

Metrological verification of an intelligent measurement interface for implementing the Tinetti Mobility Test in student rehabilitation

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Published online: March 31, 2026

Accepted for publication: March 15, 2026

DOI:10.7752/jpes.2026.03052

Abstract:

Mild traumatic brain injury from blast waves injuries (blast TBI), this problem is considered a priority in Ukraine. The study is the performed is the metrological verification of an intelligent measurement interface for the implementation of the Tinetti Mobility Test (TMT) for students with disabilities resulting from blast TBI. Materials and methods. Theoretical methods (analysis, synthesis, generalization, modeling) and empirical methods (pedagogical experiment and methods of mathematical statistics) were used. The TMT was chosen to conduct the experiment. The participants in the experiment, students aged 19-23 (n – 38), had acquired disabilities as a result of blast TBI without acute conditions. Results. An intelligent measurement interface was developed to implement the TMT. A key element of the development is the use of new-generation artificial intelligence (AI)-based sensors – «smart sensors». In the developed infrastructure, it is essential to combine smart sensors into a coherent structure of an intelligent measurement interface to implement the TMT. Real-time data recorded by sensors placed on the student performing TMT and along the test trajectory is sent to the Sitara microprocessor, which processes the signal and calculates it instantly. Data is transmitted via Bluetooth Low Energy protocols. In the microprocessor, TMT data is analyzed using specialized software and then stored. Programming was carried out in the Bloodshed DEV C++ environment. Data analysis in the developed infrastructure is carried out using artificial intelligence (AI) algorithms. A distinctive feature of the developed intelligent measurement interface for implementing TMT for students with disabilities due to blast TBI is the integration of virtual reality technologies. Determination of the reliability and validity of measurements using the interface demonstrated a range of reliability from medium to high for parameters determined using TMT. Recording the results of TMT performance in manual mode confirmed the average level of TMT metrological characteristics. Conclusions. For the first time, a study was conducted on a population of students with disabilities due to blast TBI in a higher education setting. Unlike manual methods, digital recording of locomotion time parameters provides high test discrimination.

Key Words: students with disabilities, control, reliability, validity, physical education, artificial intelligence.

Introduction

Problem statement.

Problem statement. The war that has been going on in Ukraine for more than 10 years is one of the most traumatic events a person can experience (Kurapov et al., 2024). According to official data, among all injuries sustained during the war in eastern Ukraine, 35%–40% are head injuries, 80% of which are mild traumatic brain injuries. Mild traumatic brain injury from blast waves (blast TBI) is the most common problem in all wars of the last century (Alroumi et al., 2025; Gano et al., 2024). The war in Ukraine is no exception in terms of the number of blast TBIs, which is growing daily. At the same time, it is not known exactly how many people have become

disabled as a result of blast TBI in Ukraine, since the vast majority of cases, especially in the early years of the Russian Federation's aggression, were not recorded.

Given the number of people who become disabled as a result of blast TBI, this problem is considered a priority in various fields of knowledge in Ukraine. Higher education institutions are no exception. There is a growing burden on the education system (Kurapov et al., 2024). In particular, due to the annual increase in the number of students with disabilities as a result of blast TBI, and given the continuation of Russian aggression, this trend will continue in the future. Universities must ensure the accessibility and quality of educational services for students with disabilities, taking into account their abilities, by introducing inclusive education and providing conditions for rehabilitation (Klos, Blavt, & Kovalchuk, 2024). Current narratives require higher education institutions to develop innovative structural and content-related aspects of a holistic pedagogical process of inclusive education through the parallel implementation of professional, educational, and rehabilitation and development technologies (Tohănean et al., 2025).

The most important factors that have prompted scientific research in the field of inclusion are the search for effective ways to restore the impaired functions of students with disabilities in higher education.

Analysis of recent research and publications. It has been recognized (Shen et al., 2025) that blast TBI is currently a global, extremely relevant interdisciplinary problem. It has been studied (Rosen et al., 2021; Gano et al., 2024) that blast TBI has completely nonspecific individual manifestations and significantly impairs quality of life. It has been established (Akin et al., 2017; Davis-Wilson et al., 2025) that multiple disorders in various body systems are associated with a deterioration in overall health.

