Rhythmic Sensory Stimulation on Gait in Patients With Chronic Stroke

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Rhythmic Sensory Stimulation on Gait in Patients with Chronic Stroke

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Abstract

Background: Patients with stroke suffer from impaired locomotion which exhibit unstable walking with increased gait variability. Rhythmic sensory stimulation is one approach for improving the gait of persons with stroke, Parkinson's disease, or the elderly. However, the effects of this approach on the gait of patients with chronic stroke are unclear. This study was conducted to identify the effects of rhythmic sensory stimulation on the gait of patients with chronic stroke.

Methods: Twenty 20 older adults with stroke (mean age ± SD, 72.10 ± 7.15 years; female/male, 8/12) and twenty age- and gender-matched healthy controls (mean age ± SD, 72.65 ± 6.93 years; female/male, 8/12) walked 60 m under four conditions: (1) normal walking with no stimulation, (2) walking with rhythmic auditory stimulation (RAS), (3) walking with rhythmic somatosensory stimulation (RSS), and (4) walking with rhythmic combined stimulation (RCS: RAS + RSS). RAS was applied through an earphone in the ear of each participant, while RSS was applied through a haptic device on the wrist of the participant. RCS was applied simultaneously via an earphone and haptic device. The gait performance (i.e., mean gait speed, stride length, gait cycle, cadence, stance ratio, swing ratio, and double support ratio) and gait variability (i.e., coefficient of variation (CV) value of stride length, gait cycle, stance ratio, swing ratio, and double support ratio) were evaluated.

Results: Gait performance in the stroke group was significantly improved in walking with RAS, RSS, and RCS compared to normal walking with no stimulation ($P < 0.008$). Gait variability was significantly decreased in the RAS, RSS, and RCS conditions compared to that during normal walking ($P < 0.008$). The gait performance and variability in the healthy control group were not significantly different under the RAS, RSS, or RCS conditions compared to those under normal walking ($P > 0.008$).

Conclusions: Rhythmic sensory stimulation is effective in improving the gait of patients with chronic stroke, regardless of the type of rhythmic stimuli, compared to healthy controls.

Trial registration: This study was approved by the Bioethics Committee (IRB-2019-04-003-001), and all participants provided written informed consent.

Keywords: Stroke, hemiplegia, gait, stimulation

Background

Stroke is a neurological disorder caused by ischemic and hemorrhagic damage to cerebrovascular vessels [1-4]. The most common symptom of stroke is a movement disorder defined as loss or limitation of muscle control and motor function [5-7]. Patients with stroke suffer from impaired locomotion in their daily lives due to movement disorders [8] and exhibit unstable walking, with increased gait variability [7, 9]. Compared with healthy controls, patients with stroke have decreased gait performance, generally expressed as the mean of spatiotemporal parameters [10-12], and increased gait variability, expressed using the standard deviations (SDs) or coefficients of variation (CVs) of the gait spatiotemporal variables [13]. Gait performance in individuals with post-stroke hemiparesis is characterized by reduced walking speed, cadence, stride length, hip joint angle at peak extension, knee joint angle at toe-off or during swinging [14, 15] and increased foot lateral displacement during swinging [15, 16]. Changes in walking variability, known as physiological signals that reflect alterations in walking characteristics due to aging and disease [17, 18], are pronounced in patients with stroke [13]. For example, Balasubramanian et al. [13] reported that the SDs of the spatiotemporal gait parameters, including the step length, swing, and stride time, for patients with stroke were greater than those of healthy individuals in the same age group. Kao et al. [19] also reported significant increases in the SDs of step length, step width, and margin of stability compared to those of healthy controls while patients with stroke walked at four different speeds (60%, 80%, 100% of their preferred speeds and as fast as possible). These results indicate that increased walking variability is closely related to walking in patients with stroke. Reducing such variability should be considered to improve walking in patients with stroke [9] because unstable walking with increased gait variability in these patients can lead to falls [13, 19-23].

Rhythmic sensory stimulation, which can be used to improve the gait of persons with stroke, Parkinson's disease, or the elderly, includes sensory feedback utilizing auditory, somatosensory, and external visual stimuli that provide spatial and temporal information to promote locomotion [24, 25]. Rhythmic auditory stimulation (RAS), which stimulates hearing with fixed rhythms; rhythmic somatosensory stimulation (RSS), which provokes the somatosensory system with rhythmic vibrations; and rhythmic visual stimuli, which stimulates vision with constant patterns, affect the motor system of the human body [26-28]. This rhythmic sensory stimulation enhances the walking ability of patients with motion impairments and reduces walking variability. For example, RAS has been shown to increase gait speed [29] and stride length [30] but to reduce the CVs of stance time and double support time in patients with stroke [9]. RSS has been shown to increase the stride length of patients with Parkinson's disease [31].

