BABEȘ-BOLYAI UNIVERSITY CLUJ-NAPOCA

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BAIAS MARIA SOFIA

EDUCATION OF STATIC BALANCE FOR STUDENTS WITH DISABILITIES THROUGH PHYSIOTHERAPY INTERVENTIONS AND INTERACTIVE DIGITAL TECHNOLOGIES

Scientific coordinator:

Prof. univ. dr. habil. IOSIF SANDOR

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Contents

LIST OF ABBREVIATIONS

SEN – Special Educational Needs

ID – Intellectual Disability

DCD – Developmental Coordination Disorder

PNF – Proprioceptive Neuromuscular Facilitation

CoP – Centre of Pressure

AP – Antero-posterior

LL – Latero-lateral

BBS – Berg Balance Scale

ADL – Activities of Daily Living

VR – Virtual Reality

AR – Augmented Reality

MIRA – Medical Interactive Recovery Assistant

SPSS – Statistical Package for the Social Sciences

CNS – Central Nervous System

INTRODUCTION

Importance and Relevance of the Topic

Physical activity is an essential factor for a child's health and functional development, influencing neuromotor organization, psychomotor maturation, and long-term quality of life (Powell & Pratt, 1996; Swift et al., 2014). In childhood, movement is not merely a means of bodily expression but a fundamental stimulus for the maturation of the central nervous system, contributing to the formation of basic motor skills and to the consolidation of the postural control mechanisms that underlie static balance (Freitas et al., 2018). In children with neuromotor disabilities, these mechanisms are frequently disrupted, which justifies the need for structured therapeutic interventions, including those supported by digital technologies.

Static balance occupies a central role in psychomotricity, being a relevant indicator of neuromotor maturation and of the capacity to maintain postural stability under variable conditions. Balance control requires the continuous integration of information from the proprioceptive, vestibular, and visual systems, together with fine adjustments of the postural musculature, in order to keep the centre of gravity within the base of support (Winter, 1995). The specialized literature shows a high prevalence of balance and coordination deficits in children with motor difficulties (Cantell et al., 1994; Geuze, 2005; Miller et al., 2001), with consequences for daily autonomy, school participation, and social integration (Bouffard et al., 1996).

The relevance of the topic is supported by the contemporary orientation of neuromotor rehabilitation towards interventions grounded in neuroplasticity and motor-learning principles, which go beyond isolated exercise and emphasize functional, repetitive, and progressive tasks (Concha-Cisternas, 2023). In parallel, the development of digital technologies applied to rehabilitation has led to the emergence of tools such as gamification and interactive rehabilitation platforms, which transform physical exercise into a playful and motivating activity, with immediate feedback and progressive adjustment of difficulty (Bonnechère et al., 2017) — aspects particularly relevant for students with special educational needs (SEN).

The specialized literature indicates growing interest in digital technologies and gamification in rehabilitation, yet most studies target specific clinical populations (for example, children with cerebral palsy or neuromuscular diseases), leaving the category of students with diverse neuromotor disabilities integrated in special education insufficiently explored (Camara Machado et al., 2024). The present research addresses this gap, investigating the impact of an integrated therapeutic program — proprioceptive neuromuscular facilitation, exercises on unstable surfaces, and interactive motor activities via the MIRA platform — on educating static balance in students with SEN.

Motivation for Choosing the Topic

The choice of topic is grounded in professional experience accumulated in school-based kinesiotherapy, which has shown that difficulties with static balance and postural control are among the most frequent and persistent problems encountered in students with neuromotor disabilities. These difficulties are not limited to instability in standing posture; they also limit the performance of transfers, the maintenance of postures required for educational activities, and participation in adapted motor tasks.

A central argument is the discrepancy between students' real needs and current therapeutic practice, which is often centred on standardized analytical exercises with limited potential for functional transfer. Proprioceptive neuromuscular facilitation (PNF), exercises on unstable surfaces (such as the Bobath balance board), and interactive digital platforms like MIRA each offer premises for overcoming these limitations: PNF activates proprioceptors and righting-reflex mechanisms (Bastian, 2006); controlled instability stimulates multisensory integration (Kachouri et al., 2016); and the interactive digital environment supports visual feedback, graded difficulty, and intrinsic motivation (Huotari & Hamari, 2012; Deci & Ryan, 2000). However, the literature review reveals a shortage of research integrating these three components into a unified framework applied in special schools, where the diversity of disabilities requires flexible interventions (Camara Machado et al., 2024).

Aim, Objectives, and Hypotheses of the Research

The general aim of the thesis is to investigate the effectiveness of an integrated kinesiotherapy program, based on PNF, exercises on unstable surfaces, and digitally assisted interactive motor activities, in educating static balance and optimizing postural control in students with neuromotor disabilities integrated in special education.

The general objective is to evaluate the impact of this integrated therapeutic program, applied in the special educational environment, on static balance and postural control. The specific objectives are: (1) to analyze the characteristics of static balance in students with neuromotor disabilities, through initial stabilometric and functional assessments, in order to identify the existing level of postural instability; (2) to implement an integrated kinesiotherapy program combining proprioceptive neuromuscular facilitation techniques, balance exercises performed under controlled instability, and digitally assisted interactive motor activities via the MIRA platform, adapted to the neuromotor particularities of the subjects; (3) to determine the changes in the biomechanical parameters of postural control, by analyzing the evolution of centre-of-pressure stabilometric indicators before and after the intervention; (4) to evaluate the functional changes in static balance using standardized instruments for assessing stability and postural control (Berg, 1989; Franchignoni et al., 2010; Horak et al., 2009); (5) to compare the results obtained pre- and post-intervention, in order to establish the effectiveness of the integrated therapeutic program; and (6) to correlate the biomechanical results with the functional ones, in order to highlight the relationship between improved postural stability and functional performance.

The general hypothesis states that the application of an integrated kinesiotherapy program, combining PNF, exercises on unstable surfaces, and digitally assisted interactive motor activities, produces significant improvements in static balance and postural control in students with neuromotor disabilities. Three specific hypotheses derive from this: (1) the program leads to a significant reduction in postural instability, evidenced by improvement in the centre-of-pressure stabilometric parameters, in the post-intervention assessment compared with the initial assessment; (2) implementation of the program will lead to significant increases in scores on functional static-balance assessment tests, compared with the initial level; (3) the improvements demonstrated at the biomechanical level are positively correlated with functional progress, indicating a direct relationship between objectively measured postural stability and functional performance.

Novelty and Scientific Contribution of the Research

The novelty of the thesis lies in its integrative approach to static balance as a central psychomotor function, analyzed simultaneously from a theoretical, methodological, and applied perspective, in the context of paediatric rehabilitation and special education. Static balance is conceptualized not as an isolated ability but as the outcome of the interaction between postural control, sensory integration, motor learning, and functional adaptation, related to the specific demands of the educational environment.

A first level of scientific contribution is the coherent integration of the concepts of postural control, psychomotricity, and neuromotor reorganization into a framework applicable to students with neuromotor disabilities, going beyond existing fragmented approaches that treat these dimensions separately. A significant added value is the integration of interactive digital technologies into the kinesiotherapy approach not as a substitute for classical intervention but as its functional extension — the MIRA platform being used to support immediate feedback, repetition, and active task engagement (Stanmore et al., 2019), facilitating the conditions necessary for motor learning and neuromotor reorganization.

A distinctive element of the approach is the systematic combination of proprioceptive neuromuscular facilitation with controlled instability and the interactive digital environment, within a unified therapeutic architecture: PNF techniques are used in functional contexts, in which the induced imbalance becomes a stimulus for developing postural righting strategies, while unstable surfaces amplify proprioceptive demand and trigger continuous postural adjustments, supported and directed by the interactive digital activities, which allow the progressive adaptation of difficulty and the maintenance of motivation (Bonnechère et al., 2017; Springer & Yogev Seligmann, 2016).

The scientific contribution is further strengthened by the applied context chosen — the special educational environment, characterized by high neuromotor and functional heterogeneity (Lord et al., 2020; Schalock et al., 2010) — the therapeutic program being adapted to students with diverse neuromotor disabilities, often associated with cognitive, sensory, or behavioural difficulties, which requires methodological flexibility and functional differentiation. Another important contribution is the multimodal evaluative approach, which correlates objective stabilometric data with standardized functional assessments (Nashner & Peters, 1990; Peterka, 2002), allowing an in-depth interpretation of the intervention's effects. From an applied perspective, the research proposes a structured, coherent, and replicable therapeutic model, compatible with the curricular requirements of the Kinesiotherapy discipline in the area of "corrective-compensatory therapies," adaptable according to institutional resources and student particularities.

PART I — THEORETICAL AND SCIENTIFIC FOUNDATIONS OF THE THESIS

CHAPTER 1. THE CONCEPT OF BALANCE

Postural control is a complex neurophysiological process that integrates multiple levels of motor and sensory control (Horak, 2006; Peterka, 2002; Taube et al., 2008). Static balance does not depend exclusively on biomechanical parameters but on the central nervous system's capacity to combine, evaluate, and reweight sensory information according to context and task. In children with disabilities, the development of these mechanisms is frequently delayed, but it can be improved through training programs based on sensorimotor re-education (Carmeli et al., 2008; Eslamdost et al., 2017; Zolghadr, Sedaghati & Daneshmandi, 2019).

Definitions and Levels of Organization of Balance

Balance can be defined as the process by which the body's centre of gravity is kept vertically above a base of support (Anderson & Behm, 2005; Hrysomallis, 2011; Winter, 1995; Zatsiorsky & Duarte, 1999), through the continuous and rapid regulation of visual, vestibular, and somatosensory information (Nashner, 1997). In Bressel et al.'s (2007) view, balance represents the ability to maintain the desired body position during movement, being at the same time an essential component of motor qualities, closely linked to coordination and dexterity (Grosu, 2009; Mateescu, 2010; Rață & Rață, 2005; Ricotti, 2011).

The specialized literature identifies four interdependent levels of balance organization (Pollock et al., 2000; Mergner, 2010; Segev-Jacubovski et al., 2011): the mechanical level (the static relationship between the centre of gravity and the base of support), the postural level (the active regulation of stability through motor strategies — ankle, hip, compensatory step), the sensorimotor level (integration of vestibular and proprioceptive information), and the cognitive level (executive functions and selective attention). According to the principles of classical mechanics, a system is in equilibrium when the sum of the forces and moments acting on it is zero (Bell, 1998), and stability depends on the position of the centre of gravity and the size of the base of support (Hall, 1991). Unlike an inert object, the human body has an active neuromuscular control system that continuously compensates for deviations and perturbations (Mergner, 2010), so that stability is not a passive state but the result of an ongoing active regulation process.

