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Examination of effect and responder to real-time auditory feedback during overground gait for stroke: a randomized cross-over study

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Real-time auditory feedback for overground gait was developed to simulate realistic gait practice. This study aimed to assess the effects of different auditory feedback conditions and identify patients with stroke who might benefit from auditory feedback based on physical function. Twenty patients with stroke participated in three 6-min gait trials: no feedback (control), auditory feedback focused on increasing ankle plantar flexion (ankle trial), and auditory feedback on increasing lower-leg extension angle (leg trial). Physical function was evaluated using the Short Physical Performance Battery (SPPB); gait function was assessed through gait speed, cadence, stride length, and joint motion using inertial sensors before and after each trial. Gait speed ($P = 0.001$), stride length ($P < 0.001$), ankle plantar flexion ($P = 0.014$), and leg extension angles ($P = 0.020$) improved significantly over time. Interaction effects between time and trial were observed for stride length ($P = 0.001$) and leg extension angle ($P = 0.003$). Among the auditory feedback trials, stride length ($P = 0.012$), length-time difference ($P = 0.003$), and leg extension angle ($P = 0.008$) increased significantly in the leg trial compared with the control trial. SPPB scores were independently associated with the benefit from the leg trial (odds ratio: 2.217, 95% confidence interval: 1.152–4.266, $P = 0.017$). Real-time auditory feedback focused on leg extension angle during gait may enhance gait speed by improving leg extension and optimizing spatial gait strategies.

Keywords Overground gait, Stroke, Real-time auditory feedback, Joint angle, Odds ratio

Gait ability is closely related to participation in daily activities and quality of life in patients with stroke[1–3]. Improving the gait ability is a primary goal of rehabilitation for such individuals. Gait speed and lower limb movement on the affected side are important factors for improving gait ability[4–6]. An increase in forward propulsion force has been reported to improve gait speed[7]. Kinematically, the lower leg extension angle and ankle plantar flexion angle in the late stance phase contribute to forward propulsion[8,9]. Therefore, enhancing these angles on the affected side is essential because patients with stroke typically experience reduced motor function on the affected side.

Previous studies used real-time feedback during gait practice to improve lower limb movement and propulsive force on the affected side[10–12]. This approach has been proven effective for improving the peak anterior ground reaction force, paretic ankle movement, and leg extension angle by providing real-time feedback on the anterior ground reaction force or joint angles. However, these feedback devices are limited to specific environments, such as treadmills, three-dimensional (3D) motion analysis systems, or force platforms. The reliance on laboratory-based equipment for biofeedback devices presents a significant challenge for clinical application.

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Treadmill gait practice is an effective method for improving gait function[13]; however, it has been noted that treadmill gait differs from overground, whether indoors or outdoors[14]. A meta-analysis comparing the effects of treadmill and overground gait demonstrated that overground gait is more effective in improving gait endurance, participation, and quality of life[15], which are important for maintaining activity levels in community-dwelling patients with chronic stroke[16]. To address these limitations, Hinton et al. has developed a visual biofeedback device designed to enhance overground gait performance in individuals post-stroke[17]. This study showed that overground visual feedback could also improve gait function in patients with stroke, highlighting its potential for clinical application. However, it remains unclear which parameters related to the propulsive force of gait are most beneficial in overground feedback and which patient populations, based on physical function, derive the greatest benefit. Moreover, magnetic inertial measurement units (IMU) provide a simple means of measuring joint angles during gait[18,19]. Certain IMUs are compatible with mobile and tablet devices, enabling easier implementation[20,21]. If the effectiveness of IMU-based feedback devices can be established, patients with stroke could practice in a more varied environment, such as outdoors or self-practice at home, potentially leading to broader clinical applications.

Real-time feedback for overground walking, which closely simulates daily life, is needed. Research has only recently begun to examine the effect of real-time feedback on overground walking[22,23]. Several questions remain unanswered regarding the most effective biofeedback condition and physical function in post-stroke patients who benefit from this treatment.

Therefore, this study had two objectives: first, to compare the immediate effects of different real-time auditory feedback conditions, focusing on ankle plantar flexion angle or lower leg extension angle related to propulsion during overground gait in individuals with stroke; second, to examine individuals with stroke who would benefit from real-time auditory feedback gait practices based on their physical function. We hypothesized that real-time auditory feedback would increase the targeted joint angles during gait, with a concomitant increase in gait speed. In addition, we hypothesized that real-time auditory feedback would be more effective for those with higher physical function.

Methods

Participants

Twenty participants with chronic stroke were included in this study (Table 1). The participation criteria were the ability to walk at least 14 m without assistance and to walk continuously for 6 min. Participants were excluded from the study if they used an ankle–foot orthosis with limited ankle plantar flexion, had multiple strokes, had severe sensory impairment, or had botulinum toxin injections.

This study was approved by the Ethics Committee of Minami Tohoku Hospital (R5-002) and registered in the University Hospital Medical Information Network Clinical Trial Registry (UMIN-CTR 000051328). Informed consent was obtained from all participants before their inclusion in the study, and adherence to the ethical standards outlined in the Declaration of Helsinki was ensured. This study was performed in accordance with the relevant guidelines and regulations.

