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Research article

An integrated approach to the assessment of balance and functional mobility in individuals with history of severe traumatic brain injury

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ABSTRACT

Individuals who experienced severe Traumatic Brain Injury (sTBI) are often characterized by relevant motor dysfunctions which are likely to negatively affect activities of daily living and quality of life and often persist for years. However, detailed objective information about their magnitude are scarce. The aim of this study was to quantitatively assess the extent of motor deficits in terms of postural control effectiveness under static and dynamic conditions and to investigate the existence of possible correlations between the results of clinical tests and instrumental measures. Postural sway and functional mobility (i.e., instrumented Timed Up and Go test, iTUG) were objectively measured in 18 individuals with sTBI and 18 healthy controls using a pressure plate and a wearable inertial sensor. Additionally, participants with history of sTBI completed the Rivermead Mobility Index (RMI). One-way ANOVA and Spearman's rank correlation analysis were employed to examine differences between the two groups and determine potential correlations between the instrumental tests and clinical scales.

The results show that people with sTBI were characterized by larger sway area and longer iTUG walking sub-phase. Significant correlations were also detected between RMI scores and iTUG total duration, as well as the walking phase. Taken together, these findings suggest that, even years after the initial injury, individuals with sTBI appear characterized by impaired postural control and functional mobility, which appears correlated with the RMI score. The integration of instrumental measures with clinical scales in the routine assessment and treatment of individuals with sTBI would result in more comprehensive, objective, and sensitive evaluations, thus improving precision in treatment planning, enabling ongoing progress monitoring, and highlighting the presence of motor deficits even years after the initial injury. Such integration is of importance for enhancing the long-term quality of life for individuals with sTBI.

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1. Introduction

With an incidence of 369 per 100,000 [1] and an average mortality rate of 10.53 per 100,000 people per year [2], Traumatic Brain Injury (TBI) represents one of the major health priorities worldwide [3]. The main cause of TBI differs according to the individual's age range: in fact, while in elderly falls represent the event mostly associated with TBI [2,4], in younger adults, road traffic accidents account for the largest proportion of most severe traumas (sTBI) [2], usually characterized by a Glasgow Coma Scale (GCS) of 8 or less [5]. In this latter case, it is well known that neurological, neuropsychological, and cognitive impairments are likely to persist for years after the injury [6]. In particular, motor dysfunctions are among the most common consequences of TBI, as a significant number of affected individuals report impairments in balance and coordination [6–8]. In this context, it's worth noting that few studies have explored the long-term effects of sTBI on biomechanical alterations related to basic motor tasks [9], involving postural control and functional mobility.

In clinical settings, residual motor abilities in individuals with a history of TBI are often assessed using clinical scales (e.g., the Functional Independence Measure-FIM [10] and the Rivermead Mobility Index-RMI [11]). However, since such tools mainly evaluate gross motor function and are highly influenced by the expertise of the rater [12] or self-reported, it would be desirable to integrate their use with some objective data. In this context, the instrumented assessment of motor functions offers the advantage of removing any operator dependency, thereby enhancing overall accuracy and reliability of results [13]. In particular, postural sway and functional mobility analysis (assessed through instrumented versions of the Timed-Up-and-Go [TUG] test) have been widely used in the last decades to test individuals affected by several neurological conditions such as Parkinson's disease, multiple sclerosis, and stroke [14–16], and thus might represent a valid option also for individuals with TBI. The former is aimed at assessing the performance of the postural control system by means of parameters derived by processing the Center of Pressure (COP) time series acquired using force or pressure platforms, while the instrumented version of the TUG (iTUG) assesses functional mobility [17] by providing data about time, speed, and acceleration associated with each TUG sub-phase (i.e., sit-to-stand, walking, 180° turns, stand-to-sit). Although some biomechanical tasks, such as gait, have been largely studied in people with history of TBI [18], few studies evaluated the residual balance and functional mobility abilities using instrumental techniques. They generally report an increase in postural sway due to TBI [7,19–22], mainly involving the mediolateral direction [23]. In the case of TUG, poorer performances (i.e., longer times required for its completion) have been reported for adults in the subacute phase [24], while results appear contrasting in the case of children [25,26]. However, it is noteworthy that most existing studies included only individuals with mild or moderate TBI tested during the acute (≤10 days) or subacute (11–90 days) phases.

