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Gait Coordination After Stroke: Benefits of Acoustically Paced Treadmill Walking

Melvyn Roerdink, Claudine JC Lamoth, Gert Kwakkel, Piet CW van Wieringen, Peter J Beek

Background and Purpose

Gait coordination often is compromised after stroke. The purpose of this study was to evaluate the efficacy of acoustically paced treadmill walking as a method for improving gait coordination in people after stroke.

Participants

Ten people after stroke volunteered for the study and comprised the experimental group. Nine elderly people who were healthy served as a control group.

Methods

Gait cycle parameters, interlimb coordination, and auditory-motor coordination were examined while participants walked on a treadmill with and without acoustic pacing.

Results

Stride frequency was adjusted to different acoustic pacing frequencies in all participants. In people after stroke, gait symmetry improved with acoustic pacing. They predominantly coordinated movements of the nonparetic limb to ipsilateral tones.

Discussion and Conclusion

The results suggest that acoustically paced treadmill walking provides an effective means for immediately modifying stride frequency and improving gait coordination in people after stroke and, therefore, may be usefully applied in physical therapist practice. Future research directions for developing guidelines for using acoustically paced treadmill walking in physical therapist practice are discussed.

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Coordination between moving body parts is essential for functional walking and is modified, often in a subtle manner, to accommodate variations in task requirements and circumstances, such as walking speed,[1,2] path curvature,[3] and environmental clutter.[4] If gait coordination is impaired as a result of an underlying pathology, then functionally adaptive walking usually is impaired as well. This connection is evident in many pathologies and is especially well documented for people after stroke.[5-8]

Compared with unimpaired walking, gait in people after stroke is characterized by reduced preferred walking speed, cadence, and stride length as well as reduced symmetry, showing prolonged stance duration on the nonparetic side and reduced step length on the paretic side.[9-11] Poor gait coordination in people after stroke is reflected in impaired relative timing in interlimb coordination and increased variability in the resultant coordination pattern,[5,6] whereas poor gait adaptation is reflected in a reduced ability to adjust gait to variations in task demands. In particular, people after stroke tend to effectuate variations in walking speed mainly through modulations of stride length rather than stride frequency,[7,8] whereas in unimpaired walking, stride frequency and stride length contribute about equally to variations in walking speed.[12] Improving gait coordination and restoring gait adaptation increasingly are being recognized in physical therapist practice as important components of improving locomotor performance.

To this end, treadmill walking often is incorporated as part of rehabilitation programs aimed at improving gait after stroke.[13,14] Indeed, treadmill training has been demonstrated to increase gait symmetry and consistency immediately[15,16] and to improve walking ability by 17%,[13] seemingly with beneficial effects for overground walking speed.[17,18] As in overground walking, however, people after stroke continue to show reduced stride frequency increases with increasing belt speeds in comparison with a control group of elderly people who are healthy.[7,8]

Apart from treadmill walking, acoustic pacing or other forms of sensory cueing have been suggested in the literature as other (or additional) therapeutic means for enhancing gait coordination after stroke.[19-21] Empirical findings have shown that acoustic pacing improves overground walking in people after stroke. In particular, acoustic pacing not only improved gait symmetry and mechanical efficiency but also helped people to achieve higher walking speeds and larger stride lengths.[13,22-25] As a consequence of these combined effects, however, it is not known whether the observed improvement in gait coordination was a direct effect of the acoustic pacing as such or rather was an indirect effect of the pacing-induced increase in walking speed.

This is an important methodological issue given that gait cycle parameters and interlimb coordination are functions of walking speed.[6,19-21] In particular, people after stroke exhibited less asymmetric gait patterns when they were asked to walk faster than their preferred walking speed.[5] Although overground gait symmetry improved with acoustic pacing, the gait of people after stroke remained relatively asymmetric.[22-25] Unfortunately, these studies did not assess the temporal coupling between tones and specific gait events, despite the fact that such a detailed examination may provide additional insight into the underlying motor control processes. In particular, studying the coupling between tones and heel-strikes could reveal how people after stroke cope with their gait asymmetry when instructed to coordinate heel-strikes with symmetric tones.

In contrast to acoustically paced overground walking,[22-25] acoustically paced treadmill walking allows for strict control of walking speed in assessing the effects of acoustic pacing on gait coordination. Thus, the observed effects can be attributed directly to sensory cueing. Furthermore, acoustically paced treadmill walking allows for an examination of gait coordination and auditory-motor coordination over a large number of strides, resulting in reliable estimates of dependent variables. Methodological considerations aside, paced treadmill walking may well provide an effective therapeutic intervention method for improving gait coordination in people after stroke. Confirmation of this expectation would be of considerable interest to physical therapists because acoustic cueing (ie, metronome or simple hand clapping) and treadmills are readily available and already used in practice to various degrees.

Although both treadmill walking and acoustic pacing have been proven to be beneficial in gait rehabilitation and training, their combined effects have not been examined to date. Specifically, acoustically paced treadmill walking may provide a means to assist people after stroke to modulate stride frequency given that it allows independent manipulation of stride frequency (as dictated by the acoustic pacing) and walking speed (as dictated by the treadmill). This is of potential relevance to physical therapist practice given the reduced ability of people after stroke to modulate their stride frequency.[7,8]

The purpose of this study was to evaluate the efficacy of acoustically paced treadmill walking as a method for improving gait coordination in people after stroke. In assessing its potential merit for physical therapist

Table 1.
Characteristics of Participants After Stroke[a]

Variable	Participant After Stroke									
	1	2	3	4	5	6	7	8	9	10
Age (y)	63	71	77	53	48	55	73	67	46	78
Sex	M	M	M	F	M	F	M	M	M	M
Time after stroke (mo)	77	3	104	24	18	24	45	12	57	13
Type of stroke	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF
Hemisphere of stroke	R	R	R	R	L	R	L	L	R	R
MMSE score (0–30)	28	30	28	28	24	30	26	27	27	26
MI_{total} (0–100)	44	96	70	49	41	66	92	96	67	100
BBS score (0–56)	56	56	46	46	54	53	55	52	54	54
FM_{total} score (0–114)	40	106	96	61	38	95	103	108	91	108
FM_{arm} score (0–66)	10	63	57	39	16	58	62	65	57	64
FM_{leg} score (0–34)	16	30	29	16	16	27	29	31	23	32
$FM_{balance}$ score (0–14)	14	13	10	6	6	10	12	12	11	12
CWS (km/h)	2.5	3.0	2.4	2.6	3.3	3.2	3.2	3.2	2.8	4.7
MWS (km/h)	3.3	3.7	3.2	3.2	4.6	3.9	3.7	3.7	3.5	5.6

