

Changes in gait patterns induced by rhythmic auditory stimulation for adolescents with acquired brain injury

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The effects of rhythmic auditory stimulation (RAS) on gait in adolescents with acquired brain injury (ABI) were investigated. A total of 14 adolescents with ABI were initially recruited, and 12 were included in the final analysis ($n = 6$ each). They were randomly assigned to the experimental (RAS) or the control (conventional gait training) groups. The experimental group received gait training with RAS three times a week for 4 weeks. For both groups, spatiotemporal parameters and kinematic data, such as dynamic motions of joints on three-dimensional planes during a gait cycle and the range of motion in each joint, were collected. Significant group differences in pre–post changes were observed in cadence, walking velocity, and step time, indicating that there were greater improvements in those parameters in the RAS group compared with the control group. Significant increases in hip and knee motions in the sagittal plane were also observed in the RAS group. The changes in kinematic data significantly differed between groups, particularly from terminal stance to mid-swing phase. An increase of both spatiotemporal parameters and corresponding kinematic changes of hip and knee joints after RAS protocol indicates that the use of rhythmic cueing may change gait patterns in adolescents with ABI.

Keywords: rhythmic auditory stimulation; gait; rehabilitation; brain injury

Gait dysfunction is one of the primary areas targeted in motor rehabilitation after brain injury. Since the ability to walk significantly influences a person's mobility, deficits in functional and controlled gait are related to an individual's personal safety, independent activity, and quality of life.^{1,2} Acquired brain injury (ABI) affects the speed, accuracy, and coordination of motor performance.^{1,3} Patients with ABI show decreased velocity and step length³ and impaired maintenance of balance during standing as well as walking.^{2,4,5} Researchers reported that decreases in maintaining stable postural control and decreased time of weight shift-

ing were sustained in pediatric patients with brain injury 3 months after incidence of trauma.^{4,6} Disturbances in coordinated gait and balance tend to remain even after a patient's ability to walk independently is restored.^{1,7} Therefore, these impairments weaken locomotive function and aggravate gait pattern for this population.⁷

Rhythmic auditory stimulation (RAS) was repeatedly evidenced to significantly improve gait parameters in individuals with neurological impairments, including stroke, traumatic brain injury, Parkinson's disease, and cerebral palsy.^{8–14} Consistent with the mechanism whereby oscillatory movement can be synchronized to regularly paced external cues, repetitive rhythmic cueing mediates motor control and facilitates execution of expected

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motor responses.¹⁵ Such rhythmic cueing-induced entrainment, in which movements are matched to a continuously timed reference, optimizes these movements by enhancing anticipatory control of muscles and decreasing the variability of movement timing within the predictable time intervals of cueing. This modulates not only temporal aspects but also kinematic control of movements.^{16,29} This is supported by findings demonstrating not only increased walking speed but also quality of gait pattern, such as enhanced movement trajectories and kinematic parameters in patients with neurological impairment who received RAS training.^{14,16,17} Likewise, multiple systematic reviews confirm that intensive and repetitive application of RAS leads to functional changes.^{18–23}

Such findings offer much promise for applying RAS to a younger population with ABI, although research on RAS training with this population is relatively less extensive, compared with older adults with brain injury. When engaging adolescents with ABI in training, their adherence to its training, with such high levels of repetition and intensity, is a key component for positive outcomes.²⁴ For adolescents, personal factors, including self-motivation and emotional stability, play critical roles in maintaining adherence to and endurance of rehabilitative training, owing to developmental and psychological immaturity and impairments to their ongoing development from the age of injury.²⁴ Strategies to maintain active engagement of this young population in repetitive tasks, such as game-based tasks, were also examined to address the boredom, which, otherwise, could lead to less adherence to the rehabilitation regimen.^{24–26} Consideration of age appropriateness and integration of patients' preferred interests and cultural backgrounds are recommended in designing effective rehabilitation for this population.^{27,28}

