The Fourth IEEE RAS/EMBS International Conference
on Biomedical Robotics and Biomechatronics
Roma, Italy. June 24-27, 2012

Robot-assisted gait training with complementary auditory feedback: results on short-term motor adaptation

Damiano Zanotto, Giulio Rosati, Federico Avanzini, Paul Stegall and Sunil K. Agrawal

Abstract— **This paper investigates how different modalities of auditory feedback may affect the short-term gait modifications induced by 4 consecutive training sessions with a robotic exoskeleton. $N = 20$ healthy subjects, 18-30 years old, were randomly assigned to 4 groups. During training, participants walked on a treadmill and were asked to modify their footpath to match a modified gait pattern, while receiving assistance by the robot (kinetic guidance). The control group received additional visual feedback, while the three experimental groups were provided with three modalities of auditory feedback. The third experimental group also received the same visual feedback as the control group. Differences in gait kinematics and symmetry among the training modalities were assessed in three post-training sessions.**

I. Introduction

Music and rhythmic auditory stimulation have become a standard protocol in the functional rehabilitation of the gait after neurological diseases [1], [2]. There is evidence, indeed, that rhythmic cues can improve subjects' effort and increase swing symmetry, walking speed, stride length and smoothness of the movements while decreasing stride time/length variability [3]–[7]. Unfortunately, the consistent use of auditory feedback in robot-assisted rehabilitation has been largely overlooked in recent related literature. Despite the evidence that a proper sound may help individuals in learning a motor task [8], [9], the precise ways that mental engagement, repetition, kinematic error and sensory information in general translate into a pattern of recovery is not well defined for rehabilitation [10]. Audio is used in many rehabilitation systems, nevertheless, in the majority of these systems the audio component plays mostly a marginal role, offering a positive or negative feedback if the patient completes or fails a task, or reinforcing the realism of a VR environment [11]. However, the use of auditory feedback can contribute to overcome some of the current limitations of rehabilitation systems in terms of user engagement, improved motor learning, acute phase rehabilitation, standardization of the rehabilitation process, and development of home rehabilitation devices [11]. In particular, sound is thought to be effective in the recovery of activities of daily living (ADLs). Indeed, ADLs rely on an essentially continuous and multimodal interaction with the world, which involves visual, kinesthetic, haptic, and auditory cues. Such cues integrate and complement each other in providing information about the environment and the interaction itself. To this regard, in order to effectively represent the environment and/or the user's movements, continuous forms of auditory feedback need to be used in conjunction with other sensory modalities.

A previous work on robot-assisted tracking movements performed with the upper limb showed that providing subjects with auditory feedback of tracking error could effectively increase subjects' effort and reduce the effects of visual distraction [12]. Similarly, related experiments performed on healthy subjects revealed how auditory feedback can also be effective in reducing tracking error. In particular, continuous task-related information provided through sound in addition to visual feedback can improve not only performance but also learning of a novel visuomotor perturbation [13]. Similar kinds of auditory feedback can more or less straightforwardly be transposed to the gait rehabilitation scenario, and this is indeed what this papers deals with. To the best of the authors' knowledge, this is the first work that specifically addresses the role of auditory feedback in robot-assisted, short-term learning of new gait trajectories.

In [14], the authors studied the short-term modifications of gait induced by 6 consecutive 10-minute long training sessions, during which the subjects walked on a treadmill while wearing the ALEX exoskeleton [15], [16]. The results supported the hypothesis that combined kinetic and visual guidance might be more effective than kinetic or visual guidance alone in inducing short-term motor adaptations. To further elaborate on this idea, we conducted a similar study with the new version of the ALEX [17]. Specifically, we investigated: 1) the possibility to induce comparable levels of adaptation by substituting combined kinetic and visual guidance with combined kinetic guidance and auditory feedback; 2) the possibility to enhance the effectiveness of combined kinetic and visual guidance by adding complementary auditory feedback.

Similar to the previous study [14], in this work kinetic guidance was delivered in the form of assistive forces exerted by the robotic leg. Visual guidance consisted of a graphic representation of the subject's current footpath, displayed to the user in a computer screen along with the prescribed footpath. The control group (CG) received combined kinetic and visual guidance. The first and the second experimental groups (SF1 and SF2) were given kinetic guidance and auditory feedback only, whereas kinetic, visual and auditory feedback were delivered to the third experimental group (SF3). The type of auditory feedback differed from group to group (Table II).

