

Effect of Rhythmic Auditory Stimulation on Hemiparetic Lower Limb Motor Function, Walking Capacity and Gait Performance of Stroke Patients

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Abstract. One reason why stroke has caused a prolonged disability in various parts of the world is that it frequently leads to disorders of movement in the lower limbs, thus impairing walking ability and hindering the independent living of older people. Rhythmic Auditory Stimulation (RAS) is a rehabilitation method based on neuromusic therapy that has recently attracted attention for its relative simplicity in implementation, low cost, and a strong basis in neuroplasticity for stroke-induced hemiplegia rehabilitation. RAS provides a stable, rhythmic sound cue for the patient, activates the brain's inherent ability to link auditory and motor circuits for controlling walking rhythm, and thus assists the patient in regulating walking time, improves gait rhythmicity and symmetry, and promotes lower limb motor function recovery. Review of clinical applications and research results for RAS in lower limb rehabilitation of stroke patients, exploration of possible mechanisms, identification of current problems in both research and practice, and proposal of future directions. The aim is to provide a reference for the promotion and fine-tuning of RAS in rehabilitation for stroke-induced hemiplegia.

Keywords: Stroke, Rhythmic auditory stimulation, Gait rehabilitation, Lower limb function, Walking capacity

1. Introduction

Stroke is a serious problem of public health and one of the primary causes of disability in older age around the world. Many stroke survivors have left-sided hemiparesis, and as a result, exhibit weakness, coordination problems, reduced balance, and abnormal walking patterns [1].

With an aging population in China, the number of people with strokes and thus the demand for rehabilitation services is also on the rise. Motor disorders in the context of stroke are relatively frequent, and the lower limbs are particularly susceptible. As a result of the above report, approximately 60 percent of the stroke patients have walking disabilities. A reduced walking speed is displayed by an abnormal gait, and this abnormal pattern can also result in secondary damage to the hip, knee and ankle joints during walking. This directly affects the patient's quality of life and ability to live in society.

First and foremost, the intention of exercise therapy for stroke is to teach people to walk again. Even after regular exercise and walking training, many of these patients are still unable to increase their walking speed, step length, stability or walking endurance. Approximately 22% of stroke survivors do not regain the ability to walk independently, and thus more effective ways need to be developed [2].

Rhythmic Auditory Stimulation (RAS) is a way to help people with neurological disorders learn. It is driven by external rhythm, such as a metronome or music with rhythm, to move. RAS operates through auditory-motor entrainment and can align movement with an external rhythm of sound [3]. Rhythmic cues can activate brain areas that are involved in motion to help to foster an internal sense of time and motor control during motor learning [4]. Over the past 20 years, more and more studies have been conducted on the efficacy of RAS for stroke rehabilitation. This review will present the latest evidence on how RAS affects the motor function of the lower limbs, walking ability, and gait in stroke patients at present.

2. RAS in the application of stroke

In recent years, a large number of studies have accumulated data on the peripheral and behavioural benefits of RAS for stroke survivors in three areas: lower limb motor function, walking ability and spatiotemporal gait parameters.

2.1. Remodeling of lower limb motor function

A single-blind historical control study included 55 patients with subacute stroke who had recently suffered a stroke (within three weeks). The control group (n=27) received 11 hours of regular physical therapy per week, and the intervention group (n=28) also had the same plus three RAS sessions per week. There were no significant differences in the main indicators of Tinetti balance and gait test, Timed Up & Go test and walking speed; however, the improvement in Functional Ambulation Classification (FAC) was relatively better in the intervention group (3.43 ± 1.17) than in the control group (2.48 ± 1.09), with a p-value of 0.002.

A systematic review of data from 21 papers and analysed the functional ambulation of 948 stroke survivors under the influence of RAS and different types of walking assistive devices [5]. All the randomised controlled trials (RCTs) and quasi-experimental studies included here used RAS (with or without music) as the experimental intervention, and the control groups received conventional therapy or other active treatments. Nine of these trials showed a significant improvement in gait ($p < 0.05$) in the RAS group or a group difference that favoured RAS. Therefore, RAS can improve the gait performance of stroke patients, but the effect of lesion location on this is not yet clear.

2.2. Enhancement of walking capacity

A RCT on 30 male stroke patients aged 45-60 with stroke onset within the last 6-24 months to study the impact of RAS combined with treadmill exercise on all-important parameters of gait. Participants were randomly divided into two groups: a control group (traditional stroke rehabilitation and treadmill training) and a study group (the same as the control group plus RAS delivered via a metronome in headphones) [6]. There were three 30-minute sessions each week for six weeks of the intervention. Both groups improved to some extent from the baseline, but the RAS group showed a much larger improvement. The increase in walking speed for the RAS group was 25.35% (from 0.71 m/s to 0.89 m/s), compared to only 8.33% in the control group (from 0.72 m/s to

0.78 m/s), with a mean difference of 0.11 m/s and $p = 0.001$. Step cycle increased by 16.66% from 4.91% ($p=0.01$). The step length of the affected side increased by 25.71% compared to 11.11% ($p = 0.03$), and the proportion of time spent on the affected foot rose to 6.69% from 2.54% ($p = 0.04$). The ambulation index was also relatively higher in the RAS group (4.70%) compared with the control group (1.47%), $p=0.01$. There are no significant differences in the non-affected-side parameters. Based on the above research, the addition of RAS to treadmill exercise can significantly increase the walking speed, step cycle, affected-side step length, weight-bearing symmetry and overall ambulation index of chronic stroke patients; therefore, RAS may be employed as an auxiliary measure to improve gait function.

Treadmill exercise by itself has shown some good results; however, in addition to single-sided step training, the combination of rhythmic auditory stimulation and this therapy (RAS + UST) has also helped improve the gait and balance of stroke patients. Khalid et al. conducted a three-arm randomised controlled trial with 61 patients who had suffered a chronic stroke, and compared RAS + UST to UST alone and conventional treadmill training (CTT). After 12 weeks of intervention, the RAS + UST group had better improvements in all functional outcomes than CTT. Timed Up and Go (TUG) time was reduced from 16.44 s to 11.19 s (-5.25 s) in the RAS + UST group, and the CTT group improved from 16.41 s to 13.75 s (+16.2 %); the difference between the two groups at 12 weeks was statistically significant ($p = 0.007$). The scores of the Berg Balance Scale (BBS) were higher in the RAS + UST group (39.48 → 49.43), while the increase in the CTT group (37.11 → 45.79, +23.4%) was relatively lower ($p=0.019$). In addition, the Postural Stability Index (PSI) improved by 42.2% (from 3.48 to 2.01) in the RAS + UST group and by 22.2% (from 3.43 to 2.67) in the CTT group ($p = 0.003$). Fall risk scores (FRS) were also reduced more significantly in the RAS+UST group (3.09 → 1.99) than in the CTT group (+19.6%) ($p = 0.033$). Based on the above studies, it can be concluded that, in combination with auditory cues and task-oriented unilateral step training, this method is more effective than using a treadmill alone to improve functional mobility, balance and postural stability in stroke patients [7].

2.3. Normalization of spatiotemporal gait parameters

A typical randomized controlled trial is shown here: researchers compared RAS gait training with and without vibrotactile feedback (i.e., RASV vs. RG) in 22 stroke patients, and both groups had 30-minute sessions five times a week for four weeks. The RASV group had significantly better gains in all the gait-and-balance indicators at the end. The step frequency of the RASV group increased from 78.23 to 91.61 steps/min (a 17.1% increase), and that of the RG group only rose slightly from 88.74 to 91.37 steps/min (an increase of only 3.0%, $p=0.004$). The speed of walking was higher in the RASV group than in the RG group. On the 10m walk test (10mWT), the RASV group reduced the cut completion time from 26.41 seconds to 21.30 seconds, an improvement of 19.4%, and the RG group only showed a small drop (3.4% improvement, $p = 0.015$). Dynamic balance, as shown by the Timed Up and Go (TUG) test, was also better in RASV. Therefore, adding vibrotactile feedback to RAS has expanded many of the advantages for gait and balance after stroke, and multiple sensory inputs may be a more effective approach to rehabilitation for stroke survivors [8].

Another study employed a prospective single-group pre-post controlled design and included 18 patients with either cerebral palsy or post-stroke hemiplegia. They received rhythmic auditory stimulation (RAS) gait training three times a week for 30 minutes each time over four weeks, and the training used keyboard and chord rhythms for rhythmic auditory cues. Kinematic and spatiotemporal parameters in the 3D motion analysis were acquired before and after treatment, and then the Gait Deviation Index (GDI) was computed. According to the results, RAS significantly

improved hip adduction (midstance), maximum knee flexion (midswing), ankle plantar flexion (initial contact and pushoff), and ankle dorsiflexion (end of stance); the GDI increased from 83.89 to 87.29, and the asymmetry in support and swing phases between the affected and healthy sides was reduced significantly. Subgroup analysis revealed the following patterns: Stroke patients with previous normal walking experience showed a greater improvement in knee flexion and ankle dorsiflexion; subacute stroke patients showed a clear increase in GDI, but chronic patients did not exhibit this change; community walkers mainly improved distal joints (knee, ankle), whereas household walkers mainly improved proximal pelvic anteversion. Therefore, RAS can improve the gait in hemiplegia to some extent; however, the extent of improvement depends on the cause, progression of the disease and walking ability.

In addition to velocity and cadence, gait symmetry is a critical spatiotemporal parameter often impaired after stroke. Bilateral RAS significantly improved gait symmetry indices, including the Symmetry Index (SI) and Gait Asymmetry (GA) score, indicating more balanced step timing between the paretic and non-paretic sides [8].

Similarly, RAS gait training for three weeks significantly increased gait velocity, stride length, and cadence, as well as standing balance measured by the Biodex balance system, further supporting the positive effects of RAS on spatiotemporal parameters [9].

3. Mechanisms underlying the effects of RAS

Firstly, auditory-motor coupling is the core neurophysiological basis of RAS. Rhythmic entrainment involves the synchronization of auditory neuron firing rates with motor neuron activity, which stabilizes the temporal relationship between rhythmic auditory signals and motor behavior, thereby enhancing motor control [10]. The rhythmic auditory signals provided by music or a metronome activate the interconnected auditory cortex, premotor area, and motor area in the brain, and involve the basal ganglia, thalamocortical and cerebellar-thalamocortical motor networks, thereby compensating for the loss of automaticity and rhythm caused by Parkinson's disease or stroke. This coupling utilizes the inherent time processing process, enabling patients to re-establish a stable gait rhythm under the external rhythmic drive. Secondly, motor synchronization and gait relearning effect: RAS promotes the synchronization of the patient's gait with external stimuli through real-time beat cues, significantly improving gait speed, stride length, gait frequency, and gait variability. The interactive RAS system (such as Walk-Mate) uses nonlinear oscillators and foot pressure sensors to track the patient's stride intervals in real time and generate mutually adaptive rhythm cues, enabling the coupling of gait with cues, thereby achieving a stronger gait relearning effect than fixed beats, manifested as an increase in fractal scaling index and more precise rhythm locking. Thirdly, multisensory integration and posture control: In stroke rehabilitation, when RAS is combined with unilateral gait training, auditory input integrates with somatosensory, proprioceptive, and visual information, helping patients more accurately perceive and control the center of gravity, expand the stability limit, and reduce the risk of postural sway and falls. RAS improves the patient's unilateral weight-bearing ability and symmetry, promotes feedforward and compensatory postural adjustments, and enhances static and dynamic balance (such as the Berg Balance Scale, overall stability index). Fourthly, RAS can reduce reliance on cognitive attention, and continuous rhythmic cues can automatically drive movement, even in patients with cognitive impairment. Additionally, different music types regulate gait parameters through emotion and familiarity: fast-paced, familiar music enhances gait speed and stride length, while slow-paced classical music may have a suppressive effect. In summary, RAS synergistically improves the motor function of neuro patients

through three paths: neural rhythmic drive, sensory-motor integration, and task-specific learning [1, 6, 7].

4. Limitation

While RAS does enhance walking and balance parameters at all times of a stroke, the ways in which functional ambulation and the use of walking aids were presented were not always consistent. RAS is undoubtedly useful, but we still do not have standardized outcome indicators.

Although there have been some positive indications recently, many limitations also need to be taken into account at present in light of this data. The first is that, although most of the studies reported good results, the actual degree of improvement varied greatly among the different studies. The above differences may be due to different durations of intervention, frequency, level of intensity, styles of training and methods of cueing. Some studies have used only a basic metronome; others have added music-based rhythmic cues and other forms of sensory feedback. The various ways in which they are studied are not uniform, and therefore the results do not necessarily coincide.

Many of the previous studies also had relatively small sample sizes. A few examples of RCTs have been taken; they involved fewer than 50 participants and thus had reduced statistical power for generalisation. Patients in the different studies were also not the same in terms of age, time since stroke, baseline walking ability, or severity of motor impairment. Therefore, it is difficult to identify the ideal recipient group for the study of RAS-based rehabilitation.

Third, most research focused only on the short term. Intervention periods were generally for four to eight weeks, and few studies have followed the participants over an extended time. Therefore, we do not know whether the improvement in gait and walking ability will be maintained after stopping the treatment. Longitudinal studies will be carried out to find out how long the benefits of RAS induction will last and what kind of effects they will have on long-term recovery.

Some essential clinical factors have been overlooked by others so far. There is a shortage of data on the impact of lesion location, stroke severity, cognitive status, sensory deficits and other health conditions on treatment response. The above reasons may affect the ability of a person to move in time with music and therefore change the results of rehabilitation. Therefore, the following research will explore what predicts whether a patient will respond well to RAS and identify the groups that will benefit most from RAS.

Most of the research has therefore focused on space-time gait characteristics, such as speed, cadence and step length. Certainly, those are the clinically relevant ones, but a wide range of indicators of rehabilitation success have been neglected, such as daily life participation, community walking, quality of life, fall prevention, and long-term functional independence. Future studies can add these patient-centered outcomes to provide more complete information on the clinical benefits of RAS.

Based on the above, it can be concluded that RAS is a suitable adjuvant therapy for gait training in stroke rehabilitation. Conduct more large-scale, high-quality randomised controlled trials (RCTs) under standardised protocols, use extended follow-up studies to strengthen the evidence foundation, determine optimal treatment parameters, and find out which groups of patients will benefit most.

5. Conclusion

Rhythmic auditory stimulation is a simple-to-implement rehabilitation method that has a relatively low cost and is based on strong neuroscience evidence; thus far, it has shown good results in improving the function of lower limbs in stroke patients with hemiplegia. Based on the current

evidence, we know that RAS can increase gait speed, cadence, step length, balance and functional ambulation, and the benefits are generally more pronounced when combined with treadmill training, vibrotactile feedback or other task-oriented rehabilitation methods. In terms of how it functions, it uses auditory-motor coupling and relearns the synchronisation of gait, multisensory integration and automatic control to improve motor function in people with neurological disorders.

Although the above research has offered some hope, many problems in the existing data collection methods remain unresolved. One is that many studies have used relatively small sample sizes, so it is difficult to extend the results to other patients; others are very inconsistent with other studies in terms of intervention period, training frequency, cueing method, outcome indicators, etc., making direct comparisons hard. In addition to the above, most of the previous studies have focused only on short-term results, and therefore we lack sufficient evidence for long-term effects of the intervention. We are still learning which factors may affect a patient's response to RAS better, such as the position of the lesion, the extent of the stroke, changes in cognition, recovery status, etc.

In the future, research will need to focus more on large-scale, high-quality randomised controlled trials that use standardised intervention protocols and include an extended follow-up period. More research needs to be carried out to determine a suitable dosage of the treatment, identify the group of patients who will benefit the most, and uncover the neural mechanisms of RAS-induced recovery. By addressing the above shortcomings, we will provide better support for building an evidence base and expanding the application of RAS in stroke rehabilitation.

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