REVIEW ARTICLE

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Non-pharmacological interventions for gait rehabilitation in children with neurodisability – A bibliometric and visualization analysis

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Abstract

Introduction and Objective. Gait impairments significantly impact the daily active participation and quality of life in children with neurodisabilities. Non-pharmacological interventions (NPIs) have demonstrated positive outcomes in gait rehabilitation, although comprehensive analyses that map the global research landscape in this domain are limited. The aim of the bibliometric review is to systematically explore and visualize global research trends, identify hotspots, and highlight emerging themes related to NPIs for gait rehabilitation in children with neurodisability. The literature coverage spans 1993–2024.

Review Methods. Literature was collected from the Web of Science Core Collection using the keywords "cerebral palsy," "rehabilitation," and "gait," and was systematically analyzed.

Brief description of the state of knowledge. A total of 455 relevant documents were included. The number of studies has steadily increased from 1993 to 2024 in this field. The United States leads in terms of publication volume and cumulative citations, with *Developmental Medicine & Child Neurology* published the highest number of papers in this area. Emerging technologies such as exoskeletons, virtual reality and robot-assisted gait training have become research hotspots.

Results. The findings of the study provide researchers and clinicians with a clear, objective understanding of the current state and future directions in this important area of research.

Summary. The study visually represented research trends on the NPIs in gait rehabilitation for children with neurodisability, revealed emerging patterns of research and areas of focus.

Key words

gait, physical therapy, Down syndrome, cerebral palsy, bibliometric analysis, non-pharmacological interventions, neurodisability

INTRODUCTION

Neurodisability (ND) refers to a group of chronic conditions including, but not limited to Down syndrome (DS) and cerebral palsy (CP), that result primarily from impairments of the neurological and/or neuromuscular system and lead to functional limitations [1–4]. The prevalence of neurodisability in children is relatively high, with documented evidence of comorbidities [5, 6]. The Global Burden of Disease Study 2021 reported the latest global estimates for the incidence, prevalence, and disability burden of specific neurodisability-related conditions [7]. Globally, approximately 8.4% of children under the age of five are affected by neurodisabilities [8]. Specifically, DS affects approximately 1 in every 700–1,000 live births, while CP prevalence ranges from 1.5–3 per 1,000 live births [9, 10]. The economic impact is substantial; for example, in England and Wales, neurodevelopmental disorders in middle childhood generate an annual economic burden of around £1.99 billion for public services, including £333 million dedicated specifically to health and social care services [11].

Despite significant heterogeneity across different neurodisabilities, neuromotor impairments, such as gait abnormalities, delayed motor milestones, and impaired postural control, remain common and often overlapping features [12, 13]. Motor function encompasses the ability to coordinate and control limb movements, including fine motor skills like writing and gross motor skills such as walking and running [14]. These functions require integrated activity between the nervous system (brain, spinal cord, and peripheral nerves) and the neuromuscular system [14, 15]. Among various motor skills, gait ability holds particular importance, as it facilitates independent mobility, social participation, environmental exploration, and physical autonomy throughout childhood and adolescence [16–18]. The World Health Organization (WHO) identifies walking as a critical developmental milestone, which is often significantly delayed or impaired in children with neurodisabilities, negatively affecting subsequent cognitive, social, and emotional development [19–21]. Furthermore, movement impairments limit physical activity and increase the risk of mental health disorders, amplifying the impact on overall health, family dynamics, caregiver burden, and broader socio-economic consequences [22, 23].

Non-pharmacological interventions (NPIs), including physical exercises, physiotherapy, assistive technologies, and lifestyle modifications, represent therapeutic approaches without reliance on pharmacological agents [24]. NPIs offer several advantages, such as reduced side-effects, flexibility

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in implementation settings, feasibility of long-term use, and enhanced potential for social integration [25, 26]. Recent studies have demonstrated promising outcomes in gait rehabilitation among children with neurodisabilities [27]. For instance, systematic reviews have indicated positive effects of active video games on gait abilities in individuals with DS and CP [28], and therapeutic exercise has been found beneficial in improving gait parameters and balance in adults with DS [29]. In addition, a recent systematic review involving children with motor impairments underscored the effectiveness of NPIs in enhancing motor outcomes [30].

Gait rehabilitation is inherently multidisciplinary collaboration, integrating exercise therapy, biomechanics, neuroscience, and assistive technology. Previous bibliometric analyses, such as those conducted by Phadke et al. and Mikolajczyk et al., have illustrated the expanding role of interdisciplinary methods and advanced technological integration in gait rehabilitation for spinal cord injury and related conditions [31, 32]. While individual NPIs have been extensively reviewed in relation to specific neurodisability, a comprehensive bibliometric exploration of global research trends, hotspots, and emerging themes related to NPIs across the broader spectrum of neurodisability remains lacking.

Given the rapid growth of research in this area and the diversity of NPIs employed, a systematic bibliometric and visualization analysis is needed to clarify the current state of knowledge, identify research gaps, and guide future interventions. Therefore, the aim of this study is to map the historical development and current research landscape, highlight key trends, and provide evidence-based insights into NPIs for gait rehabilitation in children with neurodisabilities, ultimately informing clinical practice and future research directions.

MATERIALS AND METHOD

The study adhered to the guidelines set out by the Bibliometric Reviews of the Biomedical Literature (BIBLIO) framework, and followed established methodological recommendations for conducting rigorous bibliometric analyses [33, 34].

Search strategy. The Web of Science Core Collection (WoSCC) database was systematically searched from its inception up to 31 December 2024. WoSCC was selected due to its authoritative scope, comprehensiveness, and frequent use in bibliometric studies [35]. The search strategy incorporated a structured combination of Medical Subject Headings (MeSH) terms aligned with the Population, Intervention, Comparator, Outcome, and Study design (PICOS) framework. Key search terms included 'neurodisability', 'children', 'exercise', 'physiotherapy', and 'gait'.

