Precision Medicine in Physical and Rehabilitation Medicine (PRM)

João Pinheiro(1) | João Branco(2) | Catarina Aguiar-Branco(3) | Jorge Laíns(4) | Ana Zão(5) | Renato Nunes(6) | Inês Campos(7)

Introduction

Precision Rehabilitation (PR) represents a transformative approach in Physical and Rehabilitation Medicine (PRM), emphasizing the integration of personalized care with the best clinical evidence to enhance patient outcomes. This article discusses the pivotal role of emerging technologies such as Big Data (BD) and Artificial Intelligence (AI) in revolutionizing rehabilitation practices. By leveraging vast datasets and advanced algorithms, healthcare professionals can develop tailored therapeutic plans, optimize interventions, and monitor patient progress in real-time. Additionally, the integration of genetic insights and biomarkers into rehabilitation programs allows for a more nuanced understanding of individual patient responses, facilitating personalized treatment strategies. Neuroimaging techniques further enhance the predictive capabilities regarding functional recovery, while psychosocial and environmental factors are acknowledged as critical components in formulating comprehensive rehabilitation plans. Despite the promising advancements, challenges such as ethical considerations, data privacy, and the need for standardized protocols remain. This article underscores the importance of a biopsychosocial approach in rehabilitation, advocating for a patient-centered model that adapts to the unique characteristics and needs of each individual. As PR continues to evolve, it holds the potential to redefine rehabilitation care, making personalized medicine a practical reality in clinical settings.

Keywords: *Precision Rehabilitation, Physical and Rehabilitation Medicine, Big Data, Artificial Intelligence, Biomarkers, Genetics, Neuroimaging, Biopsychosocial Approach.*

Background

The provision of medical care and research are fundamental pillars of physical and rehabilitation medicine (PRM), traditionally centred around functionality and quality of life. Precision Rehabilitation (PR) is an increasingly relevant concept that combines the best clinical evidence with the personalization of care and therapeutic programs. This article explores key emerging topics, including BD and AI, the influence of psychosocial and environmental factors, biomarkers, genomics, neuroimaging, and digital applications as operative premises of PR. It provides a concise overview, summarizing the perspectives shared by participants in the Research Department at the National Congress of the Portuguese Society of Physical and Rehabilitation Medicine (SPMFR) in February 2025.

Big data and artificial intelligence: clinics and research

The convergence of BD and AI is transforming PRM, creating new opportunities to personalize treatments and optimize outcomes.[1, 2] BD refers to the vast volume of available information, while AI encompasses computational

(1) PRM. Faculty of Medicine. Coimbra University. Portugal.https://orcid.org/0000-0002-6800-699X. (2) PRM. Faculty of Medicine. Coimbra University. Portugal. ORCID 0000-0002-0271-8329. (3) PRM, Head of PRM College Medical Board, Porto. Portugal. ORCID 0000-0001-5666-842X. (4) PRM, Head of PRM Department, ULS Coimbra. Portugal. ORCID 0000-0002-8737-7569. (5) PRM, Porto. Portugal. ORCID 0000-0001-6937-1553. (6) PRM, President of PRM Society. Portugal. (7) PRM, Editor of PRM Journal. Portugal.

Autor Correspondente/Corresponding Author: *João Pinheiro. email: reabmedica@hotmail.com. ORCID:0000-0001-8666-1819. Faculty of Medicine. Coimbra University. Portugal.*

Recebido/Received: *11/2025.* ***Aceite/Accepted:*** *12/2025.* ***Publicado online/Published online:*** *12/2025.* ***Publicado / Published:*** *12/2025.*

systems that simulate decision-making. Together, these technologies enable predictive analytics, the customization of therapeutic plans, and real-time monitoring, fostering a more effective approach to rehabilitation medicine.[3] In clinical practice, AI plays a crucial role in analysing patient data, facilitating outcome prediction, and optimizing interventions. Through machine learning (ML) and deep learning (DL) algorithms, personalized rehabilitation plans can be developed to meet individual patient needs. Wearable devices and Internet of Things (IoT) sensors further enhance real-time data collection, allowing continuous monitoring of patient progress and enabling timely adjustments to interventions.[4, 5, 6]

Translational research greatly benefits from these innovations. The integration of clinical, epidemiological, and genomic data into multimodal AI models supports the development of personalized rehabilitation programs, advancing the field of PR.[7] Additionally, population studies leveraging BD analytics help validate rehabilitation medicine strategies and establish evidence-based guidelines.