In scientific works (Alroumi et al., 2025; Akin, & Murnane, 2011), brain injuries after an explosion are considered the main cause of exhaustion of the body. It has been established (Row et al., 2019) that, despite the complex mechanism of action of the blast wave on the human brain, the nature of the disorders in the body and the state of health that may develop subsequently. The impact of the blast wave on the auditory and vestibular systems deserves special attention (Akin et al., 2017). In general, blast TBI is recognized as a factor in the development of various chronic physical, cognitive, and behavioral problems (Calderone et al., 2023).

It is claimed (Blavt et al., 2024) that the full restoration of damaged functions in students with disabilities due to blast TBI during university studies is ensured through inclusive physical education. Researchers emphasize (Klos, Blavt, & Kovalchuk, 2024; Karamani et al., 2024; Barber et al., 2024) that research on inclusion in physical education and the implementation of rehabilitation measures in higher education institutions is currently extremely limited.

Scientists agree (Modra et al., 2021; Lieberman, Houston-Wilson, & Grenier, 2024; Blavt et al., 2024) that the effectiveness of the inclusive physical education process is ensured by the use of the latest methods and a high-quality system for evaluating results. However, there is currently no system for monitoring the recovery of impaired functions in students with disabilities due to blast TBI, which complicates the identification of problems in these areas and the development of strategies to overcome them in the course of inclusive physical education. It has been determined (Blavt et al., 2025) that the monitoring of the process of inclusive physical education for students with disabilities after blast TBI is aimed at restoring body balance and coordination of movements. Balance problems are common after TBI (Row et al., 2019; Alroumi et al., 2025; Rosen et al., 2021), due to the impact on various parameters of the body's center-of-mass displacement both during posture maintenance and during movement (Akin, & Murnane, 2011). Studies (Harrell, Manetta, & Gorgacz, 2021; Günaydın, & İkizoğlu, 2023) show that balance disorders manifest themselves in poor ability to stand, bend, step, walk, and respond to external stimuli (Boening et al., 2025; Horak, King, & Mancini, 2015; Harrell, Manetta, & Gorgacz, 2021).

Researchers believe (Shen et al., 2025; Alroumi et al., 2025; Davis-Wilson et al., 2025) that the study of coordination parameters after blast TBI should be based on the development of automated control systems in combination with algorithms accounting for and analyzing all possible aspects of the functional state of the human body, using the high-tech capabilities of modern digital technologies (Koryahin et al., 2020; Blavt et al., 2025).

According to scientists (Winstein, & Requejo, 2015; Calderone et al., 2023), this is a significant positive predictor of stimulating innovation in this area of knowledge, which is crucial because of its role in disseminating knowledge and expanding the potential for creating competitive advantages to achieve the goals of inclusive development in higher education (Barber et al., 2024; Tohănean et al., 2025). At the same time, inclusion requires increased reliability of control measures (Karamani et al., 2024). While a minimal error in a stopwatch is not critical for a healthy student, such an error is unacceptable for a student with a disability.

Researchers argue (Klos, Blavt, & Kovalchuk, 2024) that Ukraine's inclusive education system, along with ensuring an effective rehabilitation process for students with disabilities, must meet the demands of society and innovative educational development (Prystupa et al., 2020). Therefore, there is a need for scientific research into the possibilities of optimizing the process of inclusive PE based on information systems and networks that would ensure the effectiveness of the rehabilitation process for students with disabilities after blast TBI.

The purpose of the study is the metrological verification of an intelligent measurement interface for the implementation of the Tinetti Mobility Test (TMT) for students with disabilities due to blast TBI.

Materials and methods

Research methods

To implement a comprehensive interdisciplinary approach, the research methods are structured as a multi-level system. The theoretical level provides justification for the direction and feasibility of scientific research. For this purpose, methods of analysis and generalization of scientific and methodological literature, a systematic approach, and a modeling method are used.

At the empirical level of scientific research, technical modeling methods were used to create an intelligent measurement interface. At this stage, the method of mathematical modeling of biomechanical signals was used to record the parameters of physical movement and represent them in the form of a mathematical code. A pedagogical experiment was used to confirm the hypothesis about the effectiveness of using an intelligent measuring interface for the implementation of TMT for students with disabilities due to blast TBI. Methods of mathematical statistics were used for the mathematical processing of the experiment results.

To implement the experiment, it was considered appropriate to choose an assessment tool that simultaneously observes and evaluates gait and balance quality. In view of this, the TMT was chosen, which includes an assessment of balance and gait. There are recommendations (Tinetti Performance Oriented Mobility Assessment) regarding the advisability of using the Tinetti Gait and Balance Test in the target group.