Eligibility criteria. The inclusion criteria were guided by the PICOS framework (Tab. 1). Eligible studies were peer-reviewed original research articles and review articles published in English, explicitly investigating NPIs targeting gait rehabilitation in children with neurodisabilities.

Study selection. All records retrieved from WoSCC were exported as plain text ('.txt') format; duplicate entries were removed using Zotero software (https://www.zotero.org). Two independent reviewers conducted blinded screening of titles and abstracts for initial eligibility assessment. Subsequently, eligible studies underwent independent full-text screening by the same reviewers. Disagreements at any stage were resolved through discussion or consultation with a third independent reviewer until consensus was reached.

Data extraction. The following bibliometric information was systematically extracted from the included studies: annual publication count, citation frequency, Web of Science subject categories, journals, countries or regions, key words, authors, institutional affiliations, highly cited articles, and funding organizations.

Bibliometric analysis. The bibliometric analysis was performed using a combination of analytical tools, including the Bibliometrix R package (https://github.com/massimoaria/bibliometrix), Microsoft Excel 2021, VOSviewer (version 1.6.20), and CiteSpace (version 6.1 R6). Annual trends in publication numbers were visualized using Microsoft Excel 2021. Bibliometric indicators such as heatmaps and geographical distribution were generated using the Bibliometrix R package. Additionally, VOSviewer and CiteSpace facilitated the visualization and analysis of networks and clusters related to countries/regions, institutions, authors, journals, key words, and reference citations from the retrieved literature.

Table 1. PICOS strategy for inclusion criteria in the bibliometric review

PICOS criteria	
Population	Studies involving children diagnosed with neurodisability. Neurodisability was defined according to the consensus definition by Morris et al., and further informed by the WHO to enhance conceptual precision.[2–4]. For the purpose of analysis, the study included neurodisability-related conditions that primarily impact motor function.
Interventions	Studies investigating NPIs, including exercise-based interventions, animal-assisted therapy, task-oriented therapy, manual and body-based therapies, sensory stimulation, technology-assisted interventions, equipment-based interventions, and adapted physical/occupational therapies.
Comparators	For studies with a control group (e.g., RCTs, controlled trials), the control group must be involved in either standard care, usual practice, no intervention, or another type of NPIs. Studies without a control group (e.g., pre-post intervention designs) were included if they met the intervention criteria.
Outcomes	Studies were included if they assessed at least one outcome related to gait performance, using either objective or subjective measurement tools. Outcomes included: kinematic, kinetic, electromyographic parameters, gait-related functional assessments, neurophysiological and neural control indicators.
Study design	Eligible study designs included interventional studies and review articles.

PICOS criteria – Population, Intervention; Comparator, Outcome, and Study design criteria; WHO – World Health Organization; NPIs – Non-Pharmacological Interventions; RCTs – randomized controlled trials

RESULTS

Literature search results. In the initial search, 1,350 relevant researches were identified, 54 duplicates were removed, and 841 studies were subsequently also removed as they did not meet the inclusion criteria. This left a final 455 studies (311 articles and 144 review articles) for bibliometric analysis.

Analysis of annual publication output. Figure 1 illustrates the annual publication trends related to NPIs for gait rehabilitation in children with neurodisability. Between 1993–2024, there was a consistent and steady increase in both the number of annual publications and citations.

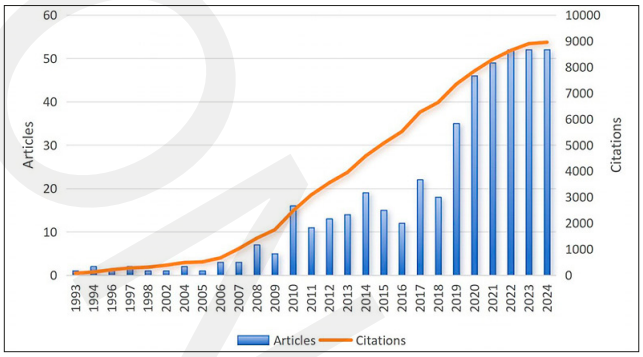

Figure 1. Annual Publication Trends and Citation Analysis in NPIs for Gait Rehabilitation in Children with Neurodisability (1993–2024).
NPIs – non-pharmacological interventions

Analysis of institutions and countries/regions. The United States is the leading country in research on NPIs for gait rehabilitation in children with neurodisability, ranking first in both the number of publications (77 articles) and cumulative citations (2,196), followed by Australia, with 43 publications and 1,141 citations. Despite ranking second in total publications (59 papers), China exhibits a comparatively lower citation count (645 citations), significantly trailing behind countries such as The Netherlands (27 papers, 978 citations), the United Kingdom (28 papers, 829 citations), and Canada (25 papers, 719 citations). It is worth noting that The Netherlands has received nearly 1,000 cumulative citations, with only 27 papers published. Similarly, Canada and Belgium display high unit output quality. Figure 2A and Figure 2B illustrate the geographical distribution and cooperation network characteristics of various countries in this field.

The United States and China have the closest cooperation relationship, followed by the United States and the United Kingdom and Australia, forming a relatively stable bilateral and multilateral cooperation system. In addition, several European countries, including the United Kingdom, The Netherlands, Belgium and Spain, have established a robust regional cooperation network.

At the institutional level, the University of Queensland in Australia emerges as the most productive institution, with 27 publications and 564 citations, followed by Cairo University (19 papers), Vrije Universiteit Amsterdam (15 papers), Katholieke Universiteit Leuven (11 papers), University of Sydney (12 papers), University of Washington (10 papers) and the Federal University of São Carlos, Brazil (10 papers). Figure 2C shows the international cooperation network structure among institutions, with the cooperation relationship divided into multiple clusters.