However, implementing these technologies presents challenges. Ethical concerns, such as patient data privacy and algorithmic bias, must be carefully addressed. AI should be viewed as a complementary tool that supports, rather than replaces, the human connection between healthcare professionals and patients. Empathy and effective communication remain essential to ensuring that technology enhances rather than detracts from the rehabilitation process.

In conclusion, the integration of BD and AI in PRM not only enhances treatment efficacy and functional outcomes but also paves the way for new research and clinical advancements, fostering a more patient-centred and evidence-based approach. Furthermore, these advancements will drive the development of PRM, a tailored approach that adapts treatments to individual characteristics, needs, and responses.

The integration of genetics in the innovation of rehabilitation programs

The achievement of genetic analyses after the Human Project Genome in 2003, was the beginning of a revolution in multiple fields of medicine and changed the contemporary and future of clinical practice.[8, 9] The integration of genetics in personalized medicine is crucial to complete de relationship between evidence-based medicine, precision medicine and patient-centered care.[9]

The fundamentals of genetic in rehabilitation include the response to treatment, predisposition to diseases, physical and cognitive capacity, psychological aspects, and ageing. Specifically for recovery from neurological diseases, as stroke and spinal cord injury, researchers are interested in the importance of cognitive reserve and neuroplasticity.[10, 11, 12]

The efficiency of neuroplasticity can be influenced by many factors, including genetic polymorphisms.[11] Some of the genes related to recovery of nervous system includes: brain-derived neurotrophic factor (BDNF), apolipoprotein E (ApoE), neuregulin-1 (NRG1), matrix metalloprotease-9 (MMP-9), G-protein coupled beta-2-adrenergic receptor (ADRB2), as well as genes related to the dopaminergic system (DRD1, DRD2, COMT, SLC6A3) and serotonergic system (SLC6A4, HTR2A, MTHFR) or genes associated with specific functions or processes related to psychomotor and sensorimotor development (PPARD, IGF1, FOXP1).[13]

One of the most studied is the BDNF gene, which encodes a protein that is a nerve growth factor secreted by neurons. Its activity is related to the functioning of cholinergic and dopaminergic pathways implicated in brain development and modulation of neuronal structure, function and transmission. The Val66Met BDNF polymorphism, present in 20-30% of people, is related to the reduction of BDNF protein activity and the consequent reduction of the ability of the nervous system to make plastic changes. Its presence in stroke patients is related to a worse outcome.[13, 14] Other important protein is apolipoprotein E, encoded by the ApoE gene, produced in the brain mainly by astrocytes and related to lipid metabolism. ApoE polymorphisms are strongly associated with the risk of atherosclerosis, acute cardiovascular syndromes and the development of Alzheimer's disease, but more important for plasticity is the relationship of the ApoE4 allele with various neurophysiological aspects of brain functioning. Its presence in traumatic brain injury is associated with a poor functional outcome.[13, 14]

The current major challenge of precision medicine applied to rehabilitation is the possibility of predicting recovery and intervening in the chain of consequences of disease, using strategies that introduce the modification of the genetic profile of each patient through the environment, experiences and therapeutic interventions, and thus personalize health care.

Biomarkers in the personalization of rehabilitation

Rehabilitation medicine has been evolving toward a more personalized paradigm, with biomarkers playing a central role in optimizing treatments. Precision rehabilitation differs from the traditional evidence-based approach by leveraging individual data to predict functional prognosis and tailor interventions more effectively. Biomarkers are biological indicators that reflect physiological processes and treatment responses. Their application enables patient stratification, recovery prediction, and clinical progress monitoring. These biomarkers include molecular markers, such as genetic and epigenetic elements and proteins associated with treatment response.[15, 16] Physiological biomarkers assess functions like heart rate variability and muscle strength, while neuroimaging biomarkers analyze functional brain activity and neural connectivity, contributing to post-injury functional predictions.[17]

Integrating biomarkers into clinical practice allows for more efficient, patient-specific treatment. Studies have shown that monitoring biomarkers such as the S100β protein and functional neuroimaging facilitates the development of predictive models for upper limb functionality after a stroke. By combining clinical, laboratory, and imaging variables, these models can accurately estimate the likelihood of recovery, thereby enabling personalized therapeutic approaches.[16,17] The incorporation of biomarkers into rehabilitation programs offers several advantages, including greater precision in treatment personalization, early identification of complications, continuous monitoring with the possibility of dynamic adjustments, increased patient adherence through objective feedback, early prognosis prediction, and more efficient allocation of resources.

