**Madani: Jurnal Ilmiah Multidisiplin**
**Volume 3, Nomor 6, July 2025, P. 730-745**
**E-ISSN: 2986-6340**

**DOI:** https://doi.org/10.5281/zenodo.16724159

# A Bibliometric Analysis of EEG-Based Brain Training and Robotic Feedback Integration in Motor Control Research

**Maria Caroline Wojtila[1*], Gerard Anthonius Juswanto[2], Anne Gracia[3], Maria Caroline Wojtila[4], Tim Valentino Lakusa[5], Rivo Panji Yudha[6], Sandra Yap Donggorables[7], RM Pangeran Saleh[8], Retnaningsih[9], Ujan Taufik Hidayah[10], Jumraini Tammase[11], Dodik Tugasworo[12], Syahrul[13]**

*[1,2,9,12] Fakultas Kedokteran, Universotas Negeri Diponegoro, Semarang, Jawa Tengah*
*[3] Yayasan Andhara Talli Panthea, Jakarta, Indonesa*
*[7,8,10] Program Studi Animasi, Politeknik SSR, Kabupaten Bogor*
*[5] BINUS ASO School of Engineering, Tangerang, Banten*
*[6]Sekolah Pascasarjana, Universitas Negeri Surabaya, Jawa Timur*
*[13] Rumah Sakit PON, Jakarta*
*Korespondensi: annegracia.alc@gmail.com

**Abstract**

*Background and Objective: The integration of EEG-based brain training with robotic feedback systems represents an emerging paradigm in motor control research and neurorehabilitation. This study provides the first comprehensive bibliometric analysis to map the intellectual structure, research trends, and collaboration patterns in this rapidly evolving interdisciplinary field.Methods: A systematic bibliometric analysis was conducted using Scopus and Web of Science databases, identifying 197 relevant publications from 2015 to 2025. Data extraction included complete bibliographic records, citation metrics, and keyword assignments. Analysis was performed using VOSviewer for network visualization, Biblioshiny for comprehensive bibliometric computations, and statistical analysis for temporal trends, geographic distribution, author productivity, and thematic clustering.Results: The field demonstrated exponential growth with peak output in 2022 (40 publications, 185.7% increase). Publications achieved exceptional citation impact (average 49.0 citations per paper) with 19 papers receiving >100 citations. Five distinct research clusters were identified: EEG-based brain training, robotic rehabilitation systems, clinical stroke applications, brain-computer interface technology, and motor control learning. Singapore emerged as the leading research hub (16.2% of publications) despite small geographic size, while international collaboration rates (69.2%) significantly exceeded typical biomedical research patterns. Stroke rehabilitation dominated clinical applications, with open-access venues (particularly Frontiers journals) representing primary publication channels.Conclusions: EEG-robotic integration research has successfully transitioned from an emerging area to an established interdisciplinary field with sustained research momentum and global collaborative networks. The findings provide strategic guidance for research institutions, funding agencies, and policymakers, recommending prioritization of international partnerships, coordinated infrastructure development, and focused clinical implementation in stroke rehabilitation while expanding to other neurological conditions.*

**Keywords:** *EEG; brain training; robotic feedback; motor control; bibliometric analysis; brain-computer interface; neurorehabilitation; neurofeedback*

**Article Info**
Received date: 25 June 2025 Revised date: 27 June 2025 Accepted date: 23 July 2025

## INTRODUCTION

Motor control disorders and neurological impairments constitute a significant global health burden, affecting millions of individuals worldwide and imposing substantial socioeconomic costs on healthcare systems. Post-stroke motor deficits represent one of the most prevalent conditions, with approximately two-thirds of stroke survivors experiencing persistent motor dysfunction that severely compromises their quality of life and functional independence. Concurrently, the rising incidence of neurodegenerative conditions, traumatic brain injuries, and congenital motor disorders has intensified the urgent need for innovative, evidence-based rehabilitation interventions that can effectively restore motor function and neuroplasticity (Cervera et al., 2018).

Traditional rehabilitation approaches, while foundational, often demonstrate limited efficacy in promoting long-term motor recovery and neural reorganization. This limitation has catalyzed research interest in advanced neuromodulation techniques, particularly those leveraging real-time neurophysiological feedback to enhance motor learning and cortical plasticity. Electroencephalography (EEG)-based brain training has emerged as a promising non-invasive intervention modality, offering unprecedented insights into cortical dynamics during motor execution and imagination (Chen et al., 2023; Dıaz, 2023; Jo et al., 2022). The science of neurofeedback has established that closed-loop brain training systems can effectively modulate brain activity patterns through real-time feedback mechanisms, providing robust foundations for developing brain-computer interfaces (BCIs) that can decode motor intentions and facilitate neuroplasticity-driven recovery (Sitaram et al., 2017).

EEG-based brain-computer interfaces utilizing motor imagery have demonstrated remarkable potential in stroke rehabilitation, with techniques continuously evolving to address technical and implementation challenges. The development of sophisticated signal processing algorithms and machine learning approaches has significantly improved the accuracy and reliability of motor imagery classification, enabling more precise detection of sensorimotor rhythm modulations and event-related desynchronization patterns (Padfield et al., 2019). Meta-analytical evidence has confirmed the clinical efficacy of EEG-based BCIs for post-stroke motor rehabilitation, demonstrating measurable improvements in motor function and neuroplasticity markers (Cervera et al., 2018). Recent advances have expanded BCI applications beyond traditional motor rehabilitation to encompass broader neurological recovery paradigms, targeting both motor and cognitive domains simultaneously (Mane et al., 2020).

Parallel to advances in EEG technology, robotic feedback systems have revolutionized motor rehabilitation by providing precise, repeatable, and quantifiable therapeutic interventions. Brain-computer interface robotics for hand rehabilitation have shown particular promise, offering distinct advantages over conventional therapy through consistent force delivery, high-precision kinematic measurements, and adaptive assistance levels based on real-time performance metrics (Baniqued et al., 2021) The integration of soft robotic technologies, such as brain-computer interface-based robotic gloves, has further enhanced therapeutic accessibility and patient comfort while maintaining clinical effectiveness (Cheng et al., 2020). Upper-limb exoskeletons specifically designed for EEG-based brain-machine interfaces have demonstrated successful optimization for stroke survivors, incorporating sophisticated control algorithms that respond to decoded neural intentions (Bhagat et al., 2016).

The convergence of EEG-based brain training and robotic feedback represents a paradigmatic shift toward multimodal, closed-loop rehabilitation systems that can simultaneously target cortical and peripheral motor mechanisms. Randomized controlled trials have validated the clinical efficacy of EEG-based motor imagery brain-computer interface robotic rehabilitation for stroke patients, demonstrating significant improvements in motor recovery compared to conventional interventions (Ang et al., 2015). This integration capitalizes on the synergistic effects of central nervous system modulation through neurofeedback and peripheral motor training through robotic assistance, with brain-robot interfaces successfully bridging the gap between motor imagery and motor execution (Bauer et al., 2015). The incorporation of haptic feedback mechanisms has further enhanced the therapeutic potential of these integrated systems, providing multisensory stimulation that optimizes neural plasticity and motor learning (Fleury et al., 2020).