In Australia, the University of Queensland forms a close cooperation group with other Australian universities, such as the University of Sydney, with Vrije Universiteit Amsterdam and the University of Groningen constituting another cooperation core. The University of Washington frequently cooperates with North American institutions, such as Drexel University. Universities in some South American countries, e.g. Brazil, are mainly concentrated in regional cooperations, with relatively few cross-border collaborations, showing a regionally concentrated cooperation model.

Analysis of authors and co-cited authors. Roslyn N. Boyd (Brisbane, Australia) was identified as the most prolific contributor, with 22 publications and a total of 390 citations, followed by Annet J. Dallmeijer (Amsterdam, The Netherlands), 11 articles, 461 citations) and Leanne Sakzewski (Brisbane, Australia), 11 articles, 157 citations). It is worth noting that although Dallmeijer has a relatively small number of publications, the total number of citations is high. Figure 3A shows the collaboration network between authors. Within the author collaboration network, Roslyn N. Boyd's cluster exhibits the strongest and most cohesive collaborative relationships, forming the central hub of the network. She maintains frequent co-authorship ties with researchers such as Iona Novak and Leanne Sakzewski. Additionally, Robert J. Palisano, Annet J. Dallmeijer, and Kaat Desloovere (Leuven, The Netherlands), also formed stable collaboration groups. Figure 3B illustrates the author co-citation network, where Roslyn N. Boyd, Annet J. Dallmeijer, and Iona Novak emerge as the most frequently co-cited authors, occupying central positions within the network.

Analysis of source journals. In terms of publication sources, *Developmental Medicine and Child Neurology* ranks as the most prolific journal, publishing 32 articles in this domain, followed by *BMJ Open* (16 articles), *Developmental Neurorehabilitation* (15 articles), *Clinical Rehabilitation* (14 articles), and *Paediatric Physical Therapy* (14 articles). Figure 4A presents the core journal sources identified based on Bradford's Law, revealing a total of 11 journals with a high frequency of publications in this research field. Figure 4B illustrates the co-occurrence network relationship between journals, highlighting the central role of *Developmental Medicine and Child Neurology* not only in publication volume but also in its integrative position within the scholarly network. Journals such as *Clinical Rehabilitation, Disability and Rehabilitation, BMJ Open,* and *Physical Therapy* also demonstrate high levels of interconnectivity and collaborative engagement.

Analysis of key word occurrence. In the domain of NPIs for gait rehabilitation in children with neurodisabilities, the key words 'cerebral palsy' appeared with the highest frequency (236 occurrences). Figure 5A presents the key word co-occurrence network. Cluster analysis based on key word co-occurrence frequency identified several closely related thematic clusters. Central key words within these clusters include 'cerebral palsy', 'gross motor function', 'rehabilitation' and 'gait'. On this basis, key words such as 'physiotherapy' and 'virtual reality' gradually expanded the research boundaries. The colour gradient, representing the average year of publication, reveals that terms like 'balance' and 'virtual reality' have emerged as recent hotspots, reflecting the evolving direction and innovation in contemporary