D. Zanotto (zanotto@udel.edu), P. Stegall (stegall@udel.edu) and S. K. Agrawal (agrawal@udel.edu) are with the Dept. of Mechanical Engineering, University of Delaware, Newark, DE 19716, USA.

G. Rosati (giulio.rosati@unipd.it) and F. Avanzini (federico.avanzini@dei.unipd.it) are with the School of Engineering, University of Padua, 35131 Padua, Italy.

TABLE I
PARTICIPANTS' DEMOGRAPHIC DETAILS, SPEED AND STRIDE PERIOD

Gr.	Gen.	Age [y]	Mass [kg]	Height [m]	CWS [m/s]	T_{str} [s]
CG	F	18	54.4	1.57	0.54	1.82
	M	20	81.6	1.9	0.89	1.6
	M	25	70.3	1.78	0.98	1.44
	F	26	43	1.61	0.63	1.64
	M	30	88.5	1.78	0.98	1.32
		23.8±4.8	67.6±18.8	1.73±0.14	0.80±0.21	1.56±0.19
SF1	M	27	73	1.73	0.67	1.64
	M	24	80	1.83	0.76	1.42
	M	28	65.7	1.68	0.85	1.37
	M	26	91	1.78	0.98	1.37
	F	26	46.3	1.52	0.89	1.39
		26.2±1.5	71.2±16.8	1.71±0.12	0.83±0.12	1.44±0.12
SF2	F	28	53	1.7	0.63	1.7
	F	25	62	1.58	0.72	1.49
	M	28	69	1.74	0.85	1.42
	F	22	61.2	1.65	0.80	1.43
	M	24	61.2	1.73	0.89	1.35
		25.4±2.6	61.3±5.7	1.68±0.07	0.78±0.11	1.48±0.13
SF3	M	20	90.7	1.93	0.76	1.64
	M	19	59	1.72	0.72	1.64
	M	27	61	1.74	0.89	1.31
	F	25	60	1.55	0.76	1.41
	M	23	81.7	1.85	0.85	1.5
		22.8±3.3	70.5±14.7	1.76±0.14	0.80±0.07	1.50±0.14
		24.6±3.3	**67.6±14.2**	**1.72±0.11**	**0.80±0.13**	**1.49±0.14**
		p=0.38	**p=0.71**	**p=0.77**	**p=0.94**	**p=0.60**

TABLE II
FEEDBACK MODALITIES

Gr.	Assistive Force (FFC)	Vis. Feedback (VG)	Sonification of Current Traj.	Ext. Auditory Pacing	Sbj-triggered Beats
CG	*	*	-	-	-
SF1	*	-	*	-	-
SF2	*	-	-	*	-
SF3	*	*	-	-	*

II. METHOD

A. Subjects

$N = 20$ young healthy subjects volunteered in this experiment and were randomly assigned to one of 4 groups (3 experimental and 1 control). Subjects were included if they were right-leg dominant and had no musculoskeletal or neurological problems. There were no significant differences between groups in age, mass, height, comfortable walking speed in the robot and stride period at baseline (Tab. I). Ethical approval for this study was obtained by the Institutional Review Board of the University of Delaware, and each subject gave informed consent before participating to the experiment.

B. Experimental Setup

The robotic device employed in this study is the ALEX II (Active Leg EXoskeleton, [17]), a unilateral exoskeleton with two active DOF (hip and knee flexion and extension). The device can operate in zero-torque mode or with force field enabled. When the Cartesian-based force field is active, a target *footpath* is loaded into the controller, which represents the locus of points which the projection of the subject's malleolus onto the sagittal plane would pass through in an ideal gait cycle. The force-field behavior is modeled by a non-linear virtual spring [15], [17] that exerts a normal force towards the prescribed footpath if the deviation of the subject's foot from the target footpath exceeds an adjustable threshold. Conversely, no force is ideally exerted by the robot to the subject's leg if his/her ankle is within this threshold.