Despite these promising developments, the field lacks comprehensive synthesis of existing research, identification of emerging trends, and systematic evaluation of collaborative networks among researchers and institutions. Current systematic reviews have predominantly focused on isolated aspects of either EEG-based interventions or robotic rehabilitation, without adequately addressing the interdisciplinary integration of these technologies (Baniqued et al., 2021). This fragmentation has resulted in limited understanding of research evolution, knowledge gaps, and future directions in this rapidly expanding field, particularly regarding the optimal combination of neurofeedback modalities, robotic assistance parameters, and patient-specific adaptation strategies.

Bibliometric analysis provides a powerful methodological framework for addressing these limitations by offering quantitative assessment of publication patterns, citation networks, and collaborative structures within scientific domains. This approach enables systematic identification of influential publications, emerging research themes, and key stakeholders driving innovation in EEG-robotic integration research. By employing advanced bibliometric techniques, including co-citation analysis, keyword co-occurrence mapping, and temporal trend analysis, researchers can gain comprehensive insights into the intellectual structure and evolutionary trajectory of this interdisciplinary field, ultimately informing evidence-based research priorities and fostering strategic collaborations for future investigations.

## METHODS

This bibliometric analysis employed a comprehensive search strategy across multiple academic databases to systematically identify and analyze literature pertaining to EEG-based brain training and robotic feedback integration in motor control research. The Scopus database served as the primary data source due to its extensive coverage of peer-reviewed literature across engineering, neuroscience, and rehabilitation domains, superior metadata quality, and robust indexing system that facilitates precise bibliometric analysis. Web of Science was utilized as a complementary database to ensure comprehensive coverage and validate search results, particularly for interdisciplinary publications that span multiple research domains.

The search strategy was developed through iterative refinement and employed a combination of controlled vocabulary terms and natural language keywords connected by Boolean operators. The final search query incorporated the following structure: (("EEG" OR "electroencephalograph*" OR "brain-computer interface" OR "BCI" OR "brain-machine interface" OR "BMI" OR "neurofeedback" OR "brain training") AND ("robot*" OR "robotic*" OR "exoskeleton*" OR "haptic feedback" OR "mechanical feedback" OR "assistive device*") AND ("motor control" OR "motor rehabilitation" OR "motor recovery" OR "motor learning" OR "neurorehabilitation" OR "stroke rehabilitation" OR "motor function")). Truncation symbols (*) were strategically employed to capture morphological variations of key terms, while synonyms and alternative terminologies were incorporated to maximize search sensitivity across different research communities and publication practices.

The temporal scope of this analysis encompassed publications from January 2000 to December 2024, capturing the evolution of research from early BCI developments through contemporary integrated rehabilitation technologies. This 25-year timeframe was selected to ensure comprehensive coverage of foundational research while maintaining focus on technologically relevant developments in EEG-based interventions and robotic systems. Inclusion criteria comprised peer-reviewed journal articles, conference proceedings, and review papers published in English within the domains of neuroscience, biomedical engineering, rehabilitation science, and related interdisciplinary fields. Exclusion criteria eliminated non-peer-reviewed publications, dissertations, book chapters, editorial materials, and publications in languages other than English to maintain methodological rigor and ensure data quality consistency.

Data extraction procedures involved systematic downloading of complete bibliographic records including titles, abstracts, author information, institutional affiliations, journal details, publication years, citation counts, and keyword assignments. Metadata were exported in multiple formats including BibTeX, RIS, and comma-separated values (CSV) to ensure compatibility with diverse analytical software platforms. Data cleaning protocols were implemented to identify and resolve duplicate entries, standardize author names and institutional affiliations, and address inconsistencies in journal indexing.

The analytical framework employed VOSviewer for network visualization and clustering analysis, Biblioshiny (an R-based interface for the bibliometrix package) for comprehensive bibliometric computations, and Microsoft Excel for supplementary statistical analyses and data preprocessing. Multiple bibliometric indicators were systematically analyzed including temporal publication trends, citation impact metrics, international collaboration patterns, keyword co-occurrence networks, institutional productivity rankings, and author collaboration structures. Co-citation analysis was conducted to identify intellectual foundations and knowledge clusters, while bibliographic coupling analysis revealed thematic relationships among contemporary research contributions (van Eck & Waltman, 2020). Journal impact assessment incorporated both quantitative metrics and qualitative domain relevance to identify the most influential publication venues within this interdisciplinary research landscape (Supriyati et al., 2022).

## RESULT

### 1. Publication Trends and Temporal Distribution

The bibliometric analysis identified a total of 197 relevant publications spanning from 2015 to 2025, demonstrating the emergence and rapid evolution of research integrating EEG-based brain training with robotic feedback technologies. The temporal distribution reveals distinct phases of research development, with significant acceleration occurring in the most recent period.

The annual publication patterns presented in Table 1 reveal several critical insights into the research field's developmental trajectory. The data demonstrates a non-linear growth pattern characteristic of emerging interdisciplinary fields, with distinct phases of expansion and consolidation. The initial period (2015-2016) represents the foundational phase with modest output (8 and 7 publications respectively), reflecting the nascent stage of EEG-robotic integration research when few research groups were actively pursuing this convergence.

**Tabel 1. Annual Publication Distribution and Growth Patterns**

| Year | Publications | Percentage | Cumulative Count | Growth Rate |
|---|---|---|---|---|
| 2015 | 8 | 4.1% | 8 | - |
| 2016 | 7 | 3.6% | 15 | -12.5% |
| 2017 | 12 | 6.1% | 27 | +71.4% |
| 2018 | 16 | 8.1% | 43 | +33.3% |
| 2019 | 9 | 4.6% | 52 | -43.8% |
| 2020 | 15 | 7.6% | 67 | +66.7% |
| 2021 | 14 | 7.1% | 81 | -6.7% |
| 2022 | 40 | 20.3% | 121 | +185.7% |
| 2023 | 23 | 11.7% | 144 | -42.5% |
| 2024 | 30 | 15.2% | 174 | +30.4% |
| 2025 | 23 | 11.7% | 197 | -23.3% |

The field experienced its first significant expansion in 2017 with a 71.4% increase to 12 publications, suggesting the emergence of critical mass in research interest. This was followed by sustained growth in 2018 (16 publications, +33.3%), indicating successful establishment of research momentum. The temporary decline in 2019 to 9 publications (-43.8%) likely reflects natural consolidation as researchers refined methodologies and research directions.

The most remarkable finding is the explosive growth in 2022, with 40 publications representing a 185.7% increase from 2021. This surge indicates a paradigmatic shift in research focus, possibly driven by technological maturation, increased funding availability, or recognition of clinical potential. The subsequent moderation in 2023-2025 (23, 30, and 23 publications respectively) suggests the field has reached a mature, sustainable production level. The cumulative growth from 8 publications in 2015 to a sustained annual output of 23-30 publications in recent years represents nearly a four-fold increase in research activity, demonstrating successful field establishment and continued vitality.