Feedback device design

Real-time auditory feedback on joint angles during gait was performed using a laptop personal computer (PC) and IMUs (MTw Awinda, Movella, Henderson, NV, USA). IMUs can calculate Euler angles using a 3D rate gyroscope, 3D accelerometer, and 3D magnetometer. Data obtained from the IMUs have been reported to have high validity[24–28]. Additionally, data from the IMUs were sampled at 40 Hz using MT manager software (Movella, Henderson, NV, USA). The coordinate systems of all sensors were matched using the MT manager for alignment reset. The IMUs were fixed to the pelvis, both anterior thighs, anterior shanks, and feet on the dorsal side[29,30]. Sensors were placed as parallel to the frontal plane as possible. Before gait measurements, shank and thigh lengths and slope were measured in a static standing position to adjust alignment[31]. The initial contact was determined based on the tilt angles of both shanks[32,33]. The joint angle in the sagittal plane was calculated as the relative angle between the IMUs, and the PC emitted a beep sound when the joint angle during the most recent gait cycle exceeded the threshold (Fig. 1). The joint angle corresponding to the auditory feedback during gait was displayed on the PC monitor. The physiotherapist confirmed the timing of the auditory feedback using the

Variables	Values
Age (y)	65.4 ± 10.1
Sex (male/female)	14/6
Affected side (right/left)	7/13
Stroke type (ischemic/hemorrhagic)	7/13
Post stroke duration (m)	63.6 ± 65.0
Use of cane at baseline, N (%)	12 (60.0)
Use of ankle–foot orthosis at baseline, N (%)	7 (35.0)
Fugl-Meyer assessment for the lower-extremities (score)	24.8 ± 4.3
Short physical performance battery (score)	8.6 ± 3.1
Functional ambulation category (score)	4.4 ± 0.7

Table 1. Characteristics of patients with stroke. Values are expressed as mean ± standard deviation.

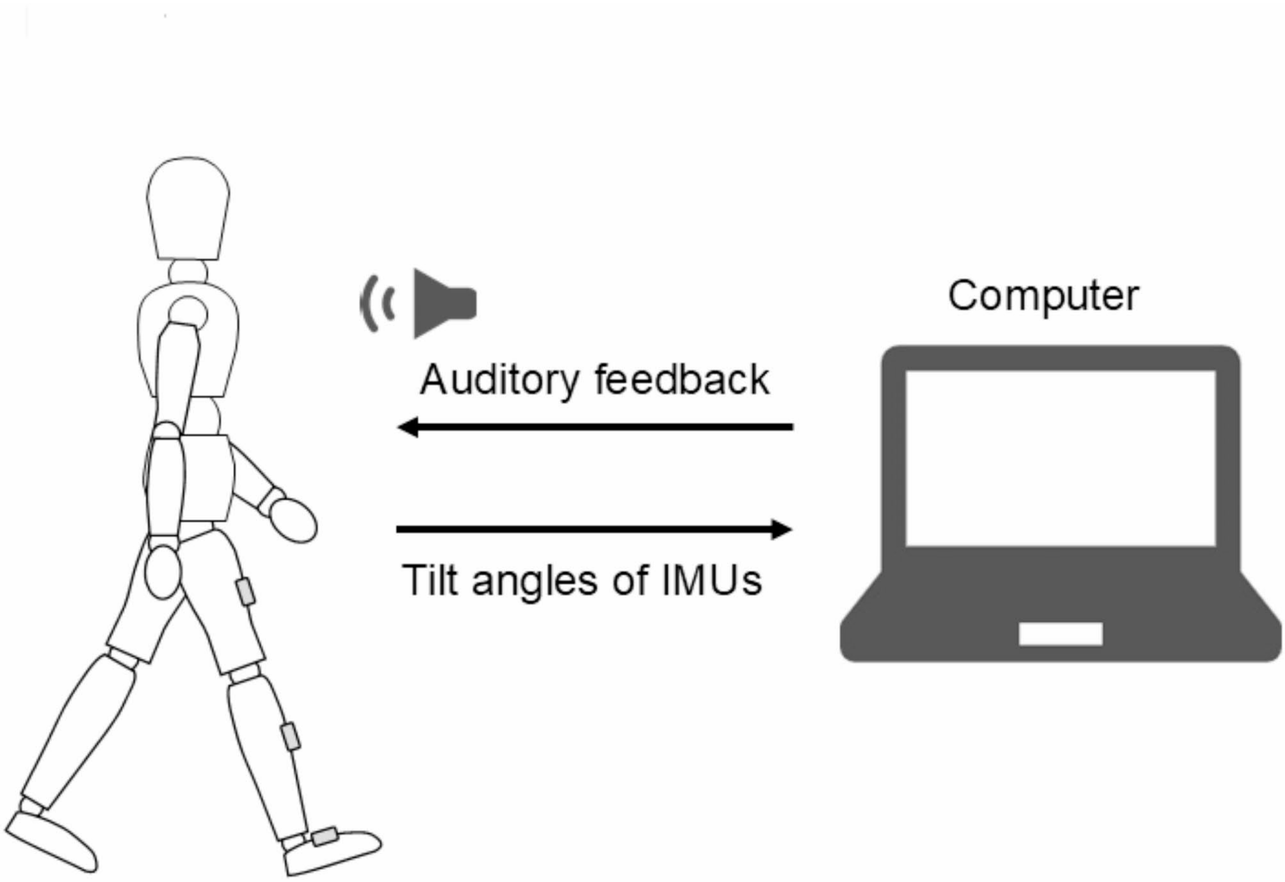

Fig. 1. Feedback devices. The threshold was determined based on auditory feedback obtained from pre-gait measurements. During the feedback trials, the participants modified their gait in response to a beep sound emitted by the computer when their joint angle reached the threshold. The threshold angle was set at a 20% increase in the peak value of each joint angle during spontaneous gait.

graph of the joint angle displayed on the monitor. Participants were not permitted to view the monitor during the trial. This auditory feedback system improved gait parameters in previous studies with older inpatients and healthy participants[23,34].