[a] BBS=Berg Balance Scale, CWS=comfortable overground walking speed, F=female, FM=Fugl-Meyer Sensorimotor Assessment (total=arm plus leg plus balance), INF=infarction, L=left, M=male, MI=Motricity Index (total=arm plus leg), MMSE=Mini-Mental State Examination, R=right.

practice, we proceeded as follows. First, we evaluated the efficacy of paced treadmill walking in evoking changes in stride frequency by manipulating the frequency of the acoustic pacing signal at a given, stationary treadmill belt speed. Next, we examined the effects of acoustic pacing on gait coordination by comparing gait in people after stroke during paced and unpaced treadmill walking at specific, treadmill-imposed speeds. Finally, we focused in detail on auditory-motor coordination in people after stroke in order to gain insight into the underlying motor control.

Method

Participants

Ten people with a first-ever ischemic cerebrovascular accident (2 women and 8 men), forming the experimental group, and 9 elderly people who were healthy (5 women and 4 men), forming a control group, participated in the experiment. The people

after stroke were, on average, 63 years of age (range=46–78), 1.76 m tall (range=1.68–1.94), and 81.0 kg in weight (range=55–98). The people in the control group were, on average, 69 years of age (range=60–78), 1.70 m tall (range=1.56–1.88), and 67.3 kg in weight (range=41–88). Independent t tests revealed no significant group differences for age, height, and weight. The people after stroke were able to walk independently (ie, Functional Ambulation Category 5[26]). All participants reported having no hearing deficits. The individual characteristics of the 10 people after stroke with respect to age, sex, time after stroke, and type and hemisphere of stroke as well as individual functional scores (ie, scores on the Mini-Mental State Examination, Motricity Index, Berg Balance Scale, Fugl-Meyer Sensorimotor Assessment, and 10-m timed walking tests at comfortable and maximal overground walking speeds) are provided in Table 1. After having

been informed about the protocol, each participant signed an informed consent form before participation.

Apparatus

A 3-dimensional active-marker motion analysis system (Optotrak 3020*), positioned around a large treadmill, was used to record movement kinematics at a sampling rate of 60 Hz. Small, lightweight, custom-made triangular frames with light-emitting diode markers (diameter=10 mm) affixed at each corner, so-called marker clusters, were mounted on the heels of the participants' shoes by means of a premolded lightweight aluminum frame and double-sided tape. Participants wore a lightweight safety harness and were accompanied alongside the treadmill by 2 people. Computer-produced rhythmic acoustic pacing stimuli were administered alternately to the left and right ears through an earphone.

* Northern Digital Inc, 103 Randall Dr, Waterloo, Ontario, Canada N2L 3V2.

Procedure

Each participant performed a standardized 10-m timed walking test to determine comfortable overground walking speed (CWS) and maximal overground walking speed (MWS)[27] (Tab. 1). The treadmill belt speed was manipulated around individual comfortable overground walking speeds, that is, belt speeds slower than comfortable (slow=CWS−ΔS), comfortable (comfortable=CWS), and faster than comfortable (fast=CWS+ΔS); ΔS was defined as one third of the difference between MWS and CWS. These individual adjustments were deemed essential in view of the large interindividual differences in comfortable and maximal attainable walking speeds.

After a period of familiarization to walking at different belt speeds, the participants were instructed to walk as naturally as possible for 90 seconds at each of the 3 experimental belt speeds (ie, slow, comfortable, and fast). The order of the belt speeds was randomized across the participants. Subsequently, the participants walked on the treadmill with acoustic pacing for about 3 minutes. The belt speed was set at the CWS determined for each participant while the frequency of acoustic pacing was increased from 90% via 100% to 110% of the preferred stride frequency (ie, slow, preferred, and fast pacing) observed during the comfortable belt speed trial. Participants walked exactly 60 seconds at their preferred stride frequency. The number of stride cycles was kept constant across the 3 pacing frequencies, implying that participants walked more (less) than 60 seconds with slow (fast) acoustic pacing. Participants were instructed to synchronize heel-strikes with ipsilateral acoustic pacing stimuli; that is, heel-strikes of the left (right) foot had to be synchronized with tones presented at the left (right) ear. Participants became acquainted with the rhythm and practiced synchronization before the pacing trial in a seated position to ensure that the instructions were fully understood. One participant after stroke (participant 8 in Tab. 1) did not perform the acoustic pacing part of the experiment.
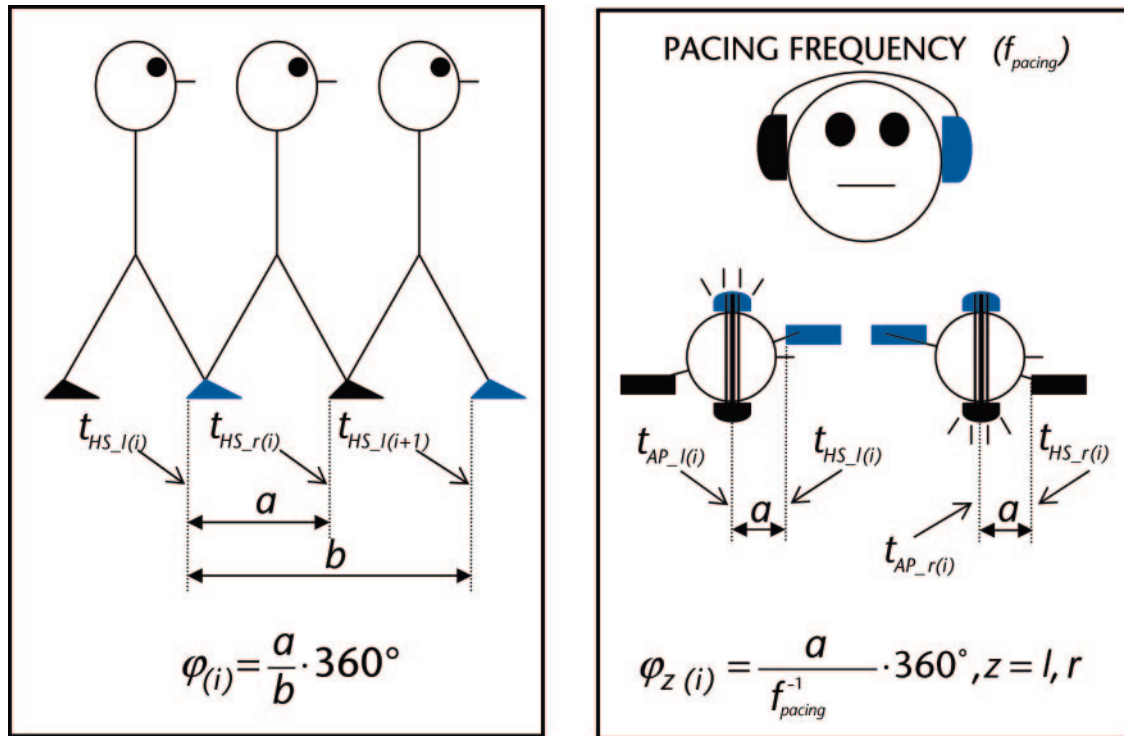
Data Analysis

