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ROBOTIC AND EXOSKELETON-ASSISTED GAIT TRAINING IN POST-STROKE REHABILITATION: A SYSTEMATIC REVIEW

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ABSTRACT

Robotic and exoskeletal gait assistance systems are becoming an increasingly important part of post-stroke rehabilitation, offering the possibility of more intensive, repetitive and individualised locomotion training than traditional methods.
The review analysed 15 studies published between 2015 and 2024. The review included studies in which an exoskeleton or gait assistance robot was the main therapeutic intervention, and the analysis was narrative and systematic.
The results of the studies indicate that interventions using exoskeletons can lead to improvements in walking speed and quality, stride length, balance and lower limb motor function. The benefits were particularly evident in the subacute phase after stroke, and some of the studies also reported changes indicative of beneficial neurophysiological reorganisation. The therapy proved to be safe and well tolerated, and patients showed high acceptance and motivation to participate in the sessions. The limitations of the analysed studies included small sample sizes, varied treatment protocols and a lack of long-term follow-up.
The evidence suggests that robotic gait training is a valuable addition to conventional rehabilitation, but larger, well-designed studies are needed to more accurately assess the effectiveness and optimal use of these technologies. Designed studies are needed to more accurately assess the effectiveness and optimal use of these technologies.
Materials and Methods: A literature review was conducted using the PubMed database, covering publications from 2015 to 2024, a period of particularly dynamic development of robotic and exoskeletal methods of gait rehabilitation after stroke. Keywords were used in the search. Based on an analysis of titles and abstracts, studies on the use of exoskeletons in gait training in stroke patients were selected. Fifteen studies meeting the substantive criteria, including randomised controlled trials, pilot projects and feasibility studies, were included in the final review [10-24]. Data on population characteristics, the therapeutic protocol used, assessment tools, clinical outcomes, and information on the tolerance and safety of the therapy were obtained from each study. The review methodology was narrative and systematic; the aim was not to create a meta-analysis, but to provide a synthetic overview of the available results, compare the therapeutic approaches used, and identify research gaps. This allowed us to capture both the strengths of the technology, such as safety and high patient acceptance, and its limitations, including small study samples, heterogeneity of protocols, and lack of long-term data.

KEYWORDS

Post-Stroke Rehabilitation, Robotic Gait Training, Exoskeletons, Neurorehabilitation, Gait Disorders, Robot-Assisted Therapy

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Introduction: Stroke remains one of the most common causes of long-term disability, and gait disorders are among its most limiting consequences. Difficulties in mobility affect not only independence, but also quality of life, risk of falls and the ability to return to social activities. Traditional physiotherapy, although it is the foundation of post-stroke care, does not always allow for the intensity and repeatability required for effective gait re-education. In recent years, robotic and exoskeletal assistive systems have become increasingly important, offering precise movement guidance, a greater number of repetitions and the possibility of early implementation of locomotion training. The dynamic development of these technologies has led to an increase in the number of clinical studies evaluating their effectiveness, safety and usefulness in everyday practice. At the same time, the literature is highly diverse in terms of device types, protocols, patient populations and methods of evaluating results, which makes it difficult to draw clear conclusions. In this situation, a systematic review of the research becomes helpful in order to organise the available evidence and assess the extent to which robotic gait re-education provides real support for conventional therapy. The aim of this study is to provide a synthetic analysis of contemporary research on robotic and exoskeletal gait training in stroke survivors.

The review focuses primarily on fifteen selected clinical studies [10-24] that allow for the assessment of the functional effects, safety, tolerance and practical aspects of using these technologies. Particular attention was paid to whether robotic systems can actually complement classic physiotherapy, which patients benefit most from them and what conditions must be met for their implementation to be effective and clinically justified.

The study also identifies key gaps in knowledge and directions for future research necessary for a more complete assessment of the therapeutic value of robotic gait re-education methods.

Characteristics of robotic exoskeleton gait assistance systems

Robotic exoskeleton gait assistance systems are a rapidly developing group of rehabilitation technologies that enable intensive, repetitive gait training in stroke patients.

Classification of devices:

Active exoskeletons use drives (e.g. electric motors) to generate movement in the joints of the lower limbs, enabling them to assist or initiate walking.