Considering these results, applying rhythmic sensory stimulation to patients with stroke could potentially reduce gait variability and improve gait performance [9, 32, 33]. Nevertheless, the effects of RAS, RSS, or rhythmic combined stimulation (RCS: RAS + RSS) on the gait of patients with stroke are unclear. In addition, a previous study examined the ability of RAS to improve gait in patients with stroke; however, the experiment included only one subject, which limits the generalizability of the results [9]. Moreover, the effects of RSS and RCS on the gait of persons with stroke remain unknown. Similar to previous studies [28, 34], which used a mixture of auditory and visual stimulation, the main concern of this study was how the combined effects of auditory and somatosensory stimuli affect the walking of patients with stroke. Therefore, this study aimed to determine whether RSS, RAS, or RCS could improve the walking ability of persons with stroke. We predicted that individuals with stroke will have worse walking performance and greater gait variability than healthy controls and that RCS will induce greater improvement in gait in individuals with stroke than RAS or RSS alone.

Methods

This study was approved by the Bioethics Committee (IRB-2019-04-003-001), and all participants provided written informed consent.

Participants

A total of 40 persons, including 20 participants with stroke and 20 gender- and age-matched healthy controls, were enrolled (Fig 1). The patients with stroke were limited to those who were able to walk independently and participate voluntarily in daily life, whereas the control group included healthy community-dwelling participants of similar age, height, weight, and gender. Table 1 lists the specific characteristics of the participants.

[Insert Table 1 near here]

Two 7D (3D accelerometer, 3D gyroscope, and 1D barometer) inertial measurement units (IMUs; Physilog 5, Gaitup, Inc., Lausanne, Switzerland) that were validated by previous studies [35-38], particularly for assessing the mobility of patients with stroke [39], were used to obtain the gait measurements. Data were extracted from two 7-axis IMU sensors attached to the feet of the participants and transferred to a spreadsheet file in conjunction with analysis software. The initial three footprints of the collected data were manually excluded to minimize experimental variations. The mean walking performance of the calculated data was determined, and the variability was determined as the CV value, which was calculated as ([standard deviation/mean] × 100) [18, 40].

Rhythmic sensory stimulation was presented as a metronome beat by linking the pulse wearable haptic device (Soundbrenner, Inc., Berlin, Germany) and earphones to the tablet PC application software provided by the manufacturer [41]. The wearable haptic device was portable and could be worn on the wrist, whereas the earphone was a small device that could be worn on the ear.

Study design

The Mini-Mental State Exam [42] and Rivermead Mobility Index (RMI) were used to assess the cognitive and motor impairment levels of the participants, respectively [43]. In addition, Up and Go tests were conducted to assess the quickness and dynamic equilibrium of the participants [44]. Thereafter, the participants rested for 5 min and then participated in gait experiments using rhythmic sensory stimulation.

The participants received sufficient explanation from the investigators before participating and performed preliminary exercises for 10 min to familiarize themselves with the experimental protocol. Two 7-axis IMU sensors were attached to both feet in all patients, who were asked to return from a 30 m "return point" for a total of 60 m of walking. The participants were tested under four conditions (Fig 2, 3): (1) no stimulation, (2) RAS, (3) RSS, and (4) RCS. Under the first condition, the participants walked normally. The investigator then matched the metronome beat with the cadence collected from the normal walking of the participant and asked the participant to step in time with the metronome beat [31]. Under the second condition, each participant wore earphones and walked to the RAS in time with the metronome beat. Under the third condition, each participant wore a wearable haptic device on the wrist without paralysis and walked to the return point following vibration of the metronome. Under the fourth condition, each participant wore earphones and the wearable haptic device and walked to the return point in time with the metronome beat and vibration. The last three conditions according to these rhythmic sensory stimuli were performed in random order. The experiment took approximately 50 min, and a 5 min rest period was provided for each experimental condition. Depending on the condition of the participant, the rest time was adjusted to 5–15 min if needed.

Data analysis

The Shapiro-Wilks normality test was performed to confirm that the data in this study were normally distributed. Gait analysis based on rhythmic sensory stimulation was performed by a two-way repeated measures analysis of variance with one between factor and one within factor, and the mean difference was verified at the 0.05 significance level. The independent variables were the group (stroke or healthy control) and type of rhythmic sensory stimulation (no stimulation, RAS, RSS, or RCS), and the dependent variables were the gait performance and variability. When there were interaction effects, three tasks (RAS, RSS, and RCS) were post-tested using the multiple comparisons, with Bonferroni correction. The significance level was corrected to 0.05/6 = 0.0083 by the Bonferroni correction. All data analyses and statistical processes were performed using SPSS ver. 20 (IBM Inc., USA) software. The effect size of the two-way repeated measures analysis of variance was calculated as partial eta-squared (η_p^2). Here, η_p^2 values of 0.01, 0.06, and 0.14 represent small, medium, and large effect sizes, respectively. In the post-hoc test for interactions, the effect size was determined as Cohen's d, where values of 0.2, 0.5, and 0.8 correspond to small, medium, and large effect sizes, respectively. The sample size of the two-way repeated measures in ANOVA was calculated using G*power 3.1.9.4 software. As a result of setting the effect size (*f*) to 0.25, significance level (α) to 0.05 and power ($1 - \beta$) to 95% in the number of samples, the optimal sample size was determined to be 38 subjects.