Paced treadmill walking trials were divided into 3 separate time series, corresponding to the 3 pacing frequencies. For all time series for all participants, the last 30 stride cycles were used for further processing, ensuring that the dependent variables were quantified over the same number of stride cycles. Note that the lowest observed stride frequency in a time series was 38 strides per minute; therefore, at least 8 stride cycles were excluded from the beginning of each time series to eliminate transient behavior.

Gait cycle parameters.

For all time series, time indices of heel-strikes of the paretic and nonparetic limbs (corresponding to left and right heel-strikes, respectively, for people without stroke) were determined by selecting the moment at which the vertical position of the heel marker reached its minimum.[†] The technique of determining time indices of heel-strikes from kinematic data is considered valid and reliable and shows minimal error between the applied algorithm and raters on the one hand and among multiple raters on the other hand.[28-30] Step time on the paretic side was quantified as the time interval between heel-strikes of the paretic limb following heel-strikes of the nonparetic limb (and vice versa for step time on the nonparetic side). Stride time interval was defined as the time interval between consecutive ipsilateral heel-strikes. Stride frequency was determined as the inverse of the average stride time interval.

Step length on the paretic side was derived by multiplying the belt speed by the time interval between heel-strikes of the paretic limb following heel-strikes of the nonparetic limb (and vice versa for step length on the nonparetic side) while correcting for spatial variations in consecutive heel-strike positions on the treadmill. The latter procedure was deemed necessary given the fact that the anterior-posterior footfall positions differed contralaterally within 1 stride when there was an asymmetry in step length. Specifically, for each step, we calculated the spatial difference with regard to the preceding footfall in the anterior-posterior (x) location of the heel marker, that is, $\Delta x = x(t_{i+1}) - x(t_i)$, in which t_i represents the time indices of heel-strikes i (where i is 1–30 strides). We added the value Δx to the coarse-grained step length, that is, step length$_j = [(t_{i+1} - t_i) \times$ belt speed]$+ [x(t_{i+1}) - x(t_i)]$. Finally, we averaged the resulting j as 1–29 step length estimates for each time series. Likewise, stride length was calculated by multiplying the belt speed by the stride time interval while correcting for the spatial separation of consecutive ipsilateral heel-strikes on the treadmill. Step width was quantified as the mean absolute mediolateral difference in the landing positions of consecutive contralateral heel-strikes.

[†] Specifically, the vertical components of the heel markers were low-pass filtered (zero-lag, second-order Butterworth filter) with a cutoff frequency of 15 Hz. Subsequently, the minimal value was subtracted from the filtered time series. A standard peak finding algorithm was applied to detect the minima in these time series, with the spatial constraint that minima must be smaller than 20% the maximal value and the temporal constraint that the time separation between the minima must be at least 70% the mean stride interval. Finally, to avoid false event detections or missing values (eg, attributable to a stumble or measurement noise), automatically detected heel-strike events were visually inspected and corrected with a graphical user interface in which time series with heel-strike event indicators could be advanced frame by frame.

Figure 1.
Interlimb coordination (left panel) and auditory-motor coordination (right panel). The point estimate of relative phase as a measure of timing between consecutive contralateral heel-strikes (left panel) or between ipsilateral instants of acoustic pacing and heel-strikes (right panel) is shown. For the people in the control group, $t_{HS\_l(i)}$ and $t_{HS\_r(i)}$ are the time instants of heel-strikes for the left and right limbs, respectively. For the people after stroke, $t_{HS\_l(i)}$ and $t_{HS\_r(i)}$ correspond to the time instants of heel-strikes for the paretic and nonparetic limbs, respectively. For interlimb coordination, a denotes the time difference between $t_{HS\_r(i)}$ and $t_{HS\_l(i)}$, where b is defined as $t_{HS\_l(i+1)} - t_{HS\_l(i)}$. The point estimate of relative phase φ was calculated twice during each stride cycle (ie, for both left and right heel-strikes) and averaged over the last 30 strides of each trial, resulting in $\bar{\varphi}$. A temporally symmetric gait pattern is denoted by $\bar{\varphi} = 180°$. For auditory-motor coordination, a signifies the temporal difference between ipsilateral instants of acoustic pacing and heel-strikes (ie, $a = t_{AP\_z(i)} - t_{HS\_z(i)}$, where z encompasses left [l] and right [r]).

Asymmetry in step length (ie, spatial asymmetry) or step time (ie, temporal asymmetry) was quantified as follows: percent asymmetry = $[(V_{paretic} - V_{nonparetic})/\max(V_{paretic}, V_{nonparetic})] \times 100$. In this equation, $V_{paretic}$ is the step length or step time for the paretic limb, and $V_{nonparetic}$ is the step length or step time for the nonparetic limb.[31] An index of 0 indicates perfect symmetry. The magnitude of the index represents the degree of asymmetry in the step time or step length, and the sign indicates the direction of the asymmetry (ie, a positive index indicates a larger step time or step length for the paretic limb).