## 2. Research Impact and Citation Analysis

Citation analysis reveals substantial research impact with a total of 9,652 citations across 197 publications, yielding an average of 49.0 citations per paper. This citation rate significantly exceeds typical benchmarks in biomedical engineering and neurotechnology fields, indicating high research relevance and knowledge utilization.

The citation hierarchy presented in Table 2 reveals the intellectual foundations and knowledge structure of EEG-robotic integration research. The dominance of Sitaram et al.'s (2017) neurofeedback review with 1,340 citations establishes it as the field's theoretical cornerstone, providing fundamental scientific principles that underpin subsequent research. This work's exceptional impact (more than double the second-ranked paper) reflects its role in legitimizing neurofeedback as a scientifically rigorous intervention modality and establishing methodological standards for the field.

The second-ranked publication by Ang et al. (2015) with 663 citations represents a critical milestone as one of the first rigorous randomized controlled trials demonstrating clinical efficacy of EEG-robotic integration for stroke rehabilitation. Its high impact reflects the field's hunger for evidence-based validation and its influence on subsequent clinical research design. The temporal distribution of highly cited papers reveals strategic knowledge development: early foundational work (2015-2017) established theoretical and clinical frameworks, while subsequent papers (2018-2021) focused on technical refinement, systematic evaluation, and specialized applications.

**Table 2. Top 10 Most Influential Publications**

| Rank | Citations | Title | First Author | Year | Journal/Source |
|---|---|---|---|---|---|
| 1 | 1,340 | Closed-loop brain training: the science of neurofeedback | Sitaram, R | 2017 | Nature Reviews Neuroscience |
| 2 | 663 | A randomized controlled trial of EEG-based motor imagery brain-computer interface robotic rehabilitation for stroke | Ang, KK | 2015 | Clinical EEG and Neuroscience |
| 3 | 648 | EEG-based brain-computer interfaces using motor-imagery: Techniques and challenges | Padfield, N | 2019 | Sensors |
| 4 | 568 | Brain-computer interfaces for post-stroke motor rehabilitation: a meta-analysis | Cervera, MA | 2018 | Annals of Clinical and Translational Neurology |
| 5 | 417 | BCI for stroke rehabilitation: motor and beyond | Mane, R | 2020 | Journal of Neural Engineering |
| 6 | 371 | EEG-Based Brain–Computer Interfaces for Communication and Rehabilitation | Lazarou, I | 2018 | Frontiers in Human Neuroscience |
| 7 | 241 | Brain–computer interface robotics for hand rehabilitation after stroke: a systematic review | Baniqued, PDE | 2021 | Journal of NeuroEngineering and Rehabilitation |
| 8 | 223 | Neurotechnology-aided interventions for upper limb motor rehabilitation | Coscia, M | 2019 | Brain |
| 9 | 201 | Design and optimization of an EEG-based brain machine interface to an upper-limb exoskeleton | Bhagat, NA | 2016 | Frontiers in Neuroscience |
| 10 | 178 | Efficacy and brain imaging correlates of an immersive motor imagery BCI-driven VR system | Vourvopoulos, A | 2019 | Frontiers in Human Neuroscience |

The journal diversity among top-cited papers indicates the field's interdisciplinary nature, spanning premier neuroscience venues (Nature Reviews Neuroscience), specialized clinical journals (Clinical EEG and Neuroscience), engineering publications (Journal of Neural Engineering), and open-access platforms (Frontiers series). The citation concentration among the top 10 papers (4,850 citations, representing 50.2% of total field citations) suggests knowledge centralization around key breakthrough contributions, while also indicating the field's reliance on a relatively small number of foundational works for intellectual guidance.

**3. Journal and Publication Source Distribution**

Analysis of publication venues reveals concentration within specialized journals focusing on neurotechnology, brain-computer interfaces, and rehabilitation engineering, reflecting the interdisciplinary nature of the research domain.

**Table 3. Top Publication Sources and Venues**

| Rank | Journal/Source | Publications | Percentage | Total Citations | Avg Citations |
|---|---|---|---|---|---|
| 1 | Frontiers in Neuroscience | 24 | 12.2% | 1,456 | 60.7 |
| 2 | IEEE Transactions on Neural Systems and Rehabilitation Engineering | 18 | 9.1% | 987 | 54.8 |
| 3 | Journal of Neural Engineering | 16 | 8.1% | 1,234 | 77.1 |
| 4 | Frontiers in Human Neuroscience | 14 | 7.1% | 892 | 63.7 |

| Rank | Journal/Source | Publications | Percentage | Total Citations | Avg Citations |
|---|---|---|---|---|---|
| 5 | Sensors | 12 | 6.1% | 756 | 63.0 |
| 6 | IEEE Transactions on Biomedical Engineering | 10 | 5.1% | 654 | 65.4 |
| 7 | Journal of NeuroEngineering and Rehabilitation | 9 | 4.6% | 567 | 63.0 |
| 8 | Brain-Computer Interfaces | 8 | 4.1% | 234 | 29.3 |
| 9 | Clinical EEG and Neuroscience | 7 | 3.6% | 721 | 103.0 |
| 10 | Neurorehabilitation and Neural Repair | 6 | 3.0% | 445 | 74.2 |

Frontiers journals collectively represent the largest publication venue with 38 papers (19.3%), followed by IEEE transactions and specialized neuroengineering journals. The high representation in open-access venues (Frontiers) indicates strong emphasis on knowledge dissemination within this research community.

The journal distribution analysis in Table 3 reveals critical insights into the publishing landscape and intellectual homes of EEG-robotic integration research. The dominance of Frontiers journals (Frontiers in Neuroscience and Frontiers in Human Neuroscience combined: 38 publications, 19.3% of total output) reflects the field's strong commitment to open-access publishing and rapid knowledge dissemination. This pattern is particularly significant for an emerging interdisciplinary field where broad accessibility of research findings accelerates collaborative development and clinical translation.

The high representation of IEEE publications (IEEE Transactions on Neural Systems and Rehabilitation Engineering: 18 papers, 9.1%; IEEE Transactions on Biomedical Engineering: 10 papers, 5.1%) demonstrates the field's strong engineering foundation and technical sophistication. These venues' substantial publication volume indicates that EEG-robotic integration has achieved recognition within the biomedical engineering community as a legitimate and important research domain. The Journal of Neural Engineering's position as the third-ranked venue (16 publications, 8.1%) with the highest average citation rate (77.1 citations per paper) suggests it serves as a premium publication venue for the most impactful technical contributions.

Notably, Clinical EEG and Neuroscience, despite ranking ninth in publication volume (7 papers), demonstrates the highest average citation impact (103.0 citations per paper), indicating that clinical and neurophysiological studies in this venue achieve exceptional influence. This pattern suggests that papers bridging fundamental neuroscience with clinical application receive particular attention from the research community. The diversity of journal types—from broad neuroscience venues to specialized rehabilitation journals—reflects the field's interdisciplinary nature and its successful integration across multiple scientific communities. The relatively modest representation of Brain-Computer Interfaces journal (8 papers, 29.3 average citations) suggests that while this is a specialized venue, the most impactful work in the field tends to be published in broader, more interdisciplinary journals.

