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Quantitative Assessment of the Effect of Instability Levels on Reactive Human Postural Control Using Different Sensory Organization Strategies

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Featured Application: By utilizing different combinations of instability levels and sensory input strategies, postural control can be intentionally destabilized, which can aid in training and rehabilitating individuals to better handle real-world balance challenges.

Abstract: Reactive postural control (RPC), essential for maintaining balance during daily activities, relies on a complex sensory system integrating visual, vestibular, and proprioceptive inputs. Deficits in RPC can lead to falls, especially in unpredictable environments where sensory inputs are challenged. Traditional rehabilitation often fails to prepare patients adequately for real-world conditions. This study aims to explore the effects of varying instability levels (ILs) and sensory integration strategies (SIS) on RPC by evaluating balance disturbances without applying additional external force. Twenty-five healthy participants (12 men, 13 women, 24.5 ± 6.1 years) performed balance tasks on Abili® platforms with adjustable ILs (0, 1, 2, 3) while altering sensory strategies (Basic, Visual, Proprioception, Vestibular) using the Modified Clinical Test of Sensory Integration and Balance (mCTSIB). RPC efficiency was measured using the 95th percentile confidence interval for chest movement's ellipsoid volume and average velocity, analyzed with Wilcoxon signed-rank tests and Cliff's delta effect size. Results showed significant increases in chest movement velocity and volume, particularly with the Vestibular strategy at higher ILs, with a 7176% increase in chest volume from Basic strategy at 0IL to Vestibular strategy at 3IL. Additionally, removing visual input (Visual and Vestibular strategies) had a greater impact on chest movement than increasing instability levels. These findings underscore the significant role of combined platform instability and reduced sensory input on postural control. This study presents a novel method for challenging balance and suggests that sensory integration with variable instability could be valuable in training and rehabilitation, even for healthy individuals.

Keywords: reactive postural control; sensory integration strategies; instability levels

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1. Introduction

Reactive postural control (RPC) in humans plays a critical role in maintaining balance and stability during daily activities [1]. This control is the ability of the body to respond quickly and effectively to unexpected perturbations or disturbances in the environment [2].

Postural stability is the ability of the body to maintain balance [3]. Human reactive postural control relies on a complex sensory system for its maintenance. This system includes visual, vestibular (inner ear balance), and proprioceptive (perception of joint and body movement) systems [1]. Each of these systems contributes unique information, and the brain integrates this data to determine the body's position in space and make the necessary adjustments to maintain balance [4,5]. Postural balance is the ability to keep the body's center of mass—its center of gravity—within the limits of stability by coordinating the forces acting on the body, such as gravity, muscle strength, and inertia [6].

Deficits in reactive postural control can lead to falls and related injuries, particularly in situations where sensory inputs are challenged, or the level of instability is high (i.e., shower floor) [7]. Many falls occur in unpredictable environments where reactive postural control is crucial for maintaining balance [8]. Postural control plays a crucial role in optimizing motor function performance and reducing the risk of injury, particularly in active individuals, where balance is essential for physical performance and injury prevention.

Traditionally, rehabilitation exercises might focus solely on improving strength and balance under controlled and predictable, or partially predictable, conditions [9–11]. However, this approach often fails to adequately prepare patients for the challenges they face in their daily lives [12].

Training patients in scenarios that closely mirror real-life situations, including different balance perturbation conditions, can enhance their ability to respond quickly and effectively, thereby reducing the risk of falls and related complications [13,14]. Accordingly, a methodological approach focused on reactive postural control perturbation, capable of simulating a wide range of daily life scenarios, may thus support balance training and rehabilitation procedures as part of patients' corrective or preventive measures.

Both the combination of different sensory inputs and varying levels of instability serve as common methods to perturb balance. These methods disturb balance by intensifying the body's internal oscillations: in the first case, by reducing sensory information, which leads to less effective corrective movements [15]; and in the second case, by altering the impact of internal corrective movements on the support area [16–18].

However, until now, little is known about how these two destabilizing pathways interact with each other and how their destabilizing effects can be compounded by their combinations [19]. Therefore, this study aims to evaluate the quantitative characteristics of reactive postural control disturbances by examining the effects of varying instability levels (ILs) and sensory integration strategies (SIS) on balance, without applying additional external force. Various combinations of instability levels and sensory integration strategies are tested to assess their influence on RPC.

2. Materials and Methods

2.1. Participants

Twenty-five healthy participants (12 males, 13 females; age: 24.5 ± 6.1 years, range 18–39; height: 172.8 ± 10.3 cm, range 155–190 cm; weight: 71.2 ± 14.9 kg, range 47.3–107 kg; BMI: 23.5 ± 3.6 kg/m^2, range 18.4–29.3 kg/m^2) volunteered for the present experimental study. Participants were screened for exclusion criteria through a pre-study questionnaire and interview. The exclusion criteria were as follows: history of neurological, musculoskeletal, or vestibular disorders; any injury or surgery affecting balance or postural control within the past 6 months; use of medications known to affect balance or postural control; and any condition that would make participation in the study unsafe or uncomfortable. In addition, a questionnaire detailing age and gender was filled out, and essential anthropometric criteria such as height, weight, and leg and arm length were measured. All participants provided informed consent before taking part in the study, in accordance with the principles of the Declaration of Helsinki.

2.2. Baseline Balance Assessment

The Y Balance Test (YBT), a comprehensive tool for balance evaluation, was used to assess the role of lower limbs in maintaining stability. This test provides valuable insights into potential weaknesses and asymmetries that could lead to injury, making it particularly useful for assessing dynamic balance and stability [20–22]. The YBT was performed in three directions (anterior, posterior-medial, posterior-lateral) with three attempts for both limbs. The Y Balance Test Composite score for each side was calculated using the following formula [23]:

$$Composite\ score = \frac{(Anterior + Posteriomedial + Posteriolateral)}{(Limb\ length \times 3)} \times 100$$

The Functional Reach Test (FRT) is a widely accepted method for assessing balance, with a special emphasis on the role of the upper body. This test measures an individual's stability by determining the maximum distance they can reach forward while standing in a fixed position [24]. Participants made three attempts using their dominant arm.

