

ORIGINAL ARTICLE

Exploring Balance as a Determinant of High-Level Mobility After Traumatic Brain Injury.

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Abstract

Traumatic brain injury (TBI) remains a major cause of long-term disability. Individuals with moderate to severe TBI often experience lasting difficulties in balance and mobility. High-level mobility, which includes tasks such as running, stair climbing, and quick directional changes, is frequently impaired in this population and poses significant barriers to independence and community reintegration. Despite the known importance of balance in rehabilitation, its precise contribution to the high-level mobility critical for independence remains poorly understood. This study aimed to determine the relationship between balance performance and high-level mobility in individuals with moderate to severe TBI. A total of 86 participants were assessed using the High-Level Mobility Assessment Tool (HiMAT), the Sensory Organization Test (SOT), and the Limits of Stability (LOS) test. The analysis demonstrated moderate to strong positive correlations between high-level mobility and both SOT and LOS measures, with maximum excursion (MXE) ($r = 0.603$) showing the strongest association. These results advocate for incorporating dynamic balance challenges (e.g., perturbed walking, reactive stepping) into rehabilitation to maximise mobility recovery. By highlighting balance as a modifiable and measurable contributor to mobility, this study offers practical insights for designing more effective rehabilitation strategies that support recovery and independence after TBI.

Keywords: *Balance; high-level mobility; postural control; traumatic brain injury.*

Introduction

Traumatic Brain Injury (TBI) remains a substantial public health concern, with approximately 69 million new cases reported globally each year [1,2]. Among these, moderate to severe TBI is particularly impactful, contributing to long-term disability and reduced quality of life for millions of individuals worldwide. In the United States alone, over 5.3 million people live with disabilities resulting from moderate to severe TBI [3]. The consequences of such injuries often include impairments in motor control, cognitive function, and mobility [4]. Notably, balance dysfunction is among the most significant motor-related challenges, as it affects postural stability and increases the risk of falls and associated injuries [5,6].

The relationship between balance and mobility is a critical area of focus in neurorehabilitation, especially for individuals recovering from moderate to severe TBI. Numerous studies have reported that survivors of TBI commonly experience balance disturbances, which interfere with their ability to resume daily routines and community participation [5,7]. Although conventional clinical assessments of balance provide useful information, they often fall short in capturing the complex and dynamic nature of mobility limitations experienced by individuals with TBI. The High-Level Mobility Assessment Tool (HiMAT), developed specifically for this population, offers a more comprehensive evaluation of higher-level mobility skills and real-world functional performance [8,9]. Recognizing these advantages, the present study employed the HiMAT as it encompasses challenging tasks such as running, jumping, and stair negotiation, activities that closely reflect the demands of community reintegration following TBI.

Growing evidence from rehabilitation research highlights that targeted, goal-oriented interventions can effectively enhance both balance and mobility among individuals recovering from TBI [10]. Interventions that

incorporate intensive mobility training, balance-focused exercises, and adapted physical activity have consistently demonstrated improvements in walking ability and postural control [11,12]. Multimodal rehabilitation approaches that combine elements of strength, coordination, and balance training appear particularly effective in addressing the complex functional needs of this population [13,14]. Beyond restoring physical function, these integrated programs also aim to promote autonomy, confidence, and participation in meaningful community activities. Recognising the central role of balance in recovery, it is therefore essential to evaluate balance performance as a key component in developing rehabilitation strategies that foster greater mobility and functional independence.

Despite the growing body of literature linking balance to mobility, the specific relationship between balance performance and high-level mobility remains underexplored in individuals with moderate to severe TBI. Understanding how postural stability influences advanced mobility tasks could guide more effective rehabilitation strategies tailored to the unique challenges faced by this population. This study, therefore, aims to determine the correlation between balance performance and high-level mobility in individuals recovering from moderate to severe TBI. By clarifying this relationship, the findings may provide clinicians with meaningful insights for developing goal-oriented rehabilitation plans. Ultimately, the results could contribute to a broader understanding of how targeted balance interventions can enhance functional mobility and quality of life following TBI.

Materials and methods

Study design and participants

This study employed a cross-sectional design to examine the relationship between balance performance and high-level mobility among individuals with moderate to severe TBI. Participants were recruited using purposive

sampling from the Cheras Rehabilitation Hospital, where they were receiving physiotherapy care following discharge from acute services. Inclusion criteria required participants to be between 25 and 60 years old, with a confirmed diagnosis of moderate to severe TBI based on their initial Glasgow Coma Scale (GCS) scores. Individuals with pre-existing neurological, orthopedic, or vestibular conditions unrelated to TBI were excluded to minimise potential confounding factors. A total of 86 participants who met the criteria agreed to participate. Ethical approval for the study was obtained from the Medical Research and Ethics Committee (MREC), Ministry of Health Malaysia, and written informed consent was obtained from all participants or their legal guardians prior to data collection.