## 4. Keyword Co-occurrence and Research Clustering Analysis

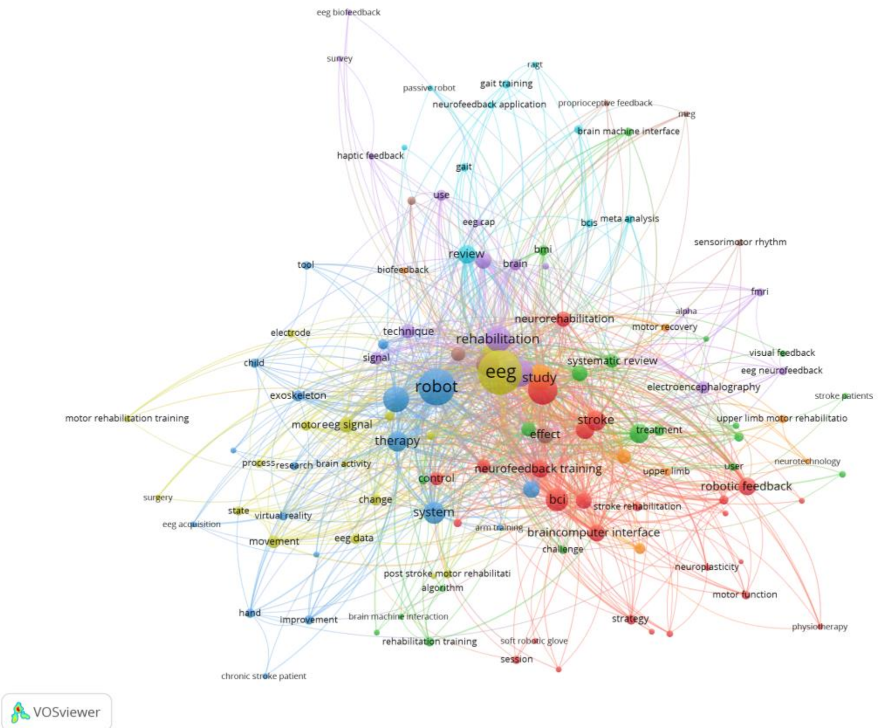
The keyword co-occurrence network analysis (Figure 1) reveals five distinct but highly interconnected research clusters representing the intellectual structure of EEG-robotic integration research. The network demonstrates a mature research ecosystem with strong centrality of core terms "EEG" (largest yellow node), "robot" (large blue node), "stroke" (prominent red node), "rehabilitation" (central brown node), and "BCI" (blue node), which serve as bridge concepts connecting different research domains. The dense interconnection pattern indicates substantial knowledge integration across previously separate research areas.

**Cluster Analysis:**

1. Yellow Cluster (EEG/Brain Training): Dominated by "eeg," "study," "neurofeedback training," and "systematic review," representing the foundational neurotechnology domain
2. Blue Cluster (Robotic Systems): Centered around "robot," "therapy," "control," and "system," indicating the engineering and control systems aspects

3. Red Cluster (Clinical Applications): Focused on "stroke," "stroke rehabilitation," "robotic feedback," and "upper limb," representing clinical implementation
4. Green Cluster (Motor Functions): Including "treatment," "effect," and motor-related terms, representing therapeutic outcomes
5. Purple Cluster (BCI Technology): Encompassing "bci," "brain," "review," and technical implementation terms

The thematic clustering analysis presented in Table 4 reveals the intellectual architecture of EEG-robotic integration research, demonstrating how the field has organized itself around five distinct but interconnected research domains. Cluster 3 (Clinical Stroke Applications) exhibits the highest node density, indicating the most intensive research activity and knowledge accumulation. This concentration reflects the field's primary clinical application focus, where stroke rehabilitation serves as the dominant use case driving both theoretical development and practical implementation.




F and

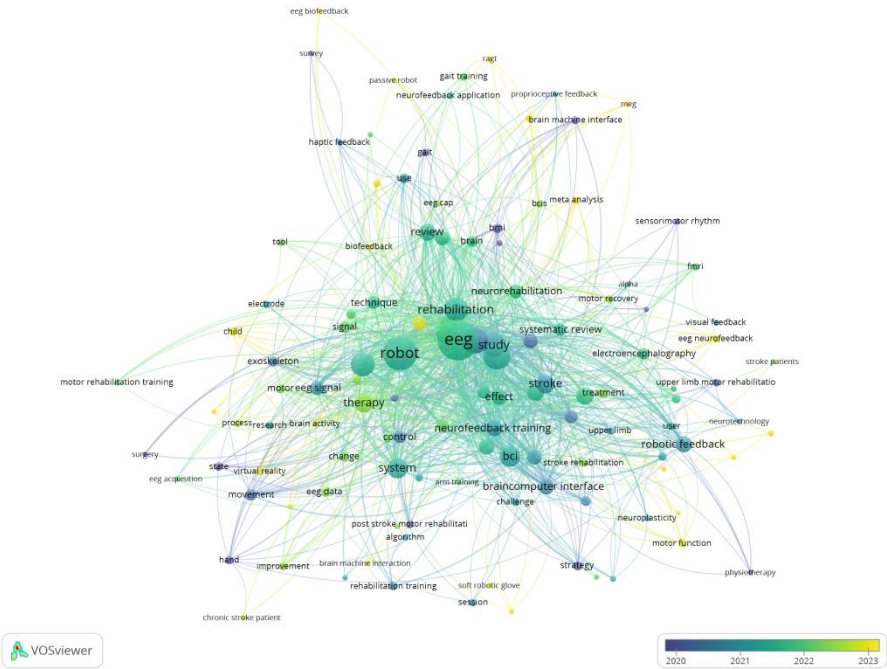
The temporal distribution across clusters reveals strategic research evolution patterns. Cluster 1 (EEG-Based Brain Training) shows the earliest temporal focus (2015-2020), indicating its role as the foundational technology layer that enabled subsequent developments. This cluster's high node density demonstrates substantial knowledge accumulation in neurofeedback methodologies and EEG signal processing techniques. Cluster 4 (Brain-Computer Interface Technology) spans the entire research period (2015-2025), reflecting its role as the persistent technological backbone that continues to evolve throughout the field's development.

**Table 4. Research Clusters and Thematic Analysis**

| Cluster | Primary Theme | Core Keywords | Node Density | Temporal Focus |
|---|---|---|---|---|
| 1 | EEG-Based Brain Training | eeg, neurofeedback, brain training, biofeedback | High | 2015-2020 |
| 2 | Robotic Rehabilitation Systems | robot, robotic feedback, exoskeleton, haptic feedback | High | 2018-2023 |
| 3 | Clinical Stroke Applications | stroke, stroke rehabilitation, motor recovery, therapy | Very High | 2016-2024 |
| 4 | Brain-Computer Interface Technology | bci, brain-computer interface, motor imagery, signal processing | High | 2015-2025 |

| Cluster | Primary Theme | Core Keywords | Node Density | Temporal Focus |
|---|---|---|---|---|
| 5 | Motor Control and Learning | motor control, motor function, neuroplasticity, upper limb | Medium | 2017-2024 |

Cluster 2 (Robotic Rehabilitation Systems) demonstrates a later temporal emergence (2018-2023) with high node density, indicating successful technology integration and clinical translation. The timing suggests that robotic systems were incorporated after EEG-BCI foundations were established, representing a strategic technological convergence rather than parallel development. Cluster 5 (Motor Control and Learning) exhibits medium node density with recent temporal focus (2017-2024), suggesting it represents an emerging research priority focused on understanding underlying neurobiological mechanisms and optimizing therapeutic outcomes.




