



Original Article

# Rhythmic auditory stimulation using a portable smart device: short-term effects on gait in chronic hemiplegic stroke patients

BYUNG-WOO KO, MSc<sup>1)</sup>, HWI-YOUNG LEE, BSc<sup>1)</sup>, WON-KYUNG SONG, PhD<sup>1)\*</sup>

<sup>1)</sup> Department of Rehabilitation and Assistive Technology, National Rehabilitation Research Institute, National Rehabilitation Center: 58 Samgaksan-ro, Gangbuk-gu, Seoul 01022, Republic of Korea

**Abstract.** [Purpose] The effects of various rhythmic auditory stimulation tempos on stroke gait pattern changes when training patients with a smartphone-based rhythmic auditory stimulation application were investigated. [Subjects and Methods] Fifteen patients with chronic stroke were included. Cadence during comfortable walking was measured (baseline). After the baseline findings were recorded, rhythmic auditory stimulation with five different tempos (i.e., -10%, -5%, 0%, +5%, and +10% change from baseline) was randomly applied. Finally, comfortable walking without rhythmic auditory stimulation was initiated to evaluate gait pattern changes. [Results] As the tempo increased, the spatiotemporal gait parameters of the stroke patients changed significantly. Gait speed, cadence, and gait cycle duration showed the greatest improvement in the +10% rhythmic auditory stimulation condition compared to baseline. After gait training with rhythmic auditory stimulation, gait speed, cadence, stride length, gait cycle duration, and step length of the affected and unaffected sides improved significantly compared to baseline. [Conclusion] Significant changes in the gait pattern of stroke patients were noted for various tempos after training with rhythmic auditory stimulation. These findings could be used to customize rehabilitative gait training for patients who experience stroke with hemiplegia.

**Key words:** Rhythmic auditory stimulation, Gait pattern, Stroke

(This article was submitted Dec. 14, 2015, and was accepted Feb. 2, 2016)

## INTRODUCTION

Stroke is the second leading cause of death and causes permanent disability in one-third of survivors<sup>1, 2)</sup>. Many stroke patients suffer from motor impairments that limit muscle control, activities of daily living, and locomotion activity. In addition, stroke patients have increased double support duration, decreased cadence, shorter stride, decreased stance time, and shorter lower limb joint range of motion compared to able-bodied persons<sup>3-5)</sup>.

Rhythmic auditory stimulation (RAS) uses musical stimuli to improve the gait performance of patients who have neurological conditions (e.g., Parkinson's disease, cerebral palsy, traumatic brain injury, stroke)<sup>6)</sup>. Because music includes temporal characteristics such as anticipation and predictability<sup>7)</sup>, RAS may act on the indicators that inform the gait-phase sequence. Stroke patients have shown better performance when engaging in conventional gait training with RAS versus conventional gait training only<sup>6)</sup>. For example, a stroke group that received RAS combined with gait training showed greater improvements in gait velocity, cadence, stride length<sup>8)</sup>, and hip joint motion symmetry and decreased vertical center of mass displacement<sup>9)</sup>. Lee et al.<sup>10)</sup> reported improvements in gait symmetry, velocity, and cadence in stroke patients when gait training by matching the footfall of the affected side with RAS and applying baseline and >30% baseline speed. Compared to the control group, the chronic stroke patients who had trained with home-based auditory stimulation showed significant improvements in affected side stride length, unaffected side stride length, stride length ratio, affected side single support time,

\*Corresponding author. Won-Kyung Song (E-mail: wksong@nrc.go.kr; wonksong@gmail.com)

©2016 The Society of Physical Therapy Science. Published by IPEC Inc.

This is an open-access article distributed under the terms of the Creative Commons Attribution Non-Commercial No Derivatives (by-nc-nd) License <<http://creativecommons.org/licenses/by-nc-nd/4.0/>>.

single support time ratio, and gait velocity<sup>11</sup>).

Recently, the results of studies with auditory cueing systems for gait rehabilitation training have been reported. One study evaluated the Walk-Mate gait support device (SSTCORP., Nagano, Japan)<sup>12, 13</sup>, which was developed to simultaneously support locomotion compensation and gait rehabilitation training using RAS methods. This device consists of a transmitter that pairs with three-axis acceleration sensors worn on each ankle and wireless headphones. The accelerometer data are recorded on a personal computer via a telemeter. Muto et al.<sup>13</sup> reported a significant decrease in ground-contact timing asymmetries and gait tempo fluctuation during gait training with the Walk-Mate device in stroke hemiplegic patients. In another study, Casamassima et al.<sup>14</sup> described inertial measurement units (IMU) based on a wearable auditory feedback system that monitors gait training with Parkinson's disease patients. This system provides real-time audio feedback and estimates spatiotemporal gait parameters via gait event data detected from IMU sensors mounted on both shoes.

Our smartphone-based RAS application was described in a previous study<sup>15</sup>. The advantages of the application include its portability, simple configuration, inclusion of various auditory stimuli, and ease of saving real-time data. This device type must have the capacity to be used during gait training anywhere at any time. In this study, two aspects of our smartphone-based RAS application were investigated: (1) the effects of various RAS tempos on stroke gait patterns and (2) the effects of short-term gait training on spatiotemporal gait parameters in stroke patients.

## SUBJECTS AND METHODS

Fifteen patients with chronic stroke were recruited for this study. The inclusion criteria were as follows: at least 6 months since stroke, no visual or auditory deficits, and independent gait >10 meters. The general characteristics of the study participants are detailed in Table 1. The Institutional Review Board of the Korea National Rehabilitation Center approved the study protocol. The purpose and procedures of the study were fully explained, and all participants were required to provide informed consent.

Gait training with RAS was performed in an unobstructed space and additional auditory stimuli were blocked in order for subjects to concentrate on the RAS sound. Each RAS condition was practiced for 10 minutes. A 3-minute adaptation period and a 7-minute gait-training period were included. All subjects walked at a comfortable speed three times, after which their mean cadence (baseline) was calculated and converted to -10%, -5%, 0%, +5%, and +10% of baseline. The mean cadence was calculated by averaging three 10-meter walk individual times, while subtracting the acceleration and deceleration periods.

The RAS application has seven sound sources (C-E-G, C-F-A, A-D-G, clap, click, gun, and robot) that could be selected and applied based on the user's preference. To adapt to the RAS sounds, participants listened to the rhythm of the application and were instructed to tap their fingers in their lap or stamp their feet when in a seated position. After the adaptation period, the five conditions were randomly assigned. Then, subjects were asked to listen carefully to the rhythm of the RAS application and heel strike to the sounds. Ten-minute intervals between trials eliminated any remaining effects that could influence the next trial.

IMU sensors (Shimmer3, Shimmer, Dublin, Ireland) were attached above both ankle joints for heel-strike detection. These sensors were connected to the RAS smartphone application via Bluetooth, and heel-strike detection information was shown on the display as a red dot. Thus, gait training focused on the timing of heel strikes on the ground and patients were asked to execute heel strikes in tandem with the RAS sound.

A validated wireless inertial sensing device (G-WALK, BTS S.P.A., Milano, Italy) was used in this study<sup>16</sup>. The sensor was attached to subjects' waists (L4-5 intervertebral space) using a semi-elastic belt to determine the acceleration values for three anatomical axes: anterior-posterior, medial-lateral, and vertical<sup>17</sup>. Park and Woo<sup>18</sup> suggested that the G-WALK represents a valid method for assessing the effectiveness of clinical therapeutic interventions of gait analysis. Their comparative study proved that there is a significant and high correlation between gait velocity and cadence and the foot pressure sensor system (GAITRite, CIR Systems, Inc., Clifton, NJ, USA), respectively. Spatiotemporal parameters such as gait speed, cadence, stride length, gait cycle duration, and step length on the affected and unaffected sides were recorded. The spatial symmetry ratio was calculated by recording the step length on the affected and unaffected sides.

Data acquisition was performed at the end of gait training. For each trial, the subjects were asked to walk a level gait way (16 m). To eliminate acceleration and deceleration effects, only the middle distance (10 m) was used for calculations. Data collection was repeated three times with 3 minutes of rest between trials. To determine the effect of various RAS tempos on gait patterns, the Kolmogorov-Smirnov test was used firstly to check if the data were normally distributed. Secondly, a one-way repeated measures analysis of variance (ANOVA) and least significant difference (LSD) post-hoc analysis were performed. Data were analyzed using SPSS Statistics for Windows, Version 21.0 (IBM Corp., Armonk, NY, USA). Significance was set at a level of <0.05.

## RESULTS

The spatiotemporal gait parameters are listed in Table 2. In the -10% RAS condition, gait speed ( $57.84 \pm 8.27$  m/min,  $F=34.219$ ), cadence ( $46.30 \pm 5.35$  steps/min,  $F=114.253$ ), stride length ( $1.27 \pm 0.17$  m,  $F=12.082$ ), step length on the affected side ( $0.65 \pm 0.09$  m,  $F=14.026$ ), and step length on the unaffected side ( $0.61 \pm 0.1$  m,  $F=13.066$ ) decreased significantly com-

**Table 1.** Participant information

	Participants (n=15)
Gender (M/F)	11/4
Age (years)	56.0 (7.4)
Height (cm)	167.7 (7.7)
Weight (kg)	68.3 (8.2)
Paretic side (left/right)	8/7
Since onset (months)	81.9 (87.8)
MMSE-K	28.4 (2.1)
MBI	96.3 (4.4)

Values are means (SD).

MMSE-K: Mini Mental State Examination-Korean version,

MBI: Modified Barthel Index

**Table 2.** Spatiotemporal gait parameters

	Baseline	-10%	-5%	0%	+5%	+10%	After RAS training
Speed (m/min)	70.53 (12.36) †‡§¶**††	57.84 (8.27) **§¶**††	64.30 (9.74) *†§¶**††	68.53 (10.89) †‡§¶**††	77.22 (16.07) *†‡§	77.53 (15.21) †‡§	79.53 (15.85) *†‡§
Cadence (steps/min)	51.89 (6.23) †‡§¶**††	46.30 (5.35) **§¶**††	48.99 (6.03) *†§¶**††	51.44 (6.07) †‡§¶**††	53.73 (6.50) *†‡§**	55.32 (6.79) †‡§¶††	53.30 (7.22) *†‡§**
Stride length (m)	1.37 (0.22) †††	1.27 (0.17) **§¶**††	1.32 (0.18) †¶**††	1.35 (0.18) †‡§¶**††	1.44 (0.22) †‡§	1.42 (0.24) †‡§††	1.50 (0.22) *†‡§**
Gait cycle duration (s)	1.18 (0.16) †‡§¶**††	1.32 (0.17) **§¶**††	1.25 (0.17) *†§¶**††	1.18 (0.16) †‡§¶**††	1.13 (0.16) *†‡§**	1.10 (0.15) †‡§¶††	1.15 (0.18) *†‡§**
Step length affected side (m)	0.69 (0.11) †††	0.65 (0.09) **§¶**††	0.67 (0.10) †¶**††	0.67 (0.09) ¶**††	0.73 (0.12) †‡§	0.72 (0.12) †‡§	0.74 (0.09) *†‡§
Step length unaffected side (m)	0.68 (0.13) †††	0.61 (0.10) **§¶**††	0.65 (0.11) †¶††	0.67 (0.10) †¶††	0.70 (0.13) †‡§	0.68 (0.13) †††	0.75 (0.15) *†‡§**
Symmetry ratio (step length)	1.04 (0.17)	1.06 (0.14)	1.04 (0.15)	1.02 (0.15)	1.06 (0.16)	1.08 (0.15)	1.02 (0.14)

Values are means (SD).

\* Significantly different from baseline (without RAS) ( $p < 0.05$ )

† Significantly different from the -10% RAS condition ( $p < 0.05$ )

‡ Significantly different from the -5% RAS condition ( $p < 0.05$ )

§ Significantly different from the 0% RAS condition ( $p < 0.05$ )

¶ Significantly different from the +5% RAS condition ( $p < 0.05$ )

\*\* Significantly different from the +10% RAS condition ( $p < 0.05$ )

†† Significantly different from after RAS training (without RAS) ( $p < 0.05$ )

pared to baseline ( $p < 0.05$ ). Furthermore, gait cycle duration ( $1.32 \pm 0.17$  s,  $F=150.236$ ) increased significantly compared to baseline ( $p < 0.05$ ). In the -5% RAS condition, gait speed ( $64.30 \pm 9.74$  m/min,  $F=34.219$ ) and cadence ( $48.99 \pm 6.03$  steps/min,  $F=114.253$ ) decreased significantly, while gait cycle duration ( $1.25 \pm 0.17$  s,  $F=150.236$ ) increased significantly compared to baseline ( $p < 0.05$ ). In the +5% RAS condition, gait speed ( $77.22 \pm 16.07$  m/min,  $F=34.219$ ) and cadence ( $53.73 \pm 6.5$  steps/min,  $F=114.253$ ) increased significantly, while gait cycle duration ( $1.13 \pm 0.16$  s,  $F=150.236$ ) decreased significantly compared to baseline ( $p < 0.05$ ). In the +10% RAS condition, gait speed ( $77.53 \pm 15.21$  m/min,  $F=34.219$ ) and cadence ( $55.32 \pm 6.79$  steps/min,  $F=114.253$ ) increased significantly, while gait cycle duration ( $1.10 \pm 0.15$  s,  $F=150.236$ ) decreased significantly compared to baseline ( $p < 0.05$ ). After gait training with RAS, gait speed ( $79.53 \pm 15.85$  m/min,  $F=34.219$ ), cadence ( $53.30 \pm 7.22$  steps/min,  $F=114.253$ ), stride length ( $1.50 \pm 0.22$  m,  $F=12.082$ ), step length on the affected side ( $0.74 \pm 0.09$  m,  $F=14.026$ ), and step length on the unaffected side ( $0.75 \pm 0.15$  m,  $F=13.066$ ) increased significantly compared to baseline ( $p < 0.05$ ). Gait cycle duration ( $0.75 \pm 0.15$  s,  $F=150.236$ ) decreased significantly compared to baseline ( $p < 0.05$ ). There were no significant differences in the symmetry ratio ( $F=1.626$ ).

## DISCUSSION

RAS is an increasingly popular form of rehabilitative exercise therapy for neurological gait disorders. Auditory-motor synchronization in the reticulospinal tract is the key concept of RAS<sup>19</sup>). Timing cues in gait motion have the capacity to improve movement control and change temporal gait parameters<sup>7</sup>). Several studies have demonstrated the effects of RAS on neurological gait disorders such as stroke, Parkinson's disease, and cerebral palsy. These studies reported improvements in gait velocity, stride length, and cadence in response to RAS rehabilitative therapeutic methods<sup>8, 19, 20</sup>). However, most studies of stroke patients have used RAS with constant speed- or time-based stimulation increases. Cha et al.<sup>21</sup>) studied the immediate effects of four RAS tempos (-10%, 0%, +10%, and +20%) on the gait patterns of hemiplegic stroke patients. The authors reported that a faster RAS tempo increased gait velocity, which indicated that there was potential to immediately improve walking abilities. In addition, double limb support decreased significantly as gait velocity increased. Suh et al.<sup>22</sup>) reported improvements in gait velocity, stride length, cadence, and standing balance in a group of hemiplegic stroke patients who received gait training with 5% and 10% increased RAS compared to a group that did not receive RAS.

In this study, the effect of various RAS tempos on gait patterns was examined and the effectiveness of short-term gait training with a smartphone-based RAS application was confirmed. The results showed significant differences in spatiotemporal gait parameters after RAS training compared with those before training. In the -10% RAS condition, gait speed, cadence, stride length, and step length on the affected and unaffected sides decreased significantly, while gait cycle duration increased significantly. In the -5% RAS condition, gait speed and cadence decreased significantly, while gait cycle duration increased significantly. In the +5% and +10% RAS conditions, gait speed and cadence increased significantly, while gait cycle duration decreased significantly. When the RAS tempo increased, all spatiotemporal gait parameters appeared to increase gradually, while the gait cycle duration decreased. Gait speed, cadence, and gait cycle duration showed the highest significant improvement in the +10% RAS condition. After gait training with RAS, gait speed, cadence, stride length, and step length on the affected and unaffected sides increased significantly; gait cycle duration decreased significantly compared to that before RAS gait training. It is especially noteworthy that step length increased significantly not only on the affected side but also on the unaffected side. Hence, it can be concluded that stride length increased significantly after training.

Increased gait speed, which is determined by cadence and stride length<sup>23</sup>), is often an outcome measure when evaluating gait function. The improvement in movement patterns activates an internal time-keeping mechanism, which leads to movement synchronization<sup>24</sup>). In our study, movement patterns were influenced by repetitive external timing cueing. Therefore, the spinal motor system was optimized for movement patterns following the reticulospinal pathway at the brainstem level<sup>25</sup>). Suteerawattananon et al.<sup>26</sup>) reported that auditory cues can increase spinal motor neuron excitability via the reticulospinal tract and decrease muscle reaction time in response to motor commands, thus improving gait speed. Therefore, the auditory information provides stimulation that bypasses the damaged anatomy, leading to good muscle performance or timing control, and modulates a motor timing-control signal that is received by the brain's compensatory network. This has a useful effect on the neurological function and movement-processing centers of the brain<sup>27</sup>).

In the 0% RAS condition, there were no noticeable changes in gait parameters compared to baseline. Prassas et al.<sup>9</sup>) reported no significant changes in stride length when baseline speed was applied with stroke patients. Another study also reported no significant differences in gait parameters such as gait velocity, cadence, or stride length in hemiplegic stroke patients when 0% RAS was applied<sup>21</sup>). Therefore, it may be inferred that rhythmical tempo variations have a positive impact on the gait of stroke patients. However, the equivalent rhythm to gait speed did not significantly affect the gait of stroke patients.

Symmetry is an important factor during exercise or therapeutic treatment, particularly after stroke. Patterson et al. recommended that step length, stance time, and swing time be used as gait parameters when determining the symmetry ratio<sup>28</sup>). In the present study, step length as it pertained to spatial symmetry was examined. Symmetry ratio appeared to improve at 0% and around the -5% RAS condition as well as after RAS training. These trends are likely related to the fact that patients walked with symmetrical auditory cueing that adjusted to a comfortable walking cadence. Although statistically significant results were not obtained, the tendencies of the spatial symmetry ratio were confirmed. Further studies involving more subjects and temporal symmetry factors such as stance time and swing time will be needed.

The present study showed that hemiplegic stroke patients' spatiotemporal gait parameters change with various RAS tempos. Moreover, significant improvements in gait speed, cadence, stride length, and step length on the affected and unaffected sides were observed after gait training. Previous studies of gait training with RAS over the course of three weeks reported significant improvements in gait velocity, stride length, cadence, and symmetry<sup>8</sup>) as well as standing balance<sup>22</sup>) for stroke patients. Future studies need to evaluate more patients and the long-term effects after a certain period of RAS gait training. A longer period of intervention could result in a higher number of positive results.

In the future, we plan to combine our RAS system with a wearable lower-limb rehabilitation robot. Zanotto et al.<sup>29</sup>) examined how different auditory feedback modalities in healthy subjects may affect gait modification through short-term gait training using an exoskeleton robot. The authors asserted that a combination of kinetic and visual guidance might be as effective as combined kinetic guidance and rhythmic cues. We also hope to conduct comparative analyses with robotic devices for various tempos.

In this study, IMU sensors were attached to both ankle joints to gather heel-strike information. The acquired information,

which was displayed on a smartphone, was used by the participants to time their heel strikes to match the RAS sound during gait training. We plan to update the RAS application for use not only in gait training but also during real-time gait evaluation (via calculations based on heel-strike information, including gait symmetry). We expect the application to be useful during gait rehabilitative training and that chronic stroke survivors in any environment may find it useful.

## ACKNOWLEDGEMENT

Funding for this paper was supplied by the MOTIE/KEIT research and development program, “Development of an overground gait rehabilitation robot technology with a success rate over 90% in gait intention detection based on biosignal interface for various gait rehabilitation of stroke patients” (Grant No. 10045164).

## REFERENCES

- 1) Mozaffarian D, Benjamin EJ, Go AS, et al.: Heart disease and stroke statistics—2015 update: a report from the American Heart Association. [https://www.heart.org/idc/groups/ahamah-public/@wcm/@sop/@smd/documents/downloadable/ucm\\_470704.pdf](https://www.heart.org/idc/groups/ahamah-public/@wcm/@sop/@smd/documents/downloadable/ucm_470704.pdf) (Accessed Oct. 14, 2015)
- 2) Christopher M, Alan L, Anthony R, et al.: The World Health Report. Geneva: World Health Organization, 2002.
- 3) Wall JC, Ashburn A: Assessment of gait disability in hemiplegics. Hemiplegic gait. *Scand J Rehabil Med*, 1979, 11: 95–103. [[Medline](#)]
- 4) Parvataneni K, Ploeg L, Olney SJ, et al.: Kinematic, kinetic and metabolic parameters of treadmill versus overground walking in healthy older adults. *Clin Biomech (Bristol, Avon)*, 2009, 24: 95–100. [[Medline](#)] [[CrossRef](#)]
- 5) Yu L, Zhang Q, Hu C, et al.: Effects of different frequencies of rhythmic auditory cueing on the stride length, cadence, and gait speed in healthy young females. *J Phys Ther Sci*, 2015, 27: 485–487. [[Medline](#)] [[CrossRef](#)]
- 6) Thaut MH: The discovery of human auditory-motor entrainment and its role in the development of neurologic music therapy. *Prog Brain Res*, 2015, 217: 253–266. [[Medline](#)] [[CrossRef](#)]
- 7) Thaut MH: Rhythm, Music, and the Brain: Scientific Foundations and Clinical Applications. New York: Routledge, 2005.
- 8) Thaut MH, Leins AK, Rice RR, et al.: Rhythmic auditory stimulation improves gait more than NDT/Bobath training in near-ambulatory patients early post-stroke: a single-blind, randomized trial. *Neurorehabil Neural Repair*, 2007, 21: 455–459. [[Medline](#)] [[CrossRef](#)]
- 9) Prassas S, Thaut MH, McIntosh GC, et al.: Effect of auditory rhythmic cuing on gait kinematic parameters of stroke patients. *Gait Posture*, 1997, 6: 218–223. [[CrossRef](#)]
- 10) Lee SH, Lee KJ, Song CH: Effects of rhythmic auditory stimulation (RAS) on gait ability and symmetry after stroke. *J Phys Ther Sci*, 2012, 24: 311–314. [[CrossRef](#)]
- 11) Kim JS, Oh DW: Home-based auditory stimulation training for gait rehabilitation of chronic stroke patients. *J Phys Ther Sci*, 2012, 24: 775–777. [[CrossRef](#)]
- 12) Miyake Y: Interpersonal synchronization of body motion and the Walk-Mate walking support robot. *IEEE Trans Robot*, 2009, 25: 638–644. [[CrossRef](#)]
- 13) Muto T, Herzberger B, Hermsdoerfer J, et al.: Interactive cueing with Walk-Mate for hemiparetic stroke rehabilitation. *J Neuroeng Rehabil*, 2012, 9: 58. [[Medline](#)] [[CrossRef](#)]
- 14) Casamassima F, Ferrari A, Milosevic B, et al.: A wearable system for gait training in subjects with Parkinson’s disease. *Sens Basel*, 2014, 14: 6229–6246. [[Medline](#)] [[CrossRef](#)]
- 15) Lee H, Ko BW, Song WK, et al.: Rhythmic auditory stimulation for robot-assisted gait rehabilitation: a preliminary study. *IEEE International Conference on Advanced Intelligent Mechatronics in Busan, Korea*, 2015, 422–426.
- 16) Bugané F, Benedetti MG, Casadio G, et al.: Estimation of spatial-temporal gait parameters in level walking based on a single accelerometer: validation on normal subjects by standard gait analysis. *Comput Methods Programs Biomed*, 2012, 108: 129–137. [[Medline](#)] [[CrossRef](#)]
- 17) Pau M, Leban B, Collu G, et al.: Effect of light and vigorous physical activity on balance and gait of older adults. *Arch Gerontol Geriatr*, 2014, 59: 568–573. [[Medline](#)] [[CrossRef](#)]
- 18) Park G, Woo Y, BHSc: Comparison between a center of mass and a foot pressure sensor system for measuring gait parameters in healthy adults. *J Phys Ther Sci*, 2015, 27: 3199–3202. [[Medline](#)] [[CrossRef](#)]
- 19) Kim SJ, Kwak EE, Park ES, et al.: Differential effects of rhythmic auditory stimulation and neurodevelopmental treatment/Bobath on gait patterns in adults with cerebral palsy: a randomized controlled trial. *Clin Rehabil*, 2012, 26: 904–914. [[Medline](#)] [[CrossRef](#)]
- 20) Fernandez del Olmo M, Cudeiro J: A simple procedure using auditory stimuli to improve movement in Parkinson’s disease: a pilot study. *Neurol Clin Neurophysiol*, 2003, 2003: 1–7. [[Medline](#)]
- 21) Cha Y, Kim Y, Chung Y: Immediate effects of rhythmic auditory stimulation with tempo changes on gait in stroke patients. *J Phys Ther Sci*, 2014, 26: 479–482. [[Medline](#)] [[CrossRef](#)]
- 22) Suh JH, Han SJ, Jeon SY, et al.: Effect of rhythmic auditory stimulation on gait and balance in hemiplegic stroke patients. *NeuroRehabilitation*, 2014, 34: 193–199. [[Medline](#)]
- 23) Patterson SL, Rodgers MM, Macko RF, et al.: Effect of treadmill exercise training on spatial and temporal gait parameters in subjects with chronic stroke: a preliminary report. *J Rehabil Res Dev*, 2008, 45: 221–228. [[Medline](#)] [[CrossRef](#)]
- 24) Kwak EE: Effect of rhythmic auditory stimulation on gait performance in children with spastic cerebral palsy. *J Music Ther*, 2007, 44: 198–216. [[Medline](#)] [[CrossRef](#)]
- 25) Thaut MH: Neural basis of rhythmic timing networks in the human brain. *Ann N Y Acad Sci*, 2003, 999: 364–373. [[Medline](#)] [[CrossRef](#)]
- 26) Suteerawattananon M, Morris GS, Etnyre BR, et al.: Effects of visual and auditory cues on gait in individuals with Parkinson’s disease. *J Neurol Sci*, 2004, 219: 63–69. [[Medline](#)] [[CrossRef](#)]

- 27) Thaut MH, Demartin M, Sanes JN: Brain networks for integrative rhythm formation. PLoS ONE, 2008, 3: e2312. [[Medline](#)] [[CrossRef](#)]
- 28) Patterson KK, Gage WH, Brooks D, et al.: Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization. Gait Posture, 2010, 31: 241–246. [[Medline](#)] [[CrossRef](#)]
- 29) Zanotto D, Rosati G, Spagnol S, et al.: Effects of complementary auditory feedback in robot-assisted lower extremity motor adaptation. IEEE Trans Neural Syst Rehabil Eng, 2013, 21: 775–786. [[Medline](#)] [[CrossRef](#)]