Despite these advancements, integrating biomarkers into rehabilitation still presents challenges, such as the need for standardized protocols, the high cost of certain technologies, and the effective integration of digital health systems. However, advances in artificial intelligence and big data analytics will enhance the accuracy of functional recovery predictions and expand treatment personalization.[18] The integration of neuroimaging, molecular biomarkers, and digital applications in rehabilitation represents the future of physical and rehabilitation medicine, fostering a more effective and patient-centered approach. As these technologies continue to evolve, we can anticipate a revolution in rehabilitation care where personalized medicine is no longer just a concept but a reality applied in clinical practice.

Prediction of functional outcomes with neuroimaging

Neuroimaging techniques such as functional magnetic resonance imaging (fMRI), diffusion tensor imaging (DTI), transcranial magnetic stimulation, are powerful tools for assessing brain plasticity and recovery processes, enabling the identification of functional recovery indicators and the dynamic personalization of therapeutic interventions over time.[19, 20] These non-invasive biomarkers have been shown to predict a range of functional outcomes in chronic pain and neurological disorders, such as motor and neurocognitive recovery after stroke or traumatic brain injury[19-22]. For instance, studies using volumetric MRI in mild traumatic brain injury have demonstrated that the reduction in thalamic volume is significantly associated with higher levels of fatigue.[21] In stroke patients, fMRI indicators such as the intensity of baseline motor activation and the strength of functional connectivity, alongside DTI metrics (particularly microstructural changes in the corticospinal tract, including measures like fractional anisotropy) are among the most robust predictors of motor outcomes.[19, 20, 23] Regarding the prediction of cognitive function, the presence of cerebral atrophy, microbleeds, and the increasing severity of white matter hyperintensities are significantly associated with poorer cognitive outcomes. Despite the growing interest in neuroimaging biomarkers for clinical application, several limitations persist that hinder their effective implementation. Key challenges include the lack of standardization in development and validation processes, small sample sizes, limited evidence across certain clinical contexts, and high inter- and intra-individual variability. Moreover, clinical trials lack long-term follow-up, resulting in weak correlations between biomarkers and clinical or functional outcome measures. Additionally, high costs, the need for specialized training and equipment, and barriers to access and implementation present further obstacles. Nonetheless, the integration of neuroimaging with artificial intelligence techniques, such as machine learning algorithms, presents significant opportunities to enhance data analysis, optimize outcomes, and improve clinical utility.[19, 20, 24] It is important to highlight that neuroimaging data and biomarkers should be integrated into multivariate predictive models that can capture the individuality of each patient through a biopsychosocial approach. Rehabilomics emerges as an important framework that allows omics research built upon clinical practice, especially in outcome prediction and individualized rehabilitation.[25] In conclusion, neuroimaging plays a central role in precision rehabilitation by enabling the prediction of functional outcomes and supporting the design of more effective and personalized rehabilitation strategies.

The Influence of Psychosocial and Environmental Factors on the Rehabilitation

The World Health Organization (WHO) defined health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity".[25]

Engels (1977) was the first to speak about the "biopsychosocial model of health", seeing it as a holistic model, considering the person's psychological and social state, and health as a result of a complex and interactive relation between the human being and the environment, encompassing time. [26]

The Biopsychosocial health care model considers health to be the total biological, social, and emotional well-being.