Taken together, these tests provide a holistic view of an individual's balance and stability, accounting for the critical roles of both the upper and lower body.

2.3. Sensory Integration

The combination of sensory inputs was adopted from the Modified Clinical Test of Sensory Integration and Balance (mCTSIB), which is widely used to evaluate an individual's ability to maintain balance under various sensory conditions. The mCTSIB systematically alters the availability of visual, proprioceptive, and vestibular information, assessing the individual's reliance on each sensory system for postural control and stability [24]. The test consists of four conditions, each with a unique combination of sensory inputs (Figure 1):

1. Eyes open, firm surface: This condition, hereafter referred to as "Basic", provides the individual with full visual, proprioceptive, and vestibular information, enabling them to rely on all three sensory systems to maintain balance.
2. Eyes closed, firm surface: In this condition, referred to as "Visual", visual input is eliminated, forcing the individual to rely primarily on proprioceptive and vestibular information for balance.
3. Eyes open, foam surface: This condition, referred to as "Proprioception", challenges the individual's proprioceptive system by providing an unstable surface while still allowing access to visual and vestibular information.
4. Eyes closed, foam surface: This condition, referred to as "Vestibular", presents the greatest challenge to the individual, as both visual and reliable proprioceptive inputs are removed, leaving only the vestibular system to maintain balance.

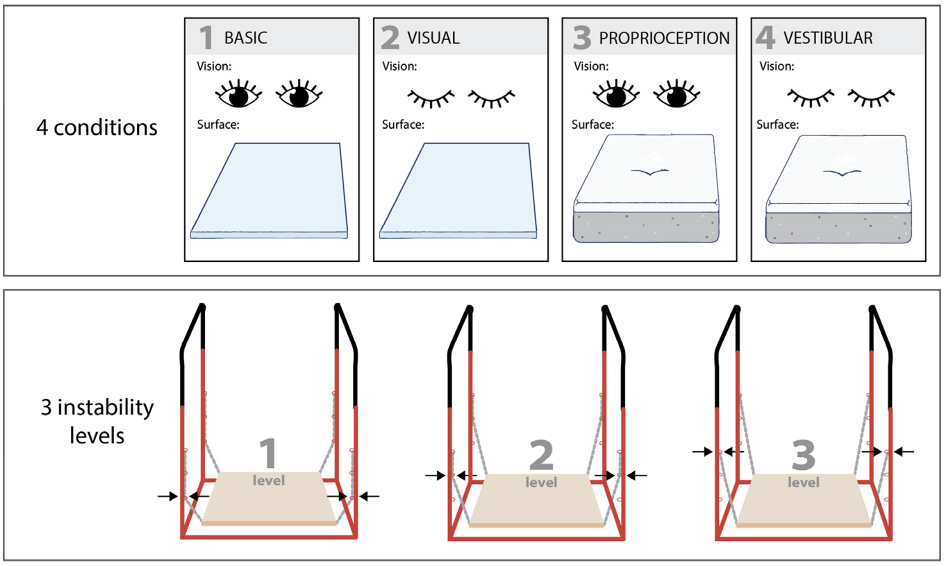

Figure 1. A representation of the testing conditions.

For the foam surface, we used the Airex Balance Pad Cloud® (Airex AG, Sins, Switzerland).

2.4. Instability Levels

To measure different levels of instability, we chose a single-plane balance platform, Abili Balance® (Ltd Abili, Kaunas, Lithuania). This tool is designed to assess an individual's balance performance under varying levels of instability. The different instability levels are adjusted by the length of the chains connected to a solid surface, thereby altering the suspension height of the platform (Figure 1). The length of the chains directly affects the difficulty of maintaining balance, with longer chains leading to greater instability. The instability levels are characterized by the force required to displace the balance board 1 cm with a 40 kg load (1 instability level—180 N, 2 instability level—70 N, 3 instability level—35 N) [25]. In this context, a 0-instability level refers to an absolutely stable surface, such as a normal floor.

2.5. Postural Control Testing

During the experiment, participants were instructed to maintain a standardized foot position, with their feet shoulder-width apart and parallel to each other. This ensured consistency in the starting posture across all participants and conditions, minimizing potential confounding factors in the analysis of postural control strategies. When participants had their eyes open, they were asked to look straight ahead at a bright red rectangle placed 5 m away. They were instructed to stay as still as possible and avoid moving the board. The sequence of the tests is shown in Table 1. Each participant completed a total of 16 postural control tests, each lasting 30 s. There was a 5-minute break between each instability level. During each test, to mitigate participant fatigue, appropriate rest periods were provided between trials.

Table 1. The sequence of the postural control tests.

ILs / SIS	Basic	Visual	Proprioception	Vestibular
0 IL	1	2	3	4
1 IL	5	6	7	8
2 IL	9	10	11	12
3 IL	13	14	15	16

2.6. Motion Capture

A Qualisys Mocap® (Qualisys AB, Göteborg, Sweden) system was used to capture the positions of the participants' chests along the x, y, and z axes at a frequency of 100 Hz. The motion capture system comprised multiple cameras situated around the testing area, which tracked reflective markers attached to the participants' bodies. Markers were carefully placed following standardized anatomical landmarks to ensure accuracy, and the motion capture system was calibrated before each session to optimize data precision and minimize measurement errors.

2.7. Data Analysis

In this study, Python 3 was utilized for data analysis and processing. The analysis incorporated libraries such as NumPy, Pandas, SciPy, Matplotlib, and Seaborn, which facilitated numerical operations, data manipulation, statistical analysis, and data visualization.