Subjects walked on a treadmill - with the robotic leg attached to their left leg - and wore sensorized shoes, each one equipped with pressure sensors. Those signals were used to trigger the rhythmic beats (subjects in SF3) as well as for offline data processing. Recorded data were sent from the robot real-time controller to a host PC, which ran the user interface [17]. A MATLAB script running on the same PC performed real-time processing on the limited set of data required for computing the auditory feedback, and sent them to a laptop via User Datagram Protocol (UDP). A real-time graphical programming environment[1] running on the laptop was used for real-time audio synthesis. Sounds were presented to the subject by means of stereo speakers located in front of the treadmill.

C. Protocol

Each subject walked for 2 minutes on the treadmill at his/her comfortable walking speed (CWS). Afterwards, his/her left leg was fitted to the device, and he/she walked on the treadmill for 10 minutes while the robot was controlled in zero-torque mode. During this warm-up session, the subject's CWS in the robot was determined. The treadmill speed was then maintained for the rest of the experiment. In this study, the robotic leg was attached to subject's non-dominant leg, i.e., the limb which is commonly recognized to be mainly involved in motion control [18].

In the following 5-minute walk (*baseline* session, BSL), the hip and knee joint angles were recorded by motor encoders. By averaging data taken from the last 30 seconds in this session, and mapping the resulting averaged footpath to the task-space (i.e., the Cartesian space), the subject's *baseline footpath* was derived. The *target footpath* was then computed by applying isotropic scaling to the set of points of the baseline footpath in the hip/knee joint space (JS), with 0.8 as the scaling factor and the origin of the hip/knee axes as the external homothetic center. This method yields a stable yet challenging gait cycle, characterized by a shorter and shallower step [17]. Similarly, the target stride period was computed from the average baseline stride period by comparing the relative positions of the heel-strike/toe-off points in the baseline footpath to the corresponding estimated positions in the target footpath.

During training, subjects walked in the robotic exoskeleton, trying to match the target footpath. Training consisted of 4, 10-minutes long sessions, during which the force field control (FFC) was always active (threshold 5mm). Conversely, when provided, visual guidance (VG) and auditory feedbacks (SF) were turned on intermittently (i.e., during the first and third quarter of each training session) to prevent subjects from over-relying on extrinsic feedbacks (see Table II). Breaks were given to subjects between each pair of consecutive training sessions. Duration of the breaks was up to the subjects, and ranged from 2 to 5 minutes. Minimal verbal cues were provided during early trainings, only if the subject found it difficult to adapt to the force field.

[1] http://puredata.info/

In addition to the kinetic guidance exerted by the robot, the control group (CG) and the experimental group SF3 received visual feedback from a screen located in front of the subject. The screen displayed the target footpath, along with the current position of the subject's ankle (VG). Rhythmic beats triggered by the subject's heel strikes were also given to participants included in SF3. Thus, auditory beats provided information about the current gait timing (i.e., performance-related feedback), whereas information about the mismatch between the prescribed and the current trajectory (i.e., error-related feedback) were delivered through the visual and somatosensory systems. It was hypothesized that this type of auditory feedback would mainly improve gait repeatability, and potentially improve the quality of the matching by acting synergistically with VG and FFC.

Subjects in SF2 received external acoustic pacing and kinetic guidance. Rhythmic beats were similar to those provided to SF3, however, their tempo was constant and corresponded to the stride period of the target trajectory. In this case, the audio channel was used to provide the user with additional information on task instead of performance. We hypothesized that subjects in SF2 would rely on both somatosensory and auditory information to adapt their gait cycle to the prescribed footpath.

Subjects in SF1 were given a continuos acoustic feedback that corresponded to the sonification of their current trajectory. Each point of the joint space path was mapped to a determined vocalized sound produced by a formant synthesis patch. In particular, the current hip angle controlled the formants of the sound (i.e., the couple of frequencies that produce a vowel), while the current knee angle was mapped to the fundamental frequency of the sound, which increased with knee flexion. Similarly to the subject-triggered beats, this auditory mode provided information on performance and was primarily designed to improve gait repeatability: information about the mismatch between the current and the goal footpath were only delivered by the kinetic guidance.

Participants included in SF1 and SF2 were shown the current ankle position and the prescribed footpath during the first 40s of each training session. This approach was meant to provide subjects with minimal information about the goal movement. Similarly, during the first 40s of each training session, people in SF3 were provided with the prescribed cadence instead of the subject-triggered one.