From a neurophysiological perspective, balance is supported by two types of postural strategies: anticipatory (predictive), which prepare the motor system for a foreseeable perturbation, and reactive (compensatory), which intervene in response to an unexpected perturbation (Horak & Nashner, 1986; Maki & McIlroy, 1997). The sensory systems involved are the vestibular system, the proprioceptive system, and the visual system (Horak & Macpherson, 1996; Mergner, 2010). The central nervous system integrates this information and reweighs it according to context, generating corrective motor commands that stabilize the centre of gravity (Lockhart & Ting, 2007).

Individual, Age, and Gender Differences

As age advances, a reduction in the efficiency of sensory systems and a slowing of central information processing are observed, leading to a slower reaction time and diminished postural stability (Horak et al., 1989; Lord et al., 2007), aggravated by sarcopenia (Granacher et al., 2011). Research shows that older adults exhibit wider centre-of-pressure oscillations and increased latency of postural responses (Carpenter et al., 2010), and the adaptability of the central nervous system to environmental changes decreases with age (Era et al., 2006).

With respect to gender differences, females tend to show superior stability in static tasks, owing to a lower centre of gravity and a relatively larger base of support (Hoffman et al., 1998), while males benefit from greater muscle strength, with more prompt reactions to perturbations (Paillard, 2017). Hormonal variations can, in turn, influence proprioceptive sensitivity and postural coordination (Kubo et al., 2001; Petrofsky et al., 2006).

Neurophysiology of Balance: Sensory Integration and Adaptation

Control of static balance relies on the cooperation of the vestibular, visual, and somatosensory-proprioceptive systems, whose information is integrated centrally — brainstem, cerebellum, basal ganglia, cortex (Assaiante & Amblard, 1995) — to generate appropriate motor responses (Horak, 2006; Ivanenko & Gurfinkel, 2018; Cullen, 2011). The vestibular system detects head accelerations and activates the vestibulo-ocular and vestibulo-spinal reflexes (Brooks & Cullen, 2013; Black et al., 2008). The visual system provides external reference points for balance regulation, and reduced visual input increases dependence on the other systems (Shumway-Cook & Woollacott, 2017). Proprioception provides information about the position of body segments (Gandevia, 2014; Buneo & Andersen, 2006).

Multisensory integration allows the construction of a unified representation of body position (Mergner, 2010), and sensory reweighting — adjusting the contribution of each system according to context — represents an essential adaptive mechanism (Peterka, 2002). Postural control results from the interaction of reflex mechanisms, subcortically mediated (Black et al., 2008), and voluntary mechanisms, dependent on cortical structures (Taube et al., 2008). Proprioception plays a determining role: in the absence of adequate visual feedback, it becomes the main support of stability, and proprioceptive deficits result in increased instability (Goble, 2010; Gandevia, 2014).

Balance is also supported by processes of motor learning and neuronal plasticity (Taube et al., 2008), with the cerebellum and motor cortex playing central roles in consolidating these adaptations (Bastian, 2006). Rehabilitation programs based on visual, vestibular, and proprioceptive feedback — including interactive systems — favour the recalibration of sensory integration and the reorganization of neural networks (Konczak et al., 2009; Sun et al., 2021).

Balance Disorders: Causes and Clinical Implications

Balance disorders can arise from impairment of any component of the sensory or central network involved in postural regulation, with causes including central nervous system dysfunctions, inner-ear lesions, as well as general or metabolic factors (Beaumont Health, 2024). In children, balance disorders are frequently associated with sensory deficits and neuromotor developmental disorders (Brandt et al., 1994; Harun et al., 2016). Through repeated training, the nervous system develops compensatory mechanisms that allow adaptation to vestibular or proprioceptive deficits (Cullen, 2011), a principle underlying the use of structured therapeutic programs, including digitally assisted ones.

Chapter conclusion: control of human balance results from the complex interaction between sensory systems and central mechanisms of integration and motor regulation. In-depth knowledge of these processes constitutes the scientific foundation for modern therapeutic strategies based on neuroplasticity and multimodal training, with direct applicability to the rehabilitation of static balance in children with neuromotor disabilities.

CHAPTER II. BALANCE DEFICITS — CHARACTERISTICS AND DIRECTIONS OF THERAPEUTIC INTERVENTION

Balance represents the foundation of most movements, influencing autonomy, social interaction, and self-confidence. In children with intellectual disabilities (ID) and developmental coordination disorder (DCD), balance deficits limit participation in daily and educational activities, increase the risk of injury, and affect quality of life.

Particularities in Children with Intellectual Disabilities

Intellectual disability is a developmental disorder characterized by significant limitations in intellectual functioning and adaptive behaviours, manifesting before adulthood (Afrooz, 2013). Its prevalence ranges between 3% and 13% of the global population, and approximately 75–90% of affected individuals present mild, "educable" forms (Walsh et al., 2018). In countries with a low level of development, prevalence is approximately 4.6% of children under 18, compared with 0.5–2.5% in industrialized states (Haveman et al., 2010). Classification is frequently based on IQ and learning capacity (Afrooz, 2013), with modern diagnostic systems prioritizing adaptive functioning, and boys being affected more frequently than girls (Haveman et al., 2010). The aetiology is multifactorial, including hereditary, prenatal, perinatal, and postnatal causes (Rostami, Rezaie & Jabari, 2015).

In addition to cognitive limitations, children with ID frequently present obesity, muscle weakness, postural deviations, balance disorders, and other associated physical disabilities (Walsh et al., 2018). Perceptual-motor performance is inferior to that of typically developing children, against a background of sensorimotor system deficits and increased postural instability (Pitchford, Dixon-Ibarra & Hauck, 2018), accompanied by reduced muscle strength and slower reaction time (Taghian, Ghasemi & Sadeghi, 2017). Static and dynamic balance is often affected, increasing the risk of falls and limiting functional autonomy (Sretenović, Nedović & Đorđević, 2019); Hoffman (1998) observed better performance in girls than boys, but both groups show a developmental lag of 2–4 years compared with typically developing children. Movement plays an essential role in environmental exploration, behavioural regulation, and enhancing self-esteem (Pise, Pradhan & Gharote, 2018).

Particularities in Children with Developmental Coordination Disorder (DCD)

DCD is a neurodevelopmental disorder characterized by marked deficits in motor coordination, in the absence of explanatory neurological, musculoskeletal, or sensory conditions (American Psychiatric Association, 2022; Blank et al., 2012). The difficulties are considered the result of deficient integration of sensorimotor information and inefficient action planning (Geuze, 2005; Polatajko & Cantin, 2005), with a significant impact on daily-life activities (Barnhart et al., 2003; Gillberg & Kadesjö, 2003). ICD-11 describes delays in the acquisition of gross and fine motor skills (World Health Organization, 2021), and typical manifestations include generalized clumsiness and difficulties in activities such as handwriting, cycling, or team sports (Gibbs, Appleton & Appleton, 2007; Kirby & Sugden, 2007).

Directions of Intervention

The literature documents the effectiveness of several types of intervention, summarized below:

Type of intervention	Population	Effects reported in the literature
Play therapy (Yalfani et al., 2017)	ID	Improves overall balance and control of antero-posterior and medio-lateral oscillations
Process-oriented strength training (Kordi et al., 2016)	DCD	Improves muscle strength and static balance; limited effect on dynamic balance
Sensorimotor stimulation (Dadmehr et al., 2014)	ID with co-occurring DCD	May improve motor coordination in mild forms
Trunk stability training (Eslamdost et al., 2017)	DCD	Improves both static and dynamic balance
Stretching / yoga (Pise et al., 2018)	ID	Improves static balance, hand-eye coordination, agility, and reaction time

Table C. Directions of therapeutic intervention documented in the international literature (adapted from the thesis)

Regular physical activities contribute, beyond the strictly motor dimension, to increased independence, social integration, and the formation of a positive self-image (Rezaei, Arabameri & Sohrabi, 2017).

Proprioception in Children with Neuromotor and Intellectual Disabilities

Proprioception represents the body's ability to perceive the position, movement, and orientation of body segments in space, independent of visual information, and is essential for motor control and the maintenance of balance (Proske & Gandevia, 2012). The concept was introduced by Sherrington (1906, cited in Levine, 2007), who differentiated it from exteroceptive and interoceptive sensitivity; kinesthesia expresses the dynamic dimension of proprioceptive information (Goble, 2010). Proprioception plays a determining role through the integration of information from neuromuscular spindles, Golgi tendon organs, and joint receptors (Gandevia, 2014), allowing the detection of minimal deviations of the centre of gravity, a process mediated by the cerebellum, cortex, and thalamic structures (Bastian, 2006).

Static balance depends directly on the processing of proprioceptive information and its integration with vestibular and visual information (Gandevia, 2014). In children with intellectual and neuromotor disabilities, deficits in proprioceptive integration manifest as postural instability and inefficient balance strategies (Carmeli et al., 2008), a phenomenon accentuated by low levels of physical activity (Sretenović et al., 2019).

The literature supports the effectiveness of proprioceptive stimulation programs through static balance exercises, activities on unstable surfaces, and centre-of-gravity control tasks (Taghian et al., 2017; Pise et al., 2018; Kachouri et al., 2016; Hosseini & Azimizadeh, 2023). Proprioceptive neuromuscular facilitation stimulates proprioceptors through rhythmic stabilization techniques, adapted resistance, and agonist–antagonist alternation (Bastian, 2006). Proprioception is the foundation of postural stability and static balance, and the efficiency of postural control directly reflects the quality of proprioceptive processing (Lee, Lee & Song, 2016); in children with intellectual and neuromotor disabilities, this relationship has particular relevance for motor performance and educational participation (Sretenović & Nedović, 2019). Integrating exercises into playful and functional contexts increases engagement and repetition (Pise et al., 2018; Rezaei et al., 2017), while interactive digital gamification platforms, such as MIRA, enhance the education of proprioception and static balance.

Chapter conclusion: balance deficits are common in children with neuromotor and intellectual disabilities and DCD, affecting autonomy, safety, and socio-educational integration. Multimodal interventions combining the development of strength, coordination, and proprioception have proven effective, and the integrative approach — controlled instability, PNF, and interactive technologies — offers a current model of paediatric rehabilitation.

CHAPTER III. POSTURAL CONTROL, STATIC BALANCE AND STABILITY — A SENSORIMOTOR APPROACH

Postural control is an essential function of the nervous system, involved in maintaining position, coordinating movements, and preventing falls (Horak, 2006), being considered a complex motor ability, resulting from the interaction of sensorimotor, biomechanical, and cognitive processes (Horak & Macpherson, 1996; Shumway-Cook & Woollacott, 2017).

Components of Static Balance and the Limits of Stability

Biomechanically, stability represents the maintenance of the centre of pressure within the base of support (Zolghadr et al., 2019). The body uses strategies such as the ankle strategy, the hip strategy, and the compensatory step (Horak, 2006). The "limits of stability" describe the area within which the centre of pressure can move without a change in the base of support, influenced by muscular, articular, and sensory factors (Zolghadr et al., 2019). The contribution of the sensory systems to postural control is adaptively distributed, with a predominantly somatosensory weighting, followed by the vestibular and visual systems (Peterka, 2002; Horak, 2006). Proprioception provides information about body position and movement, allowing the anticipation and correction of motor errors (Taylor, 2009; Marasco & de Nooij, 2023; Goble, 2010).