For each conducted test, the 95% confidence ellipsoid volume and the average velocity were calculated. The 95% confidence ellipsoid volume provides a measure of the spatial extent within which the data points for chest movement are expected to fall with a 95% confidence level. On the other hand, the average velocity represents the overall speed of chest movement in each direction.

2.8. Statistical Analysis

The Shapiro–Wilk test was used to evaluate the normality of the data. For the analysis of paired observations, such as instability levels and sensory strategies, the Wilcoxon signed-rank test was utilized. This test facilitated the comparison of paired observations, providing *p*-values to evaluate the significance of the differences observed. A *p*-value less than 0.05 was considered statistically significant. Additionally, Cliff's delta was used to measure the effect size, quantifying the magnitude of differences between groups. This measure of effect size aids in determining the practical significance of the differences observed.

3. Results

All participants completed all balance testing tasks, resulting in a total of 225 tasks for YBT, 75 tasks for FRT, and 400 tasks for the combination tests involving Instability Levels and Sensory Integration Strategies throughout the study.

3.1. Baseline Balance

The average YBT Composite score was 91.4 (SD = 5.7, range 81.8–104.7) for the left side and 91.8 (SD = 5.9, range 81.8–102.8) for the right side.

Regarding YBT asymmetry, the average anterior asymmetry was 3.0 cm (SD = 2.0, range 0.3–8.1), with 84% of participants having less than 4 cm of anterior asymmetry. The average Posterior Lateral (PL) asymmetry was 4.1 cm (SD = 3.7, range 0.3–14.9), and the average Posterior Medial (PM) asymmetry was 3.4 cm (SD = 2.6, range 0.1–9.3). In 68% of participants, both PL and PM asymmetry were less than 4 cm.

In addition, the Anterior Functional Reach Test (FRT), resulted in an average reach of 39.9 cm (SD = 5.4, range 30–54 cm).

3.2. Effects of Instability Level and Sensory Information on Movement Characteristics

3.2.1. Chest Movement Velocity

This analysis presents a comparison of chest movement velocities under different ILs and SIS. The data from the study is summarized in Table 2.

Table 2. A comparison of chest velocity (cm/s) of different instability levels (ILs) under different sensory integration strategies (SIS) with median values and color scale (green: lower, yellow: moderate, red: higher).

SIS / IL	0 IL		1 IL		2 IL		3 IL	
	Median	**IQR**	**Median**	**IQR**	**Median**	**IQR**	**Median**	**IQR**
Basic	0.78	0.21	0.88	0.18	1.07	0.32	0.98	0.28
Visual	0.86	0.23	1.08	0.46	2.20	2.33	1.93	0.95
Proprioception	1.20	0.18	1.22	0.36	1.46	0.44	1.54	0.35
Vestibular	2.00	0.50	2.95	0.93	4.19	1.77	4.53	1.87

The velocity of chest movement shows an increasing trend moving from the Basic towards the Vestibular strategy at both lower and higher instability levels. At the 0IL level, the chest velocity in the Basic strategy is approximately 0.78 cm/s, which increases to around 2.0 cm/s in the Vestibular strategy. Comparing chest velocity between Basic 3IL and Vestibular 3IL, we observe a larger increase of 462%.

The trend is even more noticeable when both the instability level and the amount of sensory information are considered together. For example, the increase in chest velocity from Basic 0IL to Vestibular 3IL is approximately 580%. Figure 2 represents the comparison of velocities at different instability levels under the different sensory integration strategies, while Figure 3 shows the general trend in how the chest movement velocity changes with different combinations of ILs and SIS. The data demonstrate a direct correlation between the level of instability and the decrease of sensory information and the velocity of chest movements.

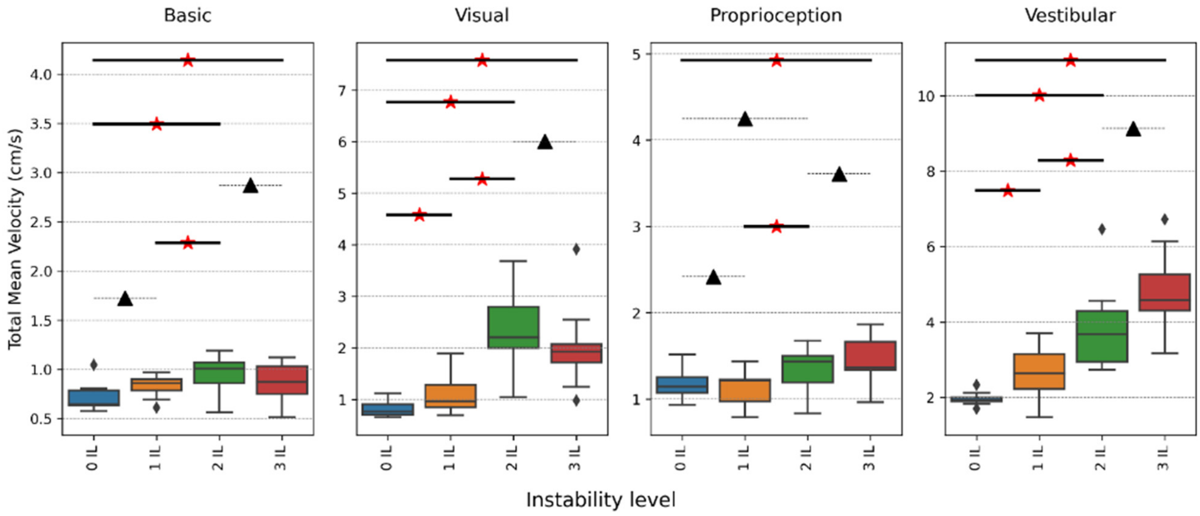

Figure 2. A comparison of velocity (cm/s) of different instability levels (ILs) under different sensory integration strategies (SIS). Lines on top with ★ represent pairs that have statistical significance; lines on top with ▲ represent pairs where we did not find statistical significance. Black-filled ◊ symbols indicate outliers, deviating from the central range.