Results

Table 2 presents the changes in gait performance and variability of the patients with stroke and healthy controls owing to rhythmic sensory stimulation. The gait speed, stride length, cadence, and swing ratio of the gait performance of the group of patients with stroke significantly decreased compared to those of the healthy control group ($P < 0.05$). In addition, the gait cycle, stance ratio, and double support ratio of the gait performance of the group of patients with stroke significantly increased compared to those of the healthy control group ($P < 0.05$). There are significant differences in gait speed, stride length, gait cycle, cadence, and double support ratio according to the rhythmic sensory stimulation ($P < 0.05$), and there are significant differences in gait speed, stride length, and double support ratio according to the interaction ($P < 0.05$).

[Insert Table 2 near here]

According to the post-hoc test, the stroke group had significantly faster gait speed under the

RAS ($P = 0.001$, $d = 0.29$), RSS ($P = 0.001$, $d = 0.30$), and RCS ($P = 0.001$, $d = 0.31$) conditions compared to that for normal walking (Fig 4a), as well as significantly increased stride length under the RAS ($P = 0.001$, $d = 0.30$), RSS ($P = 0.001$, $d = 0.27$), and RCS ($P = 0.001$, $d = 0.27$) conditions compared to that for normal walking (Fig 4b). Moreover, the stroke group showed significantly reduced double support ratios under the RAS ($P = 0.001$, $d = 0.28$) and RCS ($P = 0.001$, $d = 0.22$) conditions compared to that for normal walking (Fig 4c).

The CVs of stride length, gait cycle, stance ratio, and swing ratio for the patients with stroke were significantly higher than those of the healthy controls ($P < 0.05$). There are significant differences in the CVs of stride length, gait cycle, stance ratio, and swing ratio according to the rhythmic sensory stimulation ($P < 0.05$), as well as significant differences in the CVs of stride length, gait cycle, stance ratio, swing ratio, and double support ratio according to the interaction ($P < 0.05$).

According to the post-hoc test, the stroke group had significantly reduced stride length CVs under the RAS ($P = 0.001$, $d = 0.77$), RSS ($P = 0.001$, $d = 0.69$), and RCS ($P = 0.001$, $d = 0.73$) conditions compared to that for normal walking (Fig 5a), as well as significantly reduced gait cycle CVs under the RAS ($P = 0.001$, $d = 0.75$), RSS ($P = 0.001$, $d = 0.63$), and RCS ($P = 0.001$, $d = 0.62$) conditions compared to that for normal walking (Fig 5b). In addition, the stroke group had significantly reduced stance ratio CVs under the RAS ($P = 0.001$, $d = 0.78$), RSS ($P = 0.001$, $d = 0.72$), and RCS ($P = 0.001$, $d = 0.79$) conditions compared to that for normal walking (Fig 5c), as well as significantly reduced swing ratio CVs for the RAS ($P = 0.001$, $d = 0.67$), RSS ($P = 0.001$, $d = 0.55$), and RCS ($P = 0.002$, $d = 0.65$) conditions compared to that for normal walking (Fig 5d). Moreover, the stroke group had a significantly reduced double support ratio CV under the RCS ($P = 0.002$, $d = 0.66$) condition compared to that for normal walking (Fig 5e).

However, the gait performance and variability in the healthy control group did not differ significantly under the RAS, RSS, and RCS conditions from those for normal walking ($P > 0.008$).

In addition, there were no significant differences between the RAS, RSS, and RCS conditions in the gait variability of the stroke and healthy control groups ($P > 0.008$).

Discussion

This study aimed to investigate the effects of rhythmic sensory stimulation on the gait performance of patients with stroke. Gait data were collected through 7-axis accelerometers under four experimental conditions for patients with stroke and healthy controls. The patients with stroke showed decreased gait performance and increased gait variability while walking compared to the healthy controls. In addition, the gait performance of the group of patients with stroke under the RAS, RSS, and RCS conditions was improved; moreover, the gait variability decreased. The walking performance of the healthy control group did not change under the same conditions. The main results of this study are as follows.

First, RAS improved the gait performance and decreased the gait variability of patients with stroke. Thus, the mean gait speed (8.6%) and stride length (7.6%), which are gait performance parameters, increased with RAS during walking compared to those of normal walking without stimulation. The double support ratio (6.6%) decreased. In addition, when RAS was applied during walking, the gait variability parameters, i.e., the CVs of stride length (25.3%), gait cycle (28.1%), stance ratio (21.7%), and swing ratio (25.9%), decreased. Similarly, previous studies have reported that RAS improves gait performance and reduces variability in patients with stroke [7, 9]. For example, Thaut et al. [7] found that RAS increases the mean gait speed and stride length in relation to the walking performance of patients with stroke. Wright et al. [9] found that RAS reduces the CVs of stance time and double support time in gait variability in patients with stroke. This improvement in walking ability results from regular modulation of the central pattern generator of RAS [45, 46].

The regular pattern of rhythmic locomotion of the human body is controlled by the central nervous system [47]. During walking, RAS is thought to help stabilize gait by inducing a certain movement pattern by periodically stimulating the central nervous system [45]. In particular, the three rhythmic sensory stimuli in this study showed significant effects in the five gait variability parameters and three gait performance parameters. These results demonstrate that rhythmic sensory stimulation is more effective at reducing gait variability than at improving overall gait performance in patients with stroke.