Particularities in Disabilities and Directions for Rehabilitation

Children with intellectual disabilities and coordination disorders frequently present balance deficits associated with deficient sensorimotor integration and reduced strength (Carmeli et al., 2008; Eslamdost et al., 2017), leading to motor delays and limited functional participation (Ahmadi et al., 2012). Fragile proprioceptive feedback causes movement errors, rigidity, and increased dependence on visual cues (Carmeli et al., 2008; Goble, 2010), and in DCD additional difficulties arise in correcting postural control errors (Sohrabi et al., 2016). Modern rehabilitation uses integrated balance training and sensorimotor exercises (Zolghadr et al., 2019); programs of approximately 8 weeks can improve static and dynamic balance in children with disabilities (Zolghadr et al., 2019; Hossaini et al., 2017), and playful activities increase adherence to the program (Pise et al., 2018; Yalfani et al., 2017).

The Role of Kinesiotherapy

Static balance represents the maintenance of posture with minimal oscillations of the centre of gravity, resulting from the interaction of neuromuscular and sensory mechanisms (Massion, 1994; Peterka, 2002; Shumway-Cook & Woollacott, 2017), and constitutes the basis for coordination and complex movements (Epuran, 2011; Da Fonseca, 2000). In children with disabilities, difficulties arise with trunk stabilization and dependence on visual feedback (Assaiante et al., 2005; Westcott & Burtner, 2004). Kinesiotherapy acts simultaneously on the biomechanical, sensory, and neuromotor components, through functional, progressive interventions grounded in the principles of neuroplasticity, repetition, and relevant feedback (Latash, 2012; Kandel et al., 2013; Herzfeld & Shadmehr, 2014). Methods used to develop proprioception include maintaining standing posture with progressive reduction of the base of support (semi-tandem, tandem, single-limb stance), changing the support surfaces, and modifying sensory conditions (eyes open/closed, dual tasks).

Proprioceptive neuromuscular facilitation stimulates proprioceptors through rhythmic stabilization techniques, adapted resistance, and alternation of agonist–antagonist contraction, with direct effects on static balance (Bastian, 2006). Reducing or altering visual feedback amplifies dependence on proprioceptive information and intensifies the activation of internal postural control mechanisms (Goble, 2010) — a principle directly exploited in the thesis's therapeutic protocol. In children with intellectual disabilities, integrating exercises into playful and functional contexts increases engagement and repetition (Pise et al., 2018; Rezaei et al., 2017).

Chapter conclusion: educating static balance in children with neuromotor disabilities requires an integrated sensorimotor approach, combining proprioceptive training, controlled instability, and technological support, in line with the modern principles of functional kinesiotherapy.

CHAPTER IV. PSYCHOMOTRICITY AND ITS INFLUENCE ON BALANCE

Psychomotricity is a concept situated at the intersection of the cognitive, affective, and motor spheres of human development, expressing the unity between body and mind (Epuran, 2011; Lapierre & Aucouturier, 1984). It plays an essential role in the formation of the body schema, spatio-temporal organization, and the development of balance (Ajuriaguerra, 1974; Cratty, 1981) — fundamental elements for autonomy, coordination, and adaptation to the environment. In children with neuromotor disabilities or developmental disorders, psychomotricity becomes not only an indicator of development but also a therapeutic approach in itself (Massion, 1998; Gandevia, 2014).

Dimensions of Psychomotricity

The specialized literature identifies several interdependent dimensions of psychomotricity, whose harmonious development ensures the child's overall formation (Silva et al., 2018): the body schema (the internal representation of one's own body and its relationship with the environment, which allows the child to locate and coordinate body segments in motion, forming the basis of orientation and balance — Assaiante et al., 2014; Ahn, 2022; Raimo et al., 2021); laterality (the process of functional differentiation between the two cerebral hemispheres, essential for spatial organization — unfixed or mixed laterality can generate difficulties with balance and spatial orientation — Epuran, 2011); general and fine coordination (the synergy between the central and peripheral nervous systems, which at the postural level translates into the regulation of muscle tone and continuous adaptation to environmental demands — Horak, 2006; Ivanenko & Gurfinkel, 2018); postural tone (the premise of any motor act, regulated through stretching activities, resistance work, and breath control — Vayer & Roncin, 1988, cited in Villerbu, 1991); and spatio-temporal orientation (the optimal placement of one's own movement within an external frame — difficulties in anticipation and spatio-temporal synchronization frequently lead to loss of balance and motor instability — Assaiante, 1998). In children with neuromotor disabilities, the incomplete structure of the body schema leads to difficulties with stability and coordination, affecting both static and dynamic balance (Assaiante & Amblard, 1995).

Neurophysiological Mechanisms and the Relationship with Balance

From a neuroscientific perspective, psychomotricity is based on the multisensory integration of proprioceptive, vestibular, and visual information, processed in the cerebellum, brainstem, and posterior parietal cortex (Bosco & Poppele, 2001; Buneo & Andersen, 2006). The vestibular system contributes to spatial orientation, and the proprioceptive system provides information about the position and movement of body segments (Proske & Gandevia, 2012). In children with neurological dysfunctions, deficits in sensory integration cause incongruities between bodily perception and motor execution (Peterka, 2002). Balance is considered the central component of psychomotricity, as it represents the expression of the synergy between perception, tone, and movement (Massion, 1998). Postural control is a fundamental component of motor development, evolving progressively in childhood (Caldani et al., 2020; García-Soidán et al., 2020; Ludwig et al., 2020; Shams et al., 2020); psychomotor exercises involving balance, support, rolling, and movement in multiple planes favour the maturation of postural reflexes (Cratty, 1981). In children with disabilities, balance is often affected by multiple factors — hypotonia, postural asymmetry, sensory deficits, or perceptual integration disorders (Horak, 2006; Gandevia, 2014) — and psychomotor interventions aim to restore this integration (Assaiante & Amblard, 1995).

In children with cerebral palsy, autism spectrum disorders, ADHD, or psychomotor delay, impaired psychomotricity manifests as postural instability, difficulties with integration, and poor perception of one's own body (Paillard, 2017). Psychomotor deficits are not only the result of motor impairment but also of poor bodily awareness (Maciak et al., 2024; Balayi et al., 2022; Ajuriaguerra, 1974). Research confirms the effectiveness of psychomotor interventions in developing balance in children with coordination disorders and in those with intellectual disabilities (Ahmadi et al., 2012; Taghian et al., 2017), yielding progress in dynamic stability and spatial orientation capacity (Granacher et al., 2011). In autism spectrum disorders, balance and coordination exercises contribute to reducing and re-educating stereotypies (Baranek, 2002; Ellinoudis et al., 2011; Venetsanou et al., 2011; Lucas et al., 2013).

Integration of Technology in Modern Psychomotor Interventions

Recent advances in rehabilitation have led to the emergence of digital technologies that extend the possibilities of psychomotor interventions. Interactive platforms such as MIRA, virtual reality systems, or Wii Fit-type consoles allow motor skills to be practised in a playful and motivating setting, increasing children's interest in the program (Springer & Yogev Seligmann, 2016; Moldovan et al., 2014). Through gamification, these systems facilitate the training of balance and coordination, stimulating both intrinsic motivation and cognitive engagement (Huotari & Hamari, 2012). Studies show that digital balance exercises improve postural control and stability in children with coordination disorders and cerebral palsy (Farr et al., 2017), while also providing objective assessments of progress through movement capture (Naito et al., 2016).

Chapter conclusion: psychomotricity is a fundamental pillar of child development and a key to understanding balance, especially in the context of neuromotor disabilities. The integration of interactive technologies into psychomotor therapy opens new perspectives on rehabilitation (Shumway-Cook & Woollacott, 2012), facilitating objective assessments and personalized training (Lapierre & Aucouturier, 1984).

CHAPTER V. DEVELOPMENT OF THE RIGHTING REFLEX FOR PREVENTING LOSS OF BALANCE

The righting reflex is an essential automatic postural mechanism through which the body maintains or regains its orientation in space, particularly through the alignment of the head relative to the trunk, supporting posture, balance, and motor acquisitions (Robănescu, 2001). In children with neuromotor disabilities, particularly in infantile cerebral palsy, these reflexes are frequently impaired by central nervous system lesions, resulting in "delayed development or defective development of statokinetic reflexes" (Wang, Zhao & Liu, 2023), with postural instability, increased fall risk, fear of movement, and limited exploration and learning.

Functional Organization and Ontogenetic Development

Righting reflexes are integrated postural responses, dependent on vestibular, proprioceptive, visual, and exteroceptive input, which ensure head–trunk alignment (Magnus, 1924, cited in Robănescu, 2001). Static righting appears early in development, whereas dynamic righting (during a fall) develops later and depends predominantly on the vestibular system (Pellis & Pellis, 1994), an important point, since assessment under stable conditions may overestimate the actual protection against loss of balance. In neuromotor disabilities, the incomplete development of righting reactions and the persistence of primitive reflexes reduce the capacity for automatic correction of imbalance (Wang, Zhao & Liu, 2023). Consequences include chronic postural instability and increased frequency of falls, associated with fear of movement and avoidance, limiting motor learning (Graham et al., 2016); deviations in segmental alignment contribute further to the risk (Graham et al., 2016; El-Shamy et al., 2019). Biomechanical factors (postural deformities, rigidity, pathological positioning) can displace the centre of gravity and reduce the base of support (Nonnekes et al., 2018; Sturnieks, 2021; Wang, Zhao & Liu, 2023), and repeated falls perpetuate instability (Bobath, 1990, cited in Graham et al., 2016; El-Shamy et al., 2019). Assessment through postural analysis and tests such as the Berg Scale and the Timed Up and Go (TUG) allows the intervention to be directed accordingly (Robănescu, 2001; Wang, Zhao & Liu, 2023).

Kinesiotherapy Interventions Oriented Towards Righting

The principles of neurodevelopmental therapy (Bobath) aim to reduce spasticity and interrupt pathological patterns through inhibitory postures, creating a "window" in which normal movements and balance reactions can be facilitated and practised (Wu et al., 2024; Mohamed et al., 2025; Robănescu, 2001). Guided handling and the use of key control points aim to modulate tone distribution and facilitate normal postural reactions (Graham et al., 2016; Robănescu, 2001); the importance of scapular and pelvic control is emphasized because these represent areas through which posture and trunk stability can be globally influenced (Bobath, 1990, cited in Graham et al., 2016; Tekin & Yarar, 2025; Wu et al., 2024). Recent clinical evidence indicates favourable effects of Bobath therapy on balance and fall risk in children with spastic cerebral palsy (Tekin & Yarar, 2025). Including core-stability training can enhance postural control and segmental coordination (Ali et al., 2019), and therapeutic Pilates and core-stability programs can contribute to increasing the time spent maintaining an upright posture and reducing postural sway (Elnaggar et al., 2024).