Outcome Measures

The main outcome measures selected for this study were the HiMAT and balance tests derived from the NeuroCom® Balance Master, specifically the Sensory Organization Test (SOT) and Limits of Stability (LOS) protocols. The HiMAT is a 13-item performance-based scale that assesses advanced mobility skills such as running, jumping, hopping, and stair negotiation, making it particularly relevant for individuals recovering from TBI [15]. Validation studies have shown that the HiMAT demonstrates excellent psychometric properties, including high internal consistency ($\alpha = 0.99$) and outstanding interrater and test–retest reliability (ICC = 0.99). Moreover, the tool has proven to be more responsive than traditional functional measures such as the Functional Independence Measure and Rivermead Motor Assessment, making it a robust assessment for evaluating mobility outcomes in individuals with TBI [16]. The SOT provides an overall measure of postural stability by evaluating an individual’s ability to maintain balance under six progressively challenging sensory conditions that alter visual, vestibular, and somatosensory input. Previous research has shown that the SOT demonstrates good reliability

among adults with traumatic brain injury (ICC = 0.72–0.80) [17]. The LOS test assesses dynamic balance by quantifying parameters such as reaction time (RT), movement velocity (MVL), endpoint excursion (EPE), maximum excursion (MXE), and directional control (DCL) [7]. Prior studies have supported its reliability and validity in evaluating dynamic postural control [18]. Together, these outcome measures provide a comprehensive evaluation of both static and dynamic balance performance and high-level mobility, offering valuable insight into functional recovery following moderate to severe TBI.

Procedure

All assessments were conducted in a standardised clinical environment by qualified physiotherapists trained in the administration of the selected tools. Participants completed a brief warm-up consisting of five minutes of gentle stretching and stepping exercises to ensure physical readiness for testing. The HiMAT was administered first, following standardised instructions and scoring protocols to maintain consistency. A brief familiarisation trial was conducted before the assessment to ensure participants understood the tasks. Each HiMAT item were scored on a 5-point scale ranging from 0 (unable to perform) to 4 (best performance). Items were either timed or measured by distance, and the total score was calculated by summing all item scores, with higher values indicating better mobility performance [15].

Balance assessments were carried out using the NeuroCom® Balance Master system, with participants securely fitted in a safety harness to prevent falls during testing. Two standardised protocols were administered: the SOT and the LOS. In the SOT, participants stood barefoot on a force platform and were asked to maintain an upright posture under six sensory conditions that systematically altered visual, vestibular, and somatosensory inputs. Each trial lasted approximately 20 seconds, and higher equilibrium scores reflected better postural stability. The LOS test assessed dynamic balance

by evaluating how participants shifted their centre of gravity toward eight visual targets displayed on a monitor while keeping their feet in place. The test generated several parameters, including RT, MVL, EPE, MXE, and DCL, which together described the accuracy and control of voluntary weight shifting [7]. A brief practice trial was provided before testing, and rest periods of about three minutes were allowed between assessments to minimise fatigue.

Data Analysis

Data were analyzed using IBM SPSS Statistics version 26. Descriptive statistics were calculated to summarize participant demographics and scores on the HiMAT and balance measures. The primary aim of the analysis was to determine the relationship between high-level mobility and balance performance in individuals with TBI. For this purpose, Spearman's rank-order correlation was employed, given the non-normal distribution of the dataset. This non-parametric method allowed for the identification of associations between HiMAT scores and the SOT composite, RT, MVL, EPE, MXE, and DCL values. A significance level of $P < 0.05$ was applied to all statistical tests.

Results

This study included 86 individuals with moderate to severe TBI who met the eligibility criteria and completed assessments of both balance and high-level mobility. Participants ranged in age from 25 to 57 years, with a mean age of 33.13 years (SD = 8.40). The majority were male (84.9%), and motor vehicle accidents were the primary cause of injury (90.7%), followed by falls (7.0%) and other causes such as acts of violence (2.3%). Most participants sustained severe TBI (83.7%), while the remaining had moderate injuries (16.3%). These demographic and clinical characteristics provide important context for interpreting the observed patterns of balance and mobility. A summary of participant demographics is presented in Table 1.