Second, RSS improved the gait performance and decreased the gait variability of the patients with stroke. The mean gait speed (8.6%) and stride length (7.6%), which are gait performance parameters, increased with RSS during walking compared to those of normal walking without stimulation in patients with stroke. In addition, when RSS was provided during walking, the gait variability parameters, i.e., the CVs of stride length (23.7%), gait cycle (24.5%), stance ratio (22.0%), and swing ratio (24.5%), decreased. Similarly, previous studies of patients with Parkinson's disease and older adults who experienced falls reported that RSS improved gait performance and reduced gait variability in both groups [26]. For example, van Wegen et al. [31] found that RSS increases the mean step length in walking performance in patients with Parkinson's disease. Galica et al. [26] argued that RSS reduces the SDs of gait variability, gait cycle, stance time, and swing time of older persons with fall histories. Previous studies also indicated that a reduction in proprioception increases gait variability and leads to unstable gait [48, 49]. RSS has been shown to induce a constant motor pattern by periodically promoting somatosensory input in patients with stroke [45]. Similarly, in this study, RSS helped induce a stable gait in patients with stroke. This is the first study to verify the positive effect of RSS on the gait of patients with stroke.

Third, in this study, RCS improved the gait performance and decreased the gait variability of patients with stroke. The gait performance parameters, mean gait speed (8.6%) and stride length

(7.6%), increased, and the double support ratio (5.3%) decreased with RCS compared to those of the natural gait without stimulation. However, when RCS was provided during walking, the gait variability parameters, i.e., stride length (25.1%), gait cycle (24.5%), stance ratio (22.7%), swing ratio (26.0%), and double support ratio (17.3%), decreased. These results were somewhat different from those of previous studies on the effects of mixed stimulation in patients with Parkinson's disease. For example, Arias and Cudeiro [28] found that mixed stimulation of auditory and visual information did not improve the mean speed in the walking performance of patients with Parkinson's disease. Suteerawattananon et al. [34] reported that mixed stimulation of auditory and visual information did not increase the mean stride length related to gait performance in patients with Parkinson's disease. It is not possible to distinguish clearly whether these conflicting results are due to the different subjects using the rhythmic sensory stimuli or the different combinations of sensory stimuli, because the subjects of the previous studies by Arias and Cudeiro [28] and Suteerawattananon et al. [34] were patients with Parkinson's disease, and the stimuli were different. Therefore, follow-up studies on the effects of various forms of rhythmic sensory stimulation on gait are required.

Study Limitations

First, the severity of patients with stroke was evaluated as RMI in this study; however, only one stroke group was considered. Stroke severity could affect the sensitivity of the sensory receptors that utilize the sensory signals in the gait process. Second, the walking speed of the patients with stroke was not sufficiently considered. Understanding how rhythmic sensory stimulation affects patient gait at various gait speeds can provide adequate information for designing an optimal program that will further improve the gait abilities of patients with stroke during rehabilitation. For reference, this study matched the cadence and metronome beats of the rhythmic sensory stimulation in the natural gait of the patients with stroke; however, the gait change of these patients may differ at different gait speeds.

Conclusions

Treatment methods using rhythmic sensory stimulation improved gait performance and decreased gait variability of patients with stroke, regardless of the type of rhythmic stimuli. These benefits were achieved despite the increases in walking speed or stride length of the patients with stroke. Rhythmic sensory stimulation was more effective at stabilizing the walking of these patients compared to that of the healthy control group. This study revealed that the use of rhythmic sensory stimulation could improve the gait of patients with stroke with a relatively high risk of falling.

List of abbreviations

Coefficient of variation (CV), inertial measurement units (IMU), rhythmic auditory stimulation (RAS), rhythmic combined stimulation (RCS), Rivermead Mobility Index (RMI), rhythmic somatosensory stimulation (RSS).

Declarations

Ethics approval and consent to participate

This study was approved by the Bioethics Committee (IRB-2019-04-003-001). All participants provided written informed consent.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

YL and SS designed the study. YL performed the data collection. YL and SS analyzed the data interpreted and wrote the manuscript for publication. SS read and approved the final manuscript.

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Figure Captions

Fig 1 Experimental design flow diagram showing experimental design.

Fig 2 a) Experimental scene of a patient with stroke during a 60-m walk. b) Rhythmic auditory stimulation (RAS) condition. c) Rhythmic somatosensory stimulation (RSS) condition. d) Raw data extracted from 7D IMU sensor.

Fig 3 Examples of gait cycle from a patient with stroke in all walking conditions. a) No stimulation: normal walking; b) RAS: rhythmic auditory stimulation; c) RSS: rhythmic somatosensory stimulation; and d) RCS: rhythmic combined stimulation (RAS + RSS). The horizontal lines are the average gait cycle of patients with stroke. CV: Coefficient of variation.

Fig 4 Effects of rhythmic sensory stimulation on gait performance compared to normal walking. a) speed; b) stride length; and c) double support. Normal: no stimulation; RAS: rhythmic auditory stimulation; RSS: rhythmic somatosensory stimulation; RCS: rhythmic combined stimulation (RAS + RSS). * indicates significant difference compared to normal condition ($P < 0.008$).