Post-tests consist of 3 sessions, 5 minutes each, the first of which started 1 minute after the conclusion of the last training session (PT1). A 5-minute break was given between consecutive sessions, therefore the second (PT2) and the third (PT3) post-tests started 11 and 21 minutes after training, respectively. The robot was controlled in zero-torque mode and subjects were instructed to walk as normally as possible during these sessions.

D. Data processing

Data were collected at 500Hz and then low-pass filtered with a forward-backward 5-th order Butterworth filter ($f_c =$ 30Hz). Then, the normalized error area (Fig. 1) and a set

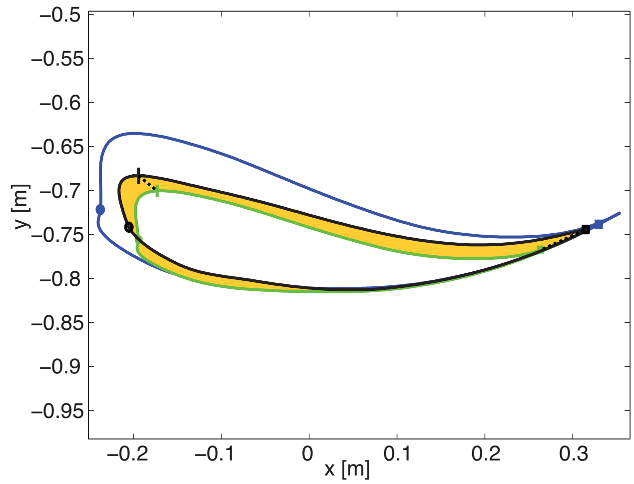

Fig. 1. Example of footpaths: baseline (blue line), target (green line), and average (black line). The area of the colored surfaces divided by the area included between the blue and the green lines yields the normalized error area err. No matter the relative position between the two curves, error areas are always regarded as positive.

of symmetry ratios were computed. The analysis presented in this paper refers to data recorded during the post-test sessions.

Data collected over a specific session (5min for baseline and post-tests, 10min for trainings) were first split into 30s time intervals. Then, metrics were computed within each time interval and subsequently averaged to yield a single value per session. For each time block, the average footpath described by the subject's ankle was computed. The area enclosed between the average and the target footpaths was taken as a measure of the average amount of deviation during the corresponding time interval (Fig. 1). To get the error metric, this value was normalized by the area enclosed between the baseline and the target footpath, yielding the *normalized error area* (err). When $err \approx 0$ the subject is perfectly matching the target trajectory, conversely, when $err \approx 1$ the average footpath is close to the baseline footpath.

The normalized error area was compared between groups to identify potential baseline differences among groups (1-way ANOVA). The Kolmogorov-Smirnov test with Lilliefors correction was performed within each group and across the sessions to check the normality assumption. Levene's test was performed at each session to verify homoscedasticity [19].

If any adaptation occurred as a consequence of training, the subject's footpath at PT1 was closer to the prescribed footpath than it was before training. Therefore, we expected a reduction in the normalized error area between BSL and PT1. Also, if this adaptation was maintained across all the retention tests, then the same result held when comparing BSL to PT2 and BSL to PT3. To test this hypotheses and check for potential differences among the training modalities, we run three separate mixed-model ANOVAs, with *group* as the between subjects factor (4 levels) and *session* as the within-subject factor (2 levels).

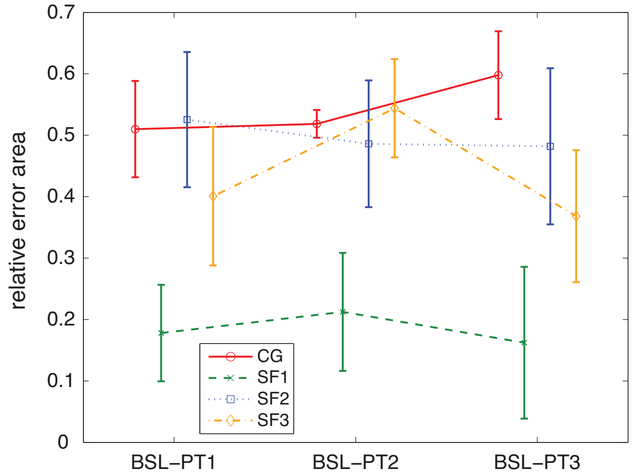

Fig. 2. Relative error area for the three post-tests (5 minutes tests starting 1 minute, 11 minutes and 21 minutes after the end of the last training session). This metrics is obtained by subtracting the normalized error area at a given post-test from the corresponding value at the BSL. Hence, high values of this parameter indicate a good matching of the prescribed footpath. Error bars indicate the standard error of the mean (SEM).