Chapter conclusion: the development and training of righting reflexes represents an essential direction of intervention for preventing loss of balance in children with neuromotor disabilities, and combining neurodevelopmental principles with core-stability exercises and controlled exposure to instability offers a coherent therapeutic framework.

CHAPTER VI. MIRA — AN INTEGRATIVE PARADIGM IN DIGITALLY ASSISTED MOTOR REHABILITATION

Defining the Concept and Its Theoretical Foundations

The digitalization of neuromotor rehabilitation has reshaped classical interventions, emphasizing feedback, repetition, and active patient participation (Holden, 2005; Takeuchi & Izumi, 2013; McGlinchey et al., 2015; Iosa et al., 2022; Johnson et al., 2022; Saposnik & Levin, 2011). MIRA (Medical Interactive Recovery Assistant) is a platform that transforms conventional therapeutic exercises into gamified interactive activities, based on motion capture and analysis (Stanmore et al., 2019, 2024; Wilson et al., 2017; Zougar et al., 2022; Gharaei et al., 2021). It can be understood as a synthesis between the motor sciences and interactive technologies, grounded in postural control, neuroplasticity, motor learning, and gamification (Shumway-Cook & Woollacott, 2012; Huotari & Hamari, 2012; Deci & Ryan, 2000) — not merely a device, but an adaptive motor re-education environment.

Technological Architecture and the Logic of Gamification

MIRA is an integrated hardware-software system, based on 3D sensors, such as Microsoft Kinect or Orbbec, and therapeutic software with exercises presented as interactive games (Czakó, Silaghi & Vizitiu, 2017; Bello et al., 2017). The 3D capture detects joints and segmental movements, and the kinematic parameters are analyzed against reference models, including through algorithms such as Dynamic Time Warping and Hidden Markov Models (Bello et al., 2017). The clinical value of the platform lies in the ability to personalize speed, amplitude, duration, and error tolerance (Stanmore et al., 2019; Wilson et al., 2017; Zougar et al., 2022; Gharaei et al., 2021; Moldovan et al., 2014). Immediate visual and auditory feedback, scores, and progressive difficulty support self-correction, task persistence, and remote monitoring (Giggins, Persson & Caulfield, 2013; Stanmore et al., 2019; Zougar et al., 2022).

Psychological Dimension and Paediatric Applicability

MIRA leverages intrinsic motivation by satisfying the needs for competence and autonomy, in accordance with self-determination theory (Deci & Ryan, 2000). Gamification maintains the child's engagement and reduces the perception of effort without diminishing the motor demands (Huotari & Hamari, 2012). From a neurophysiological perspective, reward and positive feedback can support the consolidation of circuits involved in motor learning (Saposnik & Levin, 2011), and the controlled environment can reduce anxiety associated with physical activity (Gallagher, 2003; Deutsch et al., 2011; Fandim et al., 2020; Giggins et al., 2013). In paediatric rehabilitation, MIRA increases tolerance for repetition and allows tasks to be graded according to the child's cognitive and motor profile, being used in cerebral palsy, orthopaedic recovery, and coordination disorders (Moldovan et al., 2014; Czakó, Silaghi & Vizitiu, 2017; Farr et al., 2017). In fall prevention, the platform supports the education of stability through multisensory stimulation, postural adjustments, and righting reactions under controlled conditions (Horak, 2006; Stanmore et al., 2019; Koh et al., 2020; Fandim et al., 2020).

MIRA as a Digitally Assisted Motor Learning Environment

In paediatric rehabilitation, MIRA combines the effectiveness of exercise with the appeal of play (Cameirão et al., 2010; Giggins et al., 2013). The platform uses 3D sensors and movement-assessment algorithms, offering personalization, immediate feedback, and longitudinal storage of performance (Bello et al., 2017; Gharaei et al., 2021). In re-educating balance, it targets weight transfers, reactive postural adjustments, and intersegmental coordination, and real-time feedback supports postural self-regulation and stability (Cameirão et al., 2010; Giggins et al., 2013; Fandim et al., 2020; Deutsch et al., 2011). However, calibration difficulties, environmental influences, and the lack of automatic detection of compensatory movements require ongoing therapeutic supervision (MIRA Rehab Ltd., 2020; McGlinchey et al., 2015; Cameirão et al., 2010) — MIRA therefore remaining complementary to conventional therapy (Stanmore et al., 2019).

Clinical Validation, Advantages, and Limitations

Existing data indicate improvements in motor function and balance following the use of MIRA in various clinical contexts (Stanmore et al., 2019; Czakó, Silaghi & Vizitiu, 2017), including increases in performance on standardized balance instruments and improvements on the paediatric balance scale in spastic hemiparesis (Berg et al., 1992; Czakó, Silaghi & Vizitiu, 2017). The platform provides objective feedback, monitoring, and cognitive-affective stimulation, which can increase compliance and reduce dropout from therapy (Bello et al., 2017; Gharaei et al., 2021; Farr et al., 2017). However, in severe deficits, calibration difficulties may arise, along with the risk of reinforcing compensatory strategies (Zougar et al., 2022; Gharaei et al., 2021; Springer & Yogev Seligmann, 2016). Future research must more rigorously investigate the relationship between digital parameters, fall risk, and associated psychological dimensions (Stanmore et al., 2024; Koh et al., 2020; Deci & Ryan, 2000).

Methodological Synthesis and Positioning of the Experimental Approach

The methodology of the thesis's applied research is built on the choice of the MIRA platform for its ability to provide objective feedback, controlled repetition, and adaptive task grading, in line with neuroplasticity and motor learning (Shumway-Cook & Woollacott, 2012; McGlinchey et al., 2015; Saposnik & Levin, 2011; Bello et al., 2017). Integrated with unstable surfaces and proprioceptive neuromuscular facilitation, the platform is used in the thesis as a digitally assisted motor learning environment (Horak, 2006; Deci & Ryan, 2000; Huotari & Hamari, 2012; Gallagher, 2003). The applied design, with pre- and post-intervention assessments, allows the effects of an integrated balance re-education program to be highlighted, providing the necessary framework for testing the hypotheses regarding the reduction of postural instability, the improvement of functional performance, and the relationship between biomechanical and functional parameters.

PART II — ORIGINAL RESEARCH ON KINESIOTHERAPY INTERVENTIONS AND INTERACTIVE DIGITAL TECHNOLOGIES

The literature review presented in Part I highlighted the complexity of the mechanisms involved in maintaining static balance and their vulnerability in children with neuromotor disabilities, as well as the fact that existing intervention methods are often applied in a fragmented manner, without a coherent integration of proprioceptive stimulation, controlled instability, and modern technological support. Based on these considerations, the applied research was designed to investigate the impact of an integrated therapeutic program on static balance in students with neuromotor disabilities, implemented under real conditions, in the special educational environment.

CHAPTER VII. PILOT STUDY — EFFECTIVENESS OF USING THE MIRA DIGITAL PLATFORM

Premises and Aim

The introduction of the MIRA Rehab digital rehabilitation platform into the therapeutic program of a special education institution raised several questions that formed the premises of the preliminary research: how students with SEN respond to virtual therapeutic approaches; whether classical PNF techniques can be applied within digital therapy programs; whether a process of neuroplasticity could be induced in educating static balance through the principle of "learning by doing" (learning through repeated practice), against a background of secondary imbalance–rebalancing on the Bobath board; and which neuromuscular constraints might limit the effectiveness of static-balance recovery.

The aim of the pilot study was to explore the methodological feasibility of the integrated, digitally assisted intervention and to observe initial trends of change in static balance, prior to conducting the large-scale experimental research. The preliminary research did not aim to validate the hypotheses through inferential statistics, but to test the suitability of the instruments, the assessment procedures, and the structure of the therapeutic program. The objectives were to verify the applicability of the MIRA platform in assessing and training static balance, to evaluate the degree of acceptance of the interactive tasks, to observe balancing strategies under conditions of digital feedback, and to formulate adjustments for optimizing the subsequent experimental design. Three orientative hypotheses were formulated, regarding the objective and reproducible assessment of balance via MIRA, the promotion of active engagement through interactive exercises, and trends of improvement in postural control.

Subjects and Methodology

The preliminary research included 14 students with special educational needs, from the primary school cycle, from a special education institution in Cluj County, aged between 10 and 13 years (4 girls and 10 boys), diagnosed with various disabilities — cerebral palsy, degenerative neuronal syndromes, and attention disorders. Inclusion criteria required the ability to stand independently for at least 1 minute, to maintain a static posture for at least 10 seconds, to walk independently (with or without an assistive device), and to maintain focused attention on a monitor at a distance of approximately 1.5 m.

Static balance was assessed through computerized posturography using the BTS P-Walk system, consisting of a sensor platform with a matrix of pressure sensors, connected to dedicated software that allows automatic acquisition of stabilometric data, under static conditions, without prior preparation of the subject. The analysis targeted the position and oscillations of the centre of pressure in bipodal standing, and the software allowed automatic comparison of the obtained values with normative data included in the software database. Active engagement was monitored through three indicators provided by the MIRA platform: "Time in Exergames" (total time spent in gamified activities, expressed in minutes), "Global Active Involvement" (the percentage of session time during which the patient actually moved), and "Correct Active Involvement" (the percentage of time during which the movement performed was correct, without the application flagging an error).

The therapeutic program combined proprioceptive neuromuscular facilitation exercises on the Bobath balance board with interactive games from the MIRA Rehab platform, including lateral abduction of the upper and lower limbs, scapulo-humeral flexions, squats, trunk flexions, and controlled trunk movements in the antero-posterior and latero-lateral planes, with visual feedback provided by the platform. Dosage was standardized at one minute for each game variant or type of movement. Assessment was carried out using the BTS P-Walk posturography software, on a fixed surface (floor) and on a mobile surface (Bobath balance board), measuring the velocity of centre-of-pressure (CoP) oscillations and the area of the CoP ellipse, as well as the level of active engagement (attention and coordination) monitored by the MIRA platform. Statistical analysis was performed using SPSS, applying the paired-samples t-test and Pearson's correlation coefficient, with the significance threshold set at $p < 0.05$.

Results

Descriptive analysis (N = 10) showed the following mean values: engagement increased from 13.30 (pre-test) to 53.80 (post-test); CoP velocity on the mobile surface decreased from 22.00 mm/s to 10.64 mm/s; the CoP ellipse area on the mobile surface decreased from 1235.06 mm² to 280.95 mm². On the fixed surface, CoP velocity decreased from 8.52 to 7.69 mm/s, and the ellipse area from 88.15 to 48.84 mm², but these differences on the fixed surface did not reach the threshold of statistical significance.