Interlimb coordination and auditory-motor coordination. Besides the more conventional spatial and temporal gait cycle parameters, interlimb coordination and auditory-motor coordination were examined by use of tools from coordination dynamics[32–34] (see also Scholz[35] for an introduction of the theoretical framework and explicit examples of its application in physical therapist practice). In order to quantify the relative timing between the limbs, the mean direction of the relative phase between consecutive contralateral heel-strikes $\bar{\varphi}$ (°) was obtained as illustrated in Figure 1. Because the relative phase is a circular measure (eg, $\varphi = 0°$ is equal to

$\varphi = 360°$, $\varphi = 30°$ is equal to $\varphi = 390°$, and so forth), circular statistics[36,37] were applied to avoid misrepresentations that are likely to occur when conventional statistics are applied to circular data. Consider, for example, the following relative phase values: $\varphi = 350°, 351°, 352°, \ldots 360°, 1°, 2°, 3°, \ldots 10°$. With conventional statistics, the mean relative phase and its variability would both be about $180°$, whereas with circular statistics, the mean relative phase would be $0°$ and its variability would be about $6°$. For this reason, the variability in the coordination pattern σ_{φ} (°) was quantified in terms of the transformed circular variance[36,37] of φ, with high values reflecting large vari-

ability. The absolute relative phase difference $|\Delta\varphi|$ between the observed $\bar{\varphi}$ and a perfect symmetric gait pattern (ie, 180°) served as a measure of symmetry (or asymmetry) in interlimb coordination.

For acoustic pacing time series, an error measure E was calculated to determine how well participants coupled their stride frequency to the acoustically prescribed pacing frequency. The error was calculated as follows: $E=c[(f_{pacing}-f_{stride})]/f_{stride}$. In this equation, c is a constant representing the number of prescribed strides included in the analysis (ie, 30 strides), f_{pacing} is the pacing frequency of the acoustic rhythm, and f_{stride} is the observed stride frequency (both of the latter in strides per minute). An error of 0 indicates perfect synchronization. Negative (positive) values of E indicate that more (fewer) strides than prescribed were taken. For example, $E=0.5$, $E=1$, and $E=2$ indicate that the participant made fewer strides than prescribed, that is, 29.5, 29, and 28 strides, respectively, instead of 30 strides. For time series with good synchronization (ie, $|E|<0.1$ stride), the relative phase variability between ipsilateral instants of acoustic pacing and heel-strikes was determined in a manner similar to that described for interlimb coordination (see also Fig. 1, right panel).

Statistics. First, independent t tests were applied to examine gait differences between people after stroke and people in the control group. Subsequently, we were interested in the differential effects of walking speed on gait in the 2 groups. A repeated-measures analysis of variance (ANOVA) was conducted with belt speed as a within-subjects factor (3 levels: slow, comfortable, and fast) and group as a between-subjects factor (2 levels: people after stroke and people in the control group). *Post hoc* testing was

performed for significant main and interaction effects by means of paired-samples t tests, conducted separately for the 2 groups in case there were significant interactions. Finally, we examined the effects of acoustic pacing in people after stroke. The effects of different pacing frequencies on gait were examined by means of a repeated-measures ANOVA with pacing frequency as a within-subjects factor (3 levels: slow, preferred, and fast) and paired-samples t tests for *post hoc* analysis. In addition, dependent variables for unpaced treadmill walking with the comfortable belt speed were compared with those for paced treadmill walking by means of paired-samples t tests. For t tests, effect size was indexed in terms of the Pearson product-moment correlation coefficient (r), whereas for the repeated-measures ANOVA, effect size was quantified with the Cohen f.[38-40] Large effect sizes were defined by convention as $r>.5$ and $f>0.4$.[38-40]

Results
Differences Between Groups
The mean comfortable walking speed for people after stroke was significantly lower than that for people in the control group (3.1 versus 4.6 km/h; $t_{17}=-5.01$, $P<.001$, $r=.77$). The same was true for the mean maximal walking speed (3.9 versus 6.1 km/h; $t_{17}=-3.80$, $P<.002$, $r=.68$). Group effects on gait cycle parameters and interlimb coordination are provided in Table 2. Given that comfortable walking speed was lower for people after stroke, it was not surprising that people after stroke also walked with significantly lower stride frequencies (larger stride times) and smaller stride lengths than people in the control group. In addition, people after stroke showed increased step widths and prominent asymmetry in step length and step time (14.9% and 24.7%, respectively). The sign of step time asymmetry was always positive,

implying longer step times on the paretic side, whereas the direction of step length asymmetry varied across people after stroke (Fig. 2). Seven people after stroke (participants 2–6, 8, and 9 in Tab. 1) made larger steps with the paretic leg (positive asymmetry index), whereas 2 people after stroke (participants 1 and 7 in Tab. 1) made larger steps with the nonparetic leg (negative asymmetry index). The remaining participant after stroke (participant 10 in Tab. 1) exhibited spatial and temporal asymmetry indices that were comparable to those observed in the control group. The absolute relative phase difference from a symmetric gait pattern ($|\Delta\varphi|$) was significantly larger for people after stroke than for people in the control group, as was the variability in interlimb coordination (σ_φ) (Tab. 2).

Effects of Belt Speed
Significant main effects of treadmill belt speed were observed for stride frequency, stride length, and stride time as well as for step length and step time (all $F_{2,34}$ values>16.9, P values<.001, and f values>1.00). Stride frequency, stride length, and step length increased with faster belt speeds, whereas stride time and step time decreased. *Post hoc* tests revealed significant differences among all 3 belt speeds (all P values<.02 and r values>.53). Belt speed did not significantly affect step width, spatial or temporal gait asymmetry, or interlimb coordination (all $F_{2,34}$ values<1.9). There were no significant group × belt speed interaction effects (all $F_{2,34}$ values<2.3). Notably, however, adjustments in stride length contributed about two thirds of the increase in walking speed in people after stroke, whereas people in the control group increased stride length and stride frequency about equally with faster belt speeds. These observations confirm the results of earlier studies indicating that people after stroke have difficulty in

Table 2.
Group Effects on Gait Cycle Parameters and Interlimb Coordination[a]

Variable	Value for the Following Group:		Statistics		
	After Stroke	Control	t_{17}	P	r
Gait cycle parameters					
Stride frequency (strides/min)	47.1	58.6	−4.97	<.01	.77
Stride length (m)	1.08	1.29	−2.49	<.05	.52
Step length, paretic side (cm)	57.4	64.9	−1.54	NS	.35
Step length, nonparetic side (cm)	50.4	64.1	−3.09	<.01	.60
Spatial asymmetry (%)	14.9	4.9	2.50	<.05	.52
Stride time (s)	1.27	1.02	4.17	<.001	.71
Step time, paretic side (s)	0.73	0.51	4.97	<.001	.77
Step time, nonparetic side (s)	0.54	0.51	0.86	NS	.20
Temporal asymmetry (%)	24.7	2.3	3.94	<.005	.69
Step width (cm)	21.7	13.4	3.45	<.005	.64
Interlimb coordination					
Relative phase difference $|\Delta\varphi|$ (°)	27.5	2.1	3.61	<.01	.66
Relative phase variability σ_φ (°)	7.5	4.1	2.78	<.05	.56