Examples include EksoAthlet, Ekso™, REX and UIPER.[1-2]

Passive exoskeletons do not have their own drives, and their operation is based on mechanical elements that support movement, e.g. Soft SRE.[3]

Stationary robots (e.g. Lokomat Free-D) integrate the exoskeleton with a treadmill and a weight bearing system, enabling gait training under controlled conditions.[4-5]

Mobile robots and wearable exoskeletons (e.g. RAGT, VR-RAGT) allow for gait training on flat and uneven surfaces, often with the possibility of use outside a medical facility.[1-2]

Mechanisms of operation and main components:

The key elements are drive systems (motors, actuators), motion sensors (force, position, acceleration sensors), and user interfaces.[3] Drive control is based on trajectory tracking algorithms, gait phase detection and adaptation to the patient's current capabilities. Modern systems increasingly use assisted, adaptive and automatic strategies.[3][6] Biofeedback (e.g. visual, auditory) and assisted control (e.g. "assist-as-needed") enable active patient involvement and optimisation of neuroplastic effects.[3][6] Integration with gait analysis (motion capture, electromyography) allows for monitoring of movement biomechanics and adjustment of training parameters to individual needs.[6-7]

Comparison of operating modes:

Assisted mode – the device guides limb movement along a programmed trajectory, minimising patient effort.

Assisted mode – the exoskeleton responds to the patient's initiation of movement, providing support only when needed ("assist-as-needed").[3][6]

Adaptive mode – the system dynamically adjusts the level of support based on the patient's current fitness and activity level.[6]

Automatic mode – full automation of movement, often used in patients with very severe functional deficits.

According to the guidelines of the American Heart Association/American Stroke Association, Robotic gait assistance systems, including exoskeletons, may be particularly

beneficial in patients with more severe motor deficits, especially in the early stages after a stroke, and the choice of operating mode and type of device should be tailored to the individual needs and capabilities of the patient. [4]

Study population and clinical context

Characteristics of post-stroke patients included in the analysed studies:

Time since stroke: The studies mainly included patients in the subacute phase (<3–6 months after stroke). Some studies also covered the chronic phase (>6 months).[8-21]

The acute phase (<1 month) was less frequently represented, but some studies included patients as early as a few days after stroke.[17]

Level of disability: Various scales were used to assess this: Fugl-Meyer (FMA-UE, FMA-LE), Functional Ambulation Category (FAC), Barthel Index, Functional Independence Measure (FIM), Berg Balance Scale (BBS), 6-Minute Walk Test (6MWT), 10-metre walk test (10MWT), 30-second Chair Stand Test, Posture Assessment Scale for Stroke Patients (PASS), Timed Up and Go (TUG), Dynamic Gait Index (DGI), Functional Ambulation Scale (FAS), TRUNK CONTROL TEST, Functional Gait Assessment, Rivermead Mobility Index.[8-11][13-20][22]

Both non-ambulatory patients (FAC 0–1) and those with moderate or mild disability (e.g., FMA-UE 23–38 points) were included, as well as individuals with chronic disability.[10][15][18-21]

FAC scale:

FAC level	Category description	Type of support	Patient characteristics
0	Cannot walk	Total support	No functional gait
1	Full physical support	Constant assistance from another person	Unable to maintain balance
2	Minimal physical support	Light support	Performs steps independently
3	Requires supervision	No physical contact	Walks but needs observation
4	Independent on flat surfaces	Without assistance	Walks independently indoors
5	Completely independent	Without assistance	Walks independently in all conditions

Inclusion/exclusion criteria:

Typical inclusion criteria: ischaemic or haemorrhagic stroke, stable clinical condition, ability to cooperate, specific level of motor impairment. [8-18][20]

Exclusion criteria: severe cognitive impairment, cardiac instability, significant spasticity, other serious conditions preventing participation in.

Intervention conditions:

Frequency and duration of therapy: Most commonly, 3–5 sessions per week for 2–8 weeks, with sessions lasting 30–60 minutes.[10-11][13-19][22]

For example: 12 sessions of 60 minutes (3 times a week), 20 sessions of 45 minutes, 10 sessions of 30 minutes (5 times a week), 6 sessions of 40 minutes, 30 sessions over 10 weeks.[15-17][22]

Combination with traditional physiotherapy: In most studies, robot-assisted interventions were added to standard physiotherapy or replaced part of it.[8][10-11][13-19]

Groups were often compared: robot + physiotherapy vs. physiotherapy alone. [10-11][13-14][16-17]

Robot settings (intensity, level of support): Settings were individualised, often with the possibility of gradually reducing support as improvement occurred functions. [10][12-13][16-17][22-23] The intensity of training was modulated (e.g. 75–85% HRmax), and the level of support was adjusted to the patient's capabilities (e.g. assistance only when deviating from the movement pattern). [13][16-17][22-23]

In summary, the studies covered a wide spectrum of post-stroke patients (from acute to chronic phase, with varying degrees of disability), and robot-assisted interventions were most often conducted as a supplement or replacement for part of standard physiotherapy, with individualised training parameters and progress monitoring. [8][10-24]

The effectiveness of robotic exoskeleton gait training

Impact on locomotion parameters:

Gait training using exoskeletons after a stroke shows clear potential for improving locomotion parameters, especially in terms of walking speed, stride length, gait rhythm and balance. Numerous studies have confirmed that the use of an exoskeleton increases the number of steps, lengthens the stride, improve gait rhythm and stability, which is particularly evident in patients with severe motor deficits. [8][13–16][20, 22] Long-term analyses have also shown faster recovery of independent gait, increased locomotion speed and distance covered in 6MWT tests in groups undergoing exoskeleton training compared to classic physiotherapy. [8][16] However, not all studies confirm the clear superiority of robotic therapy over standard rehabilitation. In some analyses, particularly those conducted in an intention-to-treat design, no significant differences were

found in walking independence (FAC), speed, stride length, rhythm or balance compared to conventional rehabilitation methods. [10][18] Despite this, exoskeletal gait training is considered safe, well tolerated and applicable in the acute, subacute and chronic phases after a stroke. [10][17][23-24] The use of different types exoskeletons – including soft exoskeletons (SRE), augmented reality devices and systems such as ExoAthlet, Lokomat Free-D and UIPER – show consistent results in terms of improved locomotion parameters, functional mobility and lower limb strength, regardless of the phase of post-stroke rehabilitation. [16-19] Robotic gait training with intensity modulation also contributes to increased walking speed, improved balance and overall functional fitness in patients. [22]

The analysed studies indicate that exoskeletal gait training is a safe and effective form of stroke rehabilitation support, leading to significant improvement in locomotion parameters, balance, symmetry and functional mobility of patients. Although not all analyses show the superiority of this method over standard therapy, its impact on accelerating the gait re-education process and improving the quality of movement is increasingly well documented. [8–24]

Impact on functional mobility recovery:

Gait training using exoskeletons after a stroke has a significant impact on functional mobility recovery, particularly in terms of locomotor independence, gait efficiency and lower limb motor function. Numerous studies have reported significant improvements in key functional scales such as the Functional Ambulation Category (FAC), Berg Balance Scale (BBS), Posture Assessment Scale for Stroke Patients (PASS), Fugl-Meyer Assessment for lower limbs (FMA-LE), modified Barthel Index (mBI) and Functional Independence Measure (FIM), confirming an increase in patient independence and the effectiveness of robotic therapy in restoring locomotor abilities. [11][13-15][22] The results of clinical studies and analyses indicate that, in terms of intention-to-treat approach, significant differences between the exoskeleton group and the standard therapy group were not always observed, but in the as-treated analysis, patients following the full robotic protocol regained walking independence (FAC) faster, achieved better results in distance tests (6-Minute Walk Test – 6MWT) and greater walking speed, confirming the positive impact of this form of therapy on functional independence. [8][10] In most studies, interventions using exoskeletons led to significant improvements in mobility assessment tests, such as the 6MWT, 10-Meter Walk Test (10MWT), Timed Up and Go (TUG), Dynamic Gait Index (DGI) and Functional Ambulation Scale (FAS), reflecting increased walking efficiency and speed, as well as improved posture control. [14-16][20-22] Studies using REX, Ekso™ or soft exoskeleton (SRE) systems have shown significant improvements not only in mobility, but also in trunk function (Trunk Control Test), balance and lower limb coordination. [11][15-16] Some analyses also showed an increase in the percentage of patients achieving minimally clinically important improvement (MCID) in walking speed and the Barthel Index scale, confirming the practical significance of exoskeleton training in improving daily functionality. [17] These changes were accompanied by an improvement in the range of motion in the hip joint and increased coordination between the limbs, as observed in kinematic analyses. [17] The use of different types of robotic devices, such as ExoAthlet, Lokomat Free-D and UIPER, led to comparable improvements in FIM, 6MWT and 30-second Chair Stand Test scores, with no advantage of one system over another. [18] The use of augmented reality exoskeletons (VR-RAGT) also resulted in improved results in the Functional Gait Assessment, Rivermead Mobility Index, BBS and FIM, although the differences compared to classic robotic gait training (RAGT) were not statistically significant. [19]

Impact on neuromuscular function and neuroplasticity:

Gait training using exoskeletons after a stroke not only improves locomotor function, but also neuromuscular function and neuroplastic processes. At the biomechanical and neurophysiological level, it has been found that exoskeletons promote a more effective and rhythmic gait pattern, which is associated with improved control of lower limb muscle activation – especially proximal muscles – and increased muscle activity in electromyography (sEMG) studies. [11-12] EMG analyses have shown that after robotic training, patients regain a controlled and rhythmic muscle activation pattern, and the observed improvement in muscle coherence indicates the involvement of cortical mechanisms in the reorganisation of motor control, which may indicate the beneficial effect of exoskeleton training on neuroplasticity. [11-12]