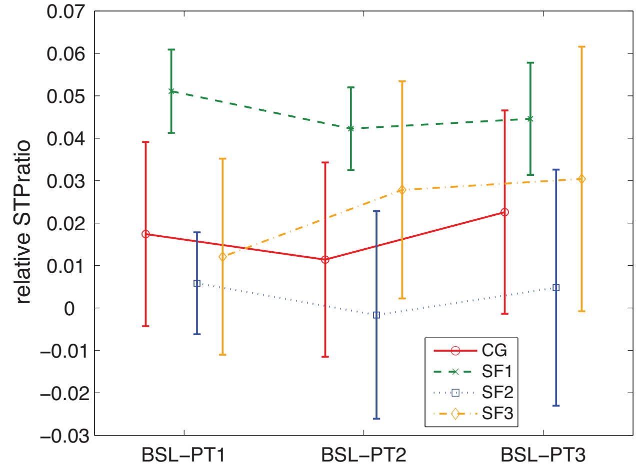

Fig. 3. Differences in the STP ratio w.r.t. baseline across the PT sessions. Positive values indicate deviation from symmetry. Error bars indicate the SEM.

If a significant effect of the within factor was found (i.e., the normalized error did actually decrease between BSL and a certain PT session), along with a group by session interaction (i.e., the amount of decrease depended on the training groups), differences among groups were further inspected by running a 1-way ANOVA, with the *relative error area* as the dependent variable. The latter was computed by subtracting the normalized error area at the specific PT session from the corresponding value at the BSL. Thus, the larger the relative area, the better the retention. Post-hoc comparisons were run to check for differences among pairs of training groups.

Instead, if a main effect of the within factor was found by the mixed-model ANOVA, along with a main effect of the between factor (i.e., mean normalized error was not the same on all the training groups), then separate repeated measures ANOVAs were run on the groups, to check for differences in the level of retention between different groups.

The same analysis was applied to the symmetry ratios: the double support ratio (DSratio), the stance period ratio (STP ratio) and the stance to swing ratio (STSW ratio) [20]. We hypothesized that wearing the exoskeleton induced a bilateral gait asymmetry whose level could potentially change between treatments and across the sessions. Symmetry ratios (left leg over right leg) were employed to verify these hypotheses

III. Results

The hypotheses of normality and homogeneity of variance couldn't be rejected in almost all the data subsets ($p > 0.05$), therefore we applied standard parametric tests in the following analysis. At BSL, subjects did not differ significantly in any of the error metrics ($p > 0.5$).

Right after the last training, all the subjects were able to significantly reduce the normalized error ($F(1, 16) = 70.181$, $p < 0.01$). However, participants in the SF1 group showed a rougher approximation of the prescribed trajectory during PT1, as confirmed by the group by session interaction which was close to significancy ($F(3, 16) = 2.769$, $p = 0.076$). Indeed, when performing pairwise comparisons on the relative error area (Fig. 2), a smaller reduction of the error was found for the SF1 group when compared either to CG ($p < 0.05$) or SF2 ($p < 0.05$).

Significant modifications of the gait were maintained during PT2 by all the groups ($F(1, 16) = 115.688$, $p < 0.01$), even though the amount of error reduction depended on groups ($F(3, 16) = 3.527$, $p < 0.05$). As suggested by Fig. 2, the interaction was due to a smaller reduction of the normalized error (i.e., smaller relative error) for subjects in SF1. Post-hoc comparisons confirmed significant differences between SF1 and the other groups: CG ($p < 0.05$), SF2 ($p < 0.05$) and SF3 ($p = 0.01$).

Gait modifications were generally retained during PT3 ($F(1, 16) = 53.905$, $p < 0.01$), and the group by session interaction only approached significance ($F(3, 16) = 2.865$, $p = 0.07$). However, a main effect of the factor group ($F(3, 16) = 3.605$, $p < 0.05$) was found as well. Thus, separate repeated-measures ANOVAs were performed on the relative error for each group, to inspect differences in the level of retention. Results showed that subjects in CG ($F(1, 4) = 69.916$, $p < 0.01$), SF2 ($F(1, 4) = 14.383$, $p < 0.05$) and SF3 ($F(1, 4) = 11.733$, $p < 0.05$) retained a modified gait path up to this session, while subjects in SF1 did not ($F(1, 4) = 1.722$, $p > 0.5$). Thus, not only did SF1 show the least accurate adaptation to the target footpath, but it also showed the shortest retention, whereas no significant differences were observed among the other groups.