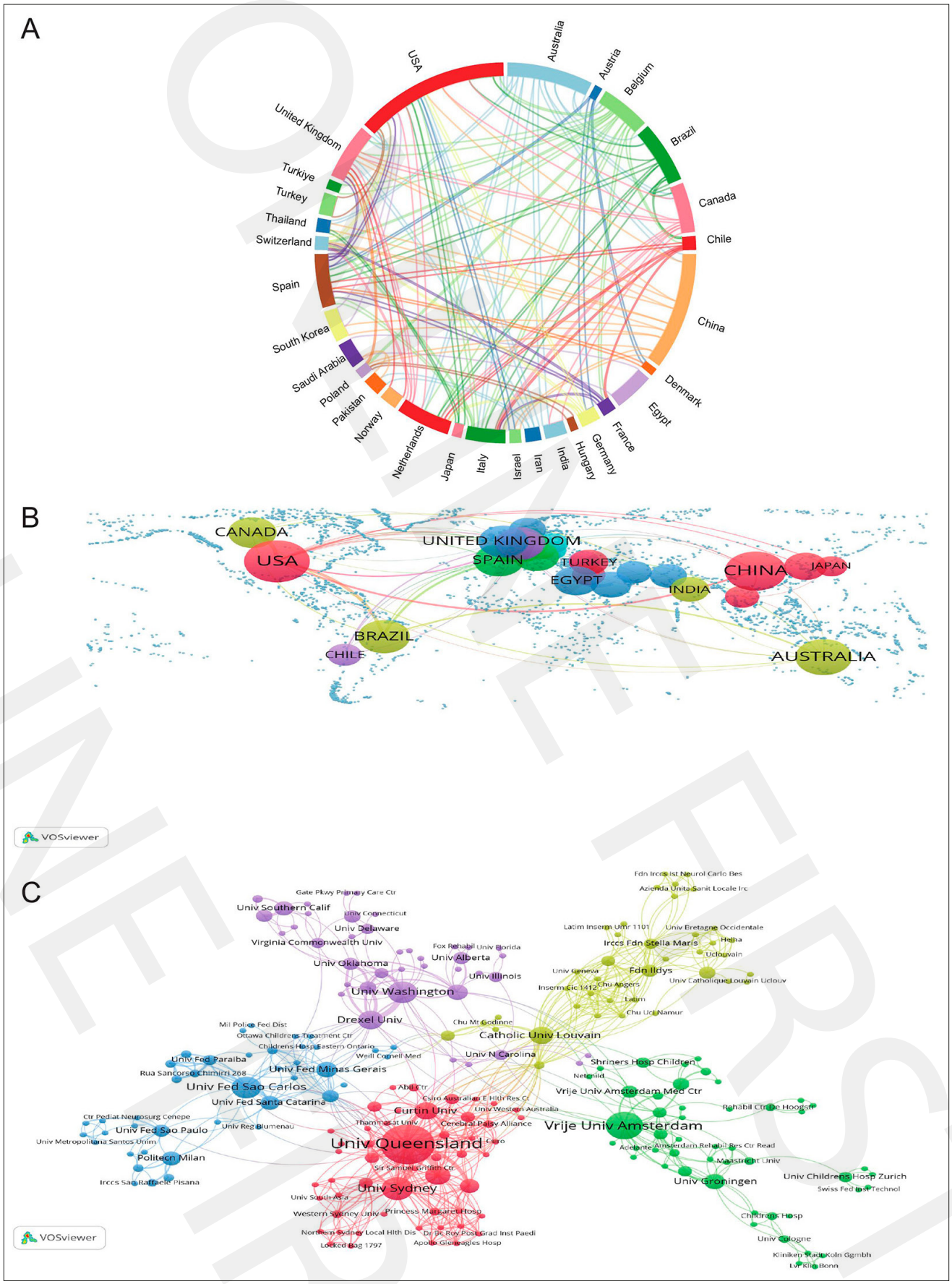

Figure 2. The collaborative network of countries/regions and institutions in the Field of NPIs for Gait Rehabilitation in Children with Neurodisabilities. (A) Chord diagram illustrating the cooperative relationships between countries. (B) Visualization of geographical distribution. (C): The collaborative network of institutions.
NPIs – non-pharmacological interventions

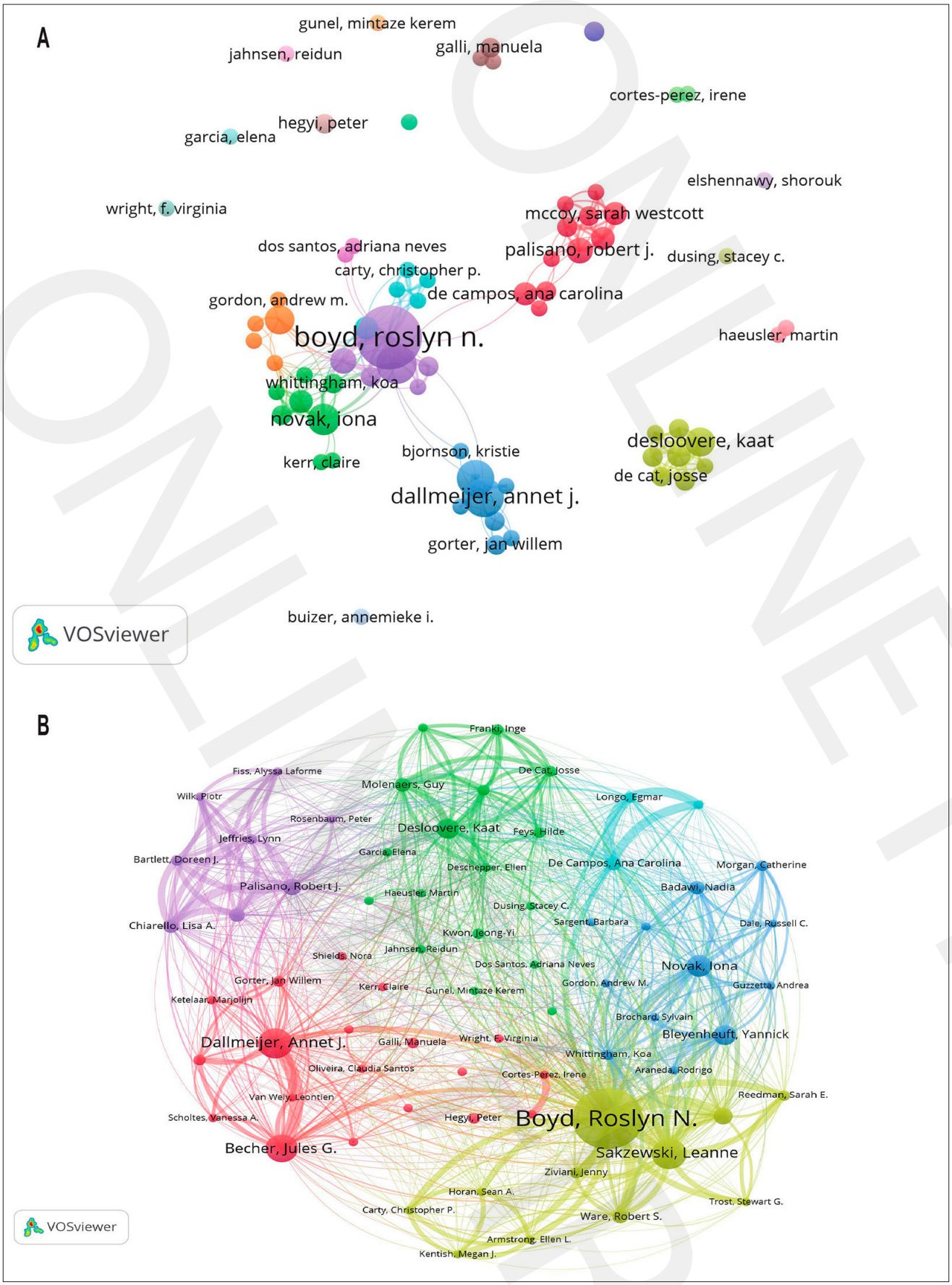

Figure 3. The collaborative network of co-authors and co-cited authors in the Field of NPIs for Gait Rehabilitation in Children with Neurodisabilities. (A) Map of co-authors provides a visual representation of the relationships between authors involved in the study. (B) Map of co-cited authors.
NPIs – non-pharmacological interventions