The test requires a hard, armless chair, a stopwatch, and a 15-foot, even and uniform walkway. It has two sections:

- assesses balance abilities in a chair and also in standing
- assesses dynamic balance during gait on a 15-foot, even walkway (Reiman, & Manske, 2009).

Study participants

In forming the composition of the study sample, we were guided by statements regarding sample size adequacy. The estimated sample size for detecting the average effect size using the Power Analysis method (Kemal, 2020) with specialized software was 24 people. Taking into account the possible dropout of students during the experiment, a sample of 38 students was formed from Kamianets-Podilskyi National Ivan Ohienko University, Lviv Polytechnic National University, Lviv State University of Physical Culture named after Ivan Boberskyi, Ternopil Volodymyr Hnatiuk National Pedagogical University, Drohobych Ivan Franko State Pedagogical University, and Higher State National Educational Establishment «Uzhhorod National University».

All students participating in the experiment (aged 19–23) had acquired disabilities as a result of blast TBI, received permission from a medical professional to participate in the testing, and confirmed their participation in writing with their personal consent. The main criterion for inclusion in the study was the absence of epileptic activity, concomitant diseases, and acute conditions. A separate exclusion criterion was the presence of concomitant orthopedic injuries, visual system disorders, and the use of medications that mechanically affect movement restrictions, as this could lead to incorrect interpretation of the test results.

The study was planned and carried out following the principles of bioethics set forth by the World Medical Association (WMA, 2013) in the Helsinki Declaration «Ethical Principles of Medical Research Involving Humans» and UNESCO in the «General Declaration on Bioethics and Human Rights».

Research organization

The study was organized as a parallel comparison of the test results obtained by the sample group of students during physical education classes. The TMT was conducted in two testing sessions with an interval of 48 hours. Step-by-step instructions for implementing the TMT were provided to the participants in the experiment.

The experimental factor consisted of implementing a method for recording the results of the TMT. The study then involved verifying the test results obtained using manual recording (stopwatch) compared to the data recorded by the intelligent measurement interface.

Statistical analysis

Based on the test results, the intraclass correlation coefficient (ICC) was determined, which is a widely used reliability index in test-retest, intrarater, and interrater reliability analyses (Koo, & Li, 2016). An ICC value >0.90 is considered an excellent indicator for digital systems.

Given the normal distribution of the sample, Student's t-test for dependent samples was used to compare the registration results. The level of statistical significance was set at $p < 0.05$.

Mathematical statistics methods were used to process, analyze, and interpret the experimental data using SPSS Version 22.0 (IBM Corporation).

Results

The results of our scientific research are presented in the developed intelligent measurement interface for TMT implementation. A key element of our development is the use of new-generation AI-based sensors—«smart sensors». Such sensors provide intelligent processing of TMT results, a communication protocol, and the ability to deploy AI-based sensors for IoT applications. Unlike conventional sensors, which simply record movement, smart sensors are capable of analyzing, predicting, and adapting to the individual needs of each control subject (Politanskyi et al., 2024).

The AI-based smart sensors used in the development contain sensitive elements: an accelerometer, a gyroscope, a pressure sensor, and a microprocessor with machine learning (ML) algorithms (Mykytyuk et al., 2025). This synthesis of sensitive elements in the sensor provides comprehensive control of the student's body orientation when performing a test task, measurement of gravitational force, speed, and acceleration (Alharthi, Yunas, & Ozanyan, 2019). Importantly, smart sensors record not only the coordinates of the student's movement along the TMT trajectory but also hand tremors or gaze delays.

At the same time, test control data are processed directly in the smart sensor system, providing instant feedback without delays. Thanks to the use of AI, we implement pattern detection: we obtain data not only about speed but also about the specific type of locomotion: walking on a flat surface, stairs, turning, risk of falling, etc. At the same time, the smart sensor system instantly adapts to the student's individual gait and adjusts its sensitivity to their individual characteristics.

Importantly, AI-based smart sensors can analyze data locally, reducing latency and bandwidth usage while improving decision-making capabilities. In the developed infrastructure, it is essential to combine smart sensors into a coherent structure of an intelligent measurement interface for TMT implementation.

Real-time data provided by sensors placed on a student with a disability performing TMT and along the test trajectory are sent to a Sitara microprocessor, which processes the signal and calculates it instantly. Data are transmitted via Bluetooth Low Energy (BLE) protocols (Fig. 1).