Symmetry ratios were highly correlated, and yielded similar results at each post-test. Therefore, only the stance period ratio (STP ratio) is discussed here. At the BSL, the STP ratio was significantly less than unity for all the groups, as indicated by separate one-sample t-tests ($p \leq 0.01$ for all groups). However, no significant differences were identified among groups ($F(3, 16) = 1.530$, $p > 0.05$).

At PT1, the STP ratio generally decreased with respect to BSL ($F(1, 16) = 5.997$, $p < 0.05$), indicating a further departure from symmetry immediately after training. However, decrements were only marginal at PT2 ($F(1, 16) = 3.405$, $p = 0.08$) and PT3 ($F(1, 16) = 4.2$, $p = 0.06$). No interactions between groups and sessions were found in each post-test. Nonetheless, the main effect of group approaching significance suggested us to analyze each group separately.

When breaking down the analysis to single groups, repeated-measures ANOVAs showed that SF1 was the only training group whose STP ratio decreased significantly w.r.t. BSL in PT1 ($F(1, 4) = 27.084$, $p < 0.01$), PT2 ($F(1, 4) = 18.831$, $p = 0.01$) and PT3 ($F(1, 4) = 11.383$, $p < 0.05$). Moreover, one-sample t-tests were run on each group to check for difference from the unitary value at all the post-tests. The average STP ratio of subjects in SF2 did not significantly differ from unity in PT1, PT2 and PT3 ($p > 0.05$), while significant differences from unity were observed for all the other groups.

Hence, symmetry ratios indicated that subjects' weight was mostly supported by the right leg when walking in the robot. The degree of asymmetry was generally more marked after training (Fig. 3), even though significant increase with respect to BSL were identified for SF1 only. Apparently, subjects who received task-related rhythm showed a different behavior, since their STP ratio did no longer differ from unity after training.

IV. Discussion

Results obtained in this study suggested that short-time modifications could be induced in healthy individuals after 4 training sessions, 10 minutes each, by combining the kinetic assistance provided by a robotic exoskeleton with either visual guidance, or auditory feedback, or both. All the groups but SF1 retained significant gait modifications up to PT3 (i.e., 26 minutes after the last training).

Subjects who received visual guidance in addition to kinetic guidance (CG) showed comparable results as those who received simple rhythmic cues and kinetic guidance (SF2) in all the post-training sessions. Should these results be confirmed by further experiments, they would suggest that additional visual feedback providing information about the task and about the mismatch between current and prescribed position may be successfully substituted with simple rhythmic cues whose frequency corresponds to the target gait cycle.

It may be objected that this result is limited to the specific task, involving a rather simple modification of the natural footpath (i.e., shorter and shallower steps). However, pilot studies showed that the goal footpaths prescribed in these tests differed greatly from a natural gait cycle performed at fast cadence. Therefore, the short-term adaptation observed in SF2 must be derived from both kinematic guidance (providing extrinsic feedback about the mismatch between current and prescribed footpath) and rhythmic cues (providing information about the ideal cadence only). It may also be objected that the role of the force feedback is predominant in the training protocol, so that people training with the force field alone would have produced similar results as those in CG and SF2. However, a recent study which employed a similar training protocol and the previous version of the ALEX [14] showed that the group which received solely kinetic assistance produced worse results at the immediate post-test than did the group which received both kinetic and visual guidance.

Based on the set of data reported in this paper, complementary auditory feedback providing information about subject's actual cadence does not favor short-term motor adaptation. Indeed, subjects who received rhythmic cues triggered by their own steps in addition to kinetic and visual guidance (SF3), did not show a significantly different relative area than did those in the CG, in any of the post-tests. Since both auditory and visual feedback require attention, which may be thought of as a finite shared resource [21], it may be that the lack of beneficial effects of the rhythmic cues observed in our study was attributable to a reduction of attention to the auditory feedback in the presence of visual guidance (i.e., a competing attentional load). This results, however, may be specific to the particular type of auditory feedback (i.e., one computed from subjects' own movements, thereby independent of task and error). Indeed, a previous work on robot-assisted tracking movements performed with the upper limb showed that providing subjects with auditory feedback of tracking error could effectively increase subjects' effort and reduce the effects of visual distraction [12].