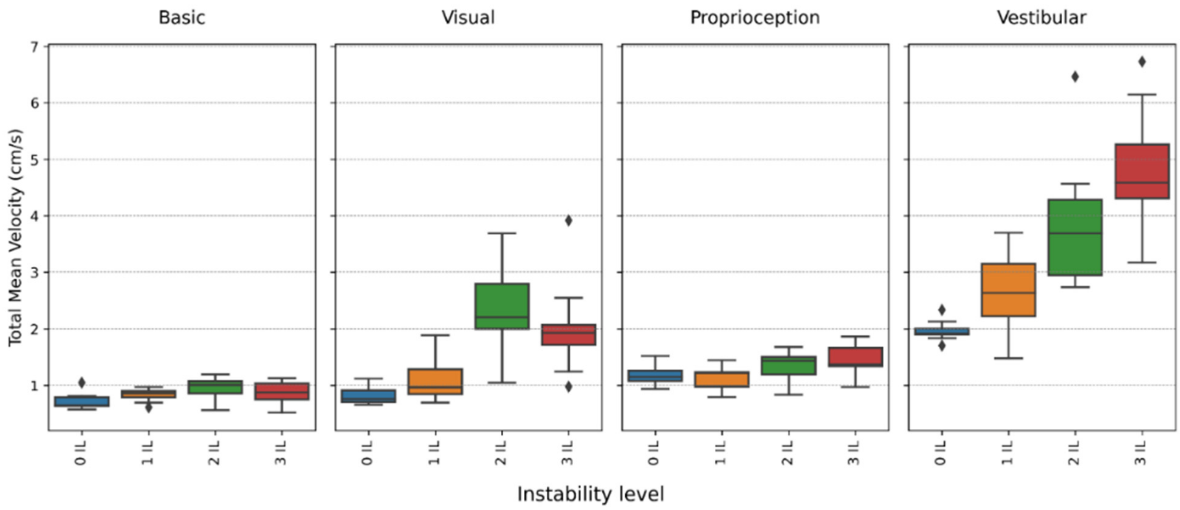

Figure 3. The general trend in how the chest movement velocity (cm/s) changes at different ILs and SIS. Black-filled ◊ symbols indicate outliers, deviating from the central range.

3.2.2. Chest Movement 95th CI Ellipsoid Volume

The data of 95th CI ellipsoid volume, across different SIS and ILs, are outlined in Table 3.

Table 3. A comparison of 95th CI Ellipsoid Volume (cm^3) of different instability levels (ILs) under different sensory integration strategies (SIS) with median values and color scale (green: lower, yellow: moderate, red: higher).

SIS / IL	0 IL		1 IL		2 IL		3 IL	
	Median	**IQR**	**Median**	**IQR**	**Median**	**IQR**	**Median**	**IQR**
Basic	179.5	261.7	561.5	551.8	771.6	833.6	692.9	855.7
Visual	186.1	188.7	653.5	683.6	3213.8	7806.3	2645.0	3163.6
Proprioception	855.7	726.5	1354.4	1117.9	1725.0	1389.9	1784.7	2104.5
Vestibular	1880.0	1633.2	4604.4	6535.5	9729.0	12,599.6	12,917.0	23,512.2

In the Basic strategy, chest volume increases from 179 cm^3 at 0 IL to 692 cm^3 at 3 IL, reflecting a 386% increase. The Vestibular strategy shows a more substantial change in chest volume, from approximately 1880 cm^3 at 0 IL to about 12,917 cm^3 at 3 IL, representing a significant 687% increase.

Comparing the volume between Basic 0 IL and Vestibular 0 IL, there is a considerable increase of about 1050%. However, the volume increase between Basic 3 IL and Vestibular 3 IL is even more drastic at 2750%.

When comparing chest volume between Basic 0 IL and Vestibular 3 IL, we observe a remarkable increase of 7176%.

Figures 4–6 represent these changes. Figure 4 presents the comparison of the 95th CI ellipsoid volume across different ILs under various SIS. Figure 5 portrays the general trend in how the 95th CI ellipsoid volume changes with different ILs and SIS. Meanwhile, Figure 6 illustrates a participant's chest movement and 95th CI ellipsoid volume under different combinations of IL and SIS.

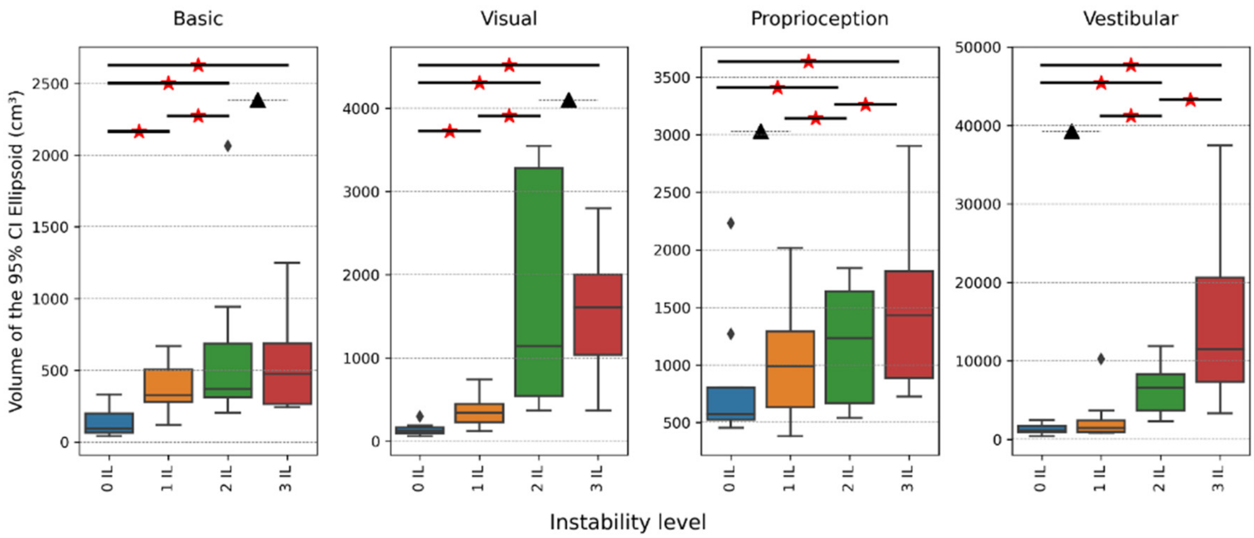

Figure 4. Comparison 95th CI ellipsoid volume (cm^3) of different instability levels (ILs) under different sensory integration strategies (SIS). Lines on top with ★ represent pairs that have statistical significance; lines on top with ▲ represent pairs where we did not find statistical significance. Black-filled ◊ symbols indicate outliers, deviating from the central range.

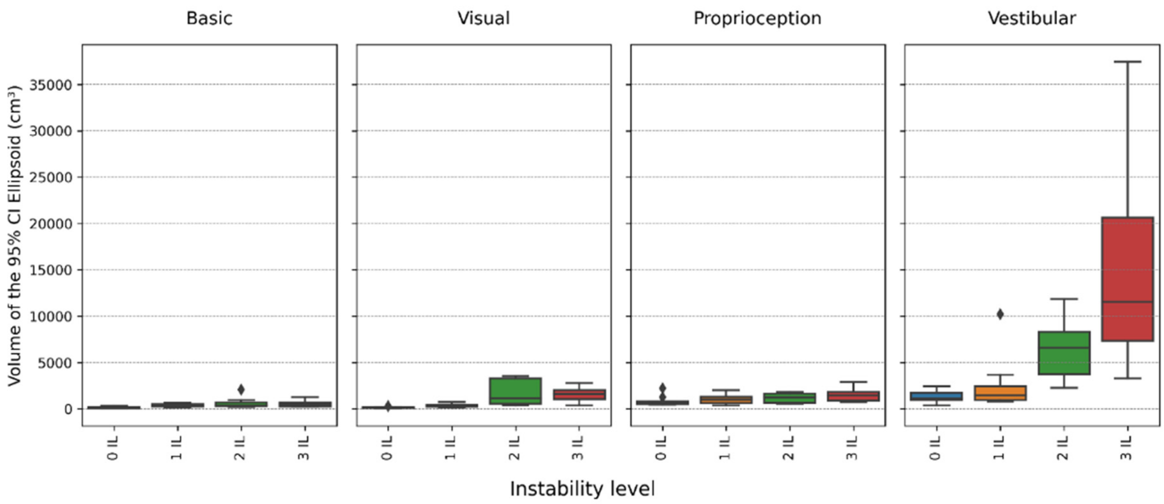

Figure 5. The general trend in how the chest movement 95th CI ellipsoid volume (cm^3) changes at different instability levels (ILs) under different sensory integration strategies (SIS). Black-filled ◊ symbols indicate outliers, deviating from the central range.

