of perturbations, and frequency are not universally agreed upon by authors, and the implementation period was only two weeks. Furthermore, future directions should incorporate objective neuropsychological assessments such as EMG latency mapping, transcranial magnetic stimulation (TMS) to assess motor cortex excitability, or wearable EEG to monitor cortical responses during perturbation. Such multimodal integration would clarify the neural mechanisms underlying observed functional gains and strengthen the case for perturbation training as a neurorehabilitative method.

6. Conclusions

This study's purpose was to evaluate the feasibility of a balance training approach that incorporated unexpected perturbations during exercise for individuals aged 65 and older.

The findings from the final tests indicated that training involving postural instability, such as perturbation balance training, had positive effects on improving balance and reducing the vulnerability to falls in older adults. Disturbance-based balance training could complement traditional exercise programs in fall prevention strategies. However, further research is needed to determine the ideal frequency, dosage, progression, and duration of perturbation training to enhance postural responses in this population. The program requires a follow-up period to assess the maintenance of the obtained results and to implement a strategy for sustaining the effects (at 1 month/twice a month).

The study's results emphasise that the implemented exercise program had a substantial effect on the measured outcomes, indicating its effectiveness. This suggests the potential for continuing, refining, or further advancing the exercise program that incorporates body imbalance induction to enhance its practical application and benefits.

In conclusion, within the group of the present study, which included older adults with balance disorders, the proposed approach was feasible. This study suggests that perturbation training can enhance balance function and lower the risk of falls in older adults living independently.

In addition to functional improvements, the observed gains may reflect central adaptations in postural neuromotor regulation, particularly involving the cerebellum, basal ganglia, and cortical sensorimotor integration pathways. These findings support the inclusion of perturbation-based methods in neurorehabilitation protocols targeting age-related declines in postural control.

Future studies should integrate neurophysiological markers (e.g., EMG latency, fMRI connectivity, or EEG-based cortical response) and examine retention over extended periods to fully elucidate the underlying mechanisms. The incorporation of task-specific, neuroadaptive training into broader fall prevention models may contribute significantly to healthy aging and independence in the elderly population.

7. Limitations of the study

The programme was implemented exclusively among institutionalised older adults, with a relatively small sample of 31 participants residing in a retirement home in Iași, and there was no follow-up period to assess the maintenance of the post-intervention results.

Due to the participants' advanced age (over 80 years old), large-magnitude perturbations could not be applied, which is why we believe that in this population category, a longer time may be needed to implement the presented training programme effectively and maximise its benefits.

Moreover, with advancing age, the fear of injury and falling increases, and the unexpected nature of the disturbances from this type of training may heighten anxiety among elderly participants, therefore, effective strategies are needed to mitigate this.

We consider that with regard to this type of training, future studies are warranted to include also seniors from the community.

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