People who received a continuous acoustic feedback corresponding to the sonification of their current foot trajectory showed less accurate adaptation to the prescribed footpath in all the post-tests. They also showed a shorter retention, their footpath not being significantly different from the baseline footpath at the last retention test. It should be noted that this kind of sound only provided information about the subject's current trajectory, while information about the task (more precisely, about the mismatch between the task and the current performance) were provided at the somatosensory level by kinetic guidance. This lack of additional auditory/visual information about the prescribed task during training might have contributed to worsen the results at the post-tests.

When walking in the robot, subjects tended to rely mostly on their right leg to support their weight. This may be due to the additional mass and inertia provided by the robot. Several studies reported the same effect when the natural mass/inertia of the leg was increased either by additional loads [22] or by a robotic exoskeleton [23], [24]. For subjects in SF1, the level of asymmetry significantly increased after training, and remained approximately unchanged across the retention tests. The increment in gait asymmetry did not reach significance for participants in CG and SF3. Conversely, people in SF2 showed a different behavior after training, their symmetry ratio becoming not significantly different from unity after training, across all the post-tests. It is believed that this improvement in gait symmetry may be directly related to the task-related rhythmic cues provided during training.

Further analysis need to be performed in the collected data. For example, different feedback modalities could have different effects in individual phases of the gait (stance, early swing and late swing). Also, It might be possible that SF1 and SF3, by emphasizing time-dependent differences in successive gait cycles, could improve repeatability. Should this be the case, those feedback modalities may play a role in increasing smoothness and reducing stride time/length variability in subjects with neurological disorders.

Our analysis did not detect any clear washout effects across the post-test, the relative error following a roughly constant or bell-shaped trend in all the groups. This might be related to the relatively short assessment period (26 minutes after training), and to aftereffects that might have affected results in PT1.

The preliminary results reported in this study must be interpreted with caution, owing to the small size of the sample. Further experiments are currently being carried out to confirm the findings reported in this work.

V. Conclusion

Short-term gait modifications were detected in all the groups, however, quality and duration of retention was dependent on the training modality. Specifically, as far as the retention of the modified footpath is concerned, we can assert that the combination of kinetic and visual guidance may be as effective as the combination of kinetic guidance and rhythmic cues, whose frequency corresponds to the cadence of the prescribed footpath. In addition, subjects who tested the latter feedback modality were capable of improving gait symmetry after training, whereas people assigned to the former modality were not. Adding a subject-triggered rhythm to kinetic and visual guidance did not worsen the deviation from the prescribed footpath measured at the retention tests, nor did it lead to significant improvements compared to the control group. Conversely, by adding to the kinetic guidance a continuos auditory feedback that conveyed information about the subject's current gait cycle, worse approximations of the prescribed gait cycle were obtained at the retention tests, and the effects of training were no longer detectable at the last post-test session (except for a significant increase of gait asymmetry). In the near future, a study will be conducted on subjects with neurological disorders, to quantify the potential benefits of complementary rhythmic auditory feedback during robot-assisted gait training.

Acknowledgment

This work was supported by the National Institute of Health, Grant No. HD 38582, and by the University of Padua, Grant No. 2009/CPDA098430.

References

[1] M. Thaut and M. Abiru, "Rhythmic auditory stimulation in rehabilitation of movement disorders: a review of current research," *Music Perception*, vol. 27, no. 4, pp. 263–269, 2010.

[2] M. Roerdink *et al.*, "Walking to the beat of different drums: practical implications for the use of acoustic rhythms in gait rehabilitation." *Gait & posture*, vol. 33, no. 4, pp. 690–4, Apr. 2011.

[3] M. Schauer and K.-H. Mauritz, "Musical motor feedback (MMF) in walking hemiparetic stroke patients: randomized trials of gait improvement," *Clinical Rehabilitation*, vol. 17, no. 7, pp. 713–722, Oct. 2003.

[4] M. Suteerawattananon *et al.*, "Effects of visual and auditory cues on gait in individuals with Parkinson's disease." *Journal of the neurological sciences*, vol. 219, no. 1-2, pp. 63–9, Apr. 2004.