Pertaining to considering personal interests and preferences associated with music selection for motor performance, the effect of preferred music on exercise has been repeatedly reported. The use of preferred music during treadmill walking produced the highest enjoyment with the exercise and the lowest perceived exertion, which led to increased endurance of intense exercise.²⁹ Likewise, when applying RAS for motor rehabilitation, not only the metronome but also the musically adopted rhythmic cueing (e.g., the use of original music familiar

to or preferred by the patients with the addition of a ticking sound or metronome beat) has been documented in the literature. Such consideration of perceptual and motivational factors can be reflected in the utilization of melodic and harmonic components for RAS via the musical variation of music preferred by young patients with ABI, while not compensating the regularly paced rhythm as the primary therapeutic agent for gait training. This study integrated the music preferences of an adolescent population into their rehabilitation while maintaining the primary mechanism of rhythm-driven gait training, which presents how a training protocol should be adapted and extended to differently and effectively reflect the distinctive needs and interests of young patients with ABI.^{8,12,15,30–32}

On the basis of the effects of gait training with RAS reported in the literature, we hypothesized that gait training with RAS that included preferred music would lead to appropriate spatiotemporal and kinematic changes in the gait of these young patients with ABI. This study used the method to analyze the outcomes after gait training with RAS in a dynamic gait cycle. A motion analysis of gait training with RAS was performed at representative points, including the maximum and minimum angles of each joint kinematic measure in the literature.^{14,17,33} However, accurate detection of individual gait events is essential for determining efficient kinematic analysis.^{34,35} Analysis of parameter changes observed during a dynamic gait cycle will expand our understanding of how rhythmic cueing affects gait in association with a gait cycle. Therefore, this study aimed to examine the effects of RAS designed for adolescents with ABI on their gait function, in terms of spatiotemporal gait parameters, dynamic analysis of kinematic parameters, and range of motion (ROM).

Materials and methods

Participants

All procedures were reviewed and approved by the Institutional Review Board (IRB No. 4-2012-0483). A total of 14 adolescents with ABI were recruited from a rehabilitation hospital. Written informed consent was obtained from each participant and their guardian. Prior to this study, all participants were screened to meet the following criteria. The functional independence measures and the modified Barthel index were administered to all participants by physical therapists who were blind to

the group assignments. Each participant had to be able to walk independently for at least 10 m without a walking aid. In addition, during walking with verbal command, each participant was assessed to show no discernible hearing or visual impairment. Participants were randomly assigned to the experimental group (RAS training) or the control group. Participants in the control group received conventional physical therapy for gait training without RAS. In the RAS group, five males and two females with the mean age of 14.5 (SD = 2.8) were assigned. Four males and three females with the mean age of 14.5 (SD = 4.3) were assigned to the control group. There were no significant differences between the two groups in terms of height ($P = 0.720$), weight ($P = 0.895$), and BMI ($P = 0.628$), indicating that the numbers of males and females in each group would not affect the gait parameters. In addition, no significant group differences were observed in terms of age ($P = 1.000$) and onset duration ($P = 0.344$).

Stimuli

RAS was provided with a four-voice chord progression with the presence of the metronome beats. To reflect patients' music preferences in the RAS, each patient's preferred music was asked before the training. Each participant reported at least two preferred musical examples, and the preferred music was included for construction of RAS. For the use of

preferred music, the rhythm of the original music was converted to a regular four-beat pattern, and harmonic and melodic structures of the music were adopted to be applicable for cueing. Meanwhile, the highest notes of chords composed the main melodic lines of the music, and the lines were maintained to characterize the primary features of the music. During the intervention, RAS was provided live by a certified music therapist playing a keyboard (DGX230, Yamaha, Japan).

Procedures

Each session was conducted in a gait-analysis laboratory with a 10-m walkway within a rehabilitation hospital. Thirty minutes of RAS training took place three times a week for 4 weeks. Two of the patients received eight sessions owing to early discharge, and the rest of the 10 patients received 10 sessions. In the initial session of training, a patient walked along a 10-m walkway four times at their self-paced speed without RAS. On the basis of the walking cadence (steps/min) measured, the tempo of RAS was set. During the subsequent training sessions, each patient was instructed to tap with the provided RAS for 30–40 s to confirm that the patient could synchronize and adapt to the cueing. Each patient then was instructed to walk the length of 10 m with RAS provided by a certified music therapist, who played a keyboard with the provision of the beats from the metronome. This

Table 1. Demographic information of participants

	RAS group ($n = 6$)	Control group ($n = 6$)
Sex (male/female)	4/2	4/2
Age (years; $M \pm SD$)	13.3 ± 2.4	14.2 ± 4.8
Diagnosis (n)		
Traumatic brain injury	2	2
Stroke	2	3
Brain tumor	2	1
Duration since onset (years; $M \pm SD$)	1.8 ± 2.4	1.1 ± 0.8
Location of brain injury		
Cerebellum and brain stem	3	3
F-P-T	2	2
Basal ganglia	1	1
Height (cm)	153.43 ± 14.23	156.43 ± 16.27
Weight (kg)	51.40 ± 21.02	50.10 ± 14.61
Body mass index (kg/m^2)	20.97 ± 4.97	19.96 ± 2.11
FIM	98.57 ± 16.16	96.86 ± 15.84
MBI	65.71 ± 31.97	74.43 ± 12.01

F-P-T, frontoparietotemporal cortex; FIM, functional independence measures; MBI, modified Barthel index.

Table 2. Comparison of spatiotemporal changes between RAS and control groups

Parameter	RAS group (<i>n</i> = 12)						Control group (<i>n</i> = 12)						Group differences in changes at posttest		
	Pretest		Posttest		Mean difference		Pretest		Posttest		Mean difference				
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	<i>t</i>	<i>P</i>	ES
Cadence (step/min) ^a	111.77	9.04	122.97	10.17	11.20	11.79	112.51	10.17	112.91	4.79	0.40	4.77	−2.831	0.005**	1.20
Velocity (m/s)	0.93	0.27	1.16	0.19	0.23	0.26	0.97	0.27	0.98	0.14	0.01	0.05	2.838	0.015*	1.18
Step length (m)	0.50	0.11	0.56	0.08	0.06	0.11	0.52	0.08	0.52	0.08	0.01	0.07	1.621	0.119	0.54
Step time (s)	0.54	0.05	0.48	0.04	−0.06	0.07	0.52	0.06	0.55	0.05	0.03	0.07	−3.004	0.007**	1.29
Step width (m)	0.22	0.05	0.21	0.06	−0.01	0.04	0.19	0.05	0.20	0.05	0.01	0.02	−1.404	0.174	0.63
Single support (%)	0.37	0.03	0.36	0.04	−0.01	0.04	0.40	0.04	0.36	0.05	−0.03	0.05	1.163	0.257	0.44
Double support (%)	0.33	0.09	0.27	0.08	−0.06	0.13	0.31	0.05	0.31	0.07	−0.00	0.09	−1.225	0.233	0.54

n: number of limbs to be measured; ES: effect size.

^aMann–Whitney *U* test. When Mann–Whitney *U* test was conducted, *Z* was calculated.

P* < 0.05. *P* < 0.01.

step was repeated 10–20 times with 1–3 min of rest between walks, depending on the endurance and fatigue level of the patient. After the entrainment to the repetitive external cueing was ensured, which was evaluated by the clinical decision of a certified music therapist and physical therapist with regard to simultaneous occurrence of foot fall and the beat of RAS, the tempo was adjusted to increase in 5% increments in order not to compromise stability.⁸ After the whole process of training, the patient walked again while RAS was faded for the independent carryover.

Measures

For measurement of changes in gait patterns, spatiotemporal and kinematic parameters were collected in the gait-analysis laboratory 2 days before RAS training and 2 days after the completion of training. The control group had the same schedule of gait analysis as the RAS group. Each patient walked barefoot along a 10-m walkway four times at their preferred walking speed without RAS.

A three-dimensional Vicon 370 Motion Analysis system (Oxford Metrics Inc., Oxford) was utilized to record information regarding body movement during gait: spatiotemporal and kinematic parameters. Spatiotemporal parameters included cadence (steps/min), walking velocity (m/s), step length (m), step time (s), step width (m), and single and double support (%). For kinematic parameters, the dynamic ROM of each joint was measured along three dimensions, including the sagittal, coronal, and transverse planes through retrospective markers tracked by six infrared cameras. Fifteen reflective markers were adhered to the sacrum, both sides of the anterior superior iliac spine, middle thigh, lateral epicondyle of the knee, middle shank of

the tibia, lateral malleolus, calcaneus, and second metatarsal head between the forefoot and midfoot. Joint angle was estimated for the motion of the pelvis (tilt, obliquity, and rotation), hip (flexion, extension, adduction, abduction, internal rotation, and external rotation), knee (flexion and extension), and ankle (plantar flexion and dorsiflexion). All spatiotemporal and kinematic data were processed and plotted using Polygon software version 3.5.1 (Oxford Metrics Inc.), interworked with the VICON motion analysis system.

For statistical data analysis, one gait cycle was randomly selected from each participant, and the ROM for each joint was analyzed by subtracting the minimum from the maximum angle of motion estimated during a gait cycle. Furthermore, to identify more specific differences in kinematic data between groups, joint angles at 51 phases during a whole gait cycle were analyzed in both limbs for all participants. Every 2% of the whole gait cycle was detected as a kinematic datum, and serial kinematic points were determined as a specific gait event. The gait events were divided into eight periods: (1) initial contact (0–2%), (2) loading response (2–14%), (3) mid stance (14–30%), (4) terminal stance (30–50%), (5) preswing (50–62%), (6) initial swing (62–76%), (7) mid-swing (76–88%), and (8) terminal swing (88–100%). As a global index of three-dimensional kinematic changes, gait deviation index (GDI) was also assessed to measure pathological gait improvement in patients after gait training with RAS compared with normal references.¹⁷ The GDI score provides information on the comprehensive kinematic changes of the lower extremity throughout the gait cycle by incorporating pelvic tilt, pelvic obliquity, pelvic rotation, hip flexion, hip adduction and abduction, hip internal and external rotation, the

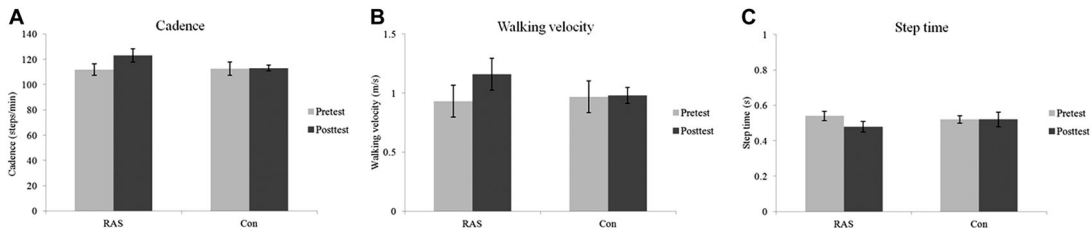


Figure 1. Group differences in cadence, walking velocity, and step time at pretest and posttest.

sagittal angles of the knee and ankle, and the foot progression in the transverse plane.³⁶

Statistical analysis

All statistical analyses were performed with SPSS Statistics 23 (IBM Corp., Armonk, NY). First, a Shapiro–Wilk test of normality was conducted to see if measured variables at pretest are normally distributed so that the use of independent *t*-test is reasonable. Then for each parameter, a Levene's test for equality for variances and an independent *t*-test were performed to assess whether the two groups showed similar levels of gait parameters at pretest. The mean differences in each spatiotemporal parameter between pretest and posttest were calculated. For kinematic parameters, changes in the ROM and values of joint angles at 51 phases during a gait cycle and the GDI at posttest compared with pretest were also measured. For the measured mean differences between pre- and posttest, an independent *t*-test or a Mann–Whitney test as a nonparametric test was conducted to compare the intergroup differences.

Results

In this study, the RAS group and the control group were compared in terms of changes in spatiotemporal gait parameters, GDI, kinematic gait parameters, and ROM during gait. After excluding two patients who showed outlier values that deviated 2 SD from the mean in gait parameters at the pretest, 12 patients were included for final analysis: six for the RAS group and six for the control group. Demographic information of patients who were included in the final analysis is displayed in Table 1.

With regard to all spatiotemporal parameters, the results of the Shapiro–Wilk test of normality showed that the data come from a normal distribution ($P = 0.725$ for walking velocity; $P = 0.463$ for step

length; $P = 0.171$ for step time; $P = 0.157$ for step width; $P = 0.120$ for single support; $P = 0.294$ for double support), except for cadence ($P = 0.004$). A Levene's test for equality for variances showed that the variances were not significantly different between groups ($P > 0.05$). Although there were no significant differences between groups at pretest in each parameter: cadence ($P = 0.152$), velocity ($P = 0.579$), step length ($P = 0.963$), step time ($P = 0.423$), step width ($P = 0.390$), single support ($P = 0.569$), and double support ($P = 0.727$), significant group differences in changes at posttest compared to pretest were observed in cadence, velocity, and step time for which large effect sizes (ranging from 1.18 to 1.29) were measured (Table 2 and Fig. 1).

With regard to kinematic parameters and maximum and minimum joint angles, the results of the Shapiro–Wilk test of normality showed that the data come from a normal distribution, except for the maximum angle of dorsiflexion of ankle ($P = 0.012$). For the ROM during gait measured by minimal angle subtracted from maximal angle, a Levene's test for equality for variances showed that the variances were not significantly different between groups ($P > 0.05$). Although there were no significant group differences in the ROM observed in each joint at pretest (anterior tilt of pelvis ($P = 0.152$), adduction/abduction of pelvis ($P = 0.735$), rotation of pelvis ($P = 0.963$), flexion/extension of hip ($P = 0.496$), adduction/abduction of hip ($P = 0.639$), rotation of hip ($P = 0.847$), flexion of knee ($P = 0.083$), and dorsiflexion/plantarflexion of ankle ($P = 0.640$)), significant group differences in changes at posttest compared to pretest were observed in the range of hip and knee motions for which large effect sizes (range 0.871–1.14) were measured (Table 3). For the knee flexion in which the greatest group difference was found, the RAS group showed increased knee movements during toe

off, which involved changes in limb advancement (Fig. 2).

With regard to kinematic parameters of joint angles, a Levene’s test for equality for variances was conducted to examine whether the two groups showed similar gait patterns at pretest. The results demonstrated that no significant differences were found in kinematic parameters in any relevant joints. For each group, changes in kinematic parameters (i.e., estimated joint angle) at pretest versus posttest in all 51 phases during a gait cycle (every 2% of a total gait cycle) were measured, and inter-group differences were analyzed by conducting an independent *t*-test. In terms of each phase during a gait cycle, changes in kinematic data significantly differed between groups during 54–60% (i.e., from preswing to initial swing phase) of a gait cycle in hip flexion and 28–50% (i.e., from midstance to preswing phase) and 72–78% (i.e., from initial swing to mid-swing phase) of a cycle in knee flexion (Fig. 3).

For the GDI, a Levene’s test for equality for variances showed that there was no significant differences between the two groups at pretest ($P = 0.765$).

The RAS group showed an index of 95.1 (SD = 9.1) at pretest and 95.9 (SD = 13.4) at posttest. The control group showed an index of 90.7 (SD = 9.9) at pretest and 91.2 (SD = 7.4) at posttest. In terms of the mean difference between pre- and posttest, there were no significant differences between groups ($t = 0.102$, $P = 0.920$).

Discussion

The effect of gait training with RAS on the gait of adolescents with ABI was investigated in terms of spatiotemporal and kinematic parameters. Results of this study corroborated that timed control of gait with external auditory cueing led to a significant increase in spatiotemporal gait parameters, compared with changes between pretest and posttest in the control group, which makes the application of RAS for this population promising, along with the large effect sizes measured. Significant changes in spatiotemporal parameters after RAS supported the literature,^{8,9,22} by demonstrating that RAS increased functional ambulatory performance of patients with ABI as evidenced by increased cadence, walking velocity, and step time.

Table 3. Comparison of changes in the range of motion between groups

Joint	RAS group (<i>n</i> = 12)						Control group (<i>n</i> = 12)						Group differences in changes at posttest		
	Pretest		Posttest		Mean difference		Pretest		Posttest		Mean difference		<i>t</i>	<i>P</i>	ES
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD			
Pelvis															
Anterior tilt /posterior tilt	4.2	2.2	4.4	1.9	0.2	1.3	5.9	3.6	5.5	3.0	−0.4	2.1	0.915	0.370	0.34
Adduction/abduction	8.0	4.2	9.6	3.7	1.6	3.5	8.5	3.3	8.0	3.8	−0.4	1.7	1.809	0.084	0.73
Internal/external rotation	14.8	7.3	14.5	5.5	−0.3	9.4	14.2	6.9	15.2	8.4	1.1	6.8	−0.405	0.690	0.17
Hip															
Flexion/extension	40.6	6.3	44.7	2.6	4.1	5.1	42.4	6.2	43.0	5.1	0.5	2.3	2.232	0.036 [*]	0.91
Adduction/abduction	13.2	3.5	15.5	4.5	2.2	3.4	11.8	4.0	11.3	4.2	−0.5	2.8	2.121	0.045 [*]	0.87
Internal/external rotation	33.3	8.4	35.9	9.1	2.6	6.9	34.2	8.7	34.6	8.0	0.4	8.8	0.689	0.498	0.28
Knee															
Flexion/extension	53.9	11.6	60.5	5.2	6.6	10.4	60.6	6.4	57.8	6.8	−2.9	5.5	2.782	0.011 [*]	1.14
Ankle ^a															
Dorsiflexion/plantarflexion	28.9	9.2	32.7	7.4	3.8	7.1	28.6	7.1	29.3	7.5	0.7	6.9	1.146	0.264	0.44

n: number of limbs to be measured; ES: effect size.
^aMann–Whitney *U* test. When Mann–Whitney *U* test was conducted, *Z* was calculated.
* $P < 0.05$.