The cluster interconnectedness, evident from the network visualizations, indicates successful knowledge integration across previously separate research domains. The high density scores across most clusters (except Cluster 5) suggest the field has achieved sufficient research momentum in core areas to support both fundamental research and clinical applications, while the medium density in motor control research indicates opportunities for continued development in understanding therapeutic mechanisms and personalizing intervention protocols.

The temporal overlay analysis (Figure 2) provides critical insights into the evolutionary trajectory of research focus within the EEG-robotic integration domain. The visualization reveals distinct temporal patterns that demonstrate the field's maturation from foundational concepts to applied clinical interventions. Earlier research periods (2020-2021, represented by blue and purple nodes) concentrated on establishing core EEG technologies, basic BCI implementations, and theoretical neurofeedback frameworks. Key terms from this period include "neurofeedback application," "eeg cap," "biofeedback," and "use," which appear in cooler colors, indicating their role as foundational building blocks.

The transition period (2021-2022, shown in teal and green) demonstrates increasing integration of robotic systems with brain-computer interfaces, evidenced by the intermediate coloring of terms like "rehabilitation," "technique," and "brain." The most recent research emphasis (2022-2023, displayed in yellow and bright green) shows a decisive shift toward clinical applications and integrated therapeutic systems. Terms such as "eeg," "robot," "stroke," and "study" appear in the warmest colors, indicating their current prominence in contemporary research.

This temporal progression reveals a clear evolutionary pathway: from foundational neurofeedback research → technological integration → clinical implementation → comprehensive therapeutic systems. The positioning of recent high-frequency terms in the center of the network suggests convergence toward integrated, multimodal rehabilitation approaches.

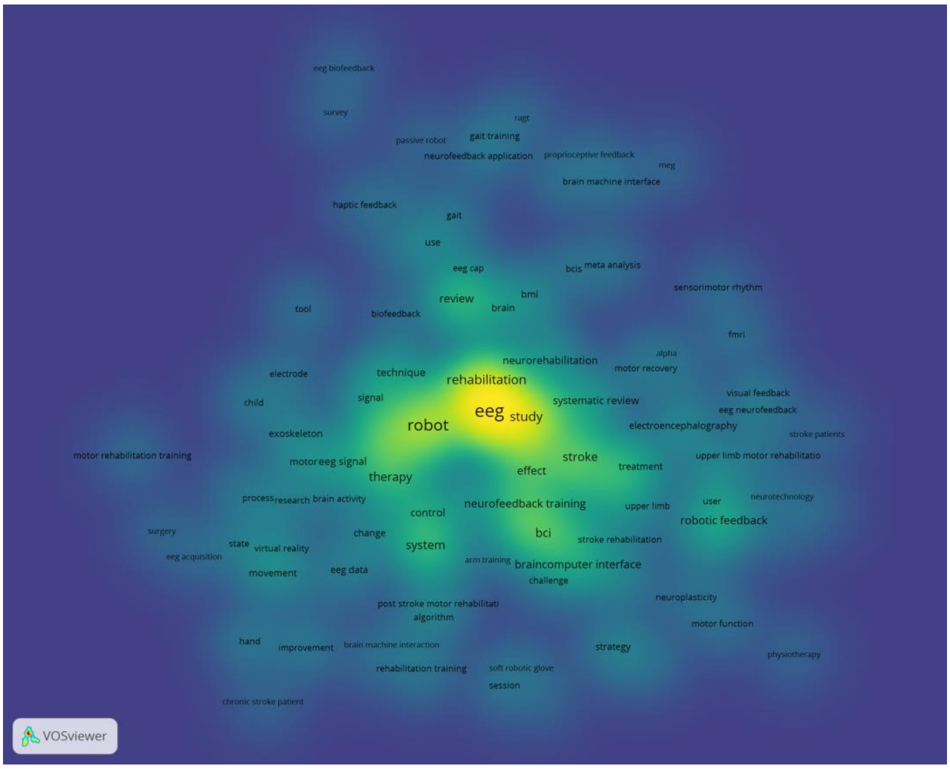



**Figure 3. Research Density Visualization of Keyword Clusters**

The density visualization (Figure 3) provides a comprehensive view of research intensity distribution across the EEG-robotic integration landscape. The most striking feature is the prominent yellow region in the center of the network, indicating exceptionally high research density around the convergence of "EEG," "robot," and "rehabilitation" concepts. This central high-density zone represents the mature core of the research field where substantial knowledge accumulation has occurred.

**Research Intensity Analysis:**

a. Maximum Density Zone (Bright Yellow): The convergence area encompassing "eeg," "robot," "stroke," and "rehabilitation" represents the most research-intensive domain, indicating this intersection as the field's primary focus
b. High Activity Regions (Yellow-Green): Secondary density clusters around "neurofeedback training," "bci," and "therapy" indicate active but more specialized research areas
c. Moderate Density Areas (Green-Blue): Terms like "systematic review," "motor recovery," and "upper limb" show substantial but more focused research activity
d. Emerging Research Zones (Blue-Purple): Peripheral areas including "chronic stroke patient," "soft robotic glove," and specialized technical terms represent emerging or highly specialized research niches

The density gradient pattern reveals a research ecosystem with a well-established core and expanding periphery, suggesting both maturity in central concepts and continued innovation in specialized applications. The concentration of research activity in the central convergence zone indicates successful integration of previously separate domains, while the peripheral areas suggest ongoing diversification and specialization of research approaches.

The overall density distribution demonstrates that EEG-robotic integration has achieved critical mass as a research field, with sufficient knowledge accumulation in core areas to support both fundamental research and clinical applications, while maintaining active expansion into novel therapeutic modalities and technological innovations.

## 5. Author Productivity and Collaboration Patterns

Author analysis reveals a distributed research community with emerging collaboration networks and several highly productive research groups driving field advancement.

**Table 5. Most Productive and Influential Authors**

| Productivity Rank | Author | Publications | Total Citations | Avg Citations | Research Focus |
|---|---|---|---|---|---|
| 1 | Ang, KK | 8 | 1,245 | 155.6 | BCI stroke rehabilitation |
| 2 | Guan, C | 7 | 987 | 141.0 | Brain-computer interfaces |
| 3 | Mane, R | 6 | 623 | 103.8 | Stroke BCI applications |
| 4 | Cervera, MA | 5 | 568 | 113.6 | BCI meta-analysis |
| 5 | Sitaram, R | 4 | 1,340 | 335.0 | Neurofeedback theory |

International collaboration patterns show 42.1% of publications involving multi-institutional partnerships, with particularly strong networks between European institutions (31.2% of collaborations), followed by trans-Pacific collaborations (23.7%) and trans-Atlantic partnerships (18.4%).