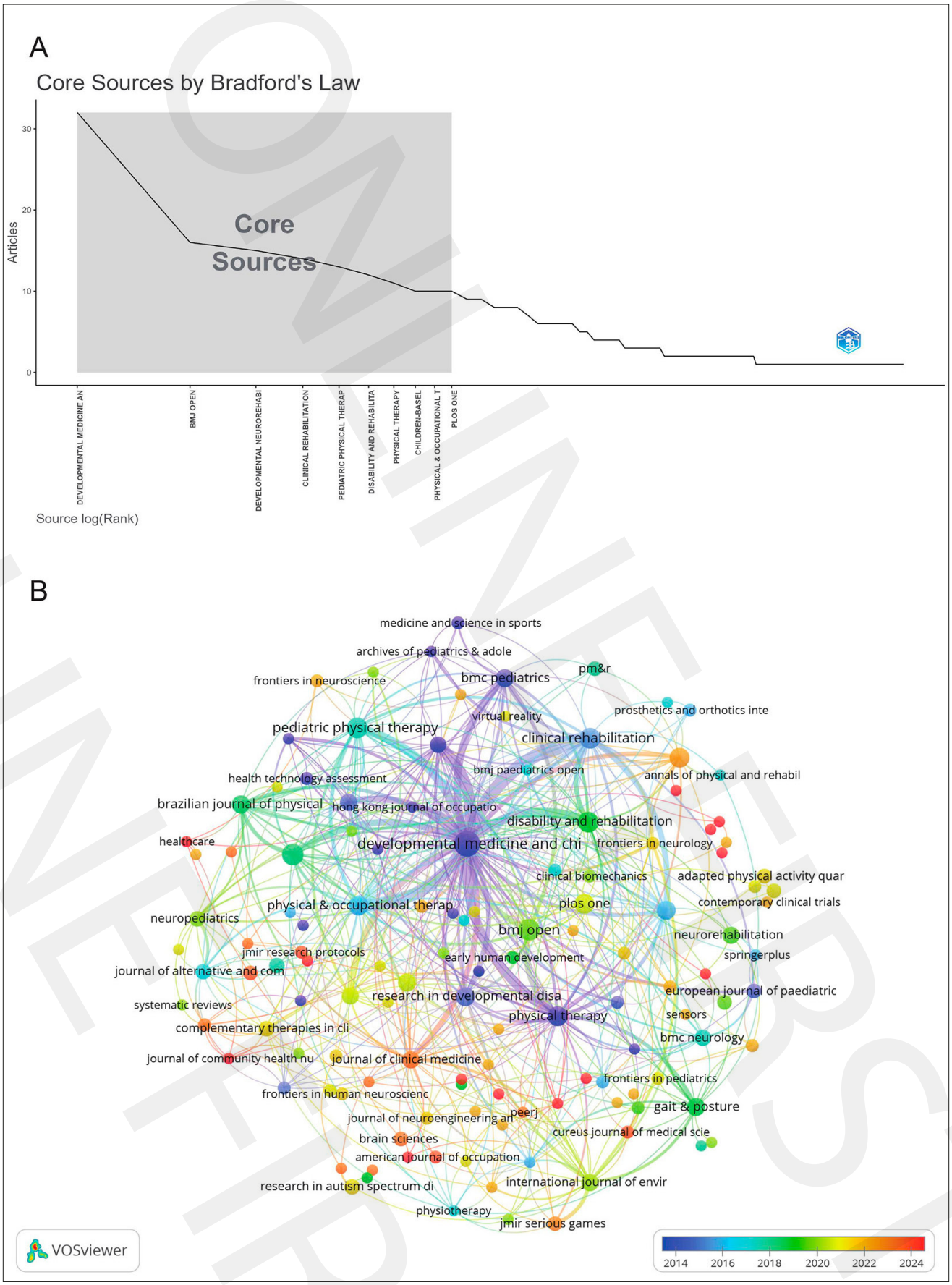

Figure 4. Analysis of academic journals in the field of NPIs for Gait Rehabilitation in Children with Neurodisabilities. (A) Distribution of core journals based on Bradford's Law. (B) Overlay visualization of journal co-occurrence based on average publication year.
NPIs – Non-pharmacological interventions