Trial design

A randomized cross-over design was used to examine the effects of different auditory feedback conditions on gait parameters. Auditory feedback was provided under three conditions: control trial (no feedback), ankle, and leg. The ankle trial used the peak ankle plantar flexion angle during the late stance as the index, whereas the leg trial used the peak leg extension angle. The leg extension angle was defined as the angle between the vertical line and the line connecting the hip and ankle joints, estimated using thigh and shank vectors in the sagittal plane[23,34]. The auditory feedback threshold was set at a 20% increase in the joint angle during comfortable gait. There was a 48-h interval between trials, and the trial order was randomized using a random number table. Each gait trial lasted for 6 min with auditory feedback given intermittently in a 1-min on and 1-min off cycle (Fig. 2A), a method shown to enhance motor learning[10,35,36]. Participants were verbally and visually instructed on the real-time auditory feedback before each trial, as shown in Fig. 2B. The control trial, "walk at your usual pace during this trial"; ankle trial, "push back the ground harder before you swing your leg so that it makes a beep sound during this trial"; leg trial, "extend your leg farther backwards before you swing your leg so that it makes a beep sound during this trial"[23,34]. Gait trials were performed on a 16-m straight line.

Measurement and analysis

Motor function of the lower limbs was measured by the Japanese version of the Fugl-Meyer assessment for the lower extremities (FMA-LE)[37]. Physical performance was measured using a short physical performance battery (SPPB)[38], which comprises balance, gait, and standing tests. Walking independence was assessed using the functional ambulation category (FAC)[39]. Gait performance was evaluated using the 10-m walk test. Participants walked at a self-selected speed during pre- and post-trial phases. Joint angles, root mean square (RMS) values, and step symmetry during gait were calculated from the IMU data obtained during the central six walking cycles of the 10-m walk test. The peak joint angles evaluated, including ankle plantar flexion and leg extension angle during late stance, were evaluated for both the affected and unaffected sides. RMS values and step symmetry

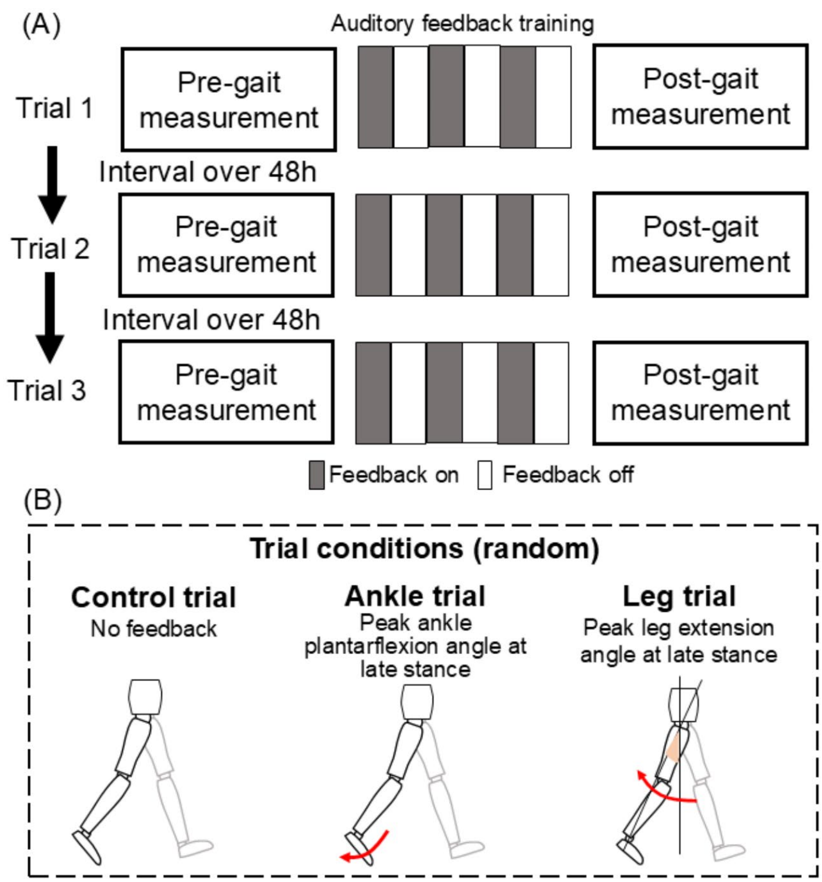

Fig. 2. Real-time auditory feedback gait trial protocol. (**A**) Three trials with randomized auditory feedback conditions were conducted, with intervals of at least 48 h between trials. Each trial lasted 6 min, with auditory feedback provided intermittently in a 1-min on, 1-min off cycle. Gait was assessed before and after each trial. (**B**) Participants received verbal and visual instructions on the real-time auditory feedback before each trial.

were calculated to determine pelvic acceleration in the anterior–posterior, lateral, and vertical directions. RMS has been widely used in studies to measure pelvic sway during gait[40,41]. To account for variations by gait speed, RMS values were normalized to the square of the gait speed, enabling the assessment of pelvic sway independent of gait speed[42]. Step symmetry was estimated from the pelvic acceleration using an autocorrelation function based on the average step-time lag[31,43]. Step symmetry can be interpreted as a measure of the symmetry between steps performed by the affected and the unaffected leg. Step symmetry was closer to 1 when the similarity of consecutive steps was high; however, only step symmetry in lateral direction was closer to – 1 when the similarity between successive steps was high. In addition, Length–Time Difference (LTD) was calculated using stride time and stride length data from IMUs before and after the trial to examine changes in gait strategy[44] Eq. (1).

$$LTD\,(\%) = \frac{(length_{post} - length_{pre})}{(length_{pre})} + \frac{(time_{post} - time_{pre})}{(time_{pre})} \tag{1}$$

A negative value of LTD indicates a time-dependent strategy, such as decreasing stride time and changing gait speed, whereas a positive value of LTD indicates a strategy of increasing stride length and changing gait speed. Therefore, the LTD can clarify the gait strategy influenced by real-time auditory feedback. The data were processed using the MATLAB R2021a software (MathWorks Inc., Natick, MA, USA).