[a] Averaged over the 3 belt speeds. NS=not significant.
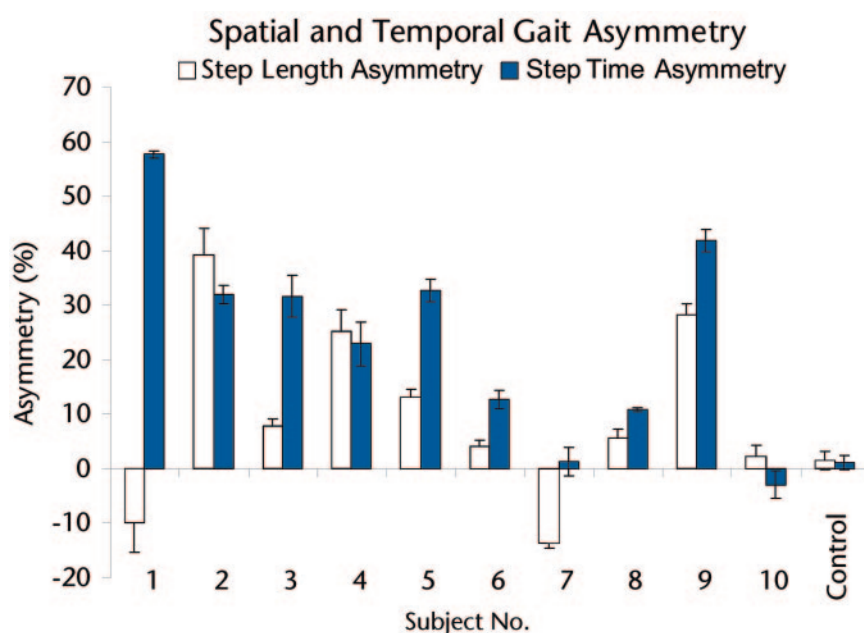
Figure 2.
Spatial and temporal gait asymmetries for the 10 people after stroke, averaged over the 3 belt speeds (error bars indicate the standard deviations of the asymmetry indices across belt speeds). For the people in the control group, the group means are depicted.

increasing stride frequency with increasing walking speed.[7,8]

Effects of Acoustic Pacing in People After Stroke

Table 3 summarizes the effects of the frequency of acoustic pacing (ie, slow, preferred, and fast pacing) on gait cycle parameters and interlimb coordination. Stride frequency increased significantly with increasing acoustic pacing frequency. Congruently, stride time, stride length, step time, and step length decreased significantly with increasing pacing frequency. *Post hoc* tests revealed significant differences among all 3 pacing frequencies (all P values<.05 and r values>.65), indicating that people after stroke adjusted their gait to the acoustic pacing signal. Furthermore, step width during the slow pacing frequency condition was significantly larger than those during the preferred (r=.80) and fast (r=.65) pacing frequency conditions. No significant effects of pacing frequency on interlimb coordination

Table 3.
Main Effects of Pacing Frequency on Gait Cycle Parameters and Interlimb Coordination for 9 Participants After Stroke[a]

Variable	Value at the Following Pacing Frequency:			Statistics		
	Slow	Preferred	Fast	$F_{2,16}$	P	f
Gait cycle parameters						
Stride frequency (strides/min)	43.1	47.2	51.6	175.5	<.001	4.66
Stride length (m)	1.17	1.07	0.98	131.8	<.001	4.07
Step length, paretic side (cm)	62.2	55.8	49.6	29.5	<.001	1.92
Step length, nonparetic side (cm)	55.2	51.0	48.6	13.4	<.005	1.29
Spatial asymmetry (%)	15.4	12.0	10.1	1.3	NS	0.41
Stride time (s)	1.39	1.27	1.16	175.5	<.001	4.66
Step time, paretic side (s)	0.80	0.72	0.66	55.3	<.001	2.63
Step time, nonparetic side (s)	0.60	0.55	0.50	33.3	<.001	2.04
Temporal asymmetry (%)	23.4	22.1	23.3	0.1	NS	0.13
Step width (cm)	23.0	21.7	21.7	6.4	<.05	0.89
Interlimb coordination						
Relative phase difference $|\Delta\varphi|$ (°)	25.8	23.7	25.9	0.4	NS	0.22
Relative phase variability σ_φ (°)	8.9	7.3	9.1	1.5	NS	0.44

[a] NS=not significant.

or spatial or temporal gait asymmetry were found (Tab. 3).

As indicated above, participants adjusted their stride frequency to the prescribed pacing frequency, but not always without error. The mean absolute error $|E|$ was 0.26 stride in 30 strides. The stringent criterion for good synchronization, that is, $|E|<0.1$ stride, was not always met. With slow acoustic pacing, 2 people after stroke (participants 3 and 5 in Tab. 1) made more strides than prescribed ($E=-0.44$ and -1.17 strides, respectively), whereas with fast acoustic pacing, 2 people after stroke (participants 5 and 9 in Tab. 1) made fewer strides than prescribed ($E=1.10$ and 2.51 strides, respectively). Note, however, that these people still adjusted their gait to the acoustic pacing signal, as evidenced by the fact that their stride frequencies differed from the preferred stride frequency with both slow and fast acoustic pacing. One participant after stroke (participant 9) made more strides than

prescribed with preferred acoustic pacing ($E=-0.98$). On the basis of the criterion of $|E|<0.1$, the above-mentioned time series were excluded from further analyses (ie, 5 of 27 time series). The mean ± standard deviation $|E|$ of the remaining 22 time series was 0.04 ± 0.03 stride, indicating perfect frequency coupling of footfalls to tones.

To illustrate the importance of this strong frequency coupling between the acoustic pacing and the timing of the foot placements, the relationship between heel marker trajectories and moments of acoustic pacing is shown in Figure 3 for 2 people after stroke (participants 1 and 5 in Tab. 1). Heel-strikes clearly were coupled to instants of acoustic pacing across all pacing frequencies, allowing a meaningful estimate of mean relative phase and relative phase variability (Fig. 3A). In contrast, as shown in Figure 3B, stride frequency was not perfectly coupled to pacing frequency in slow and fast

pacing time series, resulting in a continuous drift in the phase relationship between acoustic pacing and heel-strikes (so-called phase wrapping).