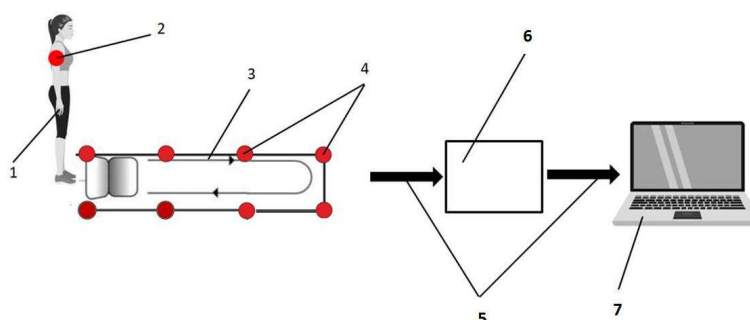


Fig. 1. Scheme of TMT implementation use of intelligent measurement interface:

1 – student, 2 – smart sensors, 3 – direction of movement, 4 – smart sensors along the TMT trajectory, 5 – infrared lines; 6 – Sitara microprocessor, 7 – PC

In the microprocessor, TMT data is analyzed using specialized software and then stored. Programming is carried out in the Bloodshed DEV C++ environment. Data analysis in the developed infrastructure is carried out using artificial intelligence (AI) algorithms. AI ensures the detection of anomalies and deviations in the equilibrium state of students with disabilities by means of appropriate actions or alerts.

To intensify the rehabilitation process, an operational feedback algorithm is integrated into the architecture of the intelligent complex. The system provides visualization of test results on an LCD panel immediately after completion of the TMT. TMT data is instantly linked to the student's ID (for example, via a QR code), which eliminates manual entry errors. This allows for the implementation of a biomechanical self-management mechanism: students are able to independently analyze the effectiveness of their actions and compare them with reference values.

TMT results are displayed on the complex's display in an easy-to-understand format (Fig. 2).

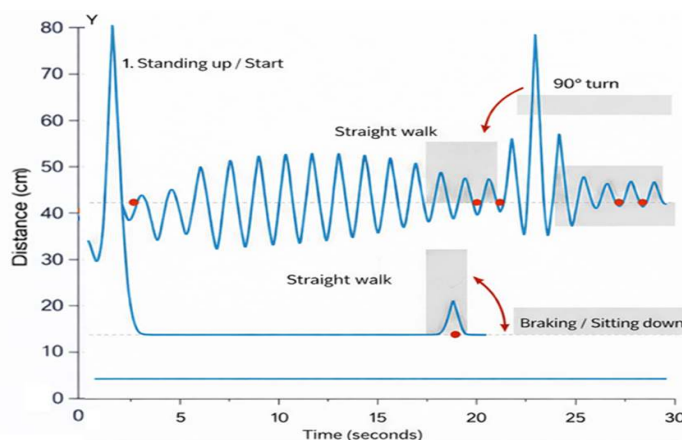


Fig. 2. Example of submitting TMT Results

Specifically, in numerical form: the actual TMT execution time, a graphical indication for visual comparison with the «model norm», and a color indication of progress (Fig. 3). The intelligent measurement interface system for TMT implementation instantly compares the result with the student's digital profile and provides recommendations on the intensity of further physical activity.

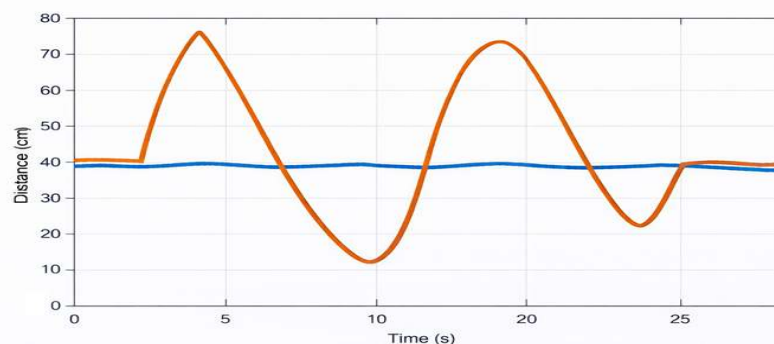


Fig. 3. Example for visual comparison with the «model norm» and a color indication of progress

A distinctive feature of the developed intelligent measurement interface for implementing TMT for students with disabilities due to blast TBI is the integration of virtual reality (VR) technologies. The display of motor activity in the VR model is implemented by synchronizing inertial data with the biomechanical skeleton of the avatar. In this way, static testing was transformed into a dynamic assessment process. The use of VR ensured not only the recording of task completion time, but also precise monitoring of spatial orientation and speed of attention switching. At the same time, the influence of external stimuli was minimized.