Fig 5 Effects of rhythmic sensory stimulation on gait variability compared to normal walking. Coefficients of variation (CV) of a) stride length; b) gait cycle; c) stance; d) swing; and e) double support. Normal: no stimulation; RAS: rhythmic auditory stimulation; RSS: rhythmic somatosensory stimulation; RCS: rhythmic combined stimulation (RAS + RSS). * indicates significant difference compared to normal condition ($P < 0.008$).

Figures

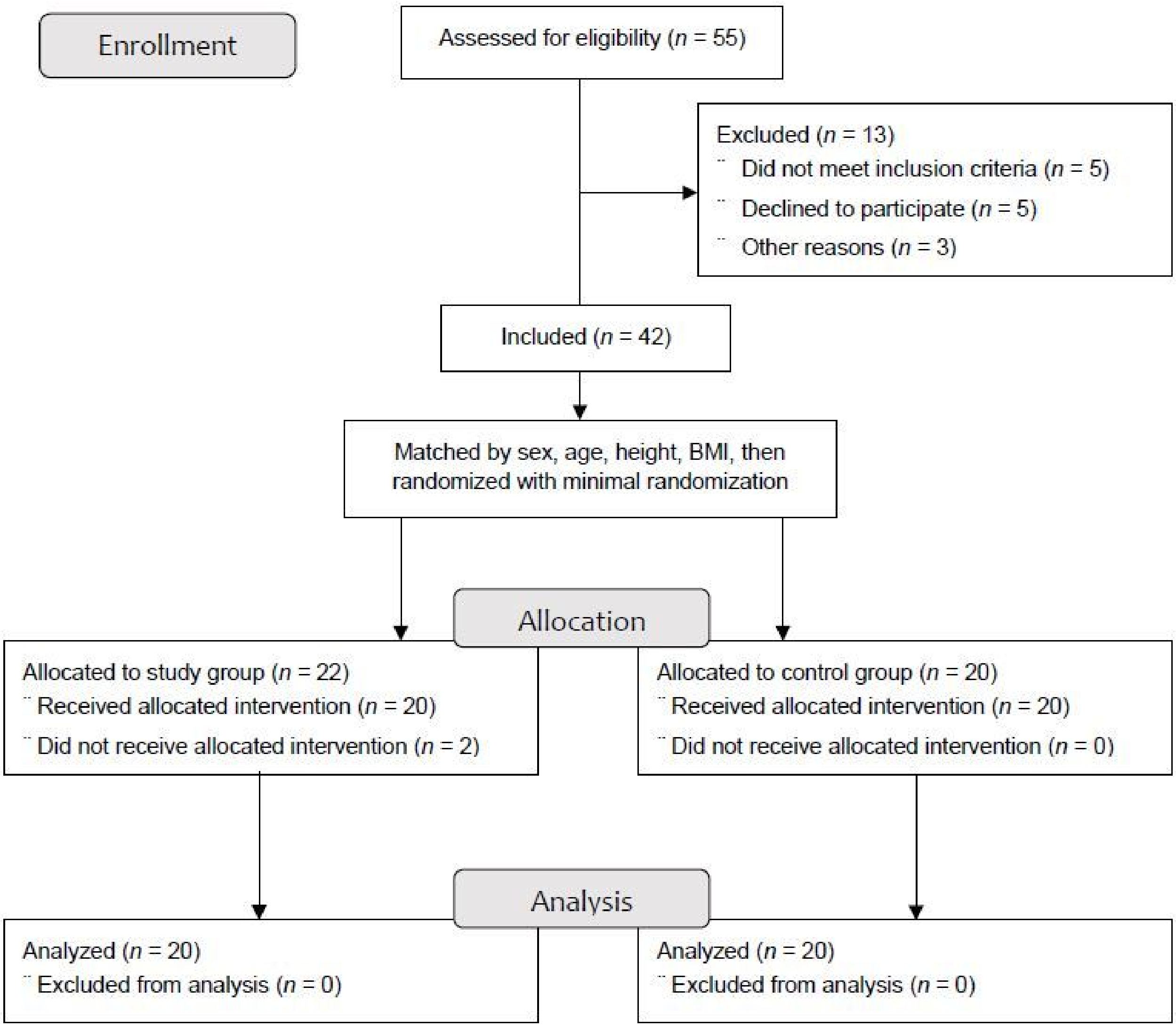

Figure 1

Experimental design flow diagram showing experimental design.

