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Research Article

Enhancing Post-Stroke Gait Rehabilitation with Robot-Assisted Therapy: A Focus on Step Repetitions and Neuroplasticity

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Abstract

Background: Stroke is a leading cause of disability worldwide, with gait impairments significantly affecting patients' independence and quality of life. Gait recovery relies heavily on neuroplasticity, which requires high-repetition, task-specific training. Conventional rehabilitation often fails to provide enough repetitions, and the shortage of therapists further highlights the need for alternative solutions.

Objective: This study explores the role of robot-assisted gait training (RAGT) in post-stroke patients, focusing on the number of repetitions achieved during the therapy.

Material and methods: Data from 264 therapies conducted on 132 post-stroke patients who underwent treatment with the RAGT end-effector system, collected from five different facilities, were analysed.

Results: Data analysis revealed that during therapy using an end-effector-based RAGT system, patients achieved an average of 1098 ± 325 steps in the first session and 1529 ± 298 steps in the final session, representing a 39% increase in step count throughout the entire treatment program.

Conclusion: The end-effector-based RAGT system addresses core neuroplasticity principles with an emphasis on high repetition rates, enabling patients to achieve up to three times the number of repetitions compared to conventional therapy. Given the increasing number of stroke survivors and the shortage of qualified personnel, the RAGT system presents a promising solution for the future of post-stroke gait rehabilitation.

Keywords: Robot-Assisted Gait Training (RAGT); Global health challenge; Stroke; Post-stroke patients; Worldwide

Introduction

Stroke background

Stroke represents a significant and increasing global health challenge. It is the leading cause of acquired physical disability in adults and the second leading cause of death worldwide [1,2]. In 2021, nearly 100 million people globally were living with the long-term effects of stroke, a number that has almost doubled in recent decades. Each year, approximately 12 million new stroke cases are reported, with 63% occurring in individuals under the age of 70 and 16% in those under 50 [3]. The majority of the global stroke burden is concentrated in low- and middle-income countries (LMICs), where 70% of strokes were recorded in 2021 [4]. Notably, both the incidence and prevalence of stroke have increased among individuals under 55, mainly due to the growing prevalence of risk factors such as hypertension, obesity, and type 2 diabetes in young adults, especially in LMICs [4,5].

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Projections indicate a substantial rise in stroke incidence in the coming years. In general, it is estimated that 1 in 4 people will experience a stroke at some point in their lifetime [3]. King et al. [6] estimate a 123% increase in stroke prevalence and a 194% rise in societal costs in the UK from 2015 to 2035 [6]. Similarly, H.A. Wafa's thirty-year projection forecasts a 27% increase in stroke cases and a 17% reduction in stroke mortality across the EU by 2047, reflecting a shift in stroke burden from mortality to morbidity. This trend is driven by an aging EU population and improved survival rates from advances in prevention and healthcare. If disability rates among stroke survivors remain unchanged, the EU will likely face a 27% increase in demand for rehabilitation and long-term care over the coming decades [7].

Stroke represents the second highest disease burden in Europe, significantly impacting both society and the economy [8]. In 2019, the global costs associated with stroke reached $2059.67 billion, accounting for 1.66% of the global GDP, with the highest economic impact observed in Central Europe [9]. The healthcare costs associated with stroke show significant variation depending on patient characteristics, with estimates ranging from approximately $6,300 to $149,000. Rehabilitation constitutes a significant portion of post-stroke care expenses, with average costs in the first year after stroke amounting to around $31,200 [8].