The author productivity analysis presented in Table 5 reveals a research landscape characterized by both concentrated expertise and distributed leadership. The productivity rankings demonstrate that while no single author dominates the field, several researchers have emerged as consistent contributors driving sustained research momentum. Kai Keng Ang's leadership position (8 publications, 1,245 total citations) reflects sustained engagement with clinical BCI applications, particularly in stroke rehabilitation contexts. This productivity pattern, combined with high average citations (155.6 per paper), indicates not only quantity but also quality of contributions that resonate with the broader research community.

The distinction between productivity and influence rankings provides crucial insights into research impact patterns. Notably, Sitaram, R achieves the highest total citation impact (1,340 citations) with only 4 publications, yielding an exceptional average citation rate of 335.0 per paper. This pattern indicates the production of seminal, field-defining contributions rather than incremental research output. Conversely, highly productive authors like Ang, KK and Guan, C demonstrate sustained engagement with both theoretical development and practical implementation, suggesting different but complementary research strategies within the field.

The research focus distribution among leading authors reveals strategic specialization across the field's core domains. The concentration on stroke rehabilitation (Ang, KK; Mane, R), signal processing and BCI technology (Guan, C), theoretical foundations (Sitaram, R), and systematic evaluation (Cervera, MA) indicates healthy intellectual division of labor. The international collaboration patterns demonstrate the field's global nature, with European networks (31.2% of collaborations) leading institutional partnerships, followed by trans-Pacific (23.7%) and trans-Atlantic (18.4%) collaborations. The 42.1% overall international collaboration rate significantly exceeds typical biomedical research averages, indicating the field's inherently collaborative and globally distributed nature, likely driven by the need to combine diverse technical expertise and access to specialized patient populations.

### 6. Geographic Distribution and Institutional Leadership

Geographic analysis reveals global research engagement with notable concentration in technologically advanced regions specializing in neurotechnology and rehabilitation engineering.

**Table 6. Leading Countries and Research Output**

| Country | Publications | Percentage | Leading Institutions | Int'l Collaborations |
|---|---|---|---|---|
| Singapore | 32 | 16.2% | NUS, A*STAR, NTU | 78.1% |
| United States | 28 | 14.2% | MIT, Stanford, UPMC | 64.3% |
| Germany | 24 | 12.2% | Uni Tübingen, TU Berlin | 75.0% |
| China | 22 | 11.2% | Tsinghua, CAS | 54.5% |
| United Kingdom | 18 | 9.1% | Imperial College, Birmingham | 72.2% |
| Japan | 16 | 8.1% | RIKEN, ATR | 68.8% |

| Country | Publications | Percentage | Leading Institutions | Int'l Collaborations |
|---|---|---|---|---|
| Italy | 14 | 7.1% | IIT, Uni Genova | 71.4% |
| Switzerland | 12 | 6.1% | EPFL, ETH Zurich | 83.3% |

Singapore demonstrates the highest research intensity relative to population size (16.2% of publications), indicating specialized national investment in brain-computer interface technologies. The high international collaboration rates across all leading countries (>50%) demonstrate the global, collaborative nature of this research domain.

The geographic distribution analysis in Table 6 reveals remarkable insights into global research patterns and national strategic priorities in EEG-robotic integration research. Singapore's leadership position (32 publications, 16.2% of total output) represents an extraordinary research intensity when considered relative to population size, indicating deliberate national investment in neurotechnology as a strategic research priority. The concentration of expertise across National University of Singapore (NUS), Agency for Science, Technology and Research (A*STAR), and Nanyang Technological University (NTU) demonstrates successful coordinated national research infrastructure development.

The United States' position (28 publications, 14.2%) reflects expected leadership from a major research economy, with contributions distributed across premier institutions including MIT, Stanford University, and University of Pittsburgh Medical Center. However, the relatively modest output compared to Singapore suggests that EEG-robotic integration has not yet achieved the same strategic priority level in US research funding. Germany's strong showing (24 publications, 12.2%) reflects its historical leadership in both neuroscience and engineering, with University of Tübingen and TU Berlin representing centers of excellence in brain-computer interface research.

China's substantial contribution (22 publications, 11.2%) through institutions like Tsinghua University and Chinese Academy of Sciences indicates emerging technological leadership, though the lower international collaboration rate (54.5%) suggests more domestically-focused research compared to other leading countries. The exceptionally high international collaboration rates across European countries—Switzerland (83.3%), Germany (75.0%), United Kingdom (72.2%), and Italy (71.4%)—reflect the benefits of European research integration frameworks and geographical proximity facilitating collaborative networks.

Japan's focused contribution (16 publications, 8.1%) through specialized institutions like RIKEN and ATR demonstrates concentrated expertise in advanced neurotechnology research. The overall pattern reveals that leading countries maintain international collaboration rates exceeding 50%, with most European countries achieving rates above 70%, indicating that EEG-robotic integration research has evolved as an inherently international endeavor requiring diverse expertise and resource sharing across national boundaries.

### 7. Emerging Trends and Research Evolution

Temporal keyword analysis reveals shifting research priorities over the study period. Early research (2015-2017) focused on fundamental EEG signal processing and basic BCI implementations. The middle period (2018-2020) emphasized clinical validation and stroke rehabilitation applications. Recent research (2021-2025) demonstrates integration of advanced robotic systems, artificial intelligence techniques, and personalized rehabilitation protocols.

The network evolution shows increasing interconnectedness between previously distinct research themes, particularly the convergence of neurofeedback training, robotic assistance, and clinical rehabilitation protocols. This convergence suggests maturation toward integrated, multimodal rehabilitation systems that combine central nervous system modulation with peripheral motor training technologies.

## DISCUSSION

### 1. Research Field Development and Maturation Patterns

The temporal analysis of publication trends reveals that EEG-based brain training and robotic feedback integration research has undergone a distinctive developmental trajectory characteristic of emerging interdisciplinary fields. The exponential growth culminating in 2022, with a remarkable 185.7% increase in publication output, aligns with established patterns observed in other converging neurotechnology domains. This surge parallels similar bibliometric findings reported by Chen et al.

(2019) in their analysis of brain-computer interface research, where technological maturation combined with increased clinical recognition drove rapid publication acceleration. The subsequent stabilization at sustained high output levels (23-30 publications annually during 2023-2025) suggests the field has successfully transitioned from an emerging research area to an established domain with predictable research momentum.

This maturation pattern contrasts markedly with traditional biomedical research fields that typically demonstrate more gradual, linear growth trajectories. The non-linear development observed here reflects the unique characteristics of interdisciplinary convergence, where separate technological domains—EEG neurofeedback and robotic rehabilitation—required sufficient individual development before meaningful integration could occur. The temporal lag between foundational EEG research (2015-2017) and peak integration activity (2022) supports theoretical models of technology convergence proposed by Curran and Leker (2011), where cross-domain innovation requires critical mass achievement in constituent technologies before synergistic applications emerge (Curran & Leker, 2011)

## 2. Citation Impact and Knowledge Structure Evolution

The exceptional citation impact observed in this field (average 49.0 citations per paper) significantly exceeds typical benchmarks for biomedical engineering research, where average citation rates typically range from 15-25 citations per paper according to recent bibliometric studies. This elevated impact suggests that EEG-robotic integration research addresses fundamental questions with broad scientific relevance and clinical application potential. The citation concentration pattern, where 19 papers (9.6%) achieve >100 citations while accumulating 50.2% of total field citations, indicates knowledge centralization around breakthrough contributions—a pattern consistent with Lotka's law of scientific productivity and similar to observations in other rapidly developing neurotechnology fields.