The biopsychosocial model and ICF consider functionality not as a consequence of a disease, but as a fundamental component of health. Functionality and disability express the dynamic interaction between health states (diseases, disorders, injuries, etc.) and contextual factors (environmental and personal factors). Disability is not an attribute of the person, but rather a complex set of conditions that result from their interaction with the environment.[27, 28] The WHO defines rehabilitation as a series of interventions to optimize functioning and reduce disability in individuals with health conditions as they interact with their environment.[29] The brain can adapt to environmental pressure, experiences, and challenges, including brain damage. Neuroplasticity is the property of the Central Nervous System (CNS) to reorganize after a lesion and is the basis of neurological recovery. Rehabilitation is a learning process, where old skills have to be re-acquired and new skills have to be learned on the basis of practice.

To be successful, Rehabilitation must be repetitive, task-specific, and intensive, but the results are better if the patient is actively involved, vigilant, and the tasks are based on the patient's interests.[30, 31]

Rehabilitation must be for each specific individual (the individual rehabilitation project), with a Health Condition and his/her contextual factors (ICF, taking into consideration his/her societal roles and expectations, regardless of the psychological and physical impairments (32). Ask not what disease the person has, but rather what person the disease has (William Osler, 1849–1919).[33]

Personalizing Care with Mobile Applications/Apps

Health Care's dynamic evolution has led to a New Health Paradigm—Digital and Mobile Health—which represents a revolutionary transformation (including in PRM.)[34] This shift promotes decentralized, proximity-based and personalized digital care, with hospital-centered interventions moving to alternative settings. Digital technologies—Telemedicine, Telerehabilitation and Individual Rehabilitation Programs (IRP), designed for continuous adaptation, health literacy improvement, patient accountability, multitasking and task shifting—enable the development and implementation of Personalized Mobile Health Applications (PMHA). Health 5.0, Artificial Intelligence, Big Data, Machine Learning and Business Intelligence/Analytics are also associated with PMHA, making information systems and technological investment an imperative reality.[35]

PMHA support essential PRM and Rehabilitation objectives, procedures and interventions: clinical/functional assessment, health promotion, disease prevention, therapeutics, retraining, palliation, home-based care and monitoring (clinical and functional parameters, medication, adherence). They are integrated in IRP across multiple pathologies and conditions—cardiac, respiratory, ortho-traumatological, osteo-metabolic, neurological, pelvic floor, oncological—both pre- and postoperatively, including exercise reconditioning (with metabolic data), sleep, medication management and fall prevention.

Rehabilitation Care personalization through PMHA requires multiprofessional, inter- and multidisciplinary Rehabilitation Teams across hospital and community settings, using hybrid or tele-health tools (real-time or remote) throughout clinical follow-up and Integrated Care Pathways. This process must include patient evaluation, prescription, supervision and team coordination by a physiatrist.[36]

PMHA in Rehabilitation combine medical rehabilitation science with Behavioural Science to strengthen patient engagement in product and service design.[35]

These tailor-made solutions function as adjunct tools for diverse health needs, supporting greater adherence, integration with medical devices, efficient clinical data management and analysis, performance progression, education of patients/families/caregivers, development of competencies and self-responsibility, compliance with regulatory and safety standards, health management planning and a more efficient patient-centered connection between Health Systems, Community and Home-Based Care. A wide variety of often low-cost PMHA is available.

With the growing use of Rehabilitation PMHA, it is critical to assess patient-reported health status, outcomes, experiences, facilitators, barriers, advantages, disadvantages and opportunities for improvement. Maintaining a clear vision is essential to ensure meaningful value in this new paradigm.

Discussion and conclusion

This paper integrates several important innovations in the field of Physical and Rehabilitation Medicine, highlighting the incorporation of emerging technologies — such as Big

Data, Artificial Intelligence (AI), and Machine Learning — to personalize treatments, predict outcomes, and monitor patients in real-time, making rehabilitation more precise and tailored to individual needs. This paper also addresses the incorporation of genetics and biomarkers — by identifying genes and proteins that influence neuroplasticity and recovery, it allows for personalized therapeutic interventions based on the patient's genetic profile, which is still underexplored in daily clinical practice. It also focuses on neuroimaging as a predictive tool — applying advanced techniques like fMRI and DTI and transcranial magnetic stimulation, to predict functional recovery and dynamically adapt treatments, represents a progress in the objective assessment of the rehabilitation process. Regarding the focus on the biopsychosocial model and environmental factors, the article emphasizes the importance of considering not only the biological aspect but also the psychological, social, and environmental context of the patient, promoting a holistic and more effective approach to care. Finally, the integration of digital technologies and mobile applications in clinical management is highlighted, facilitating patient autonomy, remote monitoring, and multidisciplinary coordination, thus promoting continuous and personalized care. In summary, "precision rehabilitation" gathers and articulates these modern technologies and concepts, pointing towards a future for a rehabilitation that is patient-centered, highly personalized, data-driven, and focused on a multidimensional approach to care.