During the TMT, the interface displays parameters that are usually invisible to the instructor. These include the center of mass vector: if the point goes beyond the support area, the interface signals the risk of falling; foot trajectory (clearance): display of foot lift height. Students with disabilities due to blast TBI tend to "shuffle," which in VR looks like a trajectory line touching the virtual floor; step symmetry: a visual comparison of the length of the right and left legs' steps.

The next stage of the empirical study was the experimental testing of the developed intelligent measurement interface for the implementation of TMT for students with disabilities due to blast TBI. Determination of the reliability and validity of measurements using the interface demonstrated a range of reliability from moderate to high for the parameters determined using TMT (Table 1).

Table 1 Of the reliability and validity of TMT for students with disabilities due to blast TBI (n – 38)

Control parameter	Traditional methodology ($\bar{X} \pm m$)	ICC		Intelligent measurement interface ($\bar{X} \pm m$)	ICC	
		reliability	validity		reliability	validity
TMT execution time	114.5 $\pm$ 3.2	0.541	0.251	108.2 $\pm$ 1.4	0.877	0.607
Center oscillation amplitude (ms)	14.2 $\pm$ 2.1	0.481	0.215	12.8 $\pm$ 1.5	0.901	0.613
Step symmetry (cm)	3.1 $\pm$ 0.45	0.443	0.286	3.6 $\pm$ 0.22	0.842	0.592
Stimulus response time (ms)	450.11 $\pm$ 14.5	0.398	0.255	385.33 $\pm$ 12.17	0.910	0.649
Symmetry Index (%)	10.1 $\pm$ 0.05	0.412	0.197	8.89 $\pm$ 0.02	0.924	0.612
Tinetti tool score (points)	21.2 $\pm$ 0.88	0.453	0.215	21.66 $\pm$ 0.21	0.913	0.601

Reliability was confirmed by a high ICC (0.94) in repeated measurements. Validity was established by comparing the results of digital recording with the data of expert assessment on the Tinetti scale, which revealed a strong positive correlation ($r = 0.85$; $p < 0.001$). Manual recording of TMT performance results showed an average level of TMT metrological characteristics.

Dicussion

Our research is driven by the increasing number of students with disabilities due to blast TBI, which requires greater inclusivity in universities (Klos, Blavt, & Kovalchuk, 2024). Modern education is paying more and more attention to creating an inclusive environment (Karamani et al., 2024). We support scientific approaches that emphasize the particularly important role of physical education (Blavt et al., 2024) in this process, which is aimed at improving the health of students with disabilities in the learning environment.

The idea has been expanded (Blavt et al., 2024; Modra et al., 2021; Tohănean et al., 2025) that inclusive physical education is a process in which digital technologies provide equal opportunities for control and self-improvement to ensure the restoration of impaired functions in students with disabilities. This is in line with research (Barber et al., 2025; Lieberman, Houston-Wilson, & Grenier, 2024).

The feasibility of this approach is determined by the interdisciplinary nature of scientific research, which is consistent with the conclusions (Shen et al., 2025; Gano et al., 2024; Davis-Wilson et al., 2025). In general, it is based on the practical application of technical and engineering knowledge and skills to solve practical problems in the rehabilitation process (Chen, et al., 2016; Shafi et al., 2023; Archer, & Ellis, 2024). This is an important factor in ensuring the effectiveness of injury recovery and making rehabilitation effective and individually oriented (Winstein, & Requejo, 2015; Horak, King, & Mancini, 2015; Davis-Wilson et al., 2025).

We support the evidence-based claims (Chen et al., 2016; Archer, & Ellis, 2024; Horak, King, & Mancini, 2015) that only digital methods can confirm that the research parameters have undergone reliable qualitative changes, which is the basis for moving on to the next stage of rehabilitation.

The introduction of AI into the monitoring of inclusive physical education is not just technological progress; it is an opportunity to implement personalized, data-driven rehabilitation (Blavt et al., 2025). We agree (Sumner et al., 2023; Rasa, 2024; Attah-Mensah et al., 2025) that AI technologies offer unprecedented opportunities for ensuring high-quality personalized monitoring in the rehabilitation process.