[5] I. Lim *et al.*, "Effects of external rhythmical cueing on gait in patients with Parkinson's disease: a systematic review," *Clinical Rehabilitation*, vol. 19, no. 7, pp. 695–713, Oct. 2005.

[6] M. H. Thaut *et al.*, "Rhythmic auditory stimulation improves gait more than NDT/Bobath training in near-ambulatory patients early poststroke: a single-blind, randomized trial." *Neurorehabilitation and neural repair*, vol. 21, no. 5, pp. 455–9, 2007.

[7] M. Roerdink *et al.*, "Rhythm perturbations in acoustically paced treadmill walking after stroke." *Neurorehabilitation and neural repair*, vol. 23, no. 7, pp. 668–78, Sep. 2009.

[8] J. A.Taylor and K. A.Thoroughman, "Divided attention impairs human motor adaptation but not feedback control," *J. Neurophysiol.*, p. 10, April 2007.

[9] M. Rath and D. Rocchesso, "Continuous sonic feedback from a rolling ball," *IEEE Multimedia*, vol. 12, no. 2, pp. 60–69, April-June 2005.

[10] D. J. Reinkensmeyer and J. Galvez, "Some key problems for robot-assisted movement therapy research: A perspective from the university of California at Irvine," in *IEEE 10th Int. Conf. Rehab. Rob. (ICORR 2007)*, 2007, pp. 1009–1015.

[11] F. Avanzini *et al.*, "Integrating auditory feedback in motor rehabilitation systems," in *International Conference on Multimodal Interfaces for Skills Transfer*, 2009.

[12] R. Secoli *et al.*, "Effect of visual distraction and auditory feedback on patient effort during robot-assisted movement training after stroke." *Journal of neuroengineering and rehabilitation*, vol. 8, no. 1, p. 21, Jan. 2011.

[13] G. Rosati *et al.*, "Improving robotics for neurorehabilitation: enhancing engagement , performance , and learning with auditory feedback," in *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on*, 2011, pp. 341–346.

[14] S. H. Kim *et al.*, "Robot-assisted modifications of gait in healthy individuals." *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, vol. 202, no. 4, pp. 809–24, May 2010.

[15] S. Banala, A. Kulpe, and S. K. Agrawal, "A powered leg orthosis for gait rehabilitation of motor-impaired patients," in *International Conference on Robotics and Automation*, no. April, Roma, Italy, 2007, pp. 10–14.

[16] S. K. Banala *et al.*, "Robot assisted gait training with active leg exoskeleton (ALEX)." *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 17, no. 1, pp. 2–8, Feb. 2009.

[17] K. Winfree, P. Stegall, and Ag, "Design of a Minimally Constraining, Passively Supported Gait Training Exoskeleton: ALEX II," in *2011 IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2011, pp. 1053–1058.

[18] H. Sadeghi *et al.*, "Symmetry and limb dominance in able-bodied gait: a review." *Gait & posture*, vol. 12, no. 1, pp. 34–45, Sep. 2000.

[19] J. H. Zar, *Biostatistical Analysis (5th Edition)*. Upper Saddle River, NJ, USA: Prentice-Hall, Inc., 2007.

[20] K. K. Patterson *et al.*, "Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization." *Gait & posture*, vol. 31, no. 2, pp. 241–6, Feb. 2010.

[21] C. Eccleston and G. Crombez, "Pain demands attention: a cognitive-affective model of the interruptive function of pain." *Psychological bulletin*, vol. 125, no. 3, pp. 356–66, May 1999.

[22] J. W. Noble and S. D. Prentice, "Adaptation to unilateral change in lower limb mechanical properties during human walking." *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, vol. 169, no. 4, pp. 482–95, Mar. 2006.

[23] E. H. F. van Asseldonk *et al.*, "The Effects on Kinematics and Muscle Activity of Walking in a Robotic Gait Trainer During Zero-Force Control." *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 16, no. 4, pp. 360–370, Aug. 2008.

[24] J.-S. Kim *et al.*, "Visual and kinesthetic locomotor imagery training integrated with auditory step rhythm for walking performance of patients with chronic stroke." *Clinical rehabilitation*, vol. 25, no. 2, pp. 134–45, Mar. 2011.