Based on these considerations, the primary aim of this study is to quantitatively characterize the main postural control and functional mobility features in adults with history of sTBI, compared to a reference group of healthy individuals. As a secondary objective, we aim to explore the relationships between the instrumental data and clinical tests. The integration of such objective assessments in clinical routine may provide accurate and reliable information about the motor abilities of individuals with sTBI, thereby supporting clinicians in designing and monitoring suitable training/rehabilitative programs. These objective and minimally time-consuming assessments can enhance the efficiency of the assessment process, helping in the identification of individuals more at risk of falling and in quantitatively document the outcome of therapeutic interventions. Moreover, understanding the relationship between static and dynamic abilities can offer insights into how different aspects of motor function are related, informing the development of targeted rehabilitation programs. Lastly, exploring the relationships between clinical scales and instrumented tests can aid clinicians in selecting the most appropriate assessment tools for individualized rehabilitative interventions.

2. Materials and methods

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Azienda Ospedaliero Universitaria of Cagliari (protocol PG/2022/1294). Informed consent was obtained from all participants involved in the study.

2.1. Participants

Between January 2022 and February 2023, a convenience sample of individuals with a history of sTBI, confirmed through medical records and assessment of coma state or GCS score equal to or lower than 8 at the time of the trauma, were recruited from the outpatient facility of the Neurorehabilitation Unit at the ARNAS G. Brotzu Hospital (Cagliari, Italy). Participants were selected based on their availability for the tests and on the following inclusion criteria: age between 18 and 65 years old, being free from cognitive impairments (i.e., Mini Mental State Examination, MMSE score >24), able to walk without any mobility aids, living with their family in the community. Additionally, participants must exhibit post-traumatic memory loss and persistent focal neuromotor deficits and not have severe, unstable comorbidities (e.g., severe medical conditions, acute or chronic co-morbidities). A total of 23 individuals who met the inclusion criteria were invited to participate in the study. However, due to personal reasons, only 18 individuals ultimately participated.

A reference set of normative data from healthy controls (HC), matched for age, sex, and anthropometric features, was built by extracting data from the reference database of the Laboratory of Biomechanics and Industrial Ergonomics of the University of Cagliari (Cagliari, Italy).

2.2. Data acquisition and processing

2.2.1. Postural sway analysis

The postural control system performance was assessed by means of postural sway analysis, carried out on the basis of COP time-series collected using a pressure platform (FDM-S, Zebris Medical GmbH, Germany), previously employed in similar studies on individuals with neurological conditions and healthy individuals [27–29]. Participants stood barefoot on the pressure platform, with their feet placed at 30°, and an approximate inter-malleolar distance of 8–10 cm. They were instructed to maintain a stable and relaxed position for 30 s, with arms alongside their lower limbs (not in contact), and gaze fixed on a target at a distance of 3 m, and at eye level. Three trials per participant were acquired, ensuring suitable rest times between them (which ranged from 30 s to 2 min).

The COP time-series were post-processed using a dedicated custom software, developed under Matlab environment (The MathWorks, Inc, Natick, MA, USA), to calculate:

- Sway area (95 % confidence ellipse, mm^2);
- Sway velocity, namely the average COP velocity during the trial, obtained by dividing overall distance travelled by the COP by the total duration of the trial (mm/s);
- COP maximum displacements, calculated as the difference between the maximum and minimum values of the selected coordinate recorded during the trial (mm); mediolateral (ML) and anteroposterior (AP) directions were taken into consideration.

The mean value obtained from three trials for each parameter was deemed representative of a particular participant and subsequently utilized in the following analyses.