Stated differently, there was no stationary phase relationship between the tones and the heel-strikes. Therefore, the variability in the relative phase between ipsilateral instants of acoustic pacing and heel-strikes (ie, $\sigma_{paretic}$ and $\sigma_{nonparetic}$ for people after stroke and σ_{left} and σ_{right} for people in the control group) was calculated only for time series with good synchronization. Paired-samples t tests, conducted separately for the 2 groups, were used to analyze this variability between legs (ie, σ_{left} versus σ_{right} and $\sigma_{paretic}$ versus $\sigma_{nonparetic}$). The variability in the left leg ($\sigma_{left}=7.8°$) did not differ significantly from that in the right leg ($\sigma_{right}=8.1°$) in people in the control group ($t_{24}=-.40$, $P>.05$, $r=.08$). In contrast, in people after stroke, the relative phase variability was signifi-
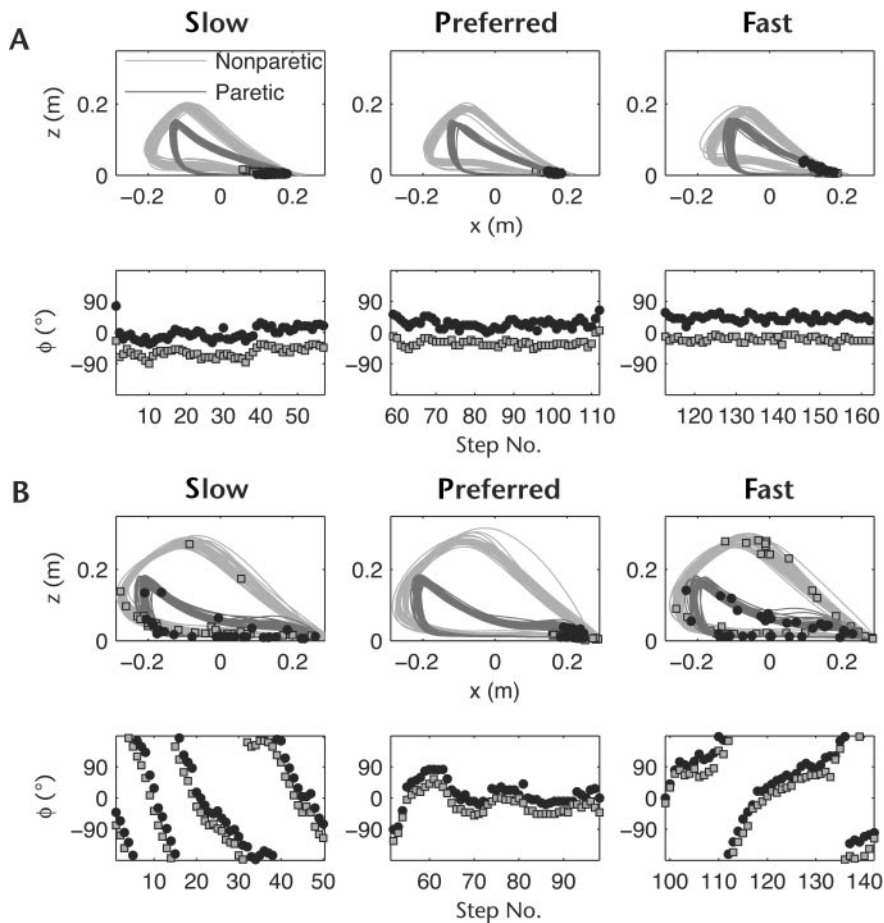
Figure 3.
Auditory-motor coupling for 2 people after stroke during slow, preferred, and fast pacing frequency conditions. (A) Heel marker trajectories of nonparetic (light solid lines) and paretic (dark solid lines) limbs of a participant after stroke (participant 1 in Tab. 1) are plotted in the sagittal plane. Gray squares and black circles represent instants of acoustic pacing on the nonparetic and paretic sides, respectively. For all 3 pacing frequencies, the local clustering of squares and circles indicates that heel-strikes were coordinated or coupled with acoustic pacing. This situation results in an approximately constant relative phase between acoustic pacing and heel-strikes. Note that the relative phase variability was lower for the nonparetic side (squares). (B) Auditory-motor coordination for a participant after stroke (participant 5 in Tab. 1) who was not able to perfectly couple stride frequency to acoustic pacing during the slow and fast pacing frequency conditions. Here, the relative phase was not constant but showed so-called phase wrapping or drift; the participant walked with a stride frequency higher than that prescribed during the slow pacing frequency condition and with a stride frequency slightly lower than that prescribed during the fast pacing frequency condition, resulting in gradually decreasing (lower left panel) and gradually increasing (lower right panel) relative phase values, respectively.

cantly lower on the less impaired side ($\sigma_{nonparetic}=14.3°$) than on the more impaired side ($\sigma_{paretic}=15.9°$) ($t_{21}=2.88$, $P<.01$, $r=.53$),[‡] suggesting that people after stroke couple the footfalls of the nonparetic leg rather than those of the paretic leg to the acoustic pacing signal (see "Discussion" section).

The effects of acoustic pacing on gait coordination were examined by evaluating spatial and temporal asymmetry indices and interlimb coordination for paced and unpaced treadmill walking (Tab. 4). Belt speeds were kept similar between these 2 conditions, and the pacing frequency corresponded to the observed stride frequency during unpaced treadmill walking. Acoustic pacing significantly improved spatial or temporal symmetry as well as the absolute relative phase difference from a symmetric gait pattern ($|\Delta\varphi|$). Step lengths and step times on the paretic side decreased with acoustic pacing, whereas step lengths and step times on the nonparetic side remained constant (or increased slightly) (Tab. 4), contributing to the general improvement in gait symmetry with acoustically paced treadmill walking. Acoustic pacing did not significantly affect the variability in interlimb coordination (σ_φ) (Tab. 4).