Statistical analysis

Gait parameters were analyzed between time (two levels) and auditory feedback conditions (three levels) using a two-way repeated-measures analysis of variance (ANOVA). LTD was assessed using a one-way repeated-measures ANOVA with auditory feedback condition as a factor. Post hoc tests, Tukey's comparison and Friedman tests were performed to examine differences among auditory feedback conditions regarding the amount of change in the parameters where interaction effects and LTD were observed.

In addition, we investigated the indications for real-time auditory feedback in patients with stroke. The participants were categorized into two groups based on their post-trial gait speed in the control and leg trials. The non-responder group exhibited a faster gait in the control trial, whereas the responder group exhibited a faster gait in the leg trial. The FMA-LE, SPPB, and FAC scores of the two groups were compared using the Mann–

Whitney U test. Forward likelihood ratio logistic regression analysis was performed to identify the responder and non-responder groups with FMA-LE, SPPB, and FAC as explanatory variables. We used a receiver operating characteristic (ROC) curve and Youden index to calculate the cutoff points for a significant model (responder vs. non-responder). The sensitivity and specificity of the cutoff point and area under the curve (AUC) were also calculated. All statistical significance levels were set at 5%. Statistical analyses were performed using SPSS version 29.0 (IBM Corporation, Armonk, NY, USA).

Results

The effects of each auditory feedback trial are summarized in Table 2. A significant main effect of time was observed in gait speed ($F = 14.130$, $P = 0.001$), stride length ($F = 21.296$, $P < 0.001$), ankle plantar flexion, and leg extension angle on the affected ($F = 7.336$, $P = 0.014$ and $F = 6.457$, $P = 0.002$, respectively) and unaffected sides ($F = 14.165$, $P = 0.001$ and $F = 11.107$, $P = 0.003$, respectively). A significant interaction effect (time × trial) was observed for the stride length ($F = 7.974$, $P = 0.001$) and leg extension angle on both sides ($F = 7.042$, $P = 0.003$; $F = 5.186$, $P = 0.010$, respectively). Among the auditory feedback trials, stride length ($P = 0.012$), LTD ($P = 0.003$), and leg extension angle ($P = 0.008$) increased significantly in the leg trial compared with the control trial. The leg extension angle on the unaffected side was significantly greater in the ankle trial than in the other trials ($P < 0.050$; Fig. 3).

To identify the indication for real-time auditory feedback post-stroke, participants were categorized into two groups: 11 in the responder group and nine in the non-responder group based on their gait speed after the control and leg trials (Tables 3 and 4). The indication for real-time auditory feedback was associated with the SPPB scores (odds ratio, 2.217; 95% confidence interval: 1.152–4.266, $P = 0.017$). The ROC curve revealed the 9.0 point to be the cut-off point for the SPPB (AUC, 0.879; sensitivity, 0.889; specificity, 0.909; $P < 0.001$; Fig. 4).

Discussion

This study examined the effectiveness of on-ground gait trials with real-time auditory feedback in patients with chronic stroke. The results revealed that auditory feedback for lower extremity extension (leg trial) could increase the leg extension angle and change the gait strategy on the affected side. In addition, the leg trial was identified as particularly effective for participants with low physical function who scored less than 9 points on the SPPB. On-ground gait practice with real-time auditory feedback using an IMU has been suggested to be effective for modifying gait strategies in patients with chronic stroke and low physical function.

Stride length and leg extension angle on the affected side increased in the leg trial compared to the control trial. These results are similar to those of previous studies on healthy participants and patients with stroke[11,12,23]. The leg extension angle is associated with the forward propulsion force during gait[9]. In patients with post-stroke, leg extension angles on the affected side are often reduced compared to those on the unaffected side[45]. However, patients with stroke have been reported to have a reserve capacity for propulsion force on the affected side[46,47]. Increasing the leg extension angle can enhance this reserve capacity for the propulsion forces[12,46]. Participants in this study also showed differences in leg extension angle between the affected and unaffected sides; auditory feedback focused on leg extension angle might increase the leg extension angle by eliciting reserve capacity, leading to increased stride length and improved gait speed.

Ankle plantar flexion also contributed to propulsion force, similar to the leg extension angle[8,9]. Interventions using functional electrical stimulation of the gastrocnemius muscle have been reported to improve gait speed in patients with stroke[48], although studies on auditory feedback focused on ankle plantar flexion are limited. In this study, the peak ankle plantar flexion angle was not significantly different between the ankle trials and the other trials. However, the leg extension angle on the unaffected side was higher in the ankle trial than in the control trial. Ankle plantar flexion is a difficult task for patients with stroke. Decreased plantar flexion muscle strength after stroke is attributed to reduced muscle capacity, reduced central nervous drive, or a combination of both impairments[49]. Patients with stroke can only voluntarily exert 51% of their maximum ankle plantar flexion muscle strength[50]. Therefore, improving ankle plantar flexion during gait through auditory feedback alone is difficult for patients with stroke and may induce compensatory strategies such as increasing the leg extension angle on the unaffected side to enhance propulsive force. Achieving greater ankle plantar flexion during walking may require combining real-time auditory feedback with interventions that improve the patient's muscle function, such as functional electrical stimulation.

Although a main effect of time was observed on gait speed, no interaction effect was observed, and the amount of change in gait speed was similar across conditions. However, the leg trial showed a positive LTD value, significantly different from the control trial. LTD indicates a change in gait strategy for increasing speed; positive values suggest length-dominated strategies, whereas negative values suggest time-dominated strategies[44]. Thus, although the improvement in gait speed was comparable between conditions, the leg trial increased gait speed using the strategy of extending stride length through increased leg extension angle during the late stance phase on the affected side. In contrast, the control trial increased gait speed by raising cadence without altering angles in the lower extremity during the late stance phase. A reduction in leg extension angle and step length asymmetry are typical symptoms of post-stroke gait[45,51]. These characteristics lead to a lack of propulsion force on the affected side[52]. Overall, real-time auditory feedback focused on leg extension angle may enhance gait speed by improving leg extension angle and changing spatial strategy during gait. This approach could be particularly beneficial for patients looking to modify their gait strategies.

The SPPB was a key factor distinguishing the responder and non-responder groups in terms of real-time auditory feedback on leg extension angle. Among the measured variables, only SPPB showed a significant difference between the two groups. The participants in this study were community-dwelling individuals who used walking aids such as canes and orthoses. Despite some participants having lower SPPB scores, almost

	Trial condition	Pre-trial	Post-trial	Change	Effect of Time		Time × trial interaction	
					F	P	F	P
Gait speed (m/s)	C	0.83 ± 0.35	0.88 ± 0.38	0.05 ± 0.09	14.130	**0.001**	0.401	0.673
	A	0.84 ± 0.32	0.88 ± 0.35	0.05 ± 0.09				
	L	0.79 ± 0.29	0.86 ± 0.32	0.07 ± 0.09				
Cadence (steps/min)	C	94.68 ± 22.29	97.95 ± 25.25	3.27 ± 7.17	0.687	0.417	2.174	0.128
	A	94.57 ± 20.90	95.19 ± 21.37	0.62 ± 6.48				
	L	92.63 ± 19.94	91.54 ± 21.78	-1.09 ± 8.46				
Stride length (m)	C	1.01 ± 0.27	1.03 ± 0.28	0.01 ± 0.08	21.296	< **0.001**	7.974	**0.001**
	A	1.02 ± 0.26	1.08 ± 0.28	0.05 ± 0.05				
	L	0.99 ± 0.23	1.09 ± 0.27	0.10 ± 0.10				
Stride time (s)	C	1.36 ± 0.42	1.34 ± 0.48	-0.02 ± 0.13	0.014	0.906	1.241	0.301
	A	1.35 ± 0.41	1.34 ± 0.41	-0.01 ± 0.10				
	L	1.37 ± 0.40	1.41 ± 0.46	0.03 ± 0.16				
LTD (%)	C	-0.01 ± 0.12						
	A	0.05 ± 0.07						
	L	0.13 ± 0.15						
Affected side								
Ankle plantarflexion (°)	C	-9.8 ± 6.8	-10.4 ± 6.8	-0.6 ± 1.8	7.336	**0.014**	2.337	0.110
	A	-9.4 ± 7.1	-12.7 ± 8.0	-3.3 ± 5.4				
	L	-10.5 ± 6.6	-12.3 ± 7.9	-1.8 ± 5.1				
Leg extension angle (°)	C	16.4 ± 5.4	16.0 ± 5.8	-0.4 ± 2.1	6.457	**0.020**	7.042	**0.003**
	A	16.7 ± 5.6	17.6 ± 5.4	1.0 ± 2.9				
	L	15.8 ± 5.5	18.2 ± 5.2	2.4 ± 2.6				
Unaffected side								
Ankle plantarflexion (°)	C	-16.9 ± 10.3	-17.8 ± 10.6	-0.9 ± 2.8	14.165	**0.001**	2.617	0.086
	A	-18.4 ± 9.7	-21.7 ± 9.8	-3.3 ± 4.9				
	L	-18.2 ± 10.7	-20.7 ± 11.3	-2.5 ± 3.6				
Leg extension angle (°)	C	18.4 ± 3.3	18.9 ± 3.7	0.5 ± 1.5	11.107	**0.003**	5.186	**0.010**
	A	17.7 ± 4.1	19.8 ± 4.4	2.1 ± 2.2				
	L	18.5 ± 3.6	19.3 ± 3.5	0.7 ± 2.4				
Root mean square								
Mediolateral	C	3.27 ± 3.16	3.23 ± 3.41	-0.04 ± 0.50	3.123	0.093	1.332	0.272
	A	3.16 ± 2.92	3.07 ± 2.90	-0.09 ± 0.53				
	L	3.30 ± 3.10	2.89 ± 2.56	-0.40 ± 1.12				
Anteroposterior	C	2.76 ± 2.18	2.73 ± 2.39	-0.04 ± 0.45	2.165	0.158	1.322	0.271
	A	2.64 ± 1.90	2.58 ± 2.03	-0.07 ± 0.43				
	L	2.85 ± 2.18	2.51 ± 1.81	-0.34 ± 1.04				
Vertical	C	3.65 ± 2.78	3.66 ± 2.89	0.01 ± 0.40	0.587	0.453	0.765	0.430
	A	3.47 ± 2.43	3.47 ± 2.41	0.00 ± 0.56				
	L	3.51 ± 2.54	3.27 ± 2.05	-0.24 ± 1.10				
Mediolateral	C	-0.38 ± 0.17	-0.38 ± 0.18	0.00 ± 0.13	0.310	0.862	0.317	0.730
	A	-0.34 ± 0.15	-0.35 ± 0.18	-0.01 ± 0.11				
	L	-0.36 ± 0.17	-0.34 ± 0.16	0.02 ± 0.08				
Anteroposterior	C	0.48 ± 0.27	0.51 ± 0.25	0.03 ± 0.08	0.252	0.622	1.465	0.244
	A	0.50 ± 0.26	0.50 ± 0.26	0.01 ± 0.08				
	L	0.49 ± 0.28	0.48 ± 0.27	-0.02 ± 0.11				
Vertical	C	0.49 ± 0.29	0.47 ± 0.29	-0.02 ± 0.09	0.001	0.970	1.507	0.234
	A	0.49 ± 0.27	0.48 ± 0.29	-0.01 ± 0.09				
	L	0.45 ± 0.26	0.48 ± 0.28	0.03 ± 0.12				

Table 2. Gait spatiotemporal and kinematical parameters pre- and post-trial in each condition. Values are expressed as mean ± standard deviation. C, control trial; A, ankle trial; L, leg trial; LTD, length–time difference. P values in bold are statistically significant.

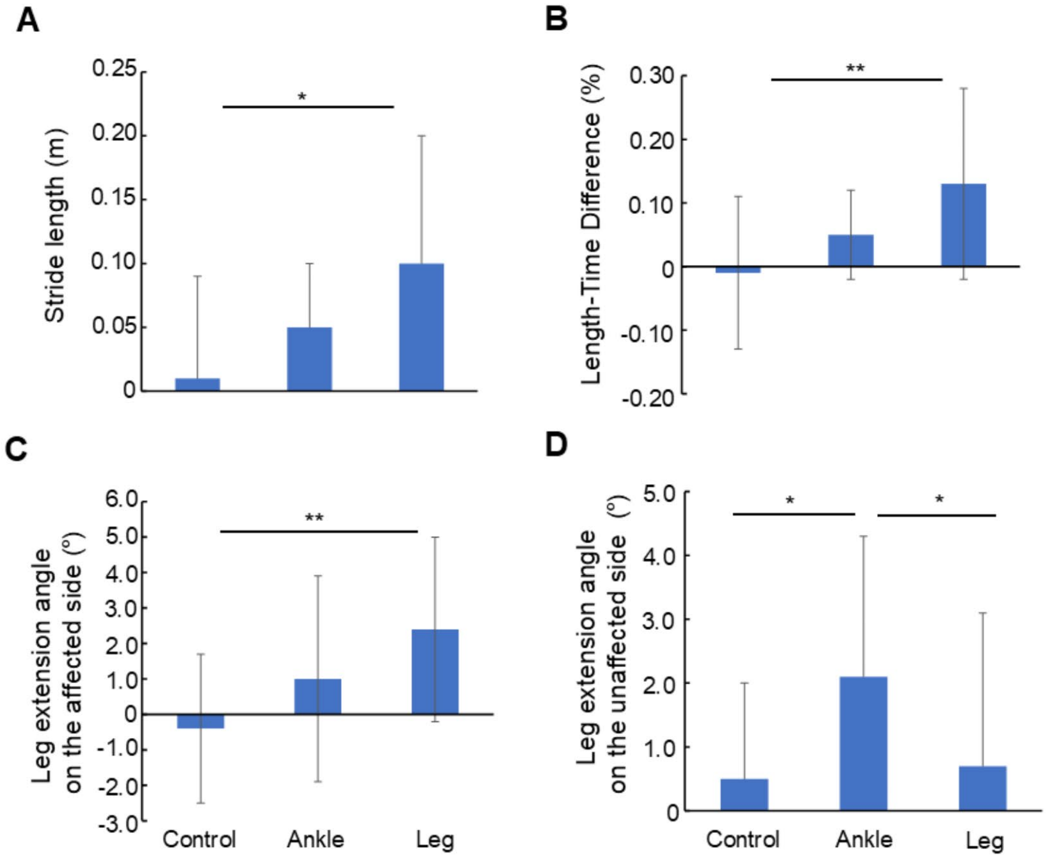

Fig. 3. Comparisons of the changes in gait parameters between each condition. (**A**) Stride length, (**B**) length–time difference, (**C**) leg extension angle on the affected side, (**D**) leg extension angle on the unaffected side. **:P < 0.01, *: P < 0.05.

Value	Group		P
	Non-responder	Responder	
Fugl-Meyer assessment for the lower extremities	26.89 ± 3.02	23.09 ± 4.61	0.080
Short physical performance battery	10.78 ± 1.56	6.73 ± 2.83	0.003
Functional ambulation category	4.56 ± 0.53	4.27 ± 0.79	0.503

Table 3. Characteristics of non-responder and responder group. Values are expressed as mean ± standard deviation.

had an FAC of 4 or higher. Although there was a trend toward differences in the FMA-LE, these differences were not statistically significant. Although FMA-LE correlates with gait speed, balance, and lower limb muscle strength are similarly associated with gait speed[4]. The SPPB includes gait speed, the five-times-sit-to-stand test, and balance measures. Therefore, the SPPB, which incorporates multiple factors related to gait, may have been more effective at distinguishing between responder and non-responder groups. The cutoff score for the SPPB was 9 points in this study. Previous studies have classified patients with SPPB scores of less than 10 as having poor physical function, with an increased odds ratio for mortality[53,54]. These findings suggest that participants with poorer physical function were in the responder group whose gait speed was improved by leg extension angle auditory feedback. Our findings contradict the hypothesis that real-time auditory feedback is more effective for individuals with higher physical function. Increased propulsive force is associated with greater ankle plantar flexion moment and lower-extremity extension angle in the late stance phase[8,9]. Hip strategies are often prioritized when increasing gait speed, as generating greater ankle plantar flexion moments is a difficult task for older adults and patients with post-stroke who have reduced physical function[55–57]. In addition, it has been noted that in patients with post-stroke and inflicted with mild paralysis, increasing lower leg angle does not contribute to increasing gait speed since they have already acquired sufficient lower leg angle[31]. A previous study conducted feedback gait training on a treadmill, targeting lower leg extension angles similar to this study[12,46]. Participants in the prior research exhibited slower gait speeds compared to those in the present study, although

	Group	Control trial			Leg trial		
		Pre-trial	Post-trial	Change	Pre-trial	Post-trial	Change
Gait speed (m/s)	Non-responder	1.05 ± 0.28	1.13 ± 0.30	0.08 ± 0.09	0.96 ± 0.18	1.03 ± 0.26	0.06 ± 0.11
	Responder	0.65 ± 0.29	0.67 ± 0.32	0.02 ± 0.07	0.65 ± 0.29	0.72 ± 0.31	0.07 ± 0.08
Cadence (steps/min)	Non-responder	107.13 ± 8.29	110.74 ± 10.70	3.61 ± 5.54	101.96 ± 5.96	100.08 ± 13.85	-1.88 ± 9.69
	Responder	84.49 ± 25.20	87.49 ± 29.20	3.00 ± 8.54	84.99 ± 24.18	84.55 ± 25.07	-0.45 ± 7.75
Stride length (m)	Non-responder	1.17 ± 0.28	1.22 ± 0.26	0.05 ± 0.08	1.13 ± 0.20	1.23 ± 0.28	0.10 ± 0.10
	Responder	0.88 ± 0.21	0.87 ± 0.19	-0.02 ± 0.07	0.88 ± 0.20	0.98 ± 0.21	0.10 ± 0.10
Stride time (s)	Non-responder	1.13 ± 0.09	1.09 ± 0.12	-0.03 ± 0.06	1.18 ± 0.07	1.22 ± 0.18	0.04 ± 0.13
	Responder	1.55 ± 0.49	1.54 ± 0.57	-0.01 ± 0.17	1.53 ± 0.48	1.56 ± 0.56	0.03 ± 0.18
LTD (%)	Non-responder	0.026 ± 0.112			0.112 ± 0.158		
	Responder	-0.311 ± 0.133			0.140 ± 0.151		
Affected side							
Ankle plantarflexion (°)	Non-responder	-11.1 ± 7.5	-10.8 ± 7.1	0.4 ± 2.0	-12.4 ± 7.6	-13.3 ± 8.1	-0.88 ± 4.56
	Responder	-8.7 ± 6.3	-10.1 ± 6.8	-1.4 ± 1.2	-8.9 ± 5.6	-11.4 ± 8.0	-2.55 ± 5.65
Leg extension angle (°)	Non-responder	18.6 ± 5.9	19.5 ± 5.2	0.9 ± 1.4	17.2 ± 5.1	20.2 ± 5.7	2.98 ± 1.58
	Responder	14.7 ± 4.5	13.2 ± 4.8	-1.4 ± 2.1	14.7 ± 5.7	16.6 ± 4.4	1.87 ± 3.19
Unaffected side							
Ankle plantarflexion (°)	Non-responder	-20.5 ± 9.6	-22.2 ± 9.9	-1.7 ± 3.5	-21.0 ± 10.5	-22.9 ± 9.9	-1.84 ± 3.87
	Responder	-14.0 ± 10.4	-14.2 ± 10.3	-0.2 ± 2.0	-15.8 ± 10.7	-18.9 ± 12.4	-3.06 ± 3.36
Leg extension angle (°)	Non-responder	20.2 ± 3.7	21.0 ± 4.0	0.8 ± 1.3	19.6 ± 3.0	20.3 ± 4.2	0.73 ± 1.95
	Responder	16.8 ± 2.0	17.1 ± 2.5	0.3 ± 1.7	17.6 ± 3.9	18.4 ± 2.7	0.75 ± 2.79
Root mean square							
Mediolateral	Non-responder	1.59 ± 0.93	1.35 ± 0.62	-0.23 ± 0.41	1.70 ± 0.92	1.67 ± 0.81	-0.03 ± 0.24
	Responder	4.64 ± 3.70	4.76 ± 4.01	0.12 ± 0.53	4.61 ± 3.66	3.90 ± 3.07	-0.71 ± 1.45
Anteroposterior	Non-responder	1.75 ± 0.78	1.54 ± 0.61	-0.21 ± 0.28	1.72 ± 0.60	1.74 ± 0.76	0.01 ± 0.23
	Responder	3.59 ± 2.61	3.70 ± 2.87	0.10 ± 0.53	3.77 ± 2.59	3.14 ± 2.19	-0.63 ± 1.35
Vertical	Non-responder	2.25 ± 1.01	2.13 ± 0.72	-0.12 ± 0.45	2.23 ± 0.89	2.31 ± 0.98	0.08 ± 0.15
	Responder	4.80 ± 3.27	4.91 ± 3.41	0.11 ± 0.34	4.56 ± 2.99	4.06 ± 2.38	-0.50 ± 1.45
Step symmetry							
Mediolateral	Non-responder	-0.46 ± 0.19	-0.46 ± 0.20	0.00 ± 0.14	-0.43 ± 0.19	-0.39 ± 0.20	0.03 ± 0.11
	Responder	-0.31 ± 0.12	-0.32 ± 0.15	0.00 ± 0.13	-0.30 ± 0.14	-0.29 ± 0.11	0.01 ± 0.06
Anteroposterior	Non-responder	0.60 ± 0.25	0.62 ± 0.25	0.02 ± 0.07	0.62 ± 0.23	0.57 ± 0.24	-0.05 ± 0.08
	Responder	0.38 ± 0.26	0.42 ± 0.23	0.04 ± 0.09	0.38 ± 0.29	0.40 ± 0.28	0.01 ± 0.12
Vertical	Non-responder	0.64 ± 0.27	0.61 ± 0.25	-0.03 ± 0.12	0.59 ± 0.22	0.62 ± 0.23	0.04 ± 0.15
	Responder	0.36 ± 0.25	0.35 ± 0.27	-0.01 ± 0.07	0.34 ± 0.25	0.37 ± 0.27	0.02 ± 0.10

Table 4. Gait spatiotemporal and kinematical parameters pre- and post-trial in non-responder and responder group. Values are expressed as mean ± standard deviation. LTD, length–time difference.

the increase in lower leg extension angle was greater than the results of this study. Therefore, gait practice with real-time auditory feedback may be more effective for post-stroke with lower physical function.

There are some limitations to this study. The first is a short gait trial time, which lasted 6 min, making it shorter than previous studies[17]. However, despite the short duration, changes in gait speed and joint angles were observed, suggesting that this time allocation was appropriate given the participant's fatigue. Second, the study assessed only immediate effects and did not examine retention effects. Long-term interventions are necessary, and objective indicators, such as the minimal clinically important difference[58], should be employed to better distinguish between responder and non-responder groups. Third, we did not evaluate the impact of gait changes on activity and participation. A previous study has shown that improvements in physical function and gait do not necessarily translate into increased activity or participation in community-dwelling post-stroke[59–61]. Further research should include long-term intervention studies to determine the lasting effects of gait practice and whether changes in gait influence activity and participation.

In conclusion, real-time auditory feedback targeted at the leg extension angle during overground gait may increase gait speed by improving the leg extension angle and altering the spatial strategy during gait. Moreover, gait practice with real-time auditory feedback may be particularly beneficial for patients with post-stroke who have impaired physical function. This study showed that real-time auditory feedback using IMUs can contribute to improving gait strategies. Further studies are needed to clarify the impact of long-term real-time auditory feedback interventions on the activity and participation of patients with stroke.

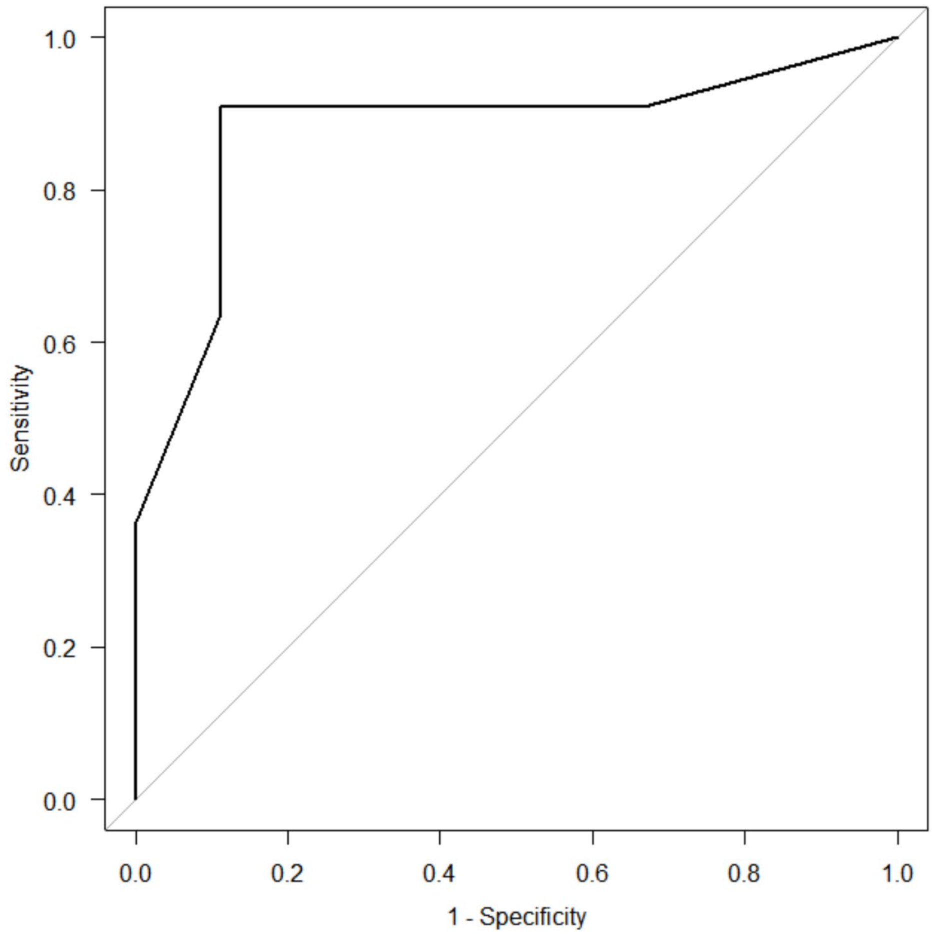

Fig. 4. Receiver operating characteristic curve for the SPPB total score. The cutoff SPPB score for identifying responders or non-responders was 9 points. The AUC, sensitivity, and specificity were 0.879, 0.889, and 0.909, respectively. SPPB, Short physical performance battery.

Data availability

The research data from this study were anonymized to protect the participants' privacy. Data supporting the findings of this study are available from the corresponding author upon request.

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Author contributions
S.A. completed the data analysis, drafted all the figures, and contributed to the design of the analysis, the data interpretation, and manuscript drafting. T.M., D.S., and Y.T. conceived of the work and contributed to the design, data interpretation, drafting, and manuscript revision. J.S., K.O., A.I., and M.T. contributed to the investigation and curated the data. R.K. contributed to the analysis plans, data interpretation, and manuscript revision. All authors reviewed the final manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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