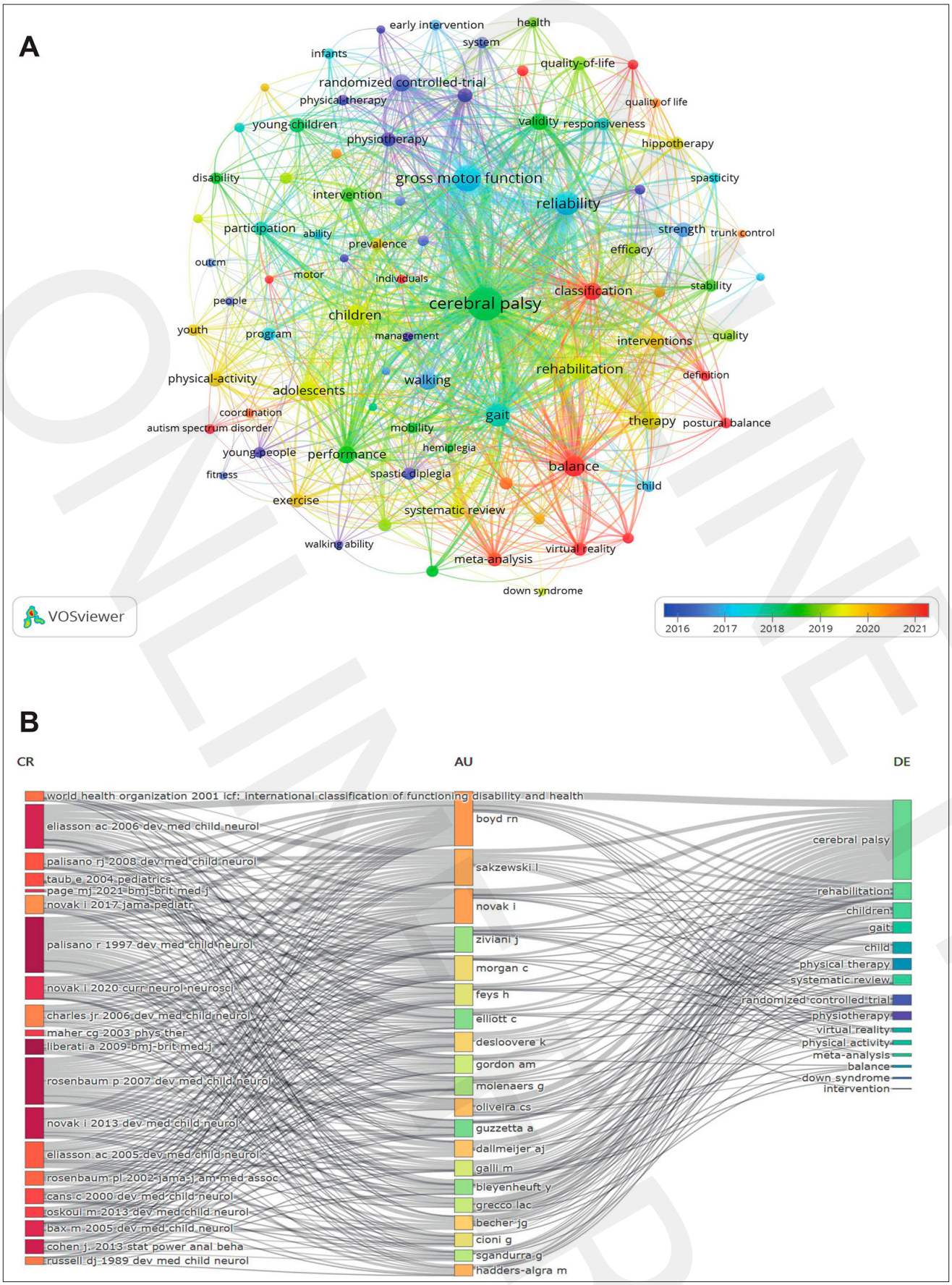

Figure 5. Analysis of key words in the field of NPIs for Gait Rehabilitation in Children with Neurodisabilities. (A) Overlay visualization of key word co-occurrence and temporal distribution. (B) Sankey diagram of key word evolution.
NPIs – non-pharmacological interventions

research. The key word evolution Sankey diagram in Figure 5B integrates the three-dimensional elements of highly-cited literature (CR), representative authors (AU) and key words (DE), and clearly shows the knowledge flow path.

The findings indicate that the primary research trajectories associated with key words such as 'cerebral palsy', 'rehabilitation' and 'systematic review' are concentrated on such highly productive and highly cited scholars as Novak, Boyd and Sakzewski, forming the knowledge base for gait rehabilitation research in children with neurological disorders. Although 'Down syndrome is not in the central pathway of the theme evolution, it has established a connection relationship with multiple intervention technology-related key words including 'balance', and 'virtual reality', reflecting that it has gradually gained attention in gait rehabilitation research as a specific type of neurodevelopmental disorder, and its research path has gradually been embedded in the mainstream research network, with late development potential.

The key word co-occurrence heat map in Figure 6A further reveals the coupling strength between terms. 'Cerebral palsy' forms a high-frequency co-occurrence relationship with key words such as 'rehabilitation', 'balance', and 'gross motor function'. In the thematic map, the key words can be divided into seven themes, and it can be further identified that 'cerebral palsy' and 'rehabilitation' are the focus of this field (Fig. 6B). Figure 6C shows a thematic strategy map based on key word density (development level) and centrality (correlation), dividing the research field into four quadrants. The upper right quadrant represents the dominant themes (Motor Themes), such as 'cerebral palsy', 'children', and 'rehabilitation', showing that the core research directions in this field have high maturity and strong cross-theme connectivity. It is worth noting that 'Down syndrome' appears in the lower right quadrant, close to the 'Basic Themes' area. Although its density is relatively low, it has established a clear connection with basic rehabilitation terms such as 'balance', 'gait', and 'rehabilitation'.

Highly cited reference analysis. The most cited article is *'Exercise training program in children and adolescents with cerebral palsy'* with 210 citations. The second most cited article is *'Effectiveness of virtual reality rehabilitation for children and adolescents with cerebral palsy: an updated evidence-based systematic review'* – 145 times) and *'Exercise interventions improve postural control in children with cerebral palsy: a systematic review'* – 145 times. Figure 7A illustrates the citation relationship network between the high-burst literature in this field. As illustrated in the network, numerous publications authored by scholars such as Robert J. Palisano, Iona Novak, and Olaf Verschuren (Utrecht, The Netherlands) occupy prominent positions, characterized by high citation frequency and strong mutual linkage. Their centrality within the network highlights their significant scholarly influence and interconnected contributions to the field. Figure 7B further presents the key references with strong citation bursts from 1998–2023. Novak's article published in 2020 has the highest citation burst intensity (7.82), and early literature such as Palisano (2000, 2008) and Bower (2001) also showed a strong burst. Recent bursts of literature, such as Chen (2018) and Sadowska M. (2020).

DISCUSSION

This study systematically sorted out the historical development and research status, cooperation network, journal distribution, core authors and hotspot evolution of NPIs in the gait rehabilitation of children with neurodisability by conducting bibliometric and visual analysis of the literature included in the WoSCC from 1993–2024.

The findings indicate a continuous increase in the volume of literature on NPIs for gait rehabilitation in children with neurodisability, with notable growth observed particularly after 2010 and 2020. This trend reflects growing academic interest and the maturing of the field, which may be closely related to the development of intervention promotion, integrated rehabilitation policies, and evidence-based paediatric rehabilitation concepts [36, 37].