The paired-samples t-test confirmed a significant reduction in CoP velocity on the mobile surface [t(9) = 3.76, p = .004], while on the fixed surface the difference was not significant [t(9) = 0.94, p = .374]. The CoP ellipse area decreased significantly on the mobile surface [t(9) = 5.02, p = .001], but not on the fixed surface [t(9) = 1.68, p = .128]. Active engagement increased significantly between pre-test and post-test [t(9) = -8.01, p < .001]. A significant positive correlation was identified between CoP velocity and CoP area in the pre-test stage (r = 0.64), a correlation that no longer held in the post-test stage, suggesting a uniformization of participants' performance as a result of the intervention.

Variable (N=10)	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Engagement pre-test	0.00	28.00	13.30	10.74
Engagement post-test	22.00	68.00	53.80	13.60
CoP velocity pre-test, mobile (mm/s)	9.30	41.70	22.00	10.52
CoP velocity post-test, mobile (mm/s)	6.10	15.60	10.64	3.26
CoP ellipse area pre-test, mobile (mm²)	401.20	2441.39	1235.06	748.95
CoP ellipse area post-test, mobile (mm²)	71.35	589.27	280.95	196.47
CoP velocity pre-test, fixed (mm/s)	4.60	11.90	8.52	2.71
CoP velocity post-test, fixed (mm/s)	4.30	11.80	7.69	2.52
CoP ellipse area pre-test, fixed (mm²)	7.27	317.49	88.15	101.10
CoP ellipse area post-test, fixed (mm²)	4.47	180.30	48.84	59.36

Table A. Descriptive statistics of the variables of interest in the pilot study (adapted from Table 3 of the thesis)

Discussion and Conclusions

The results confirm the favourable impact of the multimodal therapeutic program, built on the interaction between stabilometric assessment via the BTS P-Walk system and digitally assisted training via the MIRA Rehab platform. Statistical analyses reveal significant changes in the essential parameters of postural control — CoP oscillation velocity and CoP ellipse area — as well as a considerable increase in participants' active engagement. The increase in active engagement observed between the pre- and post-test stages demonstrates the reorganization of attentional mechanisms and the consolidation of intrinsic motivation, a finding supported by recent literature on gamification in rehabilitation, which shows that interaction with stimulating virtual environments promotes behavioural self-regulation, sustained attention, and active participation (Burke et al., 2019; Morelli et al., 2020). Gamification platforms amplify motivation and task persistence through immediate feedback, exercise variability, symbolic rewards, and visual monitoring of performance (Gonçalves et al., 2021).

Regarding the stabilometric parameters, the decrease in CoP oscillation velocity and the reduction of the CoP ellipse area on the mobile surface suggest the consolidation of neuromuscular balancing strategies. The specialized literature confirms that sensorimotor training conducted in unstable environments stimulates the integration of visual, proprioceptive, and vestibular information and contributes to the development of more efficient postural strategies (Winter, 1995; Shumway-Cook & Woollacott, 2017). Several studies show that repeated exposure to interactive motor tasks increases the accuracy of postural adjustments and reduces the variability of compensatory movements (Meldrum et al., 2015; Gatica-Rojas & Méndez-Rebolledo, 2014), an aspect also confirmed by the stabilometric values in the post-test stage of the present research.

The marked improvements on the mobile surface, in contrast to the lack of statistical significance on the fixed surface, are explained by the differentiated level of demand: stable surfaces generate reduced postural variability and are less sensitive to subtle changes in motor strategies (Prieto et al., 1996), so that the level of challenge offered by the Bobath board allowed the real progress in postural control mechanisms to be highlighted. The significant positive correlation between CoP velocity and CoP area in the pre-test stage reflects the well-documented association between increased instability and the need for rapid postural adjustments (Palmieri et al., 2002); the absence of this correlation in the post-test stage can be interpreted in the context of the uniformization of performance levels and the reduction of inter-individual variability as a result of the intervention, a phenomenon described in the literature on neuromuscular adaptation, where repeated training leads to the standardization of control strategies (Horak, 2006).

Overall, the results are in line with international evidence supporting the effectiveness of digital platforms in the rehabilitation of children with neuromotor disabilities (Meldrum et al., 2015; Bonnechère et al., 2016), aligning with four trends described in the contemporary literature:

gamification increases engagement and motivation, directly influencing the effectiveness of motor training (Barry et al., 2016; Staiano & Calvert, 2011); interactive platforms optimize postural control through real-time visual feedback and by stimulating sensory integration (Goble et al., 2014); training on unstable surfaces induces rapid neuromuscular adaptations, improving stability and reducing CoP variability (Paillard, 2017); and digital rehabilitation facilitates neuroplasticity through ecological, repeatable, and engaging tasks correlated with functional objectives (Lohse et al., 2014).

The preliminary research provided consistent exploratory evidence regarding the feasibility and relevance of a multimodal therapeutic program, built on the use of computerized therapeutic exercises provided by the MIRA Rehab platform and stabilometric assessment/monitoring via the BTS P-Walk system. Implementation of this integrated protocol was associated with significant functional changes in postural control, motor engagement, and neuromuscular adaptations. The results indicate a substantial increase in the level of participants' active engagement in therapeutic tasks after the intervention, supporting the role of motivational, gamified, and multisensory components in facilitating motor-learning and neuroplasticity processes — increased engagement not being merely a behavioural indicator, but potentially functioning as a facilitating factor for neuromotor reorganization.

The preliminary conclusions formulated were: (1) systematic practice of digitally assisted therapeutic exercises is associated with improvements in reactive balance control; (2) functionally oriented interventions, combined with PNF, appear more effective than one-dimensional strategies; (3) integrating interactive software and unstable surfaces contributes to optimizing reactive balance control; (4) postural oscillation velocity emerges as a relevant indicator of stability; (5) attention, coordination, and active engagement directly influence the acquisition of stability in standing posture.

The limitations of the pilot study consisted of the small sample size (N = 10), interruptions caused by medical issues specific to the population, attention difficulties in some subjects with autism spectrum disorders, absenteeism, and limited curricular resources (a maximum of two hours of kinesiotherapy per week, according to the national curriculum for special schools). Based on these findings, the thesis's applied research aimed to expand the sample, introduce a control group, use an extended battery of standardized functional tests, assess dynamic balance by integrating the BTS G-Walk system, and use more advanced biomechanical parameters — directions that directly informed the design of the personal study presented in the next chapter.

CHAPTER VIII. PERSONAL STUDY — EFFECTS OF APPLYING THE INTEGRATED THERAPEUTIC PROGRAM

Aim, Hypotheses, and Objectives

The aim of the personal study was to analyze the effects of applying an integrated therapeutic program on postural righting and stabilization in students with neuromotor disabilities, by combining digitally assisted exercises (the MIRA platform) with proprioceptive activities on unstable surfaces (the Bobath balance board).

The general hypothesis assumed that the application of an integrated therapeutic program, based on proprioceptive neuromuscular facilitation induced through repeated exposure to controlled instability, combined with digitally assisted intervention via the MIRA platform, leads to significant improvements in static balance and postural control. The secondary hypotheses were: (H1a) the program produces a statistically significant reduction in the stabilometric parameters of the centre of pressure (CoP ellipse area and antero-posterior and latero-lateral deviations); (H1b) the program leads to significant improvements in Mini-BESTest, Brief-BESTest, and Berg Scale scores, reflecting the transfer of postural progress to functional performance.

The general objective was to evaluate the impact of the combined program (PNF + MIRA platform + exercises on the Bobath board) on the development of static balance in students with neuromotor disabilities, by determining the initial level of static balance, analyzing changes in centre-of-pressure deviation on the antero-posterior and latero-lateral axes, and correlating the biomechanical results with the functional ones.

Design, Sample, and Stages of the Research

The research had a quasi-experimental, pre-test–post-test design, with an experimental group and a control group, conducted over the 2023–2024 school year. Thirty subjects were evaluated — students with neuromotor disabilities and special educational needs, other than those in the pilot study — distributed into 15 subjects in the experimental group (Transilvania Special Secondary School and the Special Centre for Inclusive Education, Cluj-Napoca) and 15 subjects in the control group ("Kozmutza Flóra" Special Secondary School, Cluj-Napoca). Eligibility criteria included the ability to maintain stability for 1 minute on the balance board and to hold a static posture for at least 10 seconds; for the experimental group, the additional criteria were the ability to maintain focused attention on a monitor for at least one minute and the ability to perceive and understand the information conveyed.

The participants' diagnostic profile was heterogeneous, including cerebral palsy, global developmental delay, intellectual disability of various degrees (Shree & Shukla, 2016), language disorders, autism spectrum disorders, ADHD, motor delay, coordination disorders, generalized hypotonia, and associated sensory impairments (congenital cataract, amblyopia, astigmatism), with most participants classified as having a severe degree of disability (Lord et al., 2020; Schalock et al., 2010). The research was conducted in stages: obtaining institutional and parental consent (September–October 2023); initial assessment (October–November 2023); implementation of the therapeutic program, successively, across the three educational institutions (November 2023 – February 2024), with the final assessment carried out progressively, at the end of the program in each institution; and data centralization and statistical analysis (March–June 2024). The therapeutic program included 10 intervention sessions.

The independent variable was the integrated therapeutic program (PNF + MIRA + Bobath board), and the dependent variables concerned the centre-of-pressure stabilometric indicators, the scores on the functional balance tests, and indicators of functional autonomy.

Assessment Instruments

Static balance was assessed with the BTS P-Walk posturography system, on a fixed surface and on a mobile surface (the Bobath board), measuring the CoP ellipse area (95%) and the standard deviation of oscillations on the X (antero-posterior) and Y (latero-lateral) axes (Duarte & Freitas, 2010; Winter, 1995; Baratto et al., 2002). Dynamic balance, during walking, was assessed with the BTS G-Walk system, which provides symmetry indices on the OX axis (tilt), the OY axis (obliquity), and a gait-cycle symmetry index. In addition, three standardized clinical instruments were applied: the Brief-BESTest (6 items, score 0–24), which provides a rapid assessment of functional balance (Padgett et al., 2012; Horak et al., 2009); the Mini-BESTest (14 items, score 0–28), which assesses postural control multidimensionally — anticipation, reactive postural control, sensory orientation, and dynamic stability during gait (Franchignoni et al., 2010; Horak et al., 2009; King et al., 2012); and the Berg Balance Scale (14 items, score 0–56), which assesses static stability and basic functional tasks, frequently used to estimate fall risk (Berg, 1989; Franjoine et al., 2010), although its sensitivity may be limited by a ceiling effect (Conradsson et al., 2007; Franchignoni et al., 2010). Each participant was tested pre-intervention and post-intervention. Statistical processing was carried out using SPSS, applying paired-samples t-tests (within-group comparisons) and independent-samples t-tests (between-group comparisons), as well as Linear Mixed Models for analyzing the clinical test scores, with a significance threshold of $p < 0.05$.