Strokes are commonly divided into two primary types: ischemic and hemorrhagic. Ischemic strokes occur when blood flow to a specific part of the brain is blocked, leading to a sudden loss of function. In contrast, hemorrhagic strokes are caused by the rupture of a blood vessel or an abnormal blood vessel structure in the brain. Ischemic strokes make up roughly 85% of all stroke cases, while hemorrhagic strokes account for the remaining 15%, although these proportions can vary across different populations [2,10]. Almost 90 % of stroke cases are related to modifiable risk factors. The impact of individual risk factors varies across countries, but globally, the largest single risk for stroke is high systolic blood pressure. Other significant factors include high BMI, high LDL cholesterol, high fasting plasma glucose, smoking, and kidney dysfunction [2,4]. Age is the most significant non-modifiable contributor to stroke risk, with the incidence doubling every decade after the age of 55 [2,4].

Post-stroke disability results in many long-term consequences, including impaired mobility, balance, muscle strength, or movement control [11]. Over 50% of patients aged 65 and older experience mobility impairments after a stroke [12], while up to 83% of survivors face balance difficulties [13]. There is a high risk for falls at all stages after stroke with walking being the most common activity associated with falls among stroke survivors [14]. Furthermore, impaired mobility can lead to secondary complications such as joint contractures, nociceptive pain or deep vein thrombosis [15]. Consequently, gait recovery is one of the primary aims of stroke rehabilitation as walking difficulties significantly affect patients' independence and overall quality of life [16].

Role of neuroplasticity in post-stroke recovery

Key to motor functional recovery after a stroke is neuroplasticity, the ability of the central nervous system to change its structure and function in response to internal and external stimuli, including experience, learning, or following injury. This process involves adaptive changes at the cellular level, such as synaptic plasticity, as well as larger-scale rewiring of brain regions, particularly in the cerebral cortex. Neuroplasticity is essential for motor skill retraining and occurs both spontaneously and as a result of rehabilitation [17,18]. Effective stroke treatment and rehabilitation must support and optimize the brain's ability to reorganize, improving recovery outcomes and quality of life [18]. Several principles of neurorehabilitation influencing the effectiveness of motor learning and recovery have been described, key among them are time, repetition, intensity, and task-specific practice [17,19].

The timing of rehabilitation after an injury plays a crucial role in neuroplasticity. Early rehabilitation is known to improve outcomes and reduce disability [17,20]. Cabral et al. [18] assessed the efficacy of neuroplasticity mechanisms in post-stroke patients compared to age-matched controls using transcranial magnetic stimulation-based assessment. Their findings indicate that during the early stages of stroke, neuroplasticity mechanisms were comparable to those in healthy controls, while in the later stages, they appeared to be diminished [18]. Similar results have been observed in animal models, which show that cortical reorganization peaks 7-14 days after a stroke and lasts for about a month [21]. This is consistent with the finding that early rehabilitation for stroke patients reduces their health and social care costs for up to five years following the stroke [22]. However it should be noted that several neuroplastic processes occur over weeks and months, with evidence indicating that patients may exhibit induced neuroplasticity changes even several years post-stroke [17].

High-Repetition as gait recovery challenge

To induce lasting changes, strengthening of neural pathways and connections through the high repetition of a task-specific movement is required [17]. Evidence from animal models shows that synaptic changes in the motor cortex occur after 400, but not after 60 reach movements, and gait training becomes effective only with 1,000–2,000 steps per session [20]. These findings highlight a dose-response relationship in stroke rehabilitation, emphasizing the need for high-repetition training to optimize outcomes. There is evidence suggesting that increasing the number of repetitions in neurorehabilitation may lead to improved outcomes [23,24]. Due to limited stroke rehabilitation time, often, the number of repetitions can be low. Several studies confirm that the number of repetitions or steps performed during a single conventional therapy session is insufficient when compared to animal studies exploring the role of neuroplasticity in stroke recovery. Lang et al. observed gait repetitions in 230 sessions at 7 sites. The calculated average number of gait steps was 357 with the larger number of steps performed during the outpatients compared with inpatients settings [25]. Similarly, Kimberley et al. examined the number of steps taken by patients after a stroke and those with traumatic brain injury. The results showed that the average number of steps during an approximately 30-minute session was around 250, with fewer repetitions observed in stroke patients—an average of 185 steps [26]. However, some studies report even lower repetition counts per gait therapy session [27-28].

Several factors contribute to the insufficient number of steps achieved during conventional therapy, including patient and therapist fatigue, lack of motivation, and the ineffective use of limited therapy time. In patients with severe impairments, interventions like body-weight-supported treadmill training (BWSTT) often rely on the therapist's manual assistance in advancing the affected leg during each step. This physically demanding task typically leads to therapist fatigue within 15–20 minutes [25,29]. Strategies to increase the therapy dosage could include incorporating weekend physical therapy, implementing circuit training classes, or extending therapy session duration [26,30]. A meta-analysis by Stewart et al. [31] revealed that additional practice in stroke rehabilitation is most commonly delivered through full supervision by qualified therapists. However, this approach is resource-intensive, costly, and unsustainable in the long term. Moreover, therapists already report time constraints as a significant challenge in meeting current stroke therapy demands [31]. As a result, there is a growing need for strategies that are less demanding on therapist time. In addition, the conventional approach often fails to meet other critical needs like measurable outcomes, repeatability, and active patient engagement, all of which are essential for stimulating the full sensorimotor coordination system [32].

Advantages of RAGT systems

One promising solution, recently discussed in stroke gait rehabilitation, is the use of robotic devices. Robot-assisted gait training (RAGT) enables task-oriented, intensive, and reproducible gait training with a high repetition rate and does not require physically demanding involvement from the therapist. The key principles of this technology make it an ideal tool for promoting neuroplasticity. There are two primary types of RAGT devices: exoskeletons and end-effector systems. Exoskeletons provide support to the entire lower limb and assist with movement at each joint, while end-effector systems focus on specific segments, typically the feet. By allowing the hip and knee joints to move freely, it promotes more active patient engagement with unrestricted pelvic movement across all anatomical planes, promoting the freedom of movement essential for effective rehabilitation and optimizing the therapeutic process [33].

Additionally, certain RAGT systems are equipped with features designed to enhance patient motivation. One such example is the use of games and real-time feedback, which track the patient's performance. These games can offer varying levels of difficulty, promoting active participation. Their primary goal is to promote even weight transfer from side to side, which actively engages the affected limb and physiological weight shift across the foot of the affected side. Alongside visual feedback, audio or haptic feedback, such as vibrations, can be employed to stimulate the affected leg during the gait cycle.

Many RAGT systems are designed with safety features such as harnesses, sensors, and monitoring systems that reduce the risk of falls or injury during rehabilitation, enabling patients to engage in more intensive training with less concern about safety. Integrated unweighting systems facilitate intensive training for patients even in the early stages following a stroke.

Another advantage is the ability to record data from each therapy session. This enables therapists to not only track the patient's progress in real-time, but also analyse the patient's progress over time and make informed adjustments to the therapy settings to optimize outcomes [32,34].

The aim of the present study is to investigate the average number of steps achievable using the end-effector-based RAGT system in post-stroke patients, thereby providing evidence of its potential to facilitate neuroplastic recovery in stroke rehabilitation.

Materials and Methods

Study design

Data on the number of steps from post-stroke patients who underwent gait rehabilitation with an end-effector-based robotic device were analysed. The data were retrospectively collected from October 2022 to June 2024 across multiple facilities using the R-Gait device (BTL Industries Ltd.).

Patient selection and therapy protocol

The inclusion criteria for patients whose data were included in the study were as follows: 1) a confirmed diagnosis of stroke, 2) a maximum time of 2 months from stroke onset to the start of rehabilitation, and 3) completion of the full rehabilitation program using the R-Gait system. Patients were excluded from the study if they: 1) had incomplete or missing step count data, 2) had a history of neurological conditions other than stroke, or 3) experienced significant changes in the rehabilitation plan that could affect the consistency of the data.

All patients were informed about the potential benefits and risks of the therapy before treatment and provided written informed consent. The treatment and data handling were conducted in compliance with the 1975 Declaration of Helsinki, as amended by the Convention on Human Rights and Biomedicine of the Council of Europe (1997) and endorsed by the General Assembly of the World Medical Association (1997-2000).

Patients underwent an average of 20 robot-assisted therapies using the R-Gait system, with therapies conducted on average 4 times per week. Each session lasted 20–40 minutes, depending on the severity of the gait impairment and the patient's current condition. RAGT was combined with conventional therapy in all patients, with the specifics depending on the standard procedures at each facility.

R-Gait therapy

Before therapy, the patient is secured in a harness connected to the lift system. In patients with severe mobility impairments, the system facilitates smooth transfer onto the machine, providing full support until the feet are correctly positioned in the footplates. The feet are secured to the footplates using adjustable bindings (Figure 1). The lift system allows dynamic weight offloading, which is adjusted in real-time according to the gait cycle phase. This ensures continuous support throughout the walking pattern. The footplates support the extension of the metatarsophalangeal joints and simulate the push-off phase of the gait cycle, replicating natural walking biomechanics. The activity of both feet and the level of weight unloading are monitored in real-time via integrated sensors within the footplates and lift system.

Figure 1: R-Gait (BTL Industries Ltd.).

At the start of the therapy, weight support (ranging from 0 to 100%), step length (up to 620 mm), and gait speed (up to 80 steps per minute) are individualized based on each patient's condition and functional abilities. Data on the outcomes achieved during therapy (step count, distance walked, and average speed) are automatically recorded by the device.

Data processing and analysis

The information about the number of steps was directly obtained from the therapy records logged by the device. From a total of 3,503 records obtained from 556 patients, 264 records from 132 patients were extracted based on the specified criteria. Due to variations in therapy settings and objectives, only data from the first and last sessions—where therapy conditions permitted direct comparison—were included in the final analyses. A detailed overview of the patient and record exclusion process is presented in Figure 2.

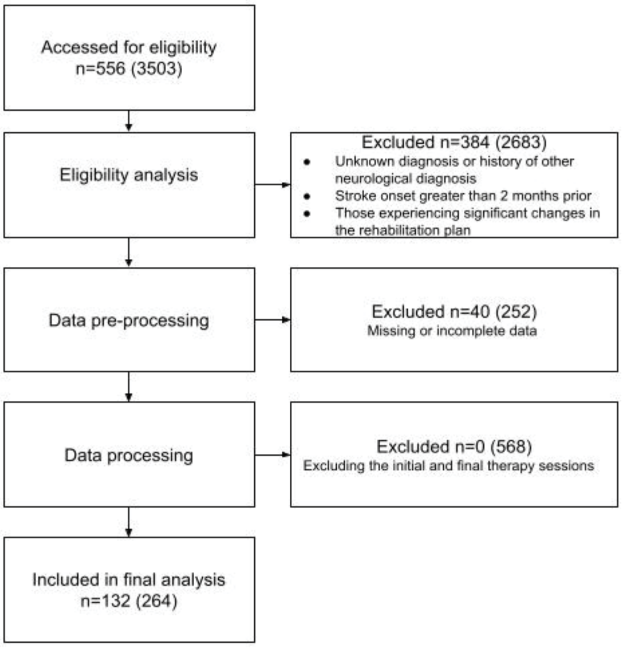

Figure 2: CONSORT diagram illustrating the exclusion of data for the final analysis; n=patients (records).

Data were analysed using Microsoft Excel 2016. For statistical evaluation, the normality of the data distribution was initially assessed using the Shapiro-Wilk test. Subsequently paired T-test was employed, with a significance threshold set at $P<0.05$.

Results

The analysis included data from 132 patients, evaluating a total of 264 therapy sessions corresponding to the first and last sessions. The mean age of the patients was 59.78 ± 12.8 years, and the majority were male. More than 75% of the patients had experienced an ischemic stroke, with robot-assisted rehabilitation initiated on average 38.2 ± 19.7 days post-stroke. Patient demographics are shown in Table 1.

Table 1: Patient demographic data.

Characteristics	n=132
Age, mean (SD), y	59.78 (12.8)
Gender (M/F), n	79/53
Side of stroke (R/L), n	71/61
Time post-stroke, mean (SD), d	38.2 (19.7)
Stroke type (Ischemic/hemorrhagic), n	105/27
SD, standard deviation; M, male; F, female; R, right; L, left.	

The results indicate that during the first therapy session, patients take an average of 1098± 325 steps, and the number of repetitions significantly increases after completing a series of sessions. By the final therapy session, patients perform an average of 1529 ± 298 steps, representing a 39% increase in step count, see Figure 3. The change in the number of steps during RAGT therapy was found to be statistically significant, with a p-value of <0.001.

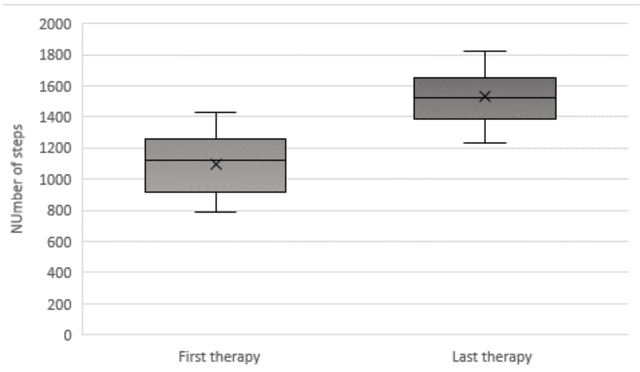

Figure 3: Number of steps achieved during the first and last therapy session with R-Gait.

Discussion

The importance of the neuroplasticity process in post-stroke gait rehabilitation is well recognized, however, some studies indicate that the number of repetitions achieved during conventional therapy is insufficient to effectively induce neuroplastic changes [25-28]. According to available research, a suitable strategy to address these limitations could be the use of RAGT devices. Based on the conducted data analysis, it is possible to achieve over 1,500 steps per therapy session, which is at least three times more compared to studies analysing the number of steps achieved during conventional therapy, typically ranging between approximately 100 and 400 steps [25-28]. This finding is consistent with the results of a previous study investigating the effectiveness of gait rehabilitation using the R-Gait system in children with various neurological disorders [34]. Similarly, studies using various types of RAGT systems have reported achieving up to 1000 steps during a 20-30 minute gait rehabilitation session for stroke patients [35,36]. Even for individuals with a higher degree of disability, RAGT rehabilitation can be initiated in the early stages following a stroke, thanks to the offloading system and full assistance provided by the device, both during therapy and when mobilizing the patient onto the device. At this stage, brain neuroplasticity is typically at its peak, allowing for more effective neuronal reorganization [18,21].

In addition to the higher step count and the possibility of early rehabilitation, several other factors contribute to the positive effects of the RAGT system. Maier et al. [19] identified an extended list of principles of motor learning in their research, some of which align with the use of RAGT [19]. An example of this includes multisensory stimulation, explicit/implicit feedback, increasing difficulty, goal-oriented practice and promoting the use of the affected limb [19]. As mentioned earlier, the integration of games and haptic stimulation of the impaired leg not only facilitates more active patient engagement during therapy and enhances motivation, but also encourages greater involvement of the affected leg. Games with varying levels of difficulty also allow the patient's attention to be directed towards the effect of the movement rather than the movement itself. According to Wu et al. [37], goal-oriented movements tend to lead to better performance compared to the same movements without a specific goal, with more challenging goals resulting in higher motor learning performance [37]. Implicit feedback is delivered through real-time haptic stimulation, which helps guide movement adjustments unconsciously during the gait cycle. Explicit feedback is offered through real-time performance metrics, such as step count and walking distance along with visual cues from the gaming module, allowing patients to track progress and stay motivated toward their therapeutic goals. Precise records of the achievements from each therapy session allow for detailed tracking of the patient's progress and provide a basis for individually increasing therapeutic goals in line with their current physical condition. This personalized approach to task difficulty, tailored to the patient's abilities, leads to more effective improvement in motor skills and optimizes the rehabilitation process, as demonstrated in various motor learning studies [38].

Although RAGT appears to be the most logical choice for post-stroke gait rehabilitation, many institutions continue to favor conventional therapy. When potential customers were asked about obstacles to acquiring robotic equipment, they identified cost as the primary barrier [39]. Although there is already considerable research confirming the clinical benefits of RAGT [32,40,41]. Studies focusing on the economic perspective remain limited. Nevertheless, some research has demonstrated that the use of robotic devices can also be cost-effective. In their meta-analysis, Carpino et al. [32] demonstrated that RAGT using operational machines is a more cost-effective and sustainable approach compared to conventional therapy and wearable robots. Additionally, RAGT has been shown to be significantly more effective in helping stroke patients regain walking independence [32]. Similarly, the study by Kloubocka et al. [42], which focused on patients with cerebral palsy, concluded that RAGT is not only more clinically effective than conventional therapy but also offers greater long-term cost-efficiency. They found that the cost of a 1% improvement in Gross Motor Function Measure (GMFM) with robot-assisted gait therapy is significantly lower than with conventional one [42]. Other studies examining the economic aspects of robotic rehabilitation in patients with various neurological conditions, such as stroke, have reported similar findings [39, 43-45].

It is undisputed that the initial costs of RAGT are significantly higher than those of conventional therapy, however, from a long-term perspective, the costs decrease in relation to the number of working hours and the device's potential lifespan. One of the main advantages of the RAGT system is its lower staffing requirements in terms of the number of therapists needed. Depending on the severity of the patient's disability, conventional therapy typically requires between 1 to 4 physical therapists. In comparison, robotic devices require only one therapist, who, in some cases, can even operate multiple robotic systems simultaneously. As a result, the effective requirement often amounts to only 0.5 of a physical therapist [39,42,46]. The use of robotic devices also reduces the physical workload of the therapist, allowing them, in theory, to manage the care of more patients within a single workday and provide longer and more intensive therapies [42]. In this context, RAGT systems could provide an effective response to the growing number of stroke survivors, particularly considering the current lack of physical therapists, which is expected to worsen primarily due to the aging population. [8,31]. By 2050, the global elderly population is expected to exceed 1.5 billion. Despite advances in medical care, over 80% of older adults experience multiple health conditions, which increases the demand for rehabilitation and healthcare services [7,9].

The study has several limitations. Although data from 132 patients were analysed, a larger sample size would improve the generalizability of the findings, especially considering the variability in stroke severity and patient demographics. Additionally, while RAGT was combined with conventional therapy in all cases, differences in therapy protocols across facilities may have influenced the outcomes, adding variability. To strengthen the study design, incorporating a control group with matched demographics receiving only conventional therapy would allow for a more objective comparison of repetition counts between RAGT and conventional therapy, offering clearer insights into the specific benefits of robotic-assisted gait rehabilitation.

Conclusion

The RAGT system shows promise for post-stroke gait rehabilitation, aligning with neuroplasticity principles essential for recovery, particularly through achieving at least three times higher step counts than conventional therapy. Economically, RAGT may provide long-term savings, addressing the growing number of stroke survivors in combination with the shortage of qualified healthcare professionals. Improved functional recovery and reduced disability could lower the lifetime cost of stroke care, making RAGT both a clinically and economically viable solution for future stroke rehabilitation demand.

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