At the national and institutional levels, the United States dominates in terms of publication volume, citation frequency, and international cooperation, reflecting its strong academic influence. Although China ranks second in the number of publications, the citation rate is relatively low, indicating that its research enthusiasm has increased but it still needs to improve its international influence and research quality. Institutions such as the University of Queensland, Vrije University Amsterdam, and the University of Washington have formed a stable cooperation network to promote the internationalization of research. Core journals such as *Developmental Medicine & Child Neurology, Disability and Rehabilitation,* and *Frontiers in Pediatrics* reflect the multidisciplinary integration characteristics of this field, covering rehabilitation, neurophysiology, paediatrics, and sports science. Novak, Boyd, and Sakzewski, among other prolific authors, have made outstanding contributions to the research on cerebral palsy rehabilitation and gait improvement, and have advocated promotion of standardized interventions and objective assessments [38, 39]. Key word analysis further verified that 'cerebral palsy', 'rehabilitation', and 'children' are the core themes; at the same time, the rise of key words such as 'Down syndrome', 'virtual reality', and 'gait analysis' indicates that the research population and intervention methods are becoming more diversified. The key words map shows that although 'Down syndrome' is still in the basic theme area, it has established links with core rehabilitation terms, showing potential for future development.

Gait rehabilitation refers to the systematic therapeutic process aimed at improving walking ability and lower limb function in individuals with gait impairments [40]. It involves assessment and targeted training of gait patterns through physical therapy, assistive technology and neuromuscular interventions, integrating rehabilitation medicine, biomechanics, neuroscience and engineering to improve mobility, independence, and quality of life [41, 42].

Neurodisability is a highly heterogeneous concept, covering CP and DS, and ASD (autism spectrum disorders) [1]. CP often results in spasticity, poor motor control, and gait asymmetry due to upper motor neuron damage, while DS is often associated with hypotonia, ligament laxity, and impaired balance, resulting in delayed and unstable gait development [43]. Although these disorders have different causes and manifestations, they all require interventions to improve gait efficiency and stability. CP has been the most extensively investigated in this field. Numerous systematic

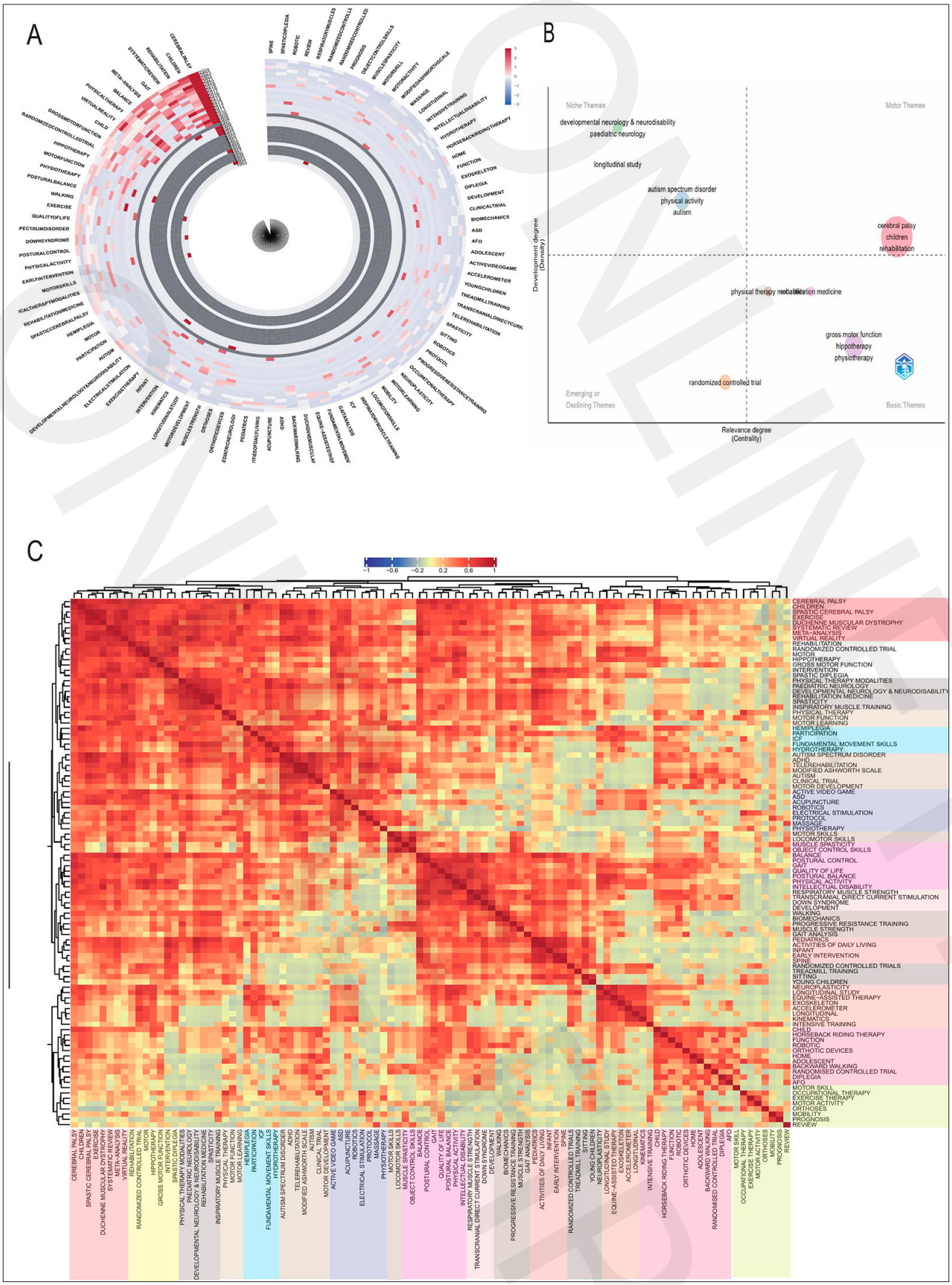

Figure 6. Analysis of key words in the field of NPIs for Gait Rehabilitation in Children with Neurodisabilities. (A) Annual heatmap of key word popularity. (B) Thematic map. (C) Key word relevance heatmap with clustering.
NPIs – non-pharmacological interventions