Dependent variable	Instrument	Indicator / item	Relevance to the hypothesis
Static balance / postural control	BTS P-WALK (posturography)	CoP ellipse area (95%)	Primary indicator for reduced instability
Static balance / direction of instability	BTS P-WALK	Antero-posterior (AP) CoP deviation	Verifies reduction of sagittal oscillations
Static balance / direction of instability	BTS P-WALK	Latero-lateral (LL) CoP deviation	Verifies frontal stability and control symmetry
Overall functional balance	Berg Balance Scale	Total score (0–56)	Confirms functional transfer of postural progress
Multidimensional postural control	Mini-BESTest	Total score (0–28)	Captures anticipatory and reactive control, sensory orientation, and gait
Rapid functional balance	Brief-BESTest	Total score (0–24)	Highlights overall post-intervention changes, useful in repeated measures
Intervention (program)	Therapeutic protocol (PNF+MIRA+unstable)	Duration, frequency, number of sessions, dosage	The variable explaining the pre–post change

Table E. Instrument–variable–indicator correspondence matrix used in the personal study (adapted from Table 16 of the thesis)

Description of the Therapeutic Protocol

The intervention program — PNF techniques via Bobath balance boards, integrated with the digital MIRA platform — was designed as an integrative approach to educating and re-educating balance, combining classical kinesiotherapy exercises with the sensorimotor stimulation induced by unstable surfaces and digital feedback. The program was organized as a progressive sequence of exercises and functional tasks, carried out on both stable and unstable surfaces (balance board and Bobath board), with a total duration of approximately 45 minutes per session, the alternation of support conditions allowing the differentiated demand of postural stabilization mechanisms, from voluntary control to reactive and anticipatory adjustments.

In the initial phase, exercises targeted maintaining standing posture on the board, bilaterally and on one leg, to activate the stabilizing musculature and consolidate axial control. Subsequently, balancing–unbalancing tasks were introduced, which required continuous postural adjustments and increased proprioceptive demands. The digitally assisted component was provided through the preset games and movements from the MIRA Rehab platform, with each game used with different movement variants (scapulo-humeral abduction and flexion, hip abduction and flexion, trunk flexions in the frontal and sagittal planes, lateral lunges, controlled alternation of the centre of pressure) to maintain task variability and the child's active engagement. In the following stage, the program was extended through the Bobath balance board, which introduced an additional level of controlled instability, aimed at amplifying proprioceptive stimulation and triggering stabilization mechanisms through co-contraction, characteristic of PNF, under the continuous visual and auditory feedback of the MIRA platform.

The program also included exercises with a functional and applied character — walking with stabilization on the balance boards, catching and throwing a ball from standing on the board, posture changes with knee semi-flexion, and active mobility exercises of the hip joint while maintaining balance — integrated into a mini applied circuit, designed to facilitate the transfer of postural acquisitions to situations close to daily-life activities. Through this structure, the program allowed the simultaneous stimulation of static and dynamic postural control, support symmetry, and segmental coordination, within a coherent therapeutic framework oriented towards the reorganization of balance strategies and the consolidation of functional autonomy in students with neuromotor disabilities.

Results — Stabilometric Parameters (BTS P-Walk / G-Walk)

In the experimental group (n = 15), the paired-samples t-test revealed significant post-test reductions compared with pre-test for: CoP ellipse area on the fixed surface [$t(14) = 2.34$, $p < .05$]; CoP ellipse area on the mobile surface [$t(14) = 3.33$, $p < .05$]; OX-axis deviation on the fixed surface [$t(14) = 3.62$, $p < .05$]; OX-axis deviation on the mobile surface [$t(14) = 2.65$, $p < .05$]; OY-axis deviation on the fixed surface [$t(14) = 2.63$, $p < .05$]; and OY-axis deviation on the mobile surface [$t(14) = 5.09$, $p < .001$]. In addition, symmetry indices increased significantly: OX symmetry index (tilt) [$t(14) = -5.35$, $p < .001$], OY symmetry index (obliquity) [$t(14) = -2.22$, $p < .05$], and gait-cycle symmetry index [$t(14) = -3.83$, $p < .05$]. The effect was present under both stable and unstable support conditions, but more pronounced on the unstable surface.

In the control group (n = 15), the trend was reversed: values worsened significantly for the mobile ellipse [$t(14) = -2.48$, $p < .05$], fixed OX deviation [$t(14) = -2.44$, $p < .05$], mobile OX deviation [$t(14) = -3.27$, $p < .05$], and fixed OY deviation [$t(14) = -2.67$, $p < .05$], and symmetry indices decreased significantly: OX (tilt) [$t(14) = 2.33$, $p < .001$], OY (obliquity) [$t(14) = 2.54$, $p < .05$], and gait cycle [$t(14) = 3.32$, $p < .05$] — suggesting a natural tendency towards increased instability in the absence of intervention.

Between-group comparison at the post-test stage (independent-samples t-tests) confirmed consistent differences in favour of the experimental group: fixed ellipse [$t(14.25) = 3.15$, $p <$

.05], mobile ellipse [$t(14.74) = 3.87$, $p < .05$], fixed OX deviation [$t(14.41) = 4.44$, $p < .05$], mobile OX deviation [$t(21.10) = 4.53$, $p < .001$], mobile OY deviation [$t(16.93) = 3.54$, $p < .05$], as well as the OX symmetry index [$t(26.51) = -2.92$, $p < .05$], OY symmetry index [$t(17.02) = -2.39$, $p < .05$], and gait-cycle index [$t(18.35) = -3.14$, $p < .05$]. The only variable without a significant difference between groups was the OY-axis deviation on the fixed surface. Gait analysis via BTS G-Walk additionally showed an increase in propulsion values, a reduction in asymmetric variations between the lower limbs, and a decrease in excessive pelvic-angle amplitudes at the post-intervention stage, suggesting a transfer of static stability gains to the dynamic parameters of gait.

Results — Standardized Clinical Tests

For the Berg Balance Scale, the linear mixed-model analysis showed that the main effect of group was not significant on its own [$F = 0.463$, $p = .500$], but the group × time interaction was strongly significant [$F = 42.593$, $p < .001$], and the effect of time was also significant [$F = 4.670$, $p = .036$]. The mean score of the control group decreased from 2.881 to 2.400 (slight regression), whereas the mean score of the experimental group increased from 2.319 to 3.276 — a substantial increase, confirming a real, differentiated impact of the intervention. The effect of items was significant [$F = 6.533$, $p < .001$], reflecting differences in difficulty among the tasks included in the scale (Berg, 1989; Berg et al., 1992), but without a significant triple interaction with the group × time factor, indicating uniform, global progress rather than progress concentrated on isolated items.

For the Mini-BESTest and Brief-BESTest, the analysis likewise revealed a significant group × time interaction, with clear score increases in the experimental group compared with pre-test, unlike the control group, where no comparable improvement was observed. Analysis of the 14 Mini-BESTest items (structured into four domains — anticipation, reactive postural control, sensory orientation, dynamic stability; Franchignoni et al., 2010; Horak et al., 2009) showed visible progress especially on the items involving single-leg stance, step correction (forward, backward, lateral), standing with feet together and eyes closed, standing on an unstable surface with eyes closed, and rapid pivoting — whereas the control group remained relatively stable or showed slight regressions on some items. The absence of a significant triple interaction (group × time × item) indicates that the effect of the intervention was not concentrated on isolated components but had a generalized character across the balance performance assessed.

Instrument / parameter	Experimental group (pre→post)	Statistical significance	Control group (pre→post)
CoP ellipse – fixed surface	Decrease	t(14)=2.34; p<.05	No relevant change
CoP ellipse – mobile surface	Decrease	t(14)=3.33; p<.05	Increase; t(14)=-2.48; p<.05
OX deviation – fixed surface	Decrease	t(14)=3.62; p<.05	Increase; t(14)=-2.44; p<.05
OX deviation – mobile surface	Decrease	t(14)=2.65; p<.05	Increase; t(14)=-3.27; p<.05
OY deviation – fixed surface	Decrease	t(14)=2.63; p<.05	Increase; t(14)=-2.67; p<.05
OY deviation – mobile surface	Decrease	t(14)=5.09; p<.001	No relevant change
OX symmetry index (tilt)	Increase	t(14)=-5.35; p<.001	Decrease; t(14)=2.33; p<.001
OY symmetry index (obliquity)	Increase	t(14)=-2.22; p<.05	Decrease; t(14)=2.54; p<.05
Gait-cycle symmetry index	Increase	t(14)=-3.83; p<.05	Decrease; t(14)=3.32; p<.05
Berg Scale (mean score)	2.319 → 3.276	Group×time interaction F=42.593; p<.001	2.881 → 2.400

Table B. Summary of the statistical results of the personal study, experimental group vs. control group (N=30)

Mini-BESTest domain	Representative items	Observed evolution
I. Anticipation	Rising on toes; single-leg stance	Significant progress in the experimental group; control group almost unchanged
II. Reactive postural control	Step correction: forward, backward, lateral	Large post-test score increase in the experimental group; control group relatively stable
III. Sensory orientation	Feet together, eyes open/closed; unstable surface, eyes closed; inclined ramp	Clear progress in the experimental group; stagnation or slight regression in the control group
IV. Dynamic stability	Change of gait speed; walking with head turns; rapid pivot; stepping over an obstacle; TUG with dual task	All items with post > pre score in the experimental group; control group approximately stable

Table D. Evolution of Mini-BESTest scores by domain, experimental group vs. control group

This domain-level analysis confirms that the intervention produced a global effect across all balance systems assessed by the Mini-BESTest, with the experimental group's post-test means being higher than those of the control group for most of the 14 items. The absence of a significant triple interaction (group × time × item) shows that the effect was not concentrated on isolated items but had a generalized character across the dynamic-balance performance assessed by the instrument — an important finding, since it suggests an overall impact of the therapeutic program, not merely a punctual improvement on certain components.

Discussion of the Results Obtained Through Stabilometric Assessment

Stabilometry offers a major advantage over clinical assessments, since it allows objective quantification of postural micro-variations that are inaccessible to direct observation

(Shumway-Cook & Woollacott, 2000). The results obtained can be interpreted, first, in biomechanical terms: maintaining balance in standing posture requires controlling the centre of gravity within the base of support, through fine adjustments made at the level of the joints and stabilizing musculature, and the reduction in postural oscillations observed in the experimental group suggests a greater efficiency of these adjustments and an increased capacity to stabilize the body relative to gravity (Nashner & Peters, 1990; Peterka, 2002), reflecting a more coherent organization of ankle- and hip-level strategies.

From a neurophysiological perspective, postural stability depends on the integration of information from the visual, vestibular, and proprioceptive systems, and the central nervous system uses this information to generate rapid corrective responses. In students with neuromotor disabilities, the literature frequently highlights difficulties in this sensory integration, manifested as increased postural oscillations (Harkness-Armstrong et al., 2023); the improvement in stabilometric parameters therefore suggests an optimization of sensory-integration processes and an increase in the efficiency of postural responses. A central element of the interpretation is the adaptation observed under unstable support conditions: maintaining balance in such situations involves an increased demand on postural control mechanisms, and the improved performance under these conditions indicates a greater capacity for adaptation and a higher efficiency of postural-righting mechanisms, confirming that controlled perturbations are effective stimuli for training stabilization responses (Yoshida et al., 2022).