At the same time, some studies have described an extension of the support phase, an increase in the angle of foot rebound, and an improvement in symmetry and coordination between the limbs, which reflects improved neuromuscular integration during gait. [13][16][20] In stroke patients who participated in exoskeleton training programmes, an increase in cortical activity in the motor areas on the affected side and in

the prefrontal cortex was also observed, as assessed by functional near infrared spectroscopy (fNIRS). [13] These changes correlated with improvements in motor function and balance, suggesting that regular training with an exoskeleton may stimulate neuroplastic processes by activating brain areas responsible for motor control and movement planning. [13] The results of available studies indicate that exoskeletons can support the restoration of neuromuscular function and promote the reorganisation of the central nervous system after a stroke, leading to more effective movement control and improved gait patterns. However, it should be emphasised that the number of studies evaluating the quality of rehabilitation using exoskeletons in the context of neuromuscular function and neuroplasticity is still limited, and further analysis is necessary to fully understand these mechanisms. [11-13][16][20]

Comparison with traditional physiotherapy:

A comparison of the effectiveness of rehabilitation using exoskeletons and traditional physiotherapy in stroke patients indicates that robotic training can be at least an equivalent and, in many cases, a more effective method of rehabilitation. Studies by Louie et al. have shown that robotic gait training is as effective as classical kinesitherapy in improving gait independence and locomotion parameters, especially in non walking patients, with the effects of therapy persisting after the end of the rehabilitation programme [8]. Similar results were obtained in analyses in which the intention-to-treat model found no advantage of the exoskeleton over standard therapy, while in the as-treated analysis, patients using robotic training regained walking independence faster and improved their locomotion speed, and the effects obtained remained under deferred observation. [10] However, in most studies, exoskeletal gait training showed a clear advantage over conventional physiotherapy in terms of improving locomotion parameters, functional mobility, balance and lower limb motor function. [11][13–17] The use of devices such as Ekso™, REX or soft systems (SRE) led to greater improvement in walking speed, stride length, locomotion rhythm and balance, as well as increased muscle activity and stimulation of neuroplasticity. [11-13][15–16] It has also been shown that exoskeleton training can improve lower limb strength, walking performance and quality of life in stroke patients more effectively than conventional kinesitherapy. [12][15] In particular, in the subacute phase after a stroke, exoskeleton therapy has been shown to be more effective in restoring functional independence and motor control. [13][15-17] Available studies indicate that rehabilitation using exoskeletons is safe, well tolerated and at least as effective as classic physiotherapy in restoring locomotor abilities after a stroke. In many cases, it surpasses it in terms of improving balance, muscle strength, gait parameters and functional independence, especially in the subacute phase. At the same time, the durability of the achieved effects and optimal training protocols require further verification in studies with larger samples and longer observation periods. [8][10-19]

Factors influencing the effectiveness of therapy

Post-stroke phase (acute, subacute, chronic) at the start of rehabilitation

The studies analysed in this article indicate that the effectiveness of rehabilitation using an exoskeleton significantly depends on the post-stroke phase, which is consistent with studies analysing this issue, suggesting greater clinical benefits in the early stages of the disease and more limited effects in the chronic phase. [1][4][7][25] In the analysed studies particularly clear and consistent results were observed in the subacute phase, [10-14][16-17][22][24] where patients achieved significant improvements in gait, balance, motor function and functional independence, with some studies also indicating a beneficial effect of exoskeleton training on cortical reorganisation and a more mature, rhythmic pattern of muscle activation. [12][13] These results are consistent with meta-analyses suggesting that early implementation of robotic gait therapy may promote neuroplasticity and intensify functional recovery. [1][4][25] Data from the acute phase are much less numerous, but the available results indicate the possibility of rapid improvement in basic locomotor parameters after short interventions, [20] which is also consistent with observations that the acute and subacute periods are characterised by the greatest susceptibility to functional modification. [1][4][7][25] In chronic patients [15][18-23], improvements in gait, balance and quality of life were reported, although these effects were less clear cut and often comparable to the results of intensive conventional rehabilitation, indicating a limited advantage of robotic therapy in this phase. [1][4][7][26] In summary, the greatest benefits of exoskeleton therapy seem to occur in the subacute period, and partly also in the acute period, but the possibility of drawing clear conclusions is limited, as the vast majority of the studies analysed included patients in the subacute phase, which makes it difficult to fully assess the differences between the phases of stroke and limits the possibility of generalising the results.

The degree of automation and adaptation of the exoskeleton

The level of automation of exoskeletons also affects the results of rehabilitation after a stroke. Advanced adaptive algorithms, such as "assist-as-needed" or Real-time personalisation of support can increase the effectiveness of therapy by better matching the intensity and nature of assistance to the patient's needs. [27-28] Fully automated overground systems such as REX, [11] Ekso™ exoskeleton, [15] or multi-joint robots providing full propulsive support [10][12][14], have often been associated with a marked improvement in gait parameters, balance and motor function, and in some studies also with neurophysiological changes indicating a more rhythmic and economical pattern of muscle activation. [12][13] A higher level of automation allows for an increase in the number of repetitions and active working time, which promotes neuroplasticity and effective motor re-education. [1][29] Adaptive exoskeletons, such as H2 with an "assist-as-needed" algorithm,[23] confirm that systems that respond to the patient's current capabilities can improve mobility and reduce compensation, although they do not always outperform automated robots with fixed parameters. Less automated devices, such as the soft ankle exoskeleton [16] or the user-initiated UIPER system [17], also led to functional improvement, but usually to a more moderate extent. Importantly, comparative studies of different robots (ExoAthlet vs. Lokomat Free-D) did not show any advantage of one system over the other [18], confirming that automation alone is not the only factor determining effectiveness. At the same time, other studies indicate that combining automatic support with biofeedback or online adaptation may lead to better results than using devices with fixed parameters. [7][28] Different levels of automation may support functional improvement after a stroke, but current data and the high heterogeneity of device designs indicate that individual adjustment of the degree of automation to the patient's capabilities is crucial, and the lack of direct comparisons makes it impossible to clearly determine which type of exoskeleton is most effective.

Level of patient involvement and training intensity

A higher level of patient involvement and appropriately high training intensity significantly enhance the effects of rehabilitation using exoskeletons after a stroke. Intensive protocols, usually 45-60 minutes of work per session, performed several times a week, lead to greater improvement in motor control, gait parameters, balance and independence than lower intensity training. [29-30][11][15][22] Active participation in task-oriented exercises and the number of repetitions are key is active participation in task-based exercises and the number of repetitions, as they directly stimulate neuroplasticity, as confirmed by cortical changes and more precise muscle activation patterns observed in studies. [27][29-30][12-13] Most of the protocols analysed required active patient participation, which further increased the effectiveness of the therapy. [11-15][17][20][22-23] However, not all studies showed an advantage over standard therapy [10]; in a study conducted by Louie, D. R. et al., despite high intensity, the effects were comparable to conventional physiotherapy, which emphasises that intensity alone is not sufficient without an appropriate level of active involvement. [10] It is worth noting that motivation and environmental conditions, which affect the quality of participation. [18][23-24] High intensity and active participation are essential elements of effective exoskeleton training, leading to faster and more pronounced functional improvement, while low intensity or passive participation significantly limit the therapeutic potential of this method. [27][29-30]

Co-existing therapies

Coexisting therapies, such as transcranial direct current stimulation (tDCS), Functional electrical stimulation (FES), virtual reality (VR) and classic manual therapy can complement gait training using an exoskeleton and increase its effectiveness in certain areas.[31-34] Reports indicate that tDCS used in parallel with robotic training may promote greater improvement in walking speed, balance and endurance than robotic therapy alone, although these effects are not yet clear enough to justify the routine use of this method.[31][34-36] FES, as a technique supporting muscle activation, can additionally strengthen neuroplastic processes and thus accelerate the recovery of motor functions.[33] In the case of VR, combining it with robotic gait training promotes the improvement of selected parameters, especially walking speed and the ability to perform dual tasks, although this does not translate clearly into higher overall rehabilitation effectiveness compared to exoskeleton training alone.[19][32] In general, adjunctive therapies can enhance certain aspects of the rehabilitation process, but their effectiveness depends on the phase of stroke, the individual capabilities of the patient, and the nature of the training used.

Safety, tolerance and practical aspects

Reported adverse effects

The analysed literature highlights the exceptionally favourable safety profile of exoskeleton therapy. Most clinical descriptions did not report any serious

injuries, falls or other significant adverse events related to the intervention itself. [10-13] Many reports also emphasised the good tolerance of the training: participants did not report pain, abrasions or fatigue severe enough to require discontinuation of exercise. [14-17] If any discomfort did occur, it was mild and transient, most often limited to temporary fatigue or minor discomfort. [15] No increase in incidents such as falls or injuries was reported, and some participants even reported an improvement in pain perception, confirming the lack of burden of therapy in this area. [18] No serious adverse events were reported in protocols enriched with virtual reality elements. [19-21]

The reported withdrawals were not related to the safety of the intervention, and their causes remained undefined. [21] Similar conclusions can be drawn from other observations, in which training sessions were described as stable, with no incidents such as falls, significant abrasions or increased pain. Participants also did not report fatigue exceeding the typical response to exercise. [22-23] The available data therefore indicate that rehabilitation using exoskeletons is characterised by a very low incidence of adverse events, and any side effects are mild and do not limit the ability to continue therapy.

Patient acceptance and motivation

In the available clinical descriptions, patients generally showed high acceptance of exoskeleton therapy and good motivation to participate in subsequent sessions.

Many observations emphasised that participants were eager to engage in training and did not report any difficulties in accepting this form of rehabilitation. [11][13] Some analyses also noted an improvement in quality of life, including in areas related to mental health, which may reflect a positive attitude towards therapy and sense of its value. [13-14][18] Some reports highlighted the clear motivation of patients to continue exercising and the good acceptance of the technology used. Participants described the sessions as engaging and the rehabilitation process itself as giving a sense of progress and control over their own fitness. [15-17] Enriched protocols, such as training with elements of virtual reality, were also received with interest and active participation. [19] Other descriptions emphasised that exoskeletons were considered easy to use, and gait training in conditions similar to everyday life was satisfying and reinforced a sense of security. Patients often expressed joy at being able to walk again, which was an important factor in strengthening their motivation. [22-23] Overall, the available data suggest that both acceptance of the technology and patients' willingness to actively participate in therapy remain high, and the experience of rehabilitation using exoskeletons is perceived as valuable and supportive of the recovery process.

Logistical challenges

Therapy using exoskeletons proves to be organisationally demanding. Sessions usually last from 30 to 60 minutes, and their number varies from a few to several dozen, which means that significant time resources must be allocated by both the patients and the staff. [11-12][14-19][21-23] The regularity of meetings and the need to work in a designated training environment mean that the entire process requires careful planning.

In addition, exoskeletons are only available in selected centres and require trained therapists to operate them. The equipment itself requires individual adjustment, which prolongs the preparation for sessions and increases staff workload. [15] The introduction of this technology into everyday clinical practice also involves a longer adaptation period and the need to ensure adequate organisational support, which in some facilities took up to several months. [22-23] Another challenge is the cost of gait rehabilitation using exoskeletons, which is significantly higher than that of standard physiotherapy, primarily due to the price of the device itself, its maintenance and the need to train the therapeutic team. [37] However, an analysis carried out in hospital conditions shows that in certain situations – especially in patients with severe gait disorders in the early stages after a stroke – this form of therapy may prove cost-effective, as it is then that the greatest gains in quality of life (QALY) are achieved. [37] In practice, the cost of a single session depends on how intensively the equipment is used and how many patients can use it in

a given centre. This technology remains less accessible, especially in smaller facilities, mainly due to high purchase and operating costs. [37] According to the current position of the American Stroke Association, exoskeletons have great potential, but further research is still needed on their cost-effectiveness and possibilities for wider implementation. [4]

The main challenges relate to the time needed to implement the programme, limited availability of equipment, and the need for qualified personnel and efficient organisational support. Costs remain an important factor that may determine the possibility of widespread implementation of this technology, although they require further, more detailed analysis.

The role of therapeutic personnel

The use of exoskeletons in post-stroke rehabilitation requires appropriate staff training, although the available studies do not indicate any significant difficulties associated with their implementation into everyday practice. Therapists are responsible for monitoring safety, adjusting device parameters and supporting patients during training, which makes their competence a key element of the entire process. [10-12] The technology requires prior training and constant supervision, and preparing the device before a session and adjusting the settings to the patient's capabilities increases the organisational requirements, although this does not constitute a barrier to its use. [14-17] Learning how to use the device is usually straightforward, but it requires commitment and gradual adaptation to the specifics of the equipment. [16] It is also pointed out that the effectiveness and safety of therapy depend largely on the experience and continuous supervision of the rehabilitation team. [18-21] In some centres, it was noted that full freedom in the use of the devices only appeared after several months, when the staff gained experience and integrated the exoskeletons more efficiently into daily clinical practice. [23-24] The available data suggest that although the technology requires a specialised team and a certain period of adaptation, it does not generate significant organisational barriers. The key factors remain the competence of the staff and their willingness to systematically improve their skills in operating the device.

New directions and technological innovations

The use of robotic exoskeletons is still a new and rapidly developing field of physiotherapy. New solutions focus on more precise mapping of movement intentions, increasing the individualisation of therapy, and creating opportunities for intensive training outside of clinical centres. Advances in biological signals, virtual reality, biofeedback, and machine learning methods are paving the way for more effective and flexible forms of robot-assisted therapy.

Exoskeletons controlled by biological signals (EMG, EEG)

One of the main areas of development is exoskeletons capable of using biological signals such as electromyography (EMG) and electroencephalography (EEG).

The introduction of EMG as a control signal enables precise detection of the gait phase and more tailored movement support, which facilitates effective therapy even at lower training intensities, especially in the subacute phase. [6] In turn, the integration of EEG allows for the monitoring of cortical activity and the decoding of movement intentions, laying the foundation for the development of brain-machine interfaces that may increase the degree of personalisation of robotic support in the future. [38]

Integration with virtual reality (VR) and sensory biofeedback

Another area of innovation is the combination of exoskeletons with virtual reality systems and various forms of biofeedback, such as vibrotactile or audiovisual signals. Real-time VR and biofeedback solutions increase patient involvement, facilitate dual-task performance and improve limb positioning, which has a positive effect on gait parameters and balance. [32][39-40] This approach promotes better mapping of functional situations and supports the motor learning process. [39-40]

Machine learning and artificial intelligence algorithms in movement adaptation

Machine learning algorithms play a significant role in the modernisation of exoskeletons. Based on data from sensors such as IMUs, they are able to automatically adjust support parameters. Such systems enable precise personalisation of training, more efficient adaptation to individual gait patterns and greater therapy effectiveness. [41-42] Online adaptation solutions reduce calibration time and make it easier to maintain an optimal level of assistance as the patient progresses. [42]

Possibilities for use in home rehabilitation and telerehabilitation

Technological advances, including component miniaturisation, the development of wireless systems, and integration with therapeutic data monitoring platforms, are conducive to transferring exoskeleton rehabilitation to the home environment. [43]

This enables intensive, task-oriented training outside the clinical centre while maintaining a high level of supervision and personalisation of therapy through remote monitoring. [43-44] The development of such solutions is particularly important for patients with limited access to rehabilitation services.

Limitations of existing studies

Small study samples and population heterogeneity

Small study groups and high participant heterogeneity are one of the main limitations of the analysed studies on gait rehabilitation after stroke using exoskeletons. In most studies, the sample size was small, often ranging from a dozen to several dozen people, which makes it difficult to draw conclusions about the widespread use of this technology.[10-12] In addition, individual teams qualified patients at very different stages of recovery for therapy, from the subactive phase to the chronic state, which resulted in significant differences in both the time since stroke and the level of disability. [13-15] Many projects included individuals with varying degrees of motor impairment, different ages and different functional capacities, which introduced further sources of variability and made it difficult to compare the effects between centres. Some studies were pilot studies, and the number of participants was extremely small, which limited the reliability of the observations and the possibility of conducting advanced statistical analyses. [22-23]

In some studies, there were also significant differences between the comparison groups, and the number of dropouts further reduced the analytical power of the results obtained. [17][21] As a result, although the available data indicate the clinical potential of exoskeleton therapy exoskeletons, discrepancies in the characteristics of the study population and small sample sizes significantly hinder the generalisation of results to a wider population of stroke patients. To obtain more conclusive data, studies involving larger, more homogeneous groups and consistent eligibility criteria are needed.

Diversity of therapeutic protocols

Another limitation of the available studies on gait rehabilitation after stroke using exoskeletons is the diversity of therapeutic protocols used.

Individual teams used different training regimens: from strictly individualised protocols,

in which the degree of assistance was adjusted to the patient's capabilities, to interventions based on fixed device operating parameters. [10] Many studies compared different forms of rehabilitation, contrasting training with the use of an exoskeleton with verticalisation, classic physiotherapy or robotic gait training conducted according to different principles. [11-14] There are also noticeable discrepancies in the type of devices used and the structure of the interventions themselves. Some projects analysed only the effects of exoskeleton training, without a control group or reference point, [15][20][23–24], while others compared different technologies, which led to further differences in the way the therapy was conducted. [18][21] These differences included the duration of the sessions, the number of repetitions, and the level of movement assistance.

There were also protocols combining exoskeletons with additional forms of stimulation, such as virtual reality training, which further complicates direct comparisons between studies. [19] It is necessary to standardise protocols or at least describe them in more detail to increase the comparability of results and enable a more precise assessment of the effects of therapy.