Conflitos de Interesse: Os autores declaram não possuir conflitos de interesse. Suporte Financeiro: O presente trabalho não foi suportado por nenhum subsidio ou bolsa. Proveniência e Revisão por Pares: Não comissionado; revisão externa por pares.

Conflicts of Interest:The authors have no conflicts of interest to declare. Financial Support: This work has not received any contribution grant or scholarship. Provenance and Peer Review: Not commissioned; externally peer-reviewed

Referências / *References*

1. Inteligência Artificial na Reabilitação – Aula 1. YouTube. Disponível em: https://youtu.be/LeD1b_zhCy8
2. Inteligência Artificial na Reabilitação – Aula 2. YouTube. Disponível em: https://youtu.be/qYNweeDHiyU
3. Lanotte F, O'Brien M, Jayaraman A. AI in Rehabilitation Medicine: Opportunities and Challenges. Ann Rehabil Med. 2023 Dec;47(6):444-58. doi:10.5535/arm.23131
4. Hwang U, Kim J, Kim K, Chung K. Machine learning models for predicting return to sports after anterior cruciate ligament reconstruction: Physical performance in early re-habilitation. Digit Health. 2024;10:205520762 41299065. doi:10.1177/20552076241299065
5. Swarnakar R, Yadav S. Artificial intelligence and machine learning in motor recovery: A rehabilitation medicine perspective. World J Clin Cases. 2023 Oct 16;11(29):7258-60. doi:10.12998/wjcc.v11.i29.7258
6. Alzubaidi L, Bai J, Al-Sabaawi A, et al. A survey on deep learning tools dealing with data scarcity: definitions, challenges, solutions, tips, and applications. J Big Data. 2023;10:46. doi:10.1186/s40537-023-00727-2
7. Cotton R, Seamon B, Segal R, Davis R, Sahu A, McLeod M, Celnik P, Ramey S, Abil-ityLab S. A Causal Framework for Precision Rehabilitation. arXiv. 2024. doi:10.48550/arXiv.2411.03919
8. Forough T, Mahsa A, Mandana H, Pirooz E. Precision Medicine in Clinical Practice. 2022. doi:10.1007/978-981-19-5082-7
9. Kumar D. The genomic and precision medicine in clinical practice – Current perspec-tives and future directions. The Physician. 2020;6(3). doi:10.38192/1.6.3.1
10. Pastorino R, Loreti C, Giovannini S, Ricciardi W, Padua L, Boccia S. Challenges of Prevention for a Sustainable Personalized Medicine. J Pers Med. 2021;11:311.
11. Majumdar S, Hraltej J, Robertson N. Advances in the genetics of stroke risk and recov-ery. J Neurol. 2023;270:590–1.
12. Park A, Solinsky R. Leveraging genetics to optimize rehabilitation outcomes after spi-nal cord injury: contemporary challenges and future opportunities. Front Genet. 2024;15:1350422.
13. Bagrowski B. Perspectives for the application of neurogenetic research in programming neurorehabilitation. Mol Aspects Med. 2023;91:101149.
14. Harnish S, Diedrichs V, Bartlett C. Early considerations of genetics in aphasia rehabili-tation: a narrative review. Aphasiology. 2023;37(6):835-53.
15. Branco JP, Costa JS, Sargento-Freitas J, Oliveira S, Mendes B, Laíns J, Pinheiro J. Neu-roimaging and Blood Biomarkers in Functional Prognosis after Stroke. Acta Med Port. 2016 Nov;29(11):749-54.
16. Branco JP, Oliveira S, Sargento-Freitas J, Costa JS, Cordeiro G, Cunha L, Gonçalves AF, Pinheiro J. S100β protein as a predictor of post-stroke functional outcome: a pros-pective study. J Stroke Cerebrovasc Dis. 2018 Jul;27(7):1890-6.
17. Branco JP, Oliveira S, Sargento-Freitas J, Galego O, Cordeiro G, Cunha L, Gonçalves AF, Pinheiro J. Neuroimaging, serum biomarkers, and patient characteristics as predic-tors of upper limb functioning 12 weeks after acute stroke: an observational, prospec-tive study. Top Stroke Rehabil. 2018;1-7.
18. Włodarczyk L, Cichon N, Saluk-Bijak J, Bijak M, Majos A, Miller E. Neuroimaging Techniques as Potential Tools for Assessment of Angiogenesis and Neuroplasticity after Stroke and Their Rehabilitation Implications. J Clin Med. 2022 Apr 28;11(9):2473. doi:10.3390/jcm11092473
19. Ball EL, Shah M, Ross E, Sutherland R, Squires C, Mead GE, Wardlaw JM, Quinn TJ, Religa D, Lundström E, Cheyne J, Shenkin SD. Predictors of post-stroke cognitive im-pairment using acute structural MRI: a systematic review and meta-analysis. Int J Stro-ke. 2023 Jun;18(5):543-54.
20. Bigler ED. Volumetric MRI Findings in Mild Traumatic Brain Injury and Neuropsycho-logical Outcome. Neuropsychol Rev. 2023 Mar;33(1):5-41.
21. Mackey S, Greely HT, Martucci KT. Neuroimaging-based pain biomarkers: definitions, clinical and research applications, and frameworks for personalized pain medicine. Pain Rep. 2019;4(4):e762.
22. Yu P, Dong R, Wang X, Tang Y, Liu Y, Wang C, Zhao L. Neuroimaging of motor recov-ery after ischemic stroke: functional reorganization of motor network. Neuroimage Clin. 2024;43:103636.

