2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Experimental assessment of gait with rhythmic auditory perturbations

Arturo Forner-Cordero, Cinthia Itiki, Rafael Sanchez Souza, João Carlos M. C. Lourenço, Hermano Igo Krebs, *Fellow, IEEE*

Abstract— **To understand the impact of implicit auditory perturbations during gait, we used a pacing task that involves the proper timing and synchrony between heel strike and metronome beats. Five individuals performed two different types of tasks presented in the following order: 1) walk on a treadmill while listening to a steady metronome (non-perturbed condition), and 2) walk on a treadmill while listening to the metronome with rhythmic auditory alteration (perturbed condition). We examined the quality of synchronization between heel strike and the metronome beat, the non-synchronous period following perturbation, and the synchronization period. The subjects followed tightly the metronome beats even for changes of less than 10 msec. In addition, we recorded the electromyographic (EMG) activity of selected muscles of the leg and we found the same pattern for the onset and offset of EMG activity. These results indicate an entrainment between the gait cadence and the metronome rhythm in healthy adults and support new therapies to stimulate changes in rhythm and symmetry.**

I. Introduction

Gait is an almost rhythmic task that can be performed under several external constraints by healthy individuals. For example, it is possible to walk on different types of floor surfaces and at different speeds. Walking on a treadmill imposes a constraint on the speed (constant speed). Healthy adults can also synchronize their gait cadence to an auditory cue, for instance to the beats of a metronome. That said, due to neurological deficits such as a stroke, Parkinson's, Alzheimer's, and Huntington's Diseases, in brain or spinal cord injuries, it is possible to walk on a very limited basis with large asymmetry between more affected and less or unaffected limbs.

In order to help in the rehabilitation process of these patients, several types of rehabilitation devices including exoskeletons, such as Lokomat [1-4] or ALEX [2, 5, 6], were created. The results so far have been inconclusive and more research is needed. Here we explore the potential benefit of using acoustic cues in combination with exoskeleton devices [1, 5].

This work was supported by CNPq (478863/2010-1) and the MIT-Brazil Program.

Arturo Forner-Cordero, Rafael Sanchez Souza and João Carlos M. C. Lourenço are with the Biomechatronics Laboratory, Department of Mechatronics and Mechanical Systems of the Escola Politécnica, University of São Paulo, São Paulo, Brazil (corresponding author: aforner@usp.br).

Cinthia Itiki is with the Department of Electrical Engineering of the Escola Politécnica, University of São Paulo, São Paulo, Brazil.

H.I. Krebs is with the Dept. of Mechanical Engineering, MIT, Cambridge, MA02139 USA.(hikrebs@mit.edu)

Prior studies have found positive benefits in the use of metronome rhythm gait [7, 8]. Furthermore, we have recently reported that subjects can alter their gait patterns based on implicit changes in the gait visual feedback [2]. Here we expanded our work on visual feedback and report on the effects of gait auditory feedback. More specifically, we examined experimentally the patterns of gait adaptation for almost imperceptible implicit variations in the metronome rhythm.

We hypothesized that the subtle auditory perturbations would enhance gait motor adaptation at the same time a varying sensory input would keep the subject more alert while performing the task, even though s/he is unaware of the fluctuation. Because it can be argued this would happen in case of even very small explicit perturbation, we designed a series of walking experiments in which the subtle fluctuations were introduced without subject awareness. Five subjects walked on the treadmill following a metronome beat at each heel strike. The frequency of the metronome was slowly varied; its beat increased or decreased in a randomized fashion, without informing the subject. This paper is organized as follows: Section II describes the methods including the experimental setup as well as the motion analyses and the recording of the electromyographic (EMG) activity of selected muscles of both legs. Section III presents the results. We conclude in Section IV discussing the results in the context of future therapy applications as well as future and on-going work including more subjects and distinct perturbation conditions.

II. Materials and Methods

A. Instrument

The experiments were carried out while subjects were walking on a treadmill (Movement – LX160 Treadmill) at a constant speed.

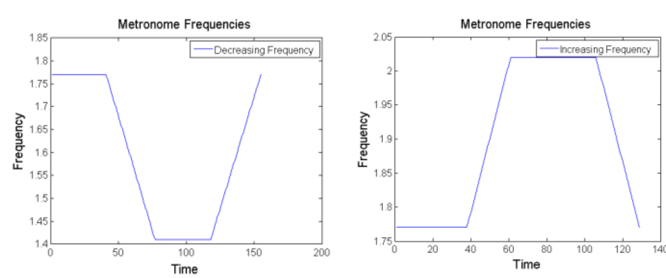


Figure 1. Metronome frequency variation

The metronome software and hardware parts were custom-made at Biomechatronics Laboratory in the Politécnica

School of São Paulo University (USP). The hardware was based on an Arduino Uno and included a custom-made circuit to trigger a set of Infra-red LEDs that can be detected by the motion capture system and interfaced with the EMG trigger input.

The period of the metronome was initialized at 566 msec. During the first block condition, this frequency remained constant for 120 sec. The beat was then increased or decreased randomly during the second block. In the decreased beat period condition (Fig. 1), the initial time interval of 566 msec was kept for 60 steps and then decreased in 28 steps of 2-3 msec until a minimum period of 494 msec. This frequency was kept for the subsequent 60 steps and then increased back to the initial beat in identical number of steps. In the increased beat period condition, the period was varied between 566 msec to 711 msec in 28 steps of 5 msec. The lower frequency was maintained for 60 steps before it decreased back to the original period of 566 msec (Fig. 1).