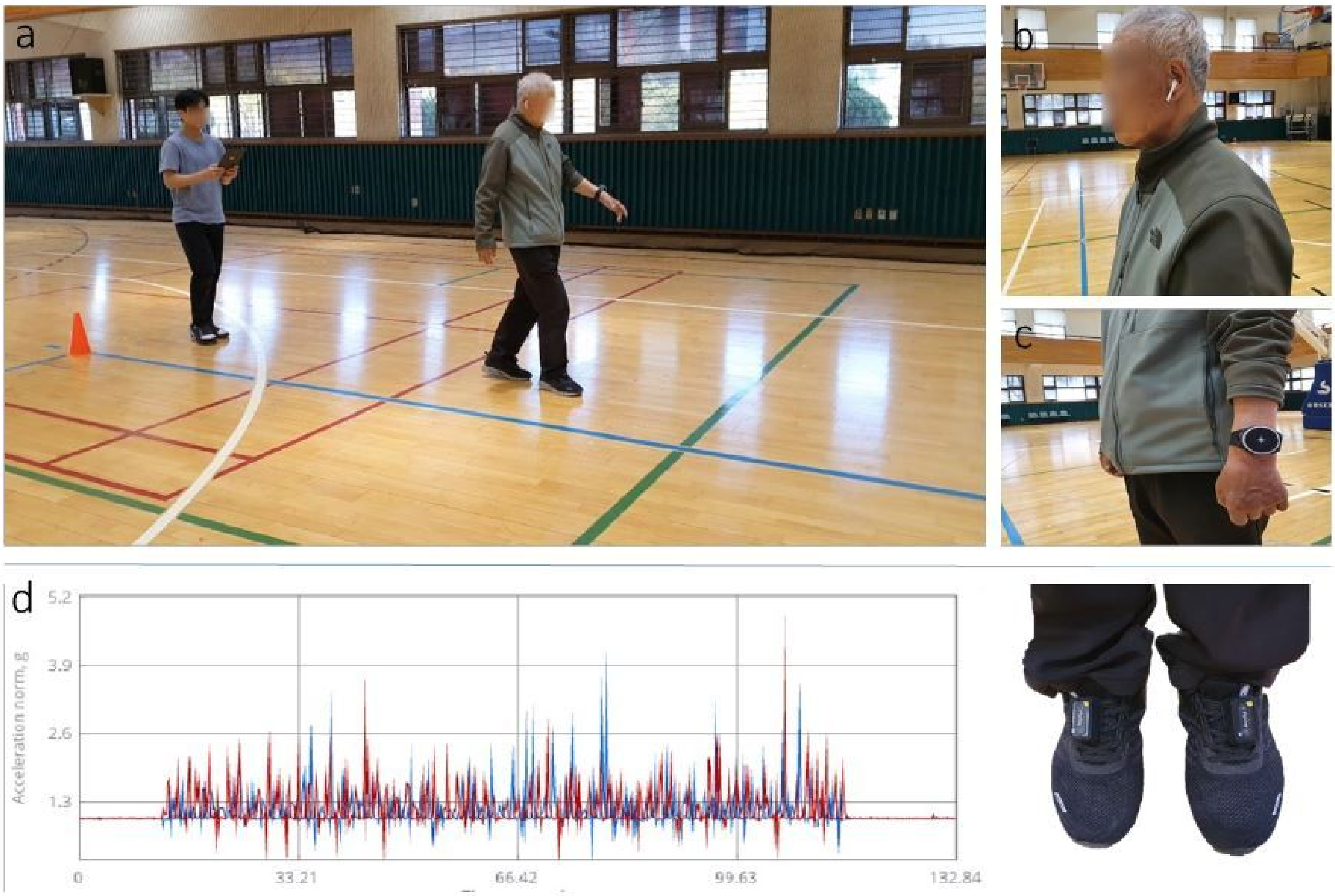

Figure 2

a) Experimental scene of a patient with stroke during a 60-m walk. b) Rhythmic auditory stimulation (RAS) condition. c) Rhythmic somatosensory stimulation (RSS) condition. d) Raw data extracted from 7D IMU sensor.

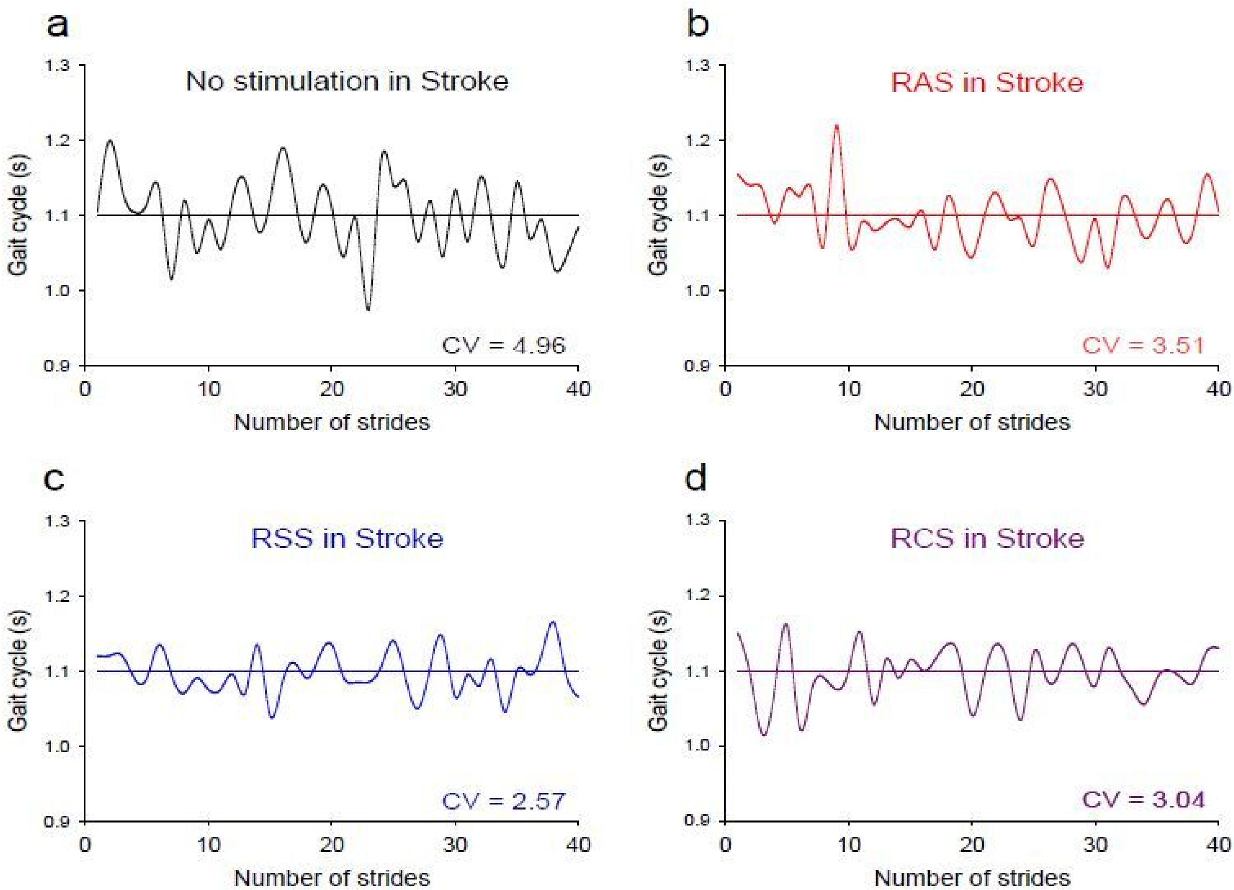

Figure 3

Examples of gait cycle from a patient with stroke in all walking conditions. a) No stimulation: normal walking; b) RAS: rhythmic auditory stimulation; c) RSS: rhythmic somatosensory stimulation; and d) RCS: rhythmic combined stimulation (RAS + RSS). The horizontal lines are the average gait cycle of patients with stroke. CV: Coefficient of variation.