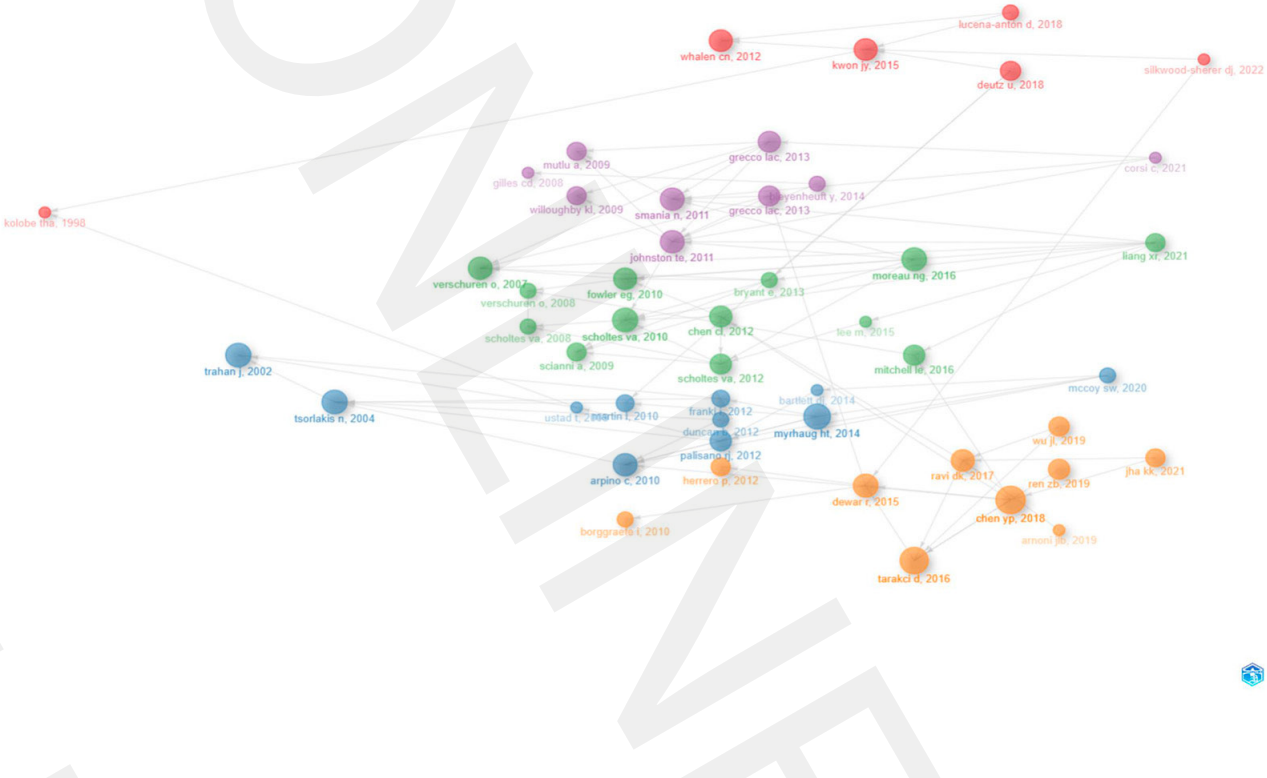

Figure 7. Analysis of highly cited references in the field of NPIs for gait rehabilitation in children with neurodisability. (A) Association network among the top 50 highly cited references; (B) Top 25 references with the strongest citation bursts (Kleinberg's algorithm, CiteSpace. NPIs: non-pharmacological Interventions

reviews and meta-analyses have synthesized evidence for CP-related interventions, contributing to a relatively mature and standardized clinical research base. For instance, studies have indicated that Whole Body Vibration (WBV) training, and different forms of walking training, can effectively improve the gait ability of individuals with CP [44, 45]. This study found that DS remains in the early stages of research development within the field of NIPs for gait rehabilitation. Although the number of studies is limited, growing attention has been directed toward exploring effective NPIs for individuals with DS. For example, studies demonstrated that the Vojta method of rehabilitation has effectively improved gait ability in individuals, especially children, with DS [46, 47].

A variety of NPIs have been explored for gait rehabilitation in children with neurodisability. Traditional methods, such as physiotherapy, balance training and neuromuscular stimulation, remain the core approach. In recent years, there has been a marked shift towards technology-assisted interventions, including VR, robot-assisted gait training, and biofeedback. These approaches offer greater potential for personalization and adaptability to individual patient needs [48]. Compared with conventional clinical models, they are not limited by clinical setting and can extend rehabilitation into home and community settings [49]. In addition, these innovative approaches may also enhance patient engagement by providing more diverse, interactive, and motivating rehabilitation experiences [50]. Further research is needed to evaluate their long-term efficacy and scalability across different neurodisability populations.

Limitations of the study. Although the current study undoubtedly has many advantages, the results need to be interpreted with caution due to the following limitations. 1) The study only included literature published in English, which may have underestimated the actual research contributions of non-English-speaking countries in this field; 2) there is a certain risk of language bias; 3) Studies accepted for publication in 2025 have not yet been included, which may have affect the comprehensive reflection of the latest research trends in this field.

CONCLUSIONS

The presented bibliometric analysis reveals a growing global interest in NPIs for gait rehabilitation in children with neurodisabilities, with the United States, Australia, and several European countries leading in the research output and collaboration. Core contributors, such as Roslyn N. Boyd, Iona Novak, and Annet J. Dallmeijer form the foundation of scholarly influence in this field. 'Cerebral palsy', 'rehabilitation', and 'gait' remain central themes, while emerging topics like 'virtual reality' and 'balance' suggest evolving research priorities. The field is advancing steadily, with increased interdisciplinary collaboration and innovation paving the way for more effective, inclusive interventions in paediatric neurorehabilitation.

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