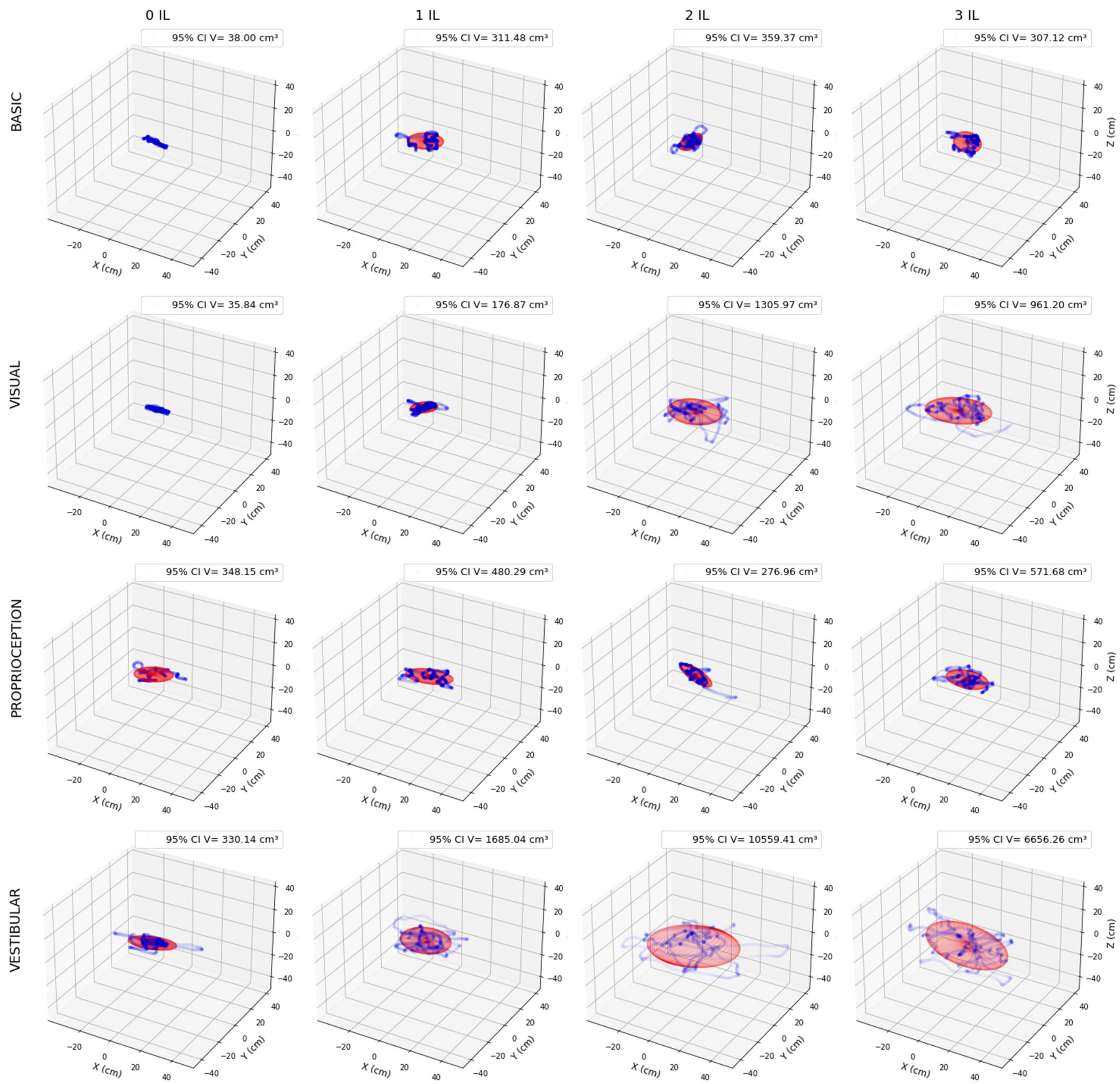

Figure 6. A participant's chest movement 95th CI ellipsoid volume (cm^3) in different combinations of instability levels (ILs) and sensory integration strategies (SIS). Blue points represent individual chest movement data, while the red ellipsoid shows the 95% CI volume, indicating the range of movement within a 95% confidence interval.

3.3. Differences Between Different Levels of Instability Across Various Sensory Strategies

When examining the statistical differences between different levels of instability across various sensory strategies, it becomes apparent that the change from instability level 2 to level 3 does not make a statistically significant difference across all sensory strategies. This indicates that increasing instability from level 2 to level 3 does not significantly change the results.

Additionally, it is noticed that the removal of visual input (in visual and vestibular strategies) has a more substantial statistical impact on both the velocity and volume.

This indicates that eliminating vision tends to make chest movements faster and more voluminous. The specific statistical differences and effects are illustrated in Figures 7 and 8.

From IL→ To IL	Basic		Visual		Proprioception		Vestibular	
	p value	Cliff's delta	p value	Cliff's delta	p value	Cliff's delta	p value	Cliff's delta
0 → 1	**0.032**	0.52	**0**	0.667	~~0.396~~	0.2	**0**	0.826
0 → 2	**0**	0.6	**0**	0.917	**0**	0.52	**0**	1
0 → 3	**0.001**	0.44	**0**	0.917	**0**	0.84	**0**	1
1 → 2	**0**	0.68	**0**	0.75	**0.024**	0.52	**0.001**	0.565
1 → 3	**0.015**	0.6	**0**	0.75	**0**	0.84	**0**	0.739
2 → 3	~~0.141~~		~~0.375~~		~~0.771~~		~~0.142~~	

Figure 7. Statistical difference and effect between different instability levels (ILs) under different sensory integration strategies (SIS) for chest movement velocity. *p*-values that are bold indicate statistical significance, while *p*-values that are strikethrough indicate no statistical significance. Effect size is not calculated for the non-significant values.

From IL→ To IL	Basic		Visual		Proprioception		Vestibular	
	p value	Cliff's delta	p value	Cliff's delta	p value	Cliff's delta	p value	Cliff's delta
0 → 1	**0.001**	0.76	**0**	0.917	**0.022**	0.36	**0.001**	0.652
0 → 2	**0**	0.76	**0**	0.917	**0**	0.68	**0**	0.913
0 → 3	**0**	0.76	**0**	1	**0**	0.76	**0**	0.913
1 → 2	**0.001**	0.68	**0**	0.75	**0.024**	0.68	**0.02**	0.478
1 → 3	**0.02**	0.36	**0**	0.833	**0.003**	0.52	**0**	0.826
2 → 3	~~0.979~~		~~0.128~~		~~0.615~~		~~0.142~~	

Figure 8. Statistical difference and effect between different instability levels (ILs) under different sensory integration strategies (SIS) for chest movement 95th CI Ellipsoid Volume. *p*-values that are bold indicate statistical significance, while *p*-values that are strikethrough indicate no statistical significance. Effect size is not calculated for the non-significant values.

3.4. The Sequential Relationship Between Chest Movement Velocity and 95th CI Ellipsoid Volume

Upon arranging the median volumes of the chest movement's 95th CI ellipsoid across different combinations of IL and SIS, from the smallest to the largest (Figure 9), it is observed that, as the volumes increase, the velocities follow suit. Increases in both velocity and volume occur gradually at first but, towards the larger end of the graph, both values start rising much more steeply. The most dramatic increase in both velocity and volume is observed in the following combinations: 3IL—Proprioception, 1IL—Proprioception, 3IL—Visual, and 3IL—Vestibular. Thus, more voluminous chest movements also tend to be faster, especially at higher instability levels or under specific sensory strategies.