[‡] Although it is possible that a lateralized difference in the consistency of footfalls on the paretic and nonparetic sides could explain the observed results, an additional analysis revealed that this was not the case. We compared the stride interval variabilities of the 2 sides with each other during unpaced treadmill walking at a comfortable belt speed. Stride interval variabilities did not differ significantly between the left side (16 milliseconds) and the right side (17 milliseconds) in people in the control group ($t_8=-0.69$, $P>.05$) or between the paretic side (44 milliseconds) and the nonparetic side (39 milliseconds) in people after stroke ($t_8=1.79$, $P>.05$).

Table 4.
Effects of Acoustic Pacing on Gait Cycle Parameters and Interlimb Coordination for 9 Participants After Stroke[a]

Variable	Value Obtained With:		Statistics		
	No Pacing	Pacing	t_8	P	r
Gait cycle parameters					
Spatial asymmetry (%)	17.0	12.0	2.69	<.05	.69
Step length, paretic side (cm)	58.8	55.8	3.59	<.01	.79
Step length, nonparetic side (cm)	50.4	51.0	−0.87	NS	.29
Temporal asymmetry (%)	26.5	22.1	2.45	<.05	.65
Step time, paretic side (s)	0.75	0.72	3.00	<.02	.73
Step time, nonparetic side (s)	0.54	0.55	−1.80	NS	.54
Interlimb coordination					
Relative phase difference $|\Delta\varphi|$ (°)	30.0	23.7	2.80	<.05	.70
Relative phase variability σ_φ (°)	7.5	7.3	0.30	NS	.11

[a] Spatial asymmetry, temporal asymmetry, and interlimb coordination are presented for walking at a comfortable walking speed without acoustic pacing (no pacing) and with acoustic pacing (pacing), the frequency of which corresponded to the preferred stride frequency for this walking speed. NS=not significant.

Discussion

The aim of this study was to evaluate the efficacy of acoustically paced treadmill walking as a potential method for improving gait coordination in people after stroke. It was anticipated that paced treadmill walking might help people after stroke to modify their stride frequency and improve gait coordination. Previous studies already have reported positive effects of acoustic pacing on gait coordination for overground walking,[22–25] although a possible confounding effect of walking speed was ignored. In the present study, paced treadmill walking allowed for an unbiased examination of the effects of acoustic pacing on gait coordination. Furthermore, we examined auditory-motor coupling in detail to determine how people after stroke coordinate their asymmetric gait pattern to a symmetric perceptual cue.

In showing that paced treadmill walking is an efficient method for modulating gait in people after stroke, we provided further empirical support for the use of external auditory rhythms in stroke rehabilitation.[13] However, the included sample of people after stroke was relatively small and heterogeneous, and generalization of the efficacy of paced treadmill walking to the general population of people after stroke is unwarranted. Specifically, our study sample was a highly functioning group with Functional Ambulation Category 5 and high Berg Balance Scale scores but with a range of Motricity Index and Fugl-Meyer Sensorimotor Assessment scores for the lower extremity (Tab. 1). This disparity notwithstanding, people after stroke walked with a lower stride frequency and a smaller stride length than people in the control group. They also walked with a larger step width, possibly to compensate for poor balance.[41] In addition, people after stroke showed marked asymmetries in step length and step time (Fig. 2), although the spatial and temporal asymmetry indices of 1 participant after stroke (participant 10 in Tab. 1) were comparable to the control group values. In line with the general observation that asymmetric coordination patterns are more variable than symmetric ones,[1,42–44] interlimb coordination during walking in people after stroke was more variable than that during unimpaired (symmetric) walking, indicating that interlimb coordination was impaired in people after stroke.[35]

All participants were able to adjust their walking speed to the belt speed. The change in speed between comfortable walking and fast walking was approximately 10% for both groups. However, a detailed analysis of the changes in stride frequency and stride length underlying this change in speed revealed striking group differences. For people in the control group, stride length and stride frequency contributed almost equally to the observed increase in walking speed.[12] In contrast, changes in stride frequency accounted for only about one third of the increase in speed in people after stroke. This result is in line with previous studies showing that people after stroke have difficulty in increasing stride frequency with increasing walking speed[7,8] and is fully consistent with the study objective of evaluating the efficacy of acoustically paced treadmill walking as a potential means of helping people after

stroke to modify their stride frequency.

Unexpectedly, in view of previous results,[5,6,20,21] the 3 belt speeds did not affect step width, spatial or temporal gait asymmetry, or interlimb coordination. Thus, for each belt speed, gait was more asymmetric and interlimb coordination was more variable in people after stroke than in people in the control group (Tab. 2). However, it is conceivable that the relatively small range of experimental speeds used in the present study (small compared with those used in other studies) may have precluded the occurrence of more pronounced effects of walking speed on gait. On the other hand, in clinical practice, the range of speeds that can be attained by people after stroke usually is limited as well, sometimes severely so. Thus, manipulating stride frequency at a given, stationary walking speed by means of acoustic pacing may be a superior method for facilitating changes in gait.

Acoustically Paced Treadmill Walking

All participants adjusted their stride frequency to the acoustic pacing frequency, although not always without error (Fig. 3). Those who were less accurate in staying with the beat (ie, $|E| > 0.1$) still decreased (increased) their stride frequency with slower (faster) acoustic pacing stimuli. This finding also underscores the efficacy of acoustically paced treadmill walking in modifying stride frequency—an important observation in view of the limited ability of people after stroke to increase stride frequency with increasing walking speed.[7,8] Step width was larger during the slow pacing frequency condition, possibly to compensate for increased postural demands[41] associated with longer stride cycle durations.

On the basis of the positive effects of acoustic pacing during overground walking in previous studies,[22–25] we expected that paced treadmill walking would result in more symmetric gait patterns in people after stroke than would unpaced treadmill walking. Spatial asymmetry was indeed reduced (Tab. 4) because of a decrease in step length on the paretic side, whereas step length on the nonparetic side remained constant or increased slightly (as it should given the fixed belt speed and stride frequency). Temporal asymmetry and the absolute difference from symmetric interlimb coordination ($|\Delta\varphi|$) decreased as well, in association with reduced step times on the paretic side (Tab. 4). These results indicate that acoustic pacing positively affects gait symmetry in people after stroke. Note that the use of a treadmill allowed accurate control of walking speed and that, in contrast to results obtained with overground walking, the improvements in gait coordination could be attributed directly to acoustic pacing. Overall, we conclude that acoustically paced treadmill walking appears to be a promising therapeutic intervention for improving gait in people after stroke in that it allows for immediate modulation of stride frequency with concomitant improvements in gait coordination.