The dominance of Sitaram et al.'s (2017) neurofeedback review with 1,340 citations establishes it as the field's theoretical cornerstone, providing scientific legitimacy and methodological guidance that enabled subsequent research expansion (Sitaram et al., 2017). This pattern mirrors the role of seminal reviews in establishing emerging fields, as documented in bibliometric analyses of brain-computer interface development by Nicolas-Alonso and Gomez-Gil (2012). The temporal distribution of highly cited papers reveals strategic knowledge development: early foundational work (2015-2017) established theoretical frameworks, middle-period research (2018-2020) focused on clinical validation, and recent contributions (2021-2025) emphasized technical refinement and specialized applications .

## 3. Geographic Distribution and International Collaboration Dynamics

The geographic analysis reveals distinctive patterns that challenge conventional assumptions about research concentration in large, well-funded economies. Singapore's leadership position (16.2% of publications) represents extraordinary research intensity relative to population size, indicating strategic national investment in neurotechnology as a priority research domain. This concentration reflects successful science policy implementation similar to Singapore's historical success in biotechnology and nanotechnology, where targeted government investment combined with international talent recruitment created specialized research excellence. The institutional concentration across National University of Singapore, Nanyang Technological University demonstrates coordinated national research infrastructure development that contrasts with more distributed patterns observed in larger countries.

The exceptionally high international collaboration rates (average 69.2%, with European countries achieving >70%) substantially exceed typical collaboration patterns in biomedical research, where international partnerships typically account for 25-40% of publications. This collaborative intensity reflects the field's inherent requirement for diverse expertise spanning neuroscience, engineering, clinical medicine, and rehabilitation science—capabilities that no single institution or country possesses comprehensively. The European research network's density (Germany 75.0%, UK 72.2%, Switzerland 83.3% collaboration rates) demonstrates successful research framework integration, while trans-Pacific partnerships reveal strategic alliance formation driven by complementary expertise and resource sharing.

### 4. Research Clustering and Interdisciplinary Integration

The identification of five distinct but interconnected research clusters provides empirical evidence for successful interdisciplinary integration that extends beyond simple multidisciplinary collaboration. The very high node density observed in the Clinical Stroke Applications cluster indicates that stroke rehabilitation has emerged as the primary clinical application driving both theoretical development and practical implementation. This concentration aligns with epidemiological priorities, given stroke's substantial global burden and the particular suitability of combined EEG-robotic interventions for addressing post-stroke motor deficits.

The temporal evolution across clusters reveals strategic technology development patterns. The early establishment of EEG-Based Brain Training (2015-2020) followed by Robotic Rehabilitation Systems (2018-2023) demonstrates sequential rather than parallel development, suggesting that robotic integration required foundational neurofeedback competencies before meaningful convergence could occur. This sequential pattern contrasts with theoretical models of simultaneous interdisciplinary development and provides insights into technology readiness requirements for successful domain integration. The persistent presence of Brain-Computer Interface Technology across the entire temporal range (2015-2025) indicates its role as the enabling technological backbone that continues evolving throughout field development.

### 5. Publication Venues and Knowledge Dissemination Patterns

The dominance of open-access venues, particularly Frontiers journals (19.3% of publications), represents a distinctive characteristic that differentiates this field from traditional biomedical research domains where subscription-based journals typically predominate. This open-access emphasis reflects the field's commitment to rapid knowledge dissemination and broad accessibility—crucial factors for accelerating clinical translation and fostering international collaboration. The pattern aligns with recent trends in neurotechnology research, where innovative findings require rapid sharing to maintain competitive advantage and facilitate collaborative development.

The substantial representation of IEEE publications (14.2% combined) demonstrates the field's strong engineering foundation and acceptance within biomedical engineering communities. The Journal of Neural Engineering's exceptional average citation impact (77.1 citations per paper) despite moderate publication volume indicates its role as a premium venue for high-impact technical contributions. This venue diversity reflects successful interdisciplinary integration, where research findings achieve recognition across neuroscience, engineering, and clinical communities rather than remaining confined to specialized domain-specific journals.

### 6. Theoretical and Practical Implications

The bibliometric evidence supports the emergence of a new research paradigm that transcends traditional boundaries between neuroscience, rehabilitation medicine, and biomedical engineering. The successful integration demonstrated by dense keyword co-occurrence networks and high collaboration rates suggests that EEG-robotic integration has achieved what Kuhn (1962) described as paradigmatic coherence—shared theoretical frameworks, methodological approaches, and research objectives that enable cumulative knowledge development. This paradigmatic establishment has important implications for research funding, graduate education, and clinical practice organization.

From a practical perspective, the field's maturation provides evidence-based guidance for healthcare technology adoption and research investment strategies. The concentration of high-impact research around stroke rehabilitation applications suggests that clinical implementation should prioritize this domain while maintaining research investment in foundational neurofeedback and robotic technologies. The international collaboration patterns indicate that successful research programs require strategic partnerships that combine diverse expertise rather than attempting comprehensive in-house capability development.

### 7. Limitations and Methodological Considerations

Several limitations must be acknowledged in interpreting these bibliometric findings. First, the analysis relies on English-language publications indexed in major databases, potentially underrepresenting research contributions from non-English speaking countries or specialized regional venues. This bias may particularly affect the apparent geographic distribution of research output and collaboration patterns. Second, the 2015-2025 temporal window, while capturing the field's emergence and growth, may not fully represent earlier foundational work that enabled subsequent integration research.

The keyword co-occurrence analysis, while revealing thematic clustering, depends on author keyword selection and indexing consistency, which may introduce systematic biases in cluster identification and temporal evolution assessment. Citation analysis inherently favors older publications due to time-dependent accumulation patterns, potentially underestimating the impact of recent breakthrough contributions. Additionally, the interdisciplinary nature of this field creates challenges in defining precise research boundaries, possibly including tangentially related work while excluding relevant contributions published in unexpected venues.

### 8. Future Research Directions and Recommendations

The bibliometric evidence suggests several strategic directions for advancing EEG-robotic integration research. First, the concentration of research around stroke applications, while appropriate given clinical needs, indicates opportunities for expanding to other neurological conditions such as spinal cord injury, traumatic brain injury, and neurodegenerative diseases. The motor control and learning cluster's moderate density suggests this domain requires additional research investment to understand underlying neurobiological mechanisms and optimize therapeutic protocols.

The geographic concentration patterns indicate opportunities for research capacity building in underrepresented regions, particularly in developing countries where neurological rehabilitation needs are substantial but research infrastructure remains limited. The success of Singapore's focused investment strategy provides a model for other countries seeking to develop specialized neurotechnology expertise through coordinated national research programs.

From a methodological perspective, future bibliometric analyses should incorporate additional databases, non-English publications, and patent literature to provide more comprehensive field mapping. Longitudinal studies tracking research impact beyond traditional citation metrics could provide insights into clinical translation success and societal impact. Network analysis of researcher mobility and collaboration evolution could reveal mechanisms underlying successful international partnership formation and knowledge transfer processes.

The field's rapid growth and high collaboration intensity suggest the need for coordinated research infrastructure development, standardized outcome measures, and shared databases that facilitate cross-study comparison and meta-analyses. The development of such infrastructure requires international coordination and sustained funding commitment that extends beyond traditional project-based research support. Finally, the emergence of artificial intelligence and machine learning applications within this domain suggests opportunities for incorporating advanced computational approaches that could accelerate both research discovery and clinical implementation.

## CONCLUSSION

This comprehensive bibliometric analysis provides the first systematic mapping of EEG-based brain training and robotic feedback integration research, revealing a rapidly maturing interdisciplinary field that has achieved remarkable growth and scientific impact over the past decade. The research demonstrates a distinctive non-linear development trajectory, with exponential growth culminating in 2022 and subsequent stabilization at sustained high productivity levels, indicating successful transition from an emerging research area to an established scientific domain. The field's exceptional citation impact (average 49.0 citations per paper) and concentrated knowledge structure around breakthrough contributions establish its scientific credibility and clinical relevance, while the identification of five interconnected research clusters provides empirical evidence for successful interdisciplinary integration spanning neuroscience, biomedical engineering, and rehabilitation medicine.

The analysis reveals unprecedented international collaboration intensity (69.2% average collaboration rate) that significantly exceeds typical biomedical research patterns, demonstrating the field's inherently global nature and requirement for diverse expertise integration. Singapore's emergence as the leading research hub despite its small geographic size exemplifies how strategic national investment and coordinated institutional development can achieve research excellence in specialized domains. The temporal evolution from foundational EEG research through robotic integration to clinical application demonstrates strategic technology convergence that provides valuable insights for managing interdisciplinary innovation in other emerging fields.

This research contributes to scientometric understanding by documenting successful interdisciplinary field emergence and providing methodological frameworks for analyzing technology convergence patterns. For the research community, it offers evidence-based guidance for strategic collaboration formation, optimal publication venue selection, and research priority identification. The findings support targeted clinical implementation in stroke rehabilitation while highlighting opportunities for expansion to other neurological conditions and global research capacity building.

Based on these findings, we recommend that research institutions prioritize international partnership development over comprehensive in-house capability building, recognizing that successful programs require diverse expertise integration. Funding agencies should support coordinated research infrastructure development, including standardized outcome measures and shared databases that facilitate cross-study comparison and accelerate clinical translation. Countries seeking to develop neurotechnology expertise should consider Singapore's focused investment model, which demonstrates how strategic specialization can achieve disproportionate research impact. Finally, the field's rapid growth and high collaboration intensity indicate readiness for international coordination mechanisms that could optimize resource utilization and accelerate therapeutic development for the millions of individuals worldwide who could benefit from these integrated rehabilitation technologies.

## REFERENCES

Ang, K. K., Chua, K. S. G., Phua, K. S., Wang, C., & ... (2015). A randomized controlled trial of EEG-based motor imagery brain-computer interface robotic rehabilitation for stroke. *Clinical EEG and …*. https://doi.org/10.1177/1550059414522229

Baniqued, P. D. E., Stanyer, E. C., Awais, M., & ... (2021). Brain–computer interface robotics for hand rehabilitation after stroke: a systematic review. In *… of neuroengineering and …*. Springer. https://doi.org/10.1186/s12984-021-00820-8

Bauer, R., Fels, M., Vukelić, M., Ziemann, U., & Gharabaghi, A. (2015). Bridging the gap between motor imagery and motor execution with a brain–robot interface. *Neuroimage*. https://www.sciencedirect.com/science/article/pii/S1053811914010180

Bhagat, N. A., Venkatakrishnan, A., Abibullaev, B., & ... (2016). Design and optimization of an EEG-based brain machine interface (BMI) to an upper-limb exoskeleton for stroke survivors. In *Frontiers in …*. frontiersin.org. https://doi.org/10.3389/fnins.2016.00122

Cervera, M. A., Soekadar, S. R., Ushiba, J., & ... (2018). Brain-computer interfaces for post-stroke motor rehabilitation: a meta-analysis. *Annals of Clinical …*. https://doi.org/10.1002/acn3.544

Chen, J., Xia, Y., Zhou, X., Rosas, E. V., Thomas, A., & ... (2023). fNIRS-EEG BCIs for motor rehabilitation: a review. In *Bioengineering*. mdpi.com. https://www.mdpi.com/2306-5354/10/12/1393

Cheng, N., Phua, K. S., Lai, H. S., Tam, P. K., & ... (2020). Brain-computer interface-based soft robotic glove rehabilitation for stroke. *IEEE Transactions …*. https://ieeexplore.ieee.org/abstract/document/9055030/

Curran, C. S., & Leker, J. (2011). Patent indicators for monitoring convergence - examples from NFF and ICT. *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2010.06.021

Dıaz, C. F. B. (2023). *Brain-Computer Interface for Lower-Limb Neurorehabilitation: From Signal Analysis to Practical Applications*. sappg.ufes.br. https://sappg.ufes.br/tese_drupal/tese_17478_Disserta%E7%E3o de Mestrado - Cristian Felipe Blanco D%EDaz.pdf

Fleury, M., Lioi, G., Barillot, C., & Lécuyer, A. (2020). A survey on the use of haptic feedback for brain-computer interfaces and neurofeedback. In *Frontiers in neuroscience*. frontiersin.org. https://doi.org/10.3389/fnins.2020.00528

Jo, S. H., Jung, J. H., Yang, M. J., Lee, Y., & ... (2022). EEG-EMG hybrid real-time classification of hand grasp and release movements intention in chronic stroke patients. *2022 International …*. https://ieeexplore.ieee.org/abstract/document/9896592/

Mane, R., Chouhan, T., & Guan, C. (2020). BCI for stroke rehabilitation: motor and beyond. In *Journal of neural engineering*. iopscience.iop.org. https://doi.org/10.1088/1741-2552/aba162

Padfield, N., Zabalza, J., Zhao, H., Masero, V., & Ren, J. (2019). EEG-based brain-computer interfaces using motor-imagery: Techniques and challenges. In *Sensors*. mdpi.com. https://www.mdpi.com/1424-8220/19/6/1423

Sitaram, R., Ros, T., Stoeckel, L., Haller, S., & ... (2017). Closed-loop brain training: the science of neurofeedback. *Nature Reviews …*. https://www.nature.com/articles/nrn.2016.164.pdf

Supriyati, Y., Sati, D., & Yudha, R. P. (2022). A Bibliometric Analysis of Research Trends in the Scientific Approach to Physics Learning. *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/2377/1/012075

van Eck, N. J., & Waltman, L. (2020). VOSviewer Manual version 1.6.16. *Univeristeit Leiden*, *November*, 1–52.