2.2.2. Instrumented Timed-Up-and-Go

The instrumented version of the TUG test (iTUG) was performed using a clinically validated wearable inertial sensor (G-Sensor, BTS Bioengineering S.p.A., Italy) employed in previous studies involving individuals with neurodegenerative [14] and neurological progressive disorders [15]. This device, attached to the subject's waist approximately at the L4-L5 vertebrae with a semi-elastic belt, collects the accelerations along three orthogonal axes during the iTUG. Data were processed using a dedicated software (G-Studio, BTS Bioengineering S.p.A., Italy). To perform the test, participants were asked to sit on a chair (seat height and width 48 cm, seat depth 40 cm, back support height 34 cm), and asked to rise from the chair, walk at a comfortable speed for 3 m, make a 180° turn and walk back to sit down again.

Participants repeated the test twice: the first attempt to familiarize with the procedure, and the second for the actual data collection. The dedicated software allows to calculate:

- iTUG time, the total time needed to perform the test (s);
- walking sub-phase time, the time needed to walk for the total 6 m (s);
- sit-to-stand time (s);
- first (intermediate) 180° turn, time needed to perform the turn inverting the gait direction (s);
- second (final) 180° turn, time needed to perform the turn necessary to reach the sitting position at the end of the TUG (s);
- stand-to-sit time, duration of the stand-sit transition at the end of the task (s).

2.2.3. Rivermead Mobility Index

The RMI was used to assess the functional mobility along with physical and cognitive disability.

- The RMI is composed by 15 items, mostly self-reported (only one is associated with a direct observation of an external rater). Each item is scored 0 if patients are not able to complete the task, and 1 if they can. Each item contributes to the total score, which ranges from 0 to 15. Higher values reflect better functional mobility [11].

2.3. Statistical analysis

At first, a one-way multivariate analysis of variance (MANOVA) was conducted to exclude the existence of significant differences in anthropometric and demographic data between the two groups of participants. Subsequently, after confirming the normality, homogeneity, and absence of outliers, a second one-way MANOVA was carried out to investigate whether sTBI introduced any differences in postural sway and iTUG parameters with respect to HC. The independent variable was the group (i.e., sTBI or HC), and the dependent variables included the four previously mentioned sway parameters and the six iTUG parameters. The significance level was set at $p = 0.05$, and the effect sizes were evaluated using the partial eta-squared coefficient. For the follow-up analysis, the significance levels were adjusted using the Bonferroni correction for multiple comparisons, resulting in $p = 0.0125$ (0.05/4) for postural sway and $p = 0.008$ (0.05/6) for iTUG.

The correlations between postural sway and iTUG parameters, and those between instrumented tests and RMI, were assessed using the Spearman's rank correlation coefficient (ρ). Correlations were classified as low (0.1–0.3), moderate (0.3–0.5), or large (>0.5) [30].

All analyses were performed using IBM SPSS Statistics version 26 (IBM, Armonk, NY, USA).

3. Results

Demographic, anthropometrical, and clinical characteristics of both groups are shown in Table 1.

3.1. Differences in postural control and functional mobility

The results of the postural sway analysis are presented in Table 2. MANOVA detected a significant main effect of the group on sway parameters [$F(4,31) = 4.26$, $p = 0.007$, Wilks $\lambda = 0.65$, $\eta_p^2 = 0.36$]. The follow-up analysis revealed that individuals with sTBI exhibited significantly larger sway areas (171.4 mm^2 vs. 90.0 mm^2, $p = 0.003$) compared to HC.

MANOVA also found a significant main effect of the group on iTUG parameters [$F(5,30) = 5.43$, $p = 0.001$, Wilks $\lambda = 0.53$, $\eta_p^2 = 0.48$]. Subsequent follow-up tests revealed a significantly longer overall iTUG walking phase duration in the sTBI group when compared to HC (5.3 s vs. 3.2 s, $p < 0.001$), as shown in Table 3.

3.2. Correlations between static and dynamic parameters and clinical measures

Regarding the sTBI group, there was a significant, large correlation between the COP displacement in the ML direction and the sit-to-stand sub-phase duration ($\rho = 0.622$, $p < 0.05$), as displayed in Table 4.