Lack of long-term observation of effects

The lack of long-term follow-up is one of the most obvious limitations of the available studies on the use of exoskeletons in stroke gait rehabilitation. Most interventions were analysed only in the short term, often covering only a few weeks of therapy, without subsequent verification of the durability of the results obtained. In many studies, no follow-up was conducted after the end of the programme, making it impossible to assess whether the improvement in gait function, balance or quality of life persists in the later stages of recovery. [11-12][15][17][21][24] Even where monitoring was used after the intervention, the period was relatively short, usually not exceeding a few weeks, most often covering 2-, 4-, 6- or 8-week time frames. [13-14][16][18-20][23] Only a few studies reached longer follow-up periods, but even these were limited to a six-month period, which still leaves the question of whether the effects persist for a year or longer. [10]

Such short assessment horizons make it difficult to determine the extent to which exoskeletons contribute to lasting the reconstruction of gait patterns, overall functional fitness or independence in stroke patients. There is also a lack of data on the possible decline in benefits over time, the need to maintain training, or the optimal frequency of maintenance therapy. For this reason, future studies should include observations lasting several months or years, enabling the assessment of the stability of effects and more informed planning of post-stroke rehabilitation using exoskeletons.

Limited standardisation of outcome assessment methods

Limited standardisation of outcome assessment methods is another significant challenge in interpreting studies on gait rehabilitation after stroke using exoskeletons.

Although many studies used well-known and widely used clinical tools, such as functional tests or motor performance assessment scales, the method of their selection and application was clearly inconsistent. Some studies used standard scales, but without fully standardising the measurement procedures, which made it difficult to compare results between groups or research projects. [10][13-14][16][18][20][22] Several studies used sets of different tools, not all of which had the status of fully validated measurement methods, which reduces reliability and reproducibility of the results obtained. [11][15][17][19][21] There were also studies based on more advanced but unvalidated techniques, such as electromyographic analysis or Capacity Score, which further increased methodological heterogeneity. [12] However, the greatest difficulties interpretation, however, stem from projects that did not use any standardised tools to assess the effects of therapy, which makes it impossible to compare their results with other studies and significantly limits their usefulness in data synthesis. [23-24] The wide variety of methods used to assess effectiveness, both in terms of the type of scales and how they are used, makes it difficult to clearly organise the results of the analysed studies. The standardisation of measurement procedures should become one of the priorities of future research in order to enable a reliable assessment of the impact of exoskeletons on gait function and to facilitate the comparison of therapy effects between different centres and protocols.

Risk of bias

The risk of bias is another obvious limitation of the analysed studies on the use of exoskeletons in gait rehabilitation after stroke. Although some projects introduced elements to minimise bias, most often in the form of basic randomisation, these solutions were usually incomplete and did not provide full control over possible sources of error. [10-11][13-14][16][18-19] In many cases, participants were not blinded, which was difficult to implement in practice for technology-based interventions, but significantly increased the risk of expectation bias on the part of the patient. At the same time, a significant proportion of studies did not use randomisation or any form of blinding, which significantly limits the possibility of attributing the observed changes solely to the exoskeleton intervention. [12][15][17][20-24] In several projects, an additional problem was the lack of a control group, which made it impossible to distinguish the effects of the intervention from natural improvement or the impact of conventional physiotherapy conducted in parallel. Taken together, this means that the reliability of some of the available data is limited and the interpretation of the effects requires caution.

In order for research on exoskeletons to provide more clear and comparable conclusions in the future, it is necessary to consistently use randomisation, appropriately designed control groups, and procedures to minimise bias among evaluators and participants.

Summary:

Robotic gait training can be considered a valuable supplement to conventional physiotherapy, especially in the area of gait re-education and intensification of work on endurance and postural control. The technology allows for a greater number of steps during a session and a more repetitive movement pattern, thus supporting the process of neuroplasticity and increasing the effectiveness of therapy. The greatest benefits are observed in patients with significant mobility limitations, especially in the early phase after a stroke, when the potential for improvement is highest. People in the chronic phase can also benefit, although usually to a lesser extent, mainly in terms of quality of life, motivation and improved exercise parameters.

The introduction of exoskeletons into clinical practice requires well-trained staff and organisational support. Therapists must be trained in the use of the equipment and in adjusting the therapy parameters to the patient's capabilities, and preparation for sessions is often more time-consuming than in standard rehabilitation. It is also crucial to use assessment scales with documented reliability and to monitor safety regularly. It is

worth emphasising that the effectiveness of such therapy largely depends on the appropriate selection of patients, a clear definition of rehabilitation goals and the consistent application of protocols that increase the intensity of work. Due to the complexity of the technology and limited equipment resources, exoskeletons are best introduced as part of a medium- or high-intensity programme in centres with the appropriate infrastructure. However, the available literature shows that many issues require further research. Most studies involve small, heterogeneous groups and short observation periods, which makes it difficult to clearly assess the durability of the effects. Larger randomised studies with longer follow-ups and standardisation of therapeutic protocols and measurement tools are needed to enable comparison of results between centres. From a systemic perspective, cost-effectiveness analyses are also important, as they could support decisions regarding wider implementation. technology in routine clinical practice, especially in the context of an ageing population and a growing number of patients with post-stroke deficits.

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