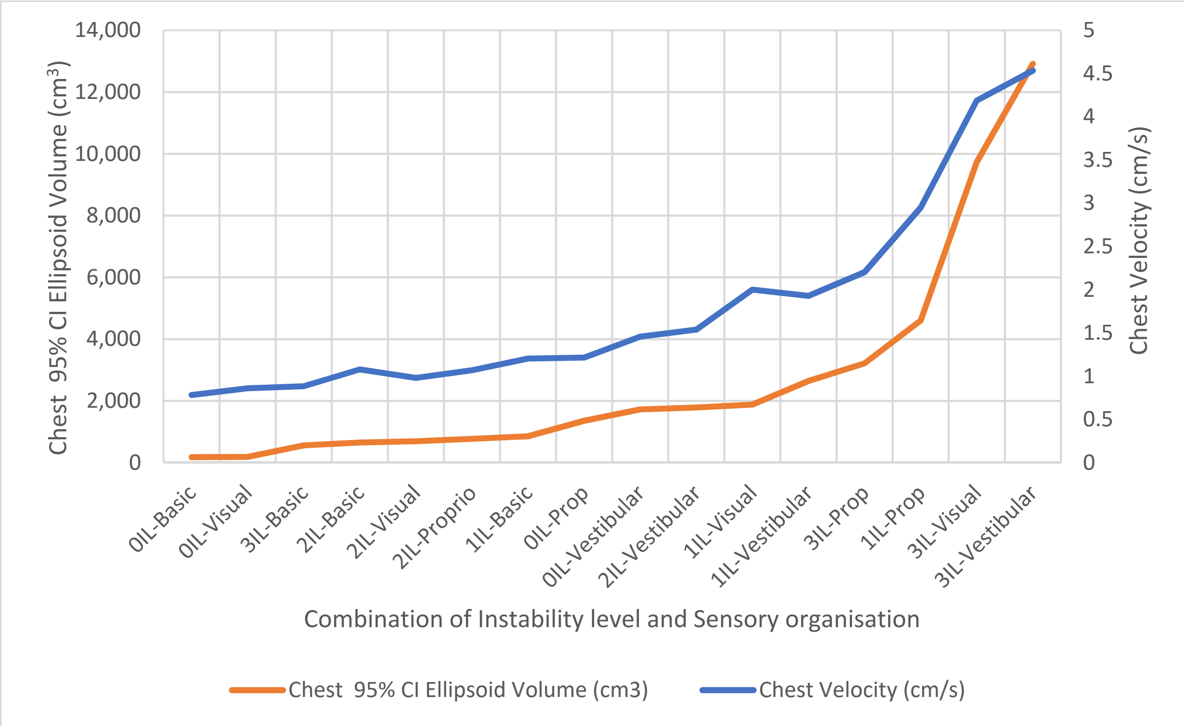

Figure 9. The sequential increase in chest movement velocity (cm/s) and 95th CI Ellipsoid Volume (cm^3) with varying instability levels (ILs) and sensory integration strategies (SIS) in combination.

4. Discussion

The main findings of the present study show that combined platform instability and reduced sensory input profoundly impact postural control, offering a method to destabilize and challenge balance across varying levels, even in healthy young individuals.

More specifically, we first established that the baseline balance score of the participants were within the range for healthy young individuals [26], with 18 out of 25 participants (72%) on the left side and 19 out of 25 participants (76%) on the right side meeting this criterion. Furthermore, nearly all participants showed proper symmetry [22,27] and functional reach [28,29] at baseline.

Once the different IL and SIS conditions were introduced, we observed an effect of decreasing sensory information as the instability level was increased, with faster movements recorded with vestibular strategy and high instability combinations. A similar trend was observed for the increase in chest volume, highlighting the effect of combining increased instability with reduced sensory input [30].

Additionally, we observed that removing visual input (i.e., visual and vestibular strategies) had a greater impact on both chest movement velocity and volume rather than increasing instability (e.g., from 2 to 3 instability level). Furthermore, we also observed that more voluminous chest movements also tend to be faster, especially at higher instability levels or under specific sensory strategies [31].

Furthermore, our results provide crucial insights into the human postural control system's adaptability. The complex sensory system used to maintain balance incorporates visual, vestibular, and proprioceptive (perception of joint and body movement) inputs [31,32]. Each of these components contributes distinct information, which the brain integrates to ascertain the body's spatial position and make necessary adjustments to maintain balance.

An essential factor to consider when assessing balance under various instability levels is the platform board's increased sensitivity to body sway at higher instability levels. Even minor body sways can trigger significant board movements, requiring less force to induce movement compared to lower instability levels. This heightened sensitivity to body sway underlines the importance of precise neuromechanical responses in maintaining balance and preventing falls.

The integration of different instability levels and sensory system strategies can facilitate understanding their interplay in postural control. Maintaining balance under different instability levels and reduced sensory input highlights the challenging interaction between various neurological reflex loops, including the vestibulospinal and cerebellar pathways, which constitute the neural controller for postural control. The vestibular system, responsible for detecting head movements and spatial orientation, plays a pivotal role in stabilizing posture, particularly when visual or proprioceptive inputs are reduced. Proprioception, providing feedback on body position and movement, complements vestibular information to maintain balance. The cerebellum, deeply involved in coordinating motor responses, integrates these sensory inputs and fine-tunes postural adjustments. In this study, the significant increases in chest movement velocity and volume, especially under vestibular conditions at higher instability levels, can be attributed to the cerebellum's role in modulating rapid corrective movements in response to sensory input challenges. The cerebellum's ability to integrate proprioceptive and vestibular feedback is crucial for maintaining postural control when sensory inputs are disrupted [33–35]. The working mechanism of this approach is illustrated in Figure 10.

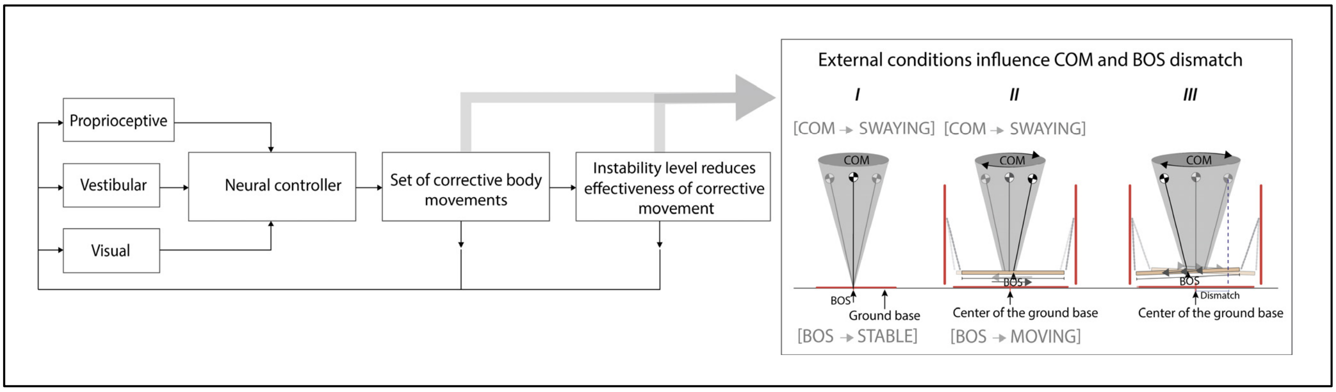

Figure 10. Principle of interaction of sensory information and instability level. The gray area (I) represents COM (center of mass) and BOS (base of support) movement while standing on a stable base.