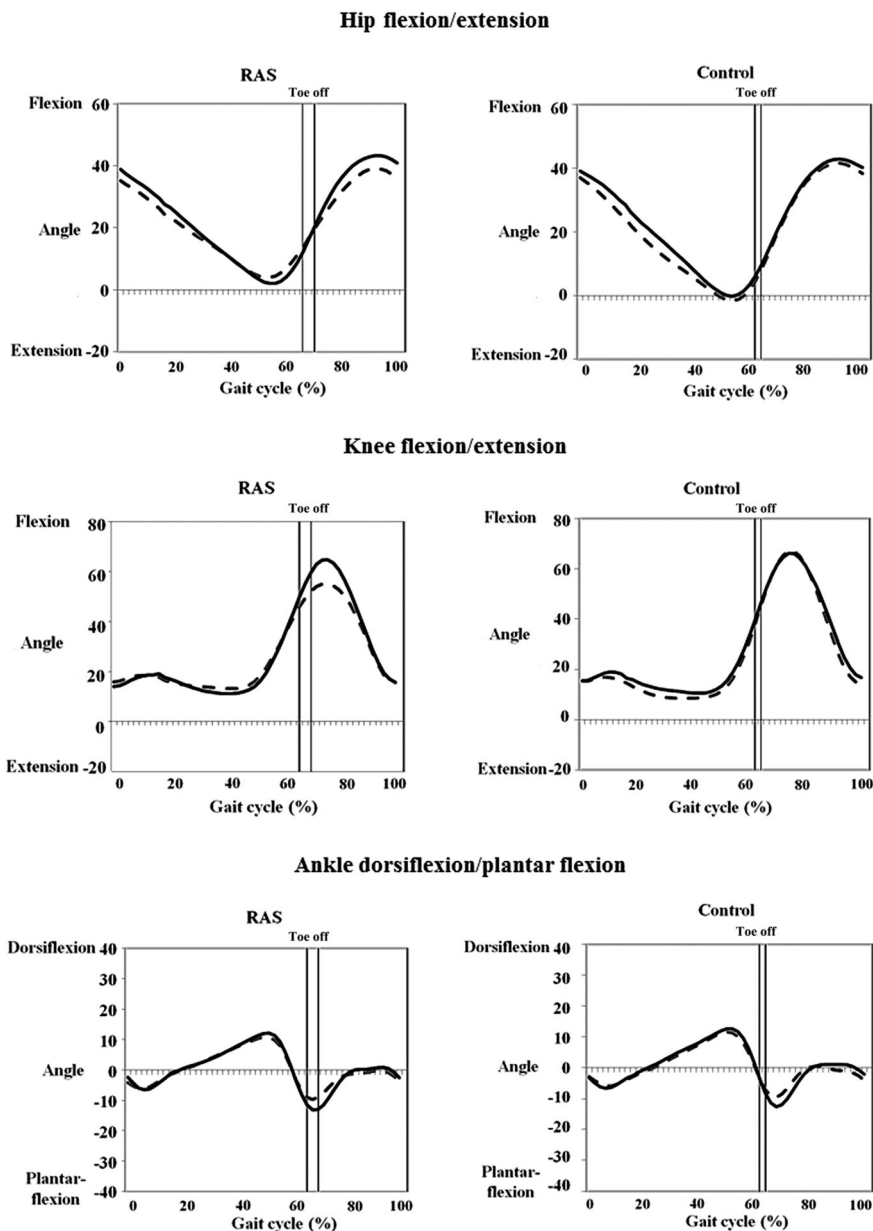
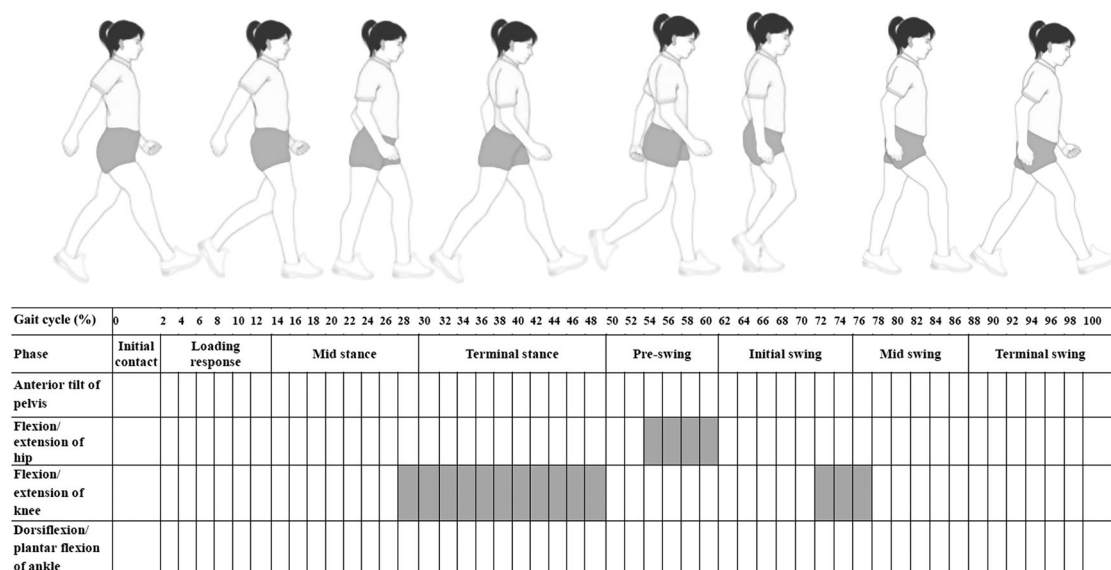


Figure 2. Changes in the angles of hip, knee, and ankle movements in the sagittal plane gait cycle. Dotted lines indicate data at pretest, and bold lines indicate data at posttest.