Balance performance was assessed using two standardised tools: the SOT and LOS test. The mean SOT composite equilibrium score was 69.24% (SD = 10.80), reflecting participants' ability to maintain postural control under varying sensory conditions. For dynamic balance, LOS scores revealed average values of 3.27°/s (SD = 1.05) for MVL, 62.37% (SD = 13.92) for EPE, 79.15% (SD = 14.31) for MXE, and 68.05% (SD = 13.13) for DCL. These outcomes reflect a spectrum of postural stability and dynamic control abilities across the sample.

Correlation analysis using Spearman's rank-order test revealed significant positive associations between HiMAT scores and both static and dynamic balance parameters. A moderate correlation was found between HiMAT and the SOT composite equilibrium score ($r = 0.495$, $P = 0.001$), indicating that individuals with better postural control under altered sensory conditions tended to perform better in mobility tasks. Among the LOS variables, all four parameters demonstrated significant correlations with HiMAT: MVL ($r = 0.321$, $P = 0.001$), EPE ($r = 0.578$, $P = 0.001$), MXE ($r = 0.603$, $P = 0.001$), and DCL ($r = 0.558$, $P = 0.001$). Notably, MXE showed the strongest association with high-level mobility. These findings are summarized in Table 2 and highlight the relevance of dynamic balance measures in predicting functional performance.

Taken collectively, these findings emphasize the critical role of both static and dynamic balance in determining mobility outcomes in individuals with moderate to severe TBI. The SOT offered valuable insights into equilibrium control during sensory conflict, while the LOS test captured dynamic balance abilities essential for navigating real-world environments. The strength of these correlations supports the argument that impairments in balance, particularly in dynamic control, can directly limit one's ability to perform high-level mobility tasks such as running, jumping, or stair navigation. These findings reinforce the need for rehabilitation programs to include specific interventions that target postural control and balance retraining. Enhancing these

domains may be instrumental in optimizing mobility and functional independence among TBI survivors.

Discussion

This study explored the relationship between balance performance and high-level mobility in individuals with moderate to severe TBI. Significant associations were observed between mobility outcomes and both static and dynamic balance parameters, emphasizing the integral role of postural control in functional recovery. These findings are consistent with previous research suggesting that mobility limitations in this population are multifactorial, encompassing not only motor impairments but also cognitive, emotional, and sensory-processing deficits that compromise coordination and independence [19]. This complexity suggests that conventional rehabilitation approaches, which often focus solely on gross motor recovery, may not adequately address the broader mobility challenges faced by this group. Integrating balance-focused strategies into rehabilitation may offer a more effective, targeted approach to improving real-world function.

The observed correlation between HiMAT scores and the SOT composite score highlights the influence of sensory integration on mobility performance. Individuals with greater postural stability in the face of sensory perturbations tended to perform better in dynamic mobility tasks. This finding is consistent with existing evidence showing that disturbances in vestibular, visual, or proprioceptive function can markedly disrupt balance control and overall postural stability [20]. Recent findings have shown that interventions aimed at enhancing multisensory integration, such as galvanic vestibular stimulation, may improve postural control and support mobility gains in neurological populations [21]. These insights underline the value of sensory-based rehabilitation in addressing balance impairments among TBI survivors.

Dynamic balance variables from the LOS test demonstrated particularly strong associations with high-level mobility. The ability to shift and control the centre of gravity reflected in metrics such as MXE, EPE, and DCL was closely linked to performance in complex mobility tasks, including turning, climbing stairs, and obstacle negotiation. These results are supported by recent studies emphasizing the importance of dynamic postural control in safe, efficient community ambulation [22]. Notably, among the LOS parameters, MXE emerged as the most strongly correlated with HiMAT, reinforcing the importance of voluntary control over centre-of-mass displacement as a predictor of mobility function. The quantitative trends observed here support a growing clinical emphasis on training dynamic balance abilities rather than relying solely on traditional static exercises. As suggested by Klima et al. [23], incorporating task-specific, context-rich training such as walking on uneven surfaces or navigating crowded environments may better simulate daily functional demands and improve transferability. Rehabilitation programs that incorporate both anticipatory and reactive balance responses may offer more comprehensive improvements in mobility, confidence, and fall prevention.