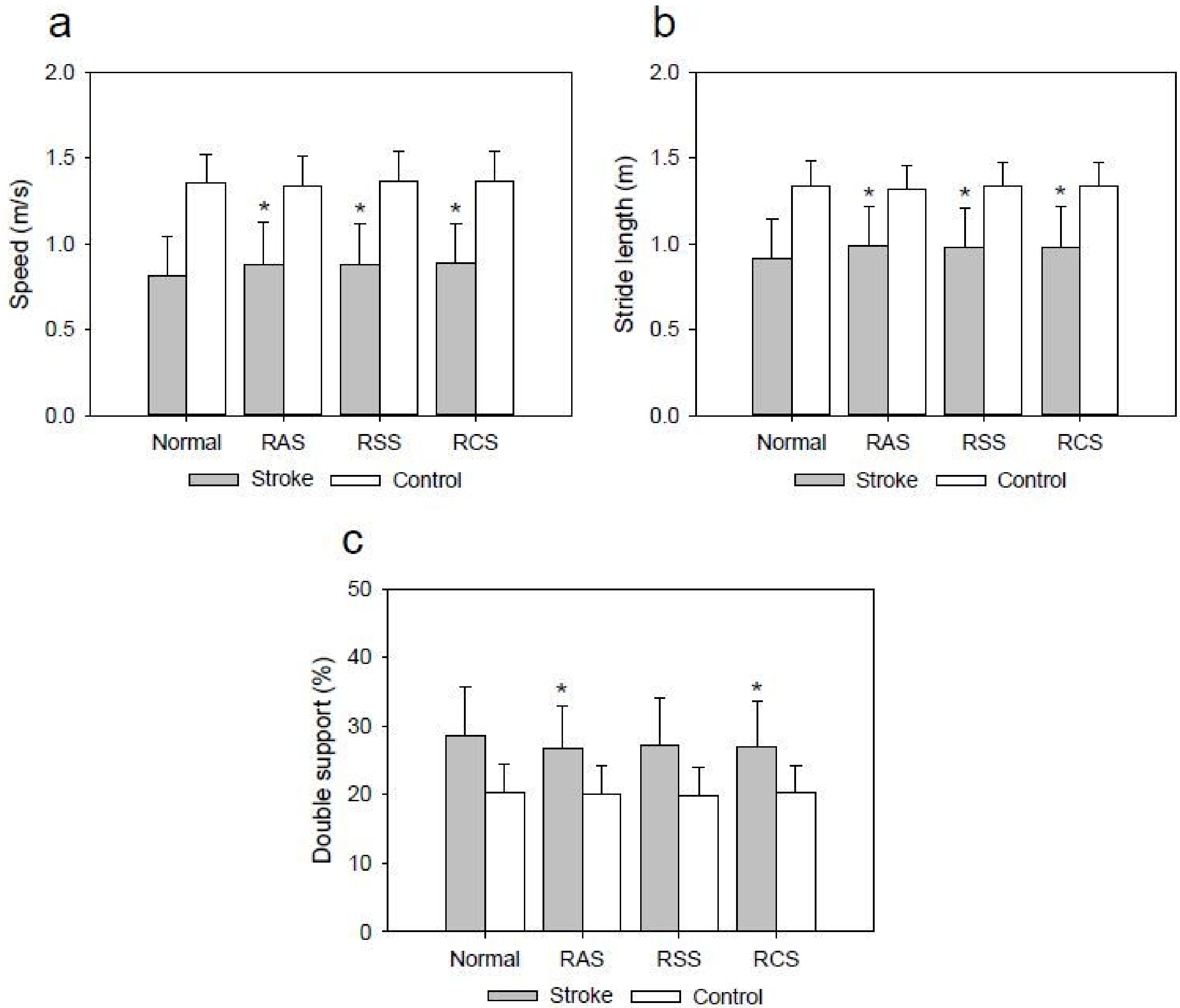

Figure 4

Effects of rhythmic sensory stimulation on gait performance compared to normal walking. a) speed; b) stride length; and c) double support. Normal: no stimulation; RAS: rhythmic auditory stimulation; RSS: rhythmic somatosensory stimulation; RCS: rhythmic combined stimulation (RAS + RSS). * indicates significant difference compared to normal condition (P < 0.008).

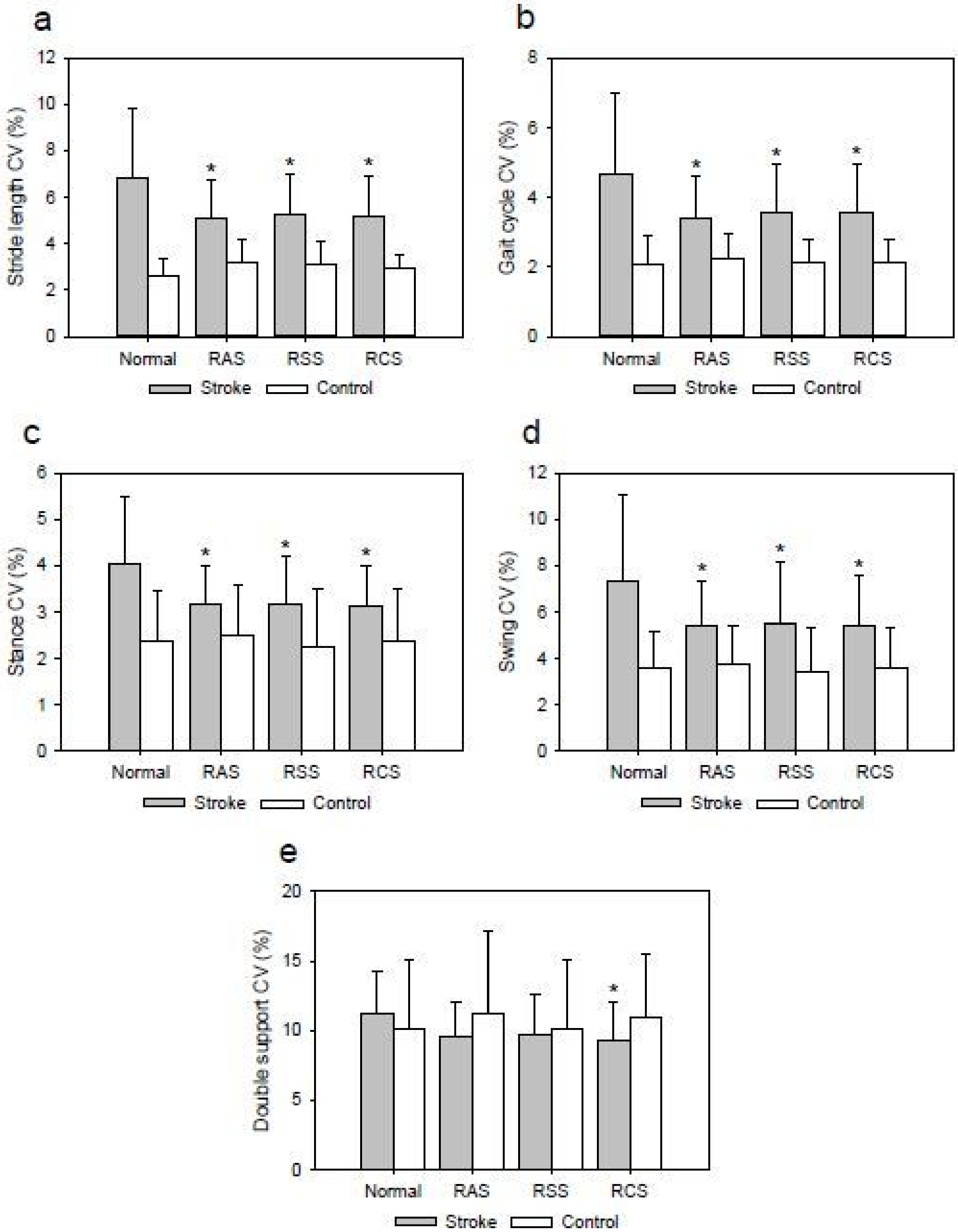

Figure 5

Effects of rhythmic sensory stimulation on gait variability compared to normal walking. Coefficients of variation (CV) of a) stride length; b) gait cycle; c) stance; d) swing; and e) double support. Normal: no stimulation; RAS: rhythmic auditory stimulation; RSS: rhythmic somatosensory stimulation; RCS: rhythmic combined stimulation (RAS + RSS). * indicates significant difference compared to normal condition ($P < 0.008$).

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- Tables.pdf