The increase in symmetry indices observed in the experimental group provides further information about the organization of postural control: a balanced distribution of support between the two body sides reflects better coordination of body segments and a more efficient postural alignment (Massion, 1998; Epuran, 2011), essential for the execution of functional movements and for reducing compensatory strategies which, in the long term, can lead to motor inefficiency and segmental overload. From the perspective of motor-learning processes, the results can be explained through neuroplasticity mechanisms: guided motor repetition and exposure to varied tasks lead to the consolidation of neural connections involved in postural control and to the automation of motor responses (Costanzo et al., 2016; Berlot et al., 2021; Sattelmayer et al., 2016), a process particularly relevant in populations with neuromotor impairment, where these processes are often disrupted.

An important aspect is the link between postural stability and everyday functionality: stability in standing posture is necessary for maintaining position in the classroom, performing transfers, moving around the school environment, or manipulating objects, and the reduction of postural oscillations can lower energy expenditure and increase tolerance for activity (Shumway-Cook & Woollacott, 2017). Integrating the stabilometric results with those obtained through clinical instruments provides a complete picture of the intervention's effects: while clinical tests reflect functional performance on specific tasks, stabilometry reveals the fine-grained mechanisms underlying this performance, sometimes before they become clinically evident (Massion, 1998; Epuran, 2011). In contrast, the absence of relevant changes in the control group shows that the adaptations observed in the experimental group are not the result of familiarization with testing or natural evolution, but are dependent on the intervention applied.

Discussion of the Results Obtained Through the Berg Balance Scale

The results obtained through the Berg Scale show a significant effect of the intervention on functional balance, supported by the differentiated evolution of the two groups and the significant interaction between the group and time factors. The importance of these results becomes clearer in relation to the structure of the scale, which includes 14 functional tasks close to everyday demands — maintaining standing posture, postural transfers, trunk control, changes of direction, rotations, and tasks under conditions of reduced support (Berg, 1989; Berg et al., 1992) — so that the improvement in scores does not merely reflect better assessment performance but suggests an optimization of fundamental functional mechanisms.

An important aspect of the interpretation is the uniform character of the progress across the scale's items: the absence of significant selective differences suggests that the intervention did not influence only an isolated component of balance but produced a global improvement in postural control, in line with contemporary models describing balance as an integrated system (Horak, 2006; Mancini & Horak, 2010; Ivanenko & Gurfinkel, 2018). Items involving balance maintenance under conditions of reduced support (standing with feet together, tandem stance, single-leg stance) are particularly relevant for assessing basic postural stability, and progress on these tasks suggests an optimization of fine control of the centre of gravity (Bell, 1998; Shumway-Cook & Woollacott, 2012). At the same time, progress on more complex tasks (transfers, rotations, picking up an object from the floor) reflects the integration of postural control into functional contexts close to daily life, with direct implications for functional autonomy and active participation in the school and family environment.

Although the literature notes limitations of the Berg Scale, particularly the possibility of a ceiling effect in individuals with a higher functional level (Conradsson et al., 2007;

Franchignoni et al., 2010), the detection of significant improvements in the present research suggests that the intervention had sufficient intensity and effectiveness to produce observable changes even with an instrument sometimes considered less sensitive to subtle changes. The validity and clinical utility of the Berg Scale are well documented in both adult neurological and paediatric populations (Berg, 1989; Berg et al., 1992; Franjoine et al., 2010; Donker et al., 2007).

Discussion of the Results Obtained Through the Mini-BESTest and Brief-BESTest

The results obtained through the Mini-BESTest show a significant effect of the intervention on postural control, confirmed by the differentiated evolution of the two groups. The Mini-BESTest has particular value in interpreting the results because it allows a multidimensional assessment of balance — anticipatory control, reactive responses, sensory orientation, and dynamic stability during gait (Franchignoni et al., 2010; Horak et al., 2009) — going beyond assessing balance as simple maintenance of position and offering an integrative perspective on how the nervous system organizes and adapts postural responses across varied contexts.

The anticipatory component has a direct functional significance, being involved in tasks such as rising from sitting, initiating gait, or changing position; when these mechanisms are optimized, movement is prepared more efficiently, the risk of imbalance decreases, and the fluency of execution increases (Mancini & Horak, 2010). Reactive responses, in turn, contribute to static stability by limiting postural deviations, and sensory orientation reflects a more efficient integration of visual, vestibular, and proprioceptive information (Horak, 2006; Peterka, 2002). Dynamic stability during gait represents the component with the most obvious transfer to activities of daily living, suggesting an increased capacity for autonomous movement and reduced dependence on external assistance in the school and family environment.

A central element of the interpretation is the global character of the improvement: the absence of a significant interaction between group, time, and items suggests that the intervention produced a generalized functional reorganization of postural control, supporting the model of balance as an integrated system, in which sensory, motor, and cognitive components function interdependently (Ivanenko & Gurfinkel, 2018).

The Brief-BESTest, as an abbreviated version of the Mini-BESTest, retains the ability to assess the main dimensions of postural control in a concise format, useful in repeated measures (Padgett et al., 2012). The increase in scores in the experimental group, corroborated with the strong correlation between the Brief-BESTest and the Mini-BESTest reported in the literature (Padgett et al., 2012; King et al., 2012), supports the consistency of the results and indicates that the intervention produced coherent effects on balance, detectable through both detailed and synthetic instruments. From the perspective of activities of daily living, the improvements shown by the Brief-BESTest can be associated with increased safety in performing routine tasks, better stability in dynamic situations, and a reduced need for external support. Research on digitally assisted interventions indicates that interactive tasks and varied demands can improve dynamic postural control and motor coordination by stimulating rapid adjustments and sensory integration (Leddy et al., 2017; King et al., 2012; Meseguer-Henarejos et al., 2025), and the results of the present study are compatible with this perspective.

Chapter Conclusions

The integration of standardized clinical tests with computerized posturography and MIRA indicators provided a comprehensive perspective on balance, coordination, and postural control in children with neuromotor disabilities (Shumway-Cook & Woollacott, 2017), allowing fine-grained identification of deficient domains, objective monitoring of progress, and grounding of therapeutic recommendations on a multimodal methodological basis. The integrated therapeutic program (MIRA + PNF + controlled instability on the Bobath board) was associated with significant improvements in postural control and functional balance, confirmed both by the reduction in CoP oscillations and the improvement in postural and gait symmetry, and by convergent progress on the standardized clinical tests. The significant group × time interactions, in favour of the experimental group, support the direct association of these effects with the applied intervention, and the relatively uniform character of the progress suggests an integrated reorganization of postural strategies, rather than the isolated improvement of a single component.

CHAPTER IX. GENERAL CONCLUSIONS

Conclusions Related to Objectives and Hypotheses

With regard to the objective of assessing biomechanical changes in postural control, the stabilometric results indicated significant reductions in the amplitude and velocity of centre-of-pressure oscillations, evidencing an improvement in postural stability after completion of the therapeutic program. With regard to the functional-assessment objective, scores on the standardized tests showed significant post-intervention increases. With regard to the objective of correlating biomechanical and functional results, the analysis revealed positive relationships between the improvement of stabilometric parameters and functional performance, confirming the complementary nature of the two types of assessment.

All three research hypotheses were confirmed: Hypothesis 1, concerning the significant improvement of the biomechanical parameters of postural control; Hypothesis 2, concerning the significant increase in functional static-balance scores; and Hypothesis 3, concerning the existence of positive correlations between stabilometric parameters and functional performance.

Final Synthesis Conclusion

The thesis investigated the possibilities of educating and optimizing static balance and postural control in children with neuromotor disabilities, through an integrated kinesiotherapy program combining proprioceptive neuromuscular facilitation, progressive exposure to instability, and interactive digital technologies, theoretically grounded in the concepts of postural control, psychomotricity, and neuroplasticity.

The pilot study demonstrated that integrating digitally assisted therapeutic gamification into a complex kinesiotherapy program is feasible and well tolerated, with the increased level of active engagement supporting the role of motivational and multisensory components in facilitating motor learning (Herzfeld & Shadmehr, 2014). The personal study, with a quasi-experimental design and a control group, confirmed these trends on a larger scale: the biomechanical progress (reduction of CoP oscillations, increased postural and gait symmetry) translated into significant functional improvements (Berg Scale, Mini-BESTest, Brief-BESTest), supported by robust group × time statistical interactions, attributable to the intervention rather than to natural variation or repeated-testing effects (Franchignoni et al., 2010).

Analysis of the stabilometric parameters revealed significant improvements in postural control under conditions of instability, reflected in the reduction of centre-of-pressure oscillation velocity and CoP ellipse area. These results suggest an optimization of reactive and anticipatory postural strategies, as well as a functional recalibration of the sensorimotor mechanisms involved in maintaining static balance. The more pronounced differences recorded on unstable surfaces confirm their relevance as an assessment and training environment for highlighting postural progress. The biomechanical progress observed translated into significant functional improvements, evidenced by the increase in Berg Scale scores: students in the experimental group demonstrated an increased ability to perform transfers, to maintain static and dynamic postures, and to carry out daily functional activities, and the significant group × time interaction confirms that these improvements are attributable to the digitally assisted intervention.

The Mini-BESTest results indicate an overall optimization of multisensory integration mechanisms, reflected in superior performance under conditions of increased sensory demand, such as reduced visual support, the use of unstable surfaces, or dynamic tasks (Shumway-Cook & Woollacott, 2017). The absence of significant interactions with the "item" factor suggests uniform and coherent progress, characteristic of the adaptive recalibration of sensory weighting, a central mechanism of efficient postural control — in this context, the intervention through MIRA functioned as a complex multisensory environment, in line with the literature on gamification (Bonnechère et al., 2016). The Brief-BESTest results, in turn, demonstrate a significant reduction in intrinsic fall risk, through the consolidation of reactive postural strategies and mechanisms for rapid balance restoration, the uniform progress across items confirming an overall functional reorganization of protective postural responses, an aspect supported by studies on fall prevention through interactive technologies (Verhoeven et al., 2020; Stanmore et al., 2019).

The motor improvements obtained are directly reflected in increased functional autonomy and greater participation of children in educational and social activities. The capacity for independent movement, the maintenance of functional postures, and safety in movement are essential factors for school inclusion, motor autonomy being recognized in the educational literature as an important predictor of participation and integration in the school environment (Florian & Black-Hawkins, 2011). The playful character of the intervention, immediate visual feedback, and the graded progression of tasks generated a high level of engagement and motivation, factors essential for consolidating motor learning and neuroplastic processes;

clinical observations confirm that gamification facilitates voluntary engagement, reduces anxiety about failure, and sustains functional repetition (Sween et al., 2017).