The RMI score was found significantly correlation with iTUG total time ($\rho = -0.564$, $p < 0.05$) and walking duration ($\rho = -0.542$, $p < 0.05$), as indicated in Table 5.

4. Discussion

The assessment of residual functions in terms of postural control and functional mobility in individuals with history of sTBI is crucial for designing and managing effective rehabilitation protocols and improving their overall quality of life. Enhancing the sensitivity and accuracy of impairment-level assessments enables therapists to detect even subtle balance or motor dysfunctions, which may lead to augmented risk of falling. Utilizing movement monitors to assess functional mobility can provide supplementary information on motor tasks commonly used in clinical practice [31]. However, this process can be challenging in the mid-/long-term. In this context, the introduction of instrumental measures in the clinical routine may support the detection of subtle alterations, not identifiable using conventional clinical tools. Our study aimed to objectively evaluate the main features of postural control and functional mobility in a cohort of sTBI survivors and compare them to age- and anthropometrically matched healthy individuals. Additionally, we aimed to explore the existence of correlations between static and dynamic abilities and between a commonly-used clinical scale and the instrumented tests in sTBI.

Our results revealed significant differences in both static balance and functional mobility between sTBI survivors and unaffected individuals. Regarding the sway parameters, individuals with sTBI generally exhibited higher values compared to the HC for all of them except for COP velocity: this is not surprising, as sway area and COP displacements reflect the overall quality of the postural control system, while sway velocity is mainly associated with the muscular activity required to perform postural corrections. It is likely that in sTBI survivors such muscular activity is somehow altered due to the past neuronal trauma. In particular, our findings are consistent with the existing studies [20,22,23], and indicate that our sample of individuals with sTBI had significantly larger sway areas compared to the control group. This is probably due to larger (34 %) COP displacements in the ML direction, even though the significance was not retained after Bonferroni's correction ($p = 0.015$). It is known that AP and ML sway components are controlled using independent strategies [32], and in particular ML stability requires greater neural resources and higher motor cortex activities [33]. Thus, the larger ML displacement observed in individuals with TBI might be linked, at least partly, to decreased structural connectivity and white matter deterioration [34], combined with a range of other factors such as muscular strength deficits, or impairments affecting the vestibular, visual, and somatosensory systems. Poor stability in the ML direction has also been reported as a typical feature of TBI-related gait [35,36], characterized by an increased base of support as an attempt to enhance stability on the frontal plane. It is noteworthy to observe that, although not statistically significant, sTBI survivors were characterized by reduced sway velocities compared to HC. This feature of postural control among TBI survivors [23] is likely connected to the persistent neural deficits [37], which result in longer times required to perform postural adjustments.

Table 1
Demographical, anthropometrical, and clinical characteristics.

	sTBI (n = 18)	HC (n = 18)
Gender (no. males)	6	6
Age (years)	37.4 (17.4)	36.3 (14.9)
Height (cm)	173.7 (6.6)	174.8 (7.3)
Body Mass (kg)	77.7 (17.3)	84.7 (36.2)
Time since trauma (months)	31.8 (18.6)	–
RMI (0-15)	13.7 (2.3)	–

Values are reported as mean (standard deviation) except as for gender.
RMI: Rivermead Mobility Index.

Table 2
Postural sway parameters for individuals with sTBI and unaffected individuals (HC). Values are reported as mean (standard deviation).

	sTBI	HC
Sway area (mm^2)	171.4 (99.7)[a]	90.0 (43.6)
Sway velocity (mm/s)	7.8 (2.7)	9.5 (3.0)
COP ML displacement (mm)	15.2 (5.5)	11.3 (3.4)
COP AP displacement (mm)	21.0 (5.9)	17.4 (4.9)

COP: Center of Pressure; ML: mediolateral; AP: anteroposterior.
[a] Significant difference vs. HC after Bonferroni correction ($p < 0.013$).