Perceptual-Motor Anchoring

Despite the apparent benefits of acoustically paced treadmill walking, gait remained relatively asymmetric. Consequently, perfect bilateral synchronization between instants of acoustic pacing and heel-strikes was not accomplished. This finding called for a detailed analysis of the manner in which the people after stroke coupled the timing of their footfalls to the acoustic pacing. As anticipated, this analysis revealed a form of auditory-motor coupling that is potentially valuable for physical therapist practice.

In particular, in people after stroke, the relative phase variability between ipsilateral instants of acoustic pacing and heel-strikes was lower on the nonparetic side than on the paretic side. This reduced variability is reminiscent of the reduction of endpoint variability that has been observed in studies of manual rhythmic coordination[45–47] and that has been dubbed "anchoring" to emphasize the notion that perception and control are organized around certain points in the work space.[48] In line with this idea, it can be hypothesized that people after stroke organize gait by coupling or anchoring the footfalls of the nonparetic limb to ipsilateral pacing stimuli. Apparently, this is the most efficient way for people after stroke to deal with their gait asymmetry when they are walking at a constant speed while being prompted to time their footfalls to (symmetric) acoustic signals.

Wagenaar and Beek[19] and Wagenaar and van Emmerik[20,21] suggested that tweaking the perception-action coupling by means of external rhythms can enhance the spatiotemporal organization of pathological movement coordination. On the basis of the effects of acoustic pacing reported here, acoustically paced treadmill walking might be expected to constitute an effective means of helping people after stroke to improve gait coordination. On the basis of the observed anchoring phenomenon, instructing people after stroke to coordinate (or time or anchor) heel-strikes of the paretic limb to acoustic pacing signals might be expected to induce larger step lengths on the paretic side during overground walking.

Limitations of the Study and Recommendations for Future Research

The present study can be considered a study of the efficacy of paced treadmill walking for the physical therapy

profession. Our results showed that acoustic pacing readily elicited changes in stride frequency and immediately improved gait coordination. Moreover, the observation that people after stroke timed the footfalls of the nonparetic limb to the tones may lead to promising future therapeutic interventions.

An important question for clinicians is who will and who will not benefit from such interventions. Given our limited study sample, we cannot answer this question, although the individual characteristics of the 3 people after stroke who were less accurate in staying with the beat (participants 3, 5, and 9 in Tab. 1) may, in principle, reveal information suggesting why their performance differed from that of the other people after stroke. Inspection of Table 1, however, does not reveal any obvious explanations in terms of functional abilities. The variation in performance was not linked to comfortable walking speed, age, Fugl-Meyer Sensorimotor Assessment score, or other clinical measures. Therefore, it would be useful to extend this research with studies involving more people after stroke in order to discern who is likely to benefit most from acoustic pacing. Furthermore, these studies also should address the effects of duration, intensity, and frequency of training as well as type of training (massed practice versus distributed practice of particular pacing frequencies). Together, the findings of such follow-up experiments may help improve clinical decision making with regard to the application of paced treadmill walking in gait rehabilitation after stroke.

Although acoustic pacing has been demonstrated to positively affect overground walking in people after stroke,[22-25] the thrust of the present study was that the combination of acoustic pacing and treadmill walk-

ing may be superior in this regard because it demands frequency modulation during walking at a constant speed. Most notable, particularly in view of the absence of prior practice, is our observation that the people after stroke were well able to directly couple their gait to the prescribed pacing frequency. This marked tendency to synchronize motor behavior to an external acoustic rhythm illustrates that paced treadmill walking constitutes an effective and powerful method for immediately modifying gait in people after stroke. It would be useful for future investigations to elaborate on the sensorimotor results obtained in the present study, for example, by assessing whether specific instructions (such as those aimed at altering auditory-motor coupling during paced walking) can further improve gait in people after stroke. These lines of inquiry may lead to valuable future therapeutic interventions for improving gait in people after stroke.

Given that the results of our study were obtained for treadmill walking, a discussion of treadmill walking versus overground walking is called for, especially because treadmill walking is widely used in gait rehabilitation after stroke and seems to allow for a different gait strategy (compared with overground walking) in a large subpopulation of people after stroke. Specifically, in the present study, the direction of step length asymmetry varied across participants (Fig. 2), a finding that was in line with the observation of Chen and colleagues[31] that 4 of 6 people after stroke exhibited a shorter step length on the nonparetic side during treadmill walking. This observation was explained by reduced peak hip extension in the paretic limb, which brought the nonparetic limb less far forward than the paretic limb during the support phase.[31] In contrast, step length generally is found to be reduced on the paretic side during

overground walking.[9-11] This difference in the direction of gait asymmetry between treadmill walking and overground walking often remains unnoticed because most studies focus only on the magnitude of gait asymmetry.[23,24,49,50]

The origin of this difference is unclear because it has been argued that treadmill walking and overground walking are identical from a biomechanical point of view,[51] that is, in the absence of body weight support, handrail use, or other physical contact with objects that are not attached to the treadmill belt. Nevertheless, treadmills offer a convenient task-oriented, repetitive practice environment for gait training because factors such as belt speed can be controlled. Moreover, with a treadmill, gait can be assessed over multiple strides, thereby increasing the reliability of gait measurements obtained with treadmill walking relative to overground walking, for which the analysis often is restricted to a small number of strides only.

Compared with unpaced treadmill walking, acoustically paced treadmill walking reduced gait asymmetry. However, the relationship between locomotor symmetry and functional walking is not yet clear and is currently under debate in the physical therapy profession. Although the restoration of locomotor symmetry does not seem to be a prerequisite for the functional recovery of gait,[52-55] gait symmetry may be positively related to energy costs,[56] gait pattern variability,[57] and local stability of walking.[58] More evidence is needed to resolve the issue of locomotor symmetry.

Conclusion

Acoustically paced treadmill walking provides an effective method for immediately eliciting changes in stride frequency in people after stroke. Furthermore, compared with unpaced

treadmill walking, paced treadmill walking improves gait in people after stroke. The finding that people after stroke preferred to time footfalls of the nonparetic limb to ipsilateral pacing stimuli may provide a promising entry point for future therapeutic interventions. Overall, the present study underscores the potential of acoustically paced treadmill walking for improving gait in people after stroke. However, more evidence is required to develop guidelines for physical therapist practice with regard to paced (treadmill) walking, especially with regard to the effectiveness of its application in various subpopulations of people after stroke.

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