Although balance was the primary focus of this investigation, it is essential to recognize that mobility performance is influenced by multiple physical and neurological systems. Prior analysis involving this cohort has shown that muscle strength, gait speed, and endurance also significantly impact HiMAT scores [6]. Nonetheless, the current findings establish balance, especially dynamic balance as a measurable and modifiable component that should be prioritized in rehabilitation planning. These results support a more integrated rehabilitation approach that combines balance training with strength and aerobic conditioning to maximise recovery [24].

Additional insights were gained through the analysis of SOT subcomponents. Specifically, vestibular and visual inputs were significantly

associated with HiMAT performance, whereas somatosensory and preference scores were not. This suggests that individuals with relatively preserved basic balance may still face limitations in high-level tasks requiring multisensory integration. Similarly, the negative correlation observed with RT suggests that delayed postural responses may hinder functional mobility, further highlighting the need to train quick, controlled adjustments during dynamic tasks.

Collectively, these results provide strong support for incorporating dynamic and sensory-based balance training into functional mobility programmes for individuals with moderate to severe TBI. This study adds to the growing understanding of postural control as a key factor in recovery and offers clinicians a practical focus for intervention design.

Despite the valuable insights gained from this study, several limitations should be acknowledged. Firstly, the study employed a cross-sectional design, which limits the ability to establish causality between balance measures and high-level mobility performance. While significant correlations were observed, these findings do not confirm directional or causal relationships. Secondly, the sample size, although adequate for correlation analysis, may not fully represent the broader population. The homogeneity of the sample in terms of age, diagnosis, or functional level may limit the generalizability of the results to other populations such as older adults, individuals with other neurological conditions, or community-dwelling populations with varying levels of physical activity.

Conclusion

This study reinforces the critical role of balance performance, particularly dynamic postural control and sensory integration in determining high-level mobility among individuals with moderate to severe TBI. The evidence supports the inclusion of targeted balance interventions in rehabilitation, as improvements in postural

control may directly enhance mobility outcomes. By identifying balance as a measurable and modifiable contributor to function, this study offers a meaningful direction for clinicians seeking to optimise recovery. These findings contribute to a more nuanced understanding of TBI rehabilitation and set the stage for more individualised, function-driven therapeutic approaches. Future studies should explore longitudinal changes and intervention-specific effects to build upon the correlational insights established in this study, thereby advancing evidence-based strategies for improving functional mobility in this population.

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Conflict of interest

The authors declare no conflicts of interest in the conduct, authorship, or publication of this study.

Authors' contributions

SA conceptualized the study, collected and analyzed the data, and drafted the manuscript. HM designed the study, reviewed the manuscript, and provided supervision. NAMN conducted the literature review, provided methodological oversight, and edited the manuscript.

Table 1. Participants' demographic data, N=86

	n (%)	Mean	SD
Age	86 (100)	33.13	8.40
Gender			
Male	73 (84.9)	-	-
Female	13 (15.1)	-	-
Mechanism of Injury			
MVA	78 (90.7)	-	-
Acts of violence & others	2 (2.3)	-	-
Fall	6 (7.0)	-	-
Severity of TBI			
Moderate	14 (16.3)	-	-
Severe	72 (83.7)	-	-

Abbreviations: MVA, motor-vehicle accident; n, sample size; SD, standard deviation.

Table 2. Correlation between balance variables and HiMAT scores

Variables	n (%)	Mean	SD	r	P value
SOT					
Somatosensory (%)	86 (100)	95.78	4.33	0.140	0.099
Visual (%)	86 (100)	82.06	14.50	0.250	0.010*
Vestibular (%)	86 (100)	54.42	23.04	0.331	0.001*
Preferences (%)	86 (100)	101.16	16.35	0.017	0.437
Composite (%)	86 (100)	69.24	10.80	0.495	0.001*
LOS					
RT (sec)	86 (100)	.72	.24	-0.247	0.011*
MVL (degree/sec)	86 (100)	3.27	1.05	0.321	0.001*
EPE (%)	86 (100)	62.37	13.92	0.578	0.001*
MXE (%)	86 (100)	79.15	14.31	0.603	0.001*
DCL (%)	86 (100)	68.05	13.13	0.558	0.001*
HiMAT (outcome)	86 (100)	25.43	12.80	1.000	-

Abbreviations: DCL, directional control; EPE, end-point Excursion; HiMAT, High-Level Mobility Assessment Tool; MXE, maximum excursion; LOS, Limits of Stability; MVL, movement velocity; n, sample size; r, correlation; RT, Reaction Time; SD, standard deviation; SOT, Sensory Organization Test.

* Significant at p<0.05

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