Table 3
iTUG parameters for sTBI and HC. Values are reported as mean (standard deviation).

	sTBI	HC
Total duration (s)	13.0 (3.6)	10.9 (2.1)
Total walking time (s)	5.3 (1.8)[‡]	3.2 (1.1)
Sit-to-stand time (s)	1.7 (0.3)	1.6 (0.3)
First 180° turn (s)	2.4 (0.8)	2.2 (0.6)
Second 180° turn (s)	2.0 (0.8)	2.1 (0.9)
Stand-to-sit time (s)	1.5 (0.7)	1.7 (0.6)

[‡] Significant difference vs. HC after Bonferroni correction ($p < 0.008$).

Table 4
Spearman's ρ correlation coefficients between static posturography and iTUG parameters.

		iTUG time	Walking duration	Sit to Stand time	Stand to sit time	First 180° turn	Second 180° turn
Sway area	sTBI	0.337	0.205	0.425	0.323	0.356	0.311
	HC	−0.177	0.166	0.058	−0.294	−0.121	−0.317
Sway velocity	sTBI	0.236	0.102	0.381	0.172	0.235	0.286
	HC	0.397	−0.117	0.427	0.342	0.352	0.369
COP ML displacement	sTBI	0.348	0.164	0.622*	0.238	0.013	0.286
	HC	−0.374	0.071	0.017	−0.383	−0.065	−0.372
COP AP displacement	sTBI	0.119	0.106	−0.030	0.458	0.043	0.238
	HC	0.058	0.317	0.207	−0.329	−0.015	−0.320

COP: Center of Pressure; ML: mediolateral; AP: anteroposterior.
*$p < 0.05$.

Table 5
Spearman's ρ correlation coefficients between RMI and instrumented tests measures.

	Parameter	Spearman's ρ
RMI vs.	Sway area	−0.098
	Sway velocity	−0.023
	iTUG Time	−0.564*
	Walking duration	−0.542*

*$p < 0.05$.

Regarding functional mobility, the iTUG test suggests that individuals with sTBI require more time to complete the test, primarily for the significant increase of the walking phase. These findings are consistent with previous studies indicating that individuals with TBI walk at a reduced speed compared to healthy individuals, because of the reduced step length [38]. Other sub-components of the iTUG test, which are more related to muscular strength and coordination, such as sit-to-stand and 180° turning, do not appear to be significantly affected. However, further studies are needed to clarify this aspect.

It is noteworthy that our results contrast with those reported by Newman and colleagues [25], who observed alterations in the sit-to-stand and turning phases of the TUG test. This inconsistency may be attributed to the different age groups of the tested subjects (children in the case of Newman et al. [25]). Even in this context, the performance of individuals with sTBI differs from that observed in neurological diseases, where longer turning times compared to a healthy population are often reported [15,39,40], emphasizing the distinctiveness of trauma-related conditions.

The correlation analysis indicated a significant association between the duration of the sit-to-stand phase of the iTUG test and the maximum COP displacements in ML direction. Such findings suggest that, in individuals with sTBI, static balance and functional mobility are somehow linked. The sit-to-stand task involves the transition from a large and stable base of support to a smaller one:

while good dynamic balance abilities are necessary to optimally perform this transition, static abilities are also essential to maintain the COP within the base of support during the initial standing phase [41]. Moreover, individuals with sTBI who exhibit larger COP displacements in the ML direction during quiet standing tend to be slower in performing the sit-to-stand task, likely due to their poorer balance. Although statistical significance was not achieved, it is worth noting the relationship between sway area, velocity, and iTUG parameters in the sTBI group. The broader context of these relationships underscores the need for in-depth investigations across larger clinical populations with different characteristics to thoroughly understand the real association between instrumented functional mobility and postural parameters, since impaired static balance may lead to compromised dynamic capabilities. The lack of further significant correlations between static and dynamic parameters could be rationalized by the intrinsic nature of these motor tasks, which involve different control systems: static balance mainly relies on information from the visual, vestibular, and proprioceptive systems, while in functional tests static standing is almost absent, and several functional abilities, including balance, are required to perform transitional movements effectively [15,42]. Additionally, the heterogeneity of the sTBI population, including variability in injury severity and individual compensatory strategies, could have contributed to the observed correlation patterns. Furthermore, our relatively small sample size may have also limited statistical power to detect subtle correlations, highlighting the importance of larger-scale assessments with more diverse clinical populations. Future research should aim to address these issues through comprehensive assessment protocols and larger sample sizes to provide a deeper understanding of motor function in individuals with sTBI.