Implementation of the intervention demonstrated the feasibility of using the MIRA platform in the special education environment, through high adaptability, ease of use, objective monitoring of progress, and increased acceptance by students and teaching staff, extending existing evidence on the applicability of MIRA in paediatric and educational, not only clinical, contexts (Verhoeven et al., 2020). Triangulation of instrumental and clinical assessments allowed a comprehensive analysis of postural control, increasing the validity of the conclusions: the biomechanical data provided objectivity and precision, while the clinical tests ensured functional and interpretive relevance, their integration representing an important contribution to the application of paediatric kinesiotherapy.

The main contribution of the thesis consists in establishing and validating an integrated methodological intervention model, which uses the MIRA platform as a digitally assisted motor-learning environment, in complementarity with established kinesiotherapy techniques, allowing objective quantification of progress, increasing program adherence, and facilitating the functional transfer of postural acquisitions towards the autonomy and educational participation of students with neuromotor disabilities.

Limitations of the Study

The limitations of the research must be interpreted in the specific context of paediatric rehabilitation applied in special education, without diminishing the validity of the conclusions drawn, but rather contributing to delimiting the methodological framework within which the data were obtained. The specialized literature consistently emphasizes that digitally assisted interventions and research conducted on populations with neuromotor disabilities are marked by clinical, ethical, and organizational constraints, which limit strict control of variables and the size of the samples investigated (Deutsch & Westcott, 2017; Koh et al., 2020).

A first limitation is the sample size (N = 30, divided between an experimental group and a control group), which restricts the generalization of the results, all the more so as the sample showed high functional heterogeneity — different levels of neuromotor impairment, autonomy, postural control, attention, and motivation, a characteristic frequently found in special school settings (Shumway-Cook & Woollacott, 2017), but one that can amplify score variability and mask subtle differences in response to the intervention. Although the use of linear mixed models allowed repeated measures to be leveraged and inter-individual variation to be controlled through the inclusion of random effects, a larger sample would have increased statistical power and the stability of the estimates; more rigorous stratification of participants by functioning level could, in future studies, facilitate the identification of differential effects of the intervention.

A second limitation concerns the duration of the intervention — 10 sessions, an interval sufficient to reveal significant changes, but relatively short in relation to long-term neuroplastic consolidation processes (Kandel et al., 2013; Verhoeven et al., 2020); the study did not include follow-up assessments (for example, at 1–3 months), which limits the appreciation of the persistence of progress and the differentiation of transient effects from consolidated ones, an aspect for which the literature recommends including longitudinal assessments in the context of therapeutic gamification (Bonnechère et al., 2016). A third limitation concerns the assessment instruments: the standardized clinical tests include an observational component that can be influenced by rater scoring variability, even under standard protocol conditions (Franchignoni et al., 2010), and advanced biomechanical parameters (directional vectors of oscillations, temporal or variability indicators) were not integrated into the main analysis, although the technologies used (MIRA and BTS) allow their extraction.

A fourth limitation derives from the natural context of the intervention: conducting the program in the special education environment increases the ecological validity of the results but limits control over external variables, such as the school schedule, daily variations in fatigue, emotional state, or contextual factors specific to the educational environment (Florian & Black-Hawkins, 2011). Motivational variability also remains a factor that is difficult to control; although gamification reduces fluctuations through its playful character and immediate feedback, participants' engagement may be influenced by daily mood, fatigue, or the relationship with the therapist (Sween et al., 2017). The results cannot automatically be extrapolated to other categories of disabilities (for example, autism spectrum disorders without a relevant motor component, or primary sensory impairments), and validation of the intervention on distinct populations is needed. Analytically, although linear mixed models allowed rigorous testing of the effects of group, time, and their interactions, predictive models or mediator/moderator analyses were not explored, which limits the identification of individual factors that determine the magnitude of the response to the intervention.

In summary, the limitations identified are inherent to applied research in paediatric rehabilitation and special education and do not affect the thesis's main conclusions, but they indicate the need for larger samples and functional stratification, the introduction of follow-up assessments, deeper biomechanical analysis, the inclusion of predictive analyses, and validation of the intervention on diverse populations and contexts (Bonnechère et al., 2016; Shumway-Cook & Woollacott, 2017; Deutsch & Westcott, 2017).

CHAPTER X. ORIGINAL CONTRIBUTIONS OF THE THESIS

The thesis brings original contributions of theoretical, methodological, empirical, and applied relevance, at the confluence of neuroscience, kinesiotherapy, digital technologies, and special education pedagogy. The originality of the approach lies in the coherent integration of the interactive digital MIRA platform into a kinesiotherapy intervention protocol designed for children with neuromotor disabilities, correlated with validated clinical assessments and objective biomechanical analyses, carried out in a real educational context.

From a theoretical perspective, the thesis proposes an integrated conceptual model of digitally assisted rehabilitation, which articulates the principles of neuroplasticity, contemporary theories of motor learning based on feedback and variable practice (Herzfeld & Shadmehr, 2014), the mechanisms of multisensory integration, and the role of motivation and active engagement in interventions designed for children with special educational needs (Deci & Ryan, 2000) — an original contribution to the Romanian specialized literature, where digital approaches are rarely analyzed from a systemic theoretical perspective.

At the methodological level, the contribution consists in the implementation of a triangulated assessment design, combining objective biomechanical assessment through computerized posturography (MIRA and BTS P-Walk) with functional clinical assessment of balance through the Berg Balance Scale, multisystem assessment of postural control through the Mini-BESTest, and estimation of fall risk through the Brief-BESTest. This combination, rarely used in paediatric studies conducted in special education, demonstrates the feasibility and value of using complementary instruments for objectifying motor progress, going beyond the limitations of exclusively observational or exclusively instrumental approaches.

From an empirical standpoint, the results of the personal study provide solid evidence regarding the effectiveness of the digitally assisted intervention in educating balance and reorganizing postural control. The data obtained indicate a reduction in postural oscillations, improved support symmetry, consolidation of anticipatory and reactive strategies, and increased stability on fixed and unstable surfaces. By correlating biomechanical parameters with the scores obtained on clinical tests, the thesis demonstrates the real transfer of progress towards activities of daily living, an aspect insufficiently documented in the existing literature on paediatric therapeutic gamification. In this sense, the work extends the field of application of the MIRA platform towards paediatric rehabilitation conducted in the school environment.

A major applied contribution consists in the development of a structured therapeutic protocol, adapted to the specifics of special schools, designed to be integrated into the educational program without disrupting institutional dynamics. The proposed protocol is replicable and offers a practical framework for using digitally assisted interventions in combination with classical kinesiotherapy methods. At the same time, the thesis establishes the use of digitally assisted interactive therapy — gamification — not only as a therapeutic instrument but also as a complementary pedagogical instrument, capable of increasing motivation, active engagement, and student autonomy, thereby contributing to the process of educational inclusion (Florian & Black-Hawkins, 2011). Given its scope and coherence, the work is among the few research studies conducted in Romania that systematically analyze digitally assisted interventions in paediatric rehabilitation carried out in the school environment, with the proposed methodological model offering a reference point for future research.

Future Research Directions

Future research directions include: expansion towards multicentre studies, by including more special schools, rehabilitation centres, and academic institutions, in order to increase sample size, enhance external validity, and analyze the influence of institutional and contextual factors on intervention effectiveness; the use of randomized controlled experimental designs, considered the gold standard in evaluating therapeutic interventions, for direct comparison between digitally assisted interventions, conventional kinesiotherapy, combined approaches, and control groups; the introduction of longitudinal follow-up assessments, carried out at intervals after the completion of the intervention, to analyze the stability of progress, the retention of postural strategies, and the long-term impact on functional autonomy, in line with the literature on neuroplasticity, which emphasizes the importance of consolidating acquisitions through sustained functional stimulation (Kandel et al., 2013); deepening the biomechanical analysis of postural control through advanced parameters, such as directional vectors of the centre of pressure, the latency of postural reactions, temporal variability of oscillations, or predominant postural control strategies; personalizing digitally assisted interventions according to individual functional profile, level of neuromotor impairment, and response to intervention, using prior progress as a predictor of evolution; exploring optimal combinations between classical kinesiotherapy, neuromuscular facilitation, gamification, and other sensorimotor methods; integrating emerging technologies, such as virtual and augmented reality, which can enable the simulation of realistic functional contexts and gradual exposure to challenging situations, offering a high degree of immersion and motivation in the special education environment; and, not least, developing a national model for implementing digitally assisted rehabilitation in special schools, aligned with European strategies on the digitalization of education and making interventions accessible for vulnerable groups.

Practical and Educational Implications

The results of the thesis provide solid scientific support for integrating digitally assisted interventions into therapeutic and educational practice. The MIRA platform proved effective in stimulating postural control, functional balance, and anticipatory and reactive mechanisms, representing a modern and adaptable alternative to conventional interventions. In paediatric rehabilitation practice, the use of digitally assisted interventions allows the individualization of motor tasks according to the child's functional level, increases the intensity and variability of postural training, and enables objective monitoring of progress through biomechanical parameters, facilitating the transfer of motor acquisitions to daily functional activities and supporting therapeutic decision-making based on objective data — not replacing traditional methods, but complementing them within a multimodal, coherent, and functionally oriented framework.

In the context of special education, the results of the thesis support the integration of interactive digital technologies as a means of developing motor autonomy and school participation. Improving balance and postural control directly influences students' capacity to participate actively in curricular activities, to move independently, and to maintain adequate functional postures in the educational environment, and the use of the MIRA platform contributes to reducing motor barriers, increases student engagement in therapeutic and educational activities, and facilitates interdisciplinary collaboration among teachers, kinesiotherapists, and other special education specialists. The research results also highlight the need to adapt initial and continuing training programs for specialists in rehabilitation and special education: integrating digital therapeutic technologies requires the development of digital competencies, the ability to interpret biomechanical data, and skills for personalizing interventions according to each child's individual profile, which is why the thesis supports the inclusion of gamification and instrumented assessments in training curricula, as well as the development of good-practice guidelines for their use in the educational environment.

Reflective Considerations on the Research Process

The doctoral undertaking went beyond the strict objective of validating experimental hypotheses, constituting a process of consolidating a mature scientific perspective on paediatric rehabilitation, in which methodological rigour is permanently correlated with the complexity of clinical and educational reality. Systematic interaction with students with neuromotor disabilities showed that therapeutic intervention cannot be reduced to correcting isolated deficits, but must be understood as a dynamic process of neuromotor reorganization, sensory integration, and reconstruction of the relationship between the child, movement, and the environment. The qualitative observations made during the intervention — increased confidence in one's own body, reduced movement-avoidance behaviours, intensified active engagement — support the idea that effective motor rehabilitation includes, alongside the biomechanical dimension, an essential motivational and psycho-educational component, particularly when working with children with neuromotor disabilities.

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