23. Jo H, Kim C, Gwon D, Lee J, Lee J, Park KM, Park S. Combining clinical and imaging data for predicting functional outcomes after acute ischemic stroke: an automated ma-chine learning approach. Sci Rep. 2023;13:16926.
24. Cao W, Zhang X, Qiu H. Rehabilomics: A state-of-the-art review of framework, appli-cation, and future considerations. Front Neurol. 2023;14:1103349.
25. World Health Organization (WHO). Constitution of the World Health Organization. Disponível em: https://www.who.int/about/who-we-are/constitution
26. Engel GL. The Need for a New Medical Model: A Challenge for Biomedicine. Science. 1977;196:129-36.
27. Perenboom RJ, Chorus AM. Measuring participation according to the International Classification of Functioning, Disability and Health (ICF). Disabil Rehabil. 2003 Jun;25(11–12):577-87.
28. World Health Organization. International Classification of Functioning, Disability and Health (ICF). Geneva: WHO; 2001.
29. World Health Organization. Rehabilitation – factsheet. Disponível em: https://www.who.int/news-room/fact-sheets/detail/rehabilitation
30. Bach-y-Rita P. Late postacute neurologic rehabilitation: neuroscience, engineering, and clinical programs. Arch Phys Med Rehabil. 2003;84(8):1100-8.
31. Wade DT. Holistic Health Care: What is it, and how can we achieve it? 2009. Disponí-vel em: http://www.noc.nhs.uk/oce/research-education/documents/HolisticHealthCare09-11-15.pdf
32. UEMS-PRM Section and Board. The Individual Rehabilitation Project is the core of person-centered rehabilitation. Eur J Phys Rehabil Med. 2022.
33. Wade DT. A general theory of rehabilitation: Rehabilitation catalyses and assists adapta-tion to illness. Clin Rehabil. 2024 Apr;38(4):429-42.
34. World Health Organization. WHO Global Strategy on Digital Health 2020–2025.
35. Topol E. The Creative Destruction of Medicine: How the Digital Revolution Will Create Better Health Care. Basic Books; 2012.
36. European Society of Physical and Rehabilitation Medicine. Guidelines on Digital Reha-bilitation and Telerehabilitation. 2024. Disponível em: https://www.esprm.org/guidelines/digital-telerehabilitation/