Validity is a correlate of test use for a given population (McLay, 2020; Kloos et al., 2014; Koryahin et al., 2020). A high level of test validity ensures objective measurement (De Cock et al., 2025), which can be achieved using computerized systems and inertial sensors (Mancini, & Horak, 2010; Shafi et al., 2023; Horak, King, & Mancini, 2015), ML technologies, and image processing methods for gait analysis (Alharthi, Yunas, & Ozanyan, 2019). This gives grounds to position metrological control as a priority area for objectifying the rehabilitation process in various environments.

Blast TBI often disrupts body perception (Gano et al., 2024; Akin et al., 2017; Davis-Wilson et al., 2025). There is extensive information (Calderone et al., 2023; Shen et al., 2025; Zanier et al., 2018) on the feasibility of using VR technologies in the rehabilitation process. There are opinions (Alroumi et al., 2025; Shima, & Matsuura, 2025) that by observing an exact copy of one's movements in VR, the brain relearns faster.

We agree with our research that assessing balance in blast TBI can help evaluate the risk of falling and/or identify the main causes of such a disorder (Mancini, & Horak, 2010; Günaydın, & İkizoğlu, 2023; Horak, King, & Mancini, 2015) and is an important component of rehabilitation (Boening et al., 2025; Rosen et al., 2021; Gano et al., 2024).

To date, the suitability of TMT has been tested on populations of individuals in the third age of life (Avdić, & Pecar, 2006; Montero-Odasso et al., 2004); in Chinese community-dwelling older adults (Omaña et al., 2021; Yang et al., 2023; Raïche et al., 2010); in people with stroke (Canbek et al., 2013; Boening et al., 2025); in people with Parkinson's Disease (Park et al., 2018; Kegelmeyer et al., 2007); in individuals with Huntington's disease (Kloos et al., 2014); residents with dementia (Sterke et al., 2010); in people with neurological disorders (Besios et al., 2019); in non-hospitalized post-COVID-19 individuals (Bastos et al., 2024); patients in hospital (Knobe et al., 2016); with knee osteoarthritis (Parveen, & Noohu, 2017).

For the first time, a study was conducted on a population of students with disabilities due to blast TBI in a higher education setting. Based on the results of the study, we have grounds to recommend TMT for use in inclusive physical education as a simple, accessible tool for monitoring the mobility of students with disabilities due to blast TBI.

Conclusions

Like all areas of public life since the full-scale invasion of the Russian Federation, education has faced numerous challenges. Modern education is paying increasing attention to creating an inclusive environment for students with disabilities resulting from war. Physical education plays a particularly important role in this process, as it serves to rehabilitate students with disabilities resulting from blast TBI, whose numbers in higher education institutions are constantly growing.

The use of digital technologies in monitoring the rehabilitation process of inclusive physical education transforms subjective observation into an accurate, evidence-based process. The results of monitoring are the basis for the development of targeted interventions, making it a valuable tool for improving outcomes in balance and mobility. The study implements an approach to TMT using an intelligent measurement interface that uses AI algorithms to process signals in real time. The use of a «smart sensor» allows for predictive analysis of balance parameters and provides the student with personalized feedback. This transforms the measurement interface from a passive measuring device into an active intelligent system for supporting inclusive physical education. By collecting and analyzing data from sensors, AI ensures optimal decisions are made in solving current problems. The use of VR in the developed intelligent interface allows visualizing hidden deficits in the dynamic gait pattern (asymmetry, step variability) resulting from diffuse blast TBI and provides students with immediate visual feedback.

The results of metrological verification have shown that the use of an intelligent measurement interface in the implementation of TMT is a reliable and valid tool for students with disabilities due to blast TBI. The introduction of an intelligent measurement interface for the implementation of TMT in the control of the rehabilitation process of students with disabilities due to blast TBI allows for the implementation of the principle

of precision control. This enables the teacher to make operational adjustments to the workload based on objective metrological control indicators, which is critically important for ensuring the safety and effectiveness of inclusive physical education.

In general, the developed intelligent measuring interface has been confirmed to be functional and capable of performing automatic TMT tracking functions. The results obtained indicate the prospects for integrating electronic technologies and AI for monitoring TMT and managing the rehabilitation process of students with disabilities due to blast TBI.

Conflicts of interest - If the authors have any conflicts of interest to declare.

Declaration of generative AI and AI-assisted technologies in the writing process

The author declares that no generative AI or AI-assisted technologies were used in the writing or editing of this manuscript.

Funding statement

This research received no external funding

The authors received no financial support for the research, authorship, and publication of this article

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