Significant correlations were observed between the RMI, overall iTUG time, and walking phase duration, underscoring the potential for self-reported measures to reflect actual functional mobility. Such findings suggest that personal perception, as reported through the RMI, does indeed have a meaningful relationship with the quantifiable aspects of mobility captured by the iTUG. In contrast, the lack of correlation between the RMI and sway parameters may be attributed to the former's focus on capturing more general functional alterations, as opposed to the precise sway variations measured by pressure platforms. This finding warrants the importance of combining both instrumental assessments for a comprehensive understanding of an individual's functional state in the context of TBI rehabilitation.

Certainly, there are some limitations to our study that should be acknowledged. Firstly, the relatively small sample size, mainly due to the local incidence of TBI cases and the availability of individuals to participate, limits the generalizability of our findings, and thus further tests on larger cohorts are desirable to confirm the results here presented. Additionally, participants were recruited from a specific outpatient facility, thereby restricting the applicability of the findings to individuals with sTBI receiving care at similar facilities. Furthermore, exclusion criteria, may have led to a sample that does not fully represent the diversity of individuals with sTBI, particularly those with more severe impairments or medical conditions. Additionally, we did not assess the fatigue levels of the participants during the tests or account for other potential factors (e.g. attention deficit hyperactivity disorder, anxiety, or subsidiary neurological diseases) that could influence postural sway or functional mobility. Future research should aim to address these limitations to provide a more comprehensive understanding of motor function in individuals with sTBI. Finally, the absence of patient-reported outcomes poses an additional limitation, as their incorporation could enhance the understanding of how instrumental measures relate to the real-life difficulties encountered by individuals with TBI.

5. Conclusions

Instrumented tests provide precise, quantitative, and objective insights into motor dysfunctions among individuals with a history of sTBI. Such data plays a crucial role in accurately assessing their recovery status, even over the long-term. Notably, our study stands among the few that objectively and quantitatively evaluate these aspects over the long term. Instrumental measures allowed for the identification of significant alterations in postural sway and functional mobility in individuals considered nearly fully recovered from sTBI. These assessments provide reliable means to evaluate static balance and functional mobility, offering distinct yet complementary information. Our findings emphasize the importance of integrating objective measures alongside clinical data in routine assessments for individuals with sTBI. By incorporating instrumental assessments, clinicians can conduct a comprehensive evaluation of motor abilities, spanning both the recovery process and the post-recovery phase. This integrated approach not only enhances the accuracy of motor function assessments but also aids in tailoring rehabilitation protocols to improve the overall quality of life for individuals with a history of sTBI.

Ethics statement

The study was approved by the Ethics Committee of Azienda Ospedaliero Universitaria di Cagliari (protocol code protocol PG/2022/1294, date January 26, 2022) and conducted in accordance with the Declaration of Helsinki.

Informed consent statement

Written informed consent was obtained from all subjects involved in the study.

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Data availability statement

Data associated with this study have not been deposited into a publicly available repository. The data presented in this study will be made available on request.

CRediT authorship contribution statement

Federico Arippa: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Massimiliano Pau:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Rosa Marcello:** Project administration, Investigation. **Laura Atzeni:** Project administration, Investigation. **Salvatore Simone Vullo:** Writing – review & editing. **Marco Monticone:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Federico Arippa reports financial support was partially provided by Sardegna Ricerche, I FAIR Program, and by the Regione Autonoma della Sardegna. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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