4.1. Potential Application for Postural Control Training and Rehabilitation

Healthy individuals are able to effectively maintain postural control under lower instability levels, even when sensory input is reduced [36]. While falls are a significant concern in older populations, postural control is equally important for injury prevention and motor function in younger, active individuals, highlighting its broader relevance across age groups. Furthermore, postural control can be maintained under various instability levels, provided that sufficient sensory information is available. However, the reliance on sensory information becomes more critical as the level of instability increases [30]. This phenomenon is exemplified when comparing the increase in chest movement volume from the Basic to Vestibular strategy: while the chest movement volume increases only 123% from 1 to 3 IL under the Basic strategy, the increase is much more significant in the Vestibular strategy, reaching 280%.

Furthermore, the percentage increases in chest movement volume observed across different sensory strategies and instability levels indicate how the postural control system adapts under varying conditions. These findings suggest that greater reliance on compensatory chest movements occurs when instability or sensory limitations challenge the body's balance mechanisms. These findings have practical implications for real-life scenarios, such as walking on uneven terrain or in environments with reduced visibility, where the ability to manage increased body sway is crucial for preventing falls. These insights can inform rehabilitation protocols, helping to train individuals to better integrate sensory inputs and manage instability, particularly for those at risk of balance disorders. The integration of sensory systems has been successfully reported in clinical settings by both earlier and recent studies [37].

Additionally, the study's findings indicate that the body's postural control can be maintained effectively with certain combinations of IL and SIS, such as 2IL-Visual and 2IL-Proprioception. Despite the differing amounts of sensory input in these strategies, the effects on postural control are similar. These findings suggest that, in the event of sensory deficits, healthy individuals can substitute other sensory information to support postural control [31,32].

By applying combinations of instability levels and SIS, it is possible to significantly enhance the effects of the sensory integration strategy. Even in healthy individuals, a high level of instability can be created without external perturbation. The level of instability can be adjusted across a wide range of destabilization—from very minimal to severe, where even healthy young individuals may struggle to compensate and maintain balance.

In clinical contexts, these findings hold potential for aiding the treatment of balance disorders stemming from sensory deficits, such as those related to vision impairment, peripheral neuropathy, or vestibular dysfunction. The strategic application of varying instability levels could potentially enhance the interaction of dominant sensory inputs, thereby improving balance control. This underlines the necessity of understanding and manipulating the sensory strategy–instability interplay for more effective therapeutic outcomes.

A wide range of destabilization levels (by combination of IL and SIS) allows patients to choose the most suitable and safe level of instability, without the need for any external force. This feature facilitates personalized balance training and rehabilitation, catering to the individual needs and abilities of each patient. This tailoring of balance exercises is crucial in ensuring that the exercises are both safe and effective, furthering patient recovery while minimizing the risk of injury.

Clinically, this threshold for postural control breakdown could be tested using balance assessments with varying instability levels, allowing practitioners to identify specific deficits in sensory or motor function and design personalized rehabilitation programs that progressively challenge and improve postural stability.

4.2. Potential Application for Postural Control Assessment

By manipulating instability levels and sensory integration strategies, the efficiency of an individual's postural control system can be observed [38]. This approach can identify the threshold at which the system can no longer compensate for increased instability, offering quantitative insights into the individual's adaptability and reserves.

The potential to assess different sensory systems separately enhances the utility of this approach. It expands the understanding of postural control and can mimic real-life scenarios—like navigating in low-light or nighttime environments, where falls are more likely to occur.

Such a method could be applied to evaluate the effectiveness of balance maintenance, serving as a measure of rehabilitation or training efficacy. The assessment of balance maintenance under demanding conditions could indirectly gauge the efficiency of the neural controller and identify potential deficiencies contributing to balance disorders.

Moreover, heightened sensitivity to body sway at higher instability levels has practical applications for designing tailored interventions in balance training and rehabilitation. For instance, identifying when postural control breaks down can inform personalized rehabilitation programs targeting the specific sensory or motor deficits of an individual. This can help optimize balance training protocols, enhance fall prevention strategies, and contribute to the development of adaptive equipment or environments that gradually increase instability to safely challenge and improve postural control in clinical or athletic populations.

4.3. Limitations

The present study carries some limitations that need to be addressed. Firstly, the sample included only healthy young individuals, thus confining the extent to which the findings can be generalized. Additionally, the study duration was lengthy, with a total duration of approximately 30 min for each participant, which may have induced fatigue and potentially impacted the results. Furthermore, the test-retest reliability, crucial for clinical measurements, was not assessed. Lastly, the sequence of testing remained the same throughout the study, and the effects of varying the test procedure sequence are unknown. Future studies should aim to diversify the participant pool, minimize testing duration, evaluate test-retest reliability, and investigate the effects of different test procedure sequences. Additionally, future studies should consider randomizing the testing sequence to minimize potential biases, such as learning effects, that may arise from a fixed order. Assessing test-retest reliability through repeated measures or intraclass correlation coefficients would also ensure consistency across sessions and strengthen the validity of the findings.

5. Conclusions

The combination of platform instability and reduced sensory input significantly impacts postural control, even in young, healthy individuals. This study demonstrates that increasing instability levels and reducing sensory input can induce notable adaptations in postural stability, offering valuable insights into how the sensory and motor systems work together to maintain balance. These findings suggest that integrating instability levels and sensory strategies can provide a robust method for assessing and improving postural control across various populations.

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