With regard to ROM, significant increases in hip and knee motions in the sagittal plane were observed in the RAS group compared with the control group, which was supported by the large effect sizes measured. Although initial kinematic patterns were not compared with healthy adolescents, observed characteristics of ABI-induced limited range of flex-

ion/extension in hip and knee joints significantly increased after RAS, while no significant change or a slight decrease in hip and knee movements was observed in the control group.

Reduced sagittal joint kinematics on the paretic lower limbs are generally reported in patients with brain impairment,^{37,38} and this sagittal limitation



may be related to compensatory movement on the frontal plane during gait. The strong relationship between magnitude of sagittal joint angle and gait speed was described in the research.^{38,39} The results of the study indicate that increases in ROM after RAS training may be attributed to significant increases in walking velocity. Limited hip and knee flexion interferes with adequate limb advancement. Significant changes in ROM in hip and knee joints after RAS imply that motor adjustment to predictable timing referent via RAS yields significant increases in joint mobility and movement control of patients with ABI leading to improvement of gait patterns.^{40,41} Such findings suggest that RAS may contribute to increased speed of walking as a key factor for increased magnitude of sagittal joint kinematics, including hip and knee joints in adolescents with ABI.⁴²

As novel parameters for locomotive function, changes in limb motions during each phase of a dynamic gait cycle were measured in this study, which aimed to better explain the improvement of dynamic joint motion during the gait cycle. After RAS, significant changes in hip flexion were observed during the preswing phase, and significant changes in knee flexion were observed during the midstance to terminal stance phase and the initial-to-mid-swing phase. Such results in terms of

kinematic parameter changes are in line with other research findings.¹⁷ Most of the adolescents with ABI in this study initially showed compensatory strategies for insufficient flexion at the hip and knee during terminal stance to swing phase. Increased walking velocity unless accompanied by kinematic appropriateness may aggravate frontal kinematic deviation.³⁹ However, the results of this study suggest that increase of both sagittal joint kinematics and gait speed implies the improvement of walking function. In other words, increased hip flexion and knee flexion during the swing phase contributes to forward progression of the body, accompanied by enhanced walking speed.

Further investigations considering many variables based on kinematic and kinetic patterns with a larger sample size will provide more plausible explanations of changed gait patterns through gait training with RAS in adolescents with ABI. In this study, when the RAS was constructed, a patient's preferred music was adopted to provide a rhythmically isochronous pattern. However, patients' perceptions of such musical variation in terms of familiarity and satisfaction were not measured. In future studies, the use of measures on patients' perceptual evaluation of the presented RAS will provide information on factors for the incorporation of a patient's preference in the RAS.

and the potential effects of musically adapted RAS as motivators or reinforcers for patients.

Although far from conclusive, this study corroborates a newer clinical approach to improve gait patterns using gait training with RAS, including the application of patients' preferred music to maximize motivation for adherence to rehabilitation for adolescents with ABI.

Conclusions

This study evidenced that RAS training with the consideration of patients' preferred music was effectively utilized to improve gait patterns in adolescents with ABI. In this study, the sagittal magnitude of hip and knee joint angles increased from terminal stance to mid-swing phase, accompanied by cadence, walking velocity, and step time after RAS training. This indicates that gait training with RAS can enhance locomotive function. This study also corroborated the rationale for applying musically adapted RAS to gait training in that increased spatiotemporal limb control with increased tempo of cueing led to the adjusted ROM, accordingly facilitating kinematic changes during gait. Additional studies are needed to clearly validate the mechanisms of RAS with the use of patients' preferred music in terms of music perception as well as temporal and motor control from a neurological perspective.

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Conflicts of interest

The authors declare no conflicts of interest.

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