The electromyography system (BTS FREEEMG-300, BTS spa, Italy) consisted of an integrated amplifier and transmitter that can be directly attached to the disposable surface electrodes. In addition, the EMG can be triggered externally by a digital TTL signal. The trigger of the EMG was connected to the metronome so the first beep initiated the EMG recording.

The motion capture system consisted of eight OptiTrack cameras working with the Arena Motion Capture software (Natural Point Inc, USA). These cameras have a frame rate of 100 frames per second.

B. *Procedure*

A group of five healthy young volunteers were recruited. They were all males between 18 and 25 years old. They were instructed to walk on a treadmill at the velocity of 4 km/h, following the rhythm cues of the metronome, but they were not informed that there would be any changes in the auditory frequency. While the subject walked on the treadmill, the frequency of the metronome was either increased or decreased linearly or remained fixed (Fig.1).Participants performed the three different routines randomly in 15 bouts, each consisting of 2-3 minutes of walking. Sixteen markers were placed on anatomical landmarks following the modified Helen Hayes´ protocol and they were recorded with the camera system. In addition, eight pairs of surface electrodes EMG were placed on the anatomical locations indicated by the SENIAM protocol [9] in order to record the EMG activity of the following muscles in each leg: Rectus Femoris, Tibialis Anterior, Biceps Femoris and Medial Gastrocnemius.

C. *Data Analysis*

The motion data was reconstructed using the commercial software Arena (Natural Point, Inc., USA) and the three-dimensional trajectories of the markers were exported to an ASCII file. Subsequently, all the processing was performed using Matlab (The Mathworks Inc, USA).

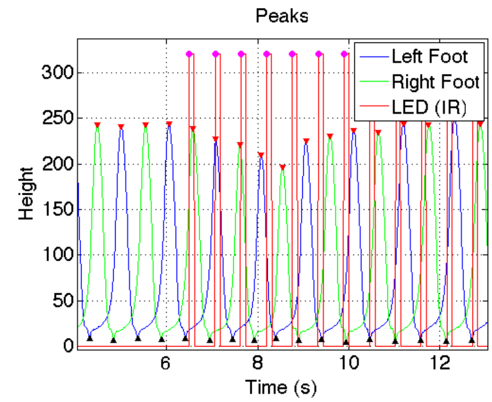


Figure 2. Detection of the heel-strike left and right and metronome.

The heel marker was used to identify the heel strikes in the right and left foot generating the following time sequences [10]:

Right step period defined as the time between the heel-strike right and the previous heel-strike left.

Left step period, defined as the time between the left heel-strike and the previous heel-strike right.

Stride period is defined as the time between consecutive heel-strikes with the same leg, left or right. Fig. 2 shows a typical example of the detection of the heel-strikes.

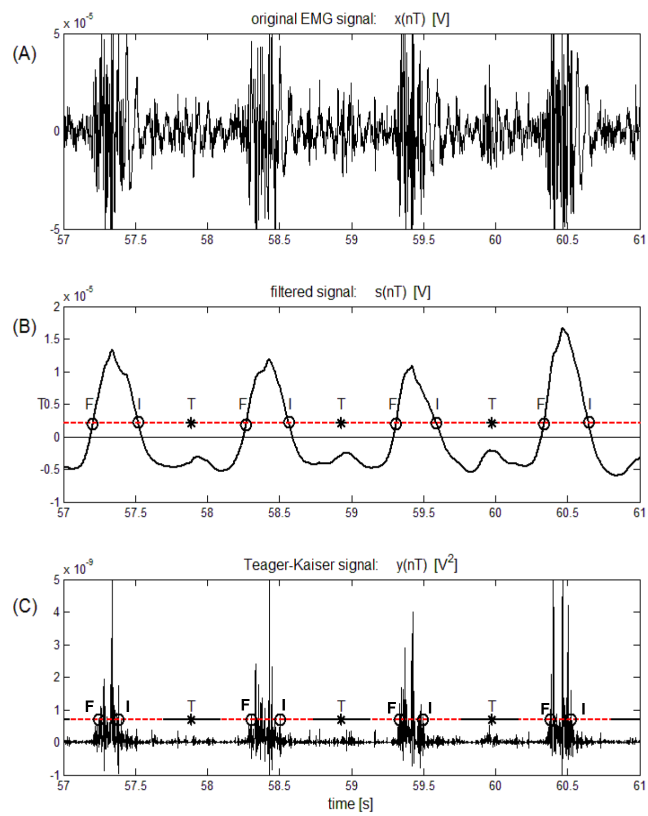


Figure 3. A short epoch of the (A) original EMG signal, (B) filtered signal, and (C) Teager-Kaiser signal. Panel C also shows the times of muscle activity initiation -I- and completion –F-, as well as the center times –T- of the 400 msec segments (continuous black line). Thresholds are indicated by dashed lines and on-off times by circles.

The EMG signals (Fig. 3.A) were acquired at 1 kHz with the initiation of the measurements triggered by the start of the metronome.

The Teager-Kaiser (TK) energy operator was applied to the acquired signals, resulting in:

$$y(nT)=x(nT)\,x(nT)-x(nT-T)\,x(nT+T)\,, \qquad (1)$$

for n=2, 3, …, N-1; where x[n] is the original EMG signal, y(nT) is the TK signal, and T is the sampling interval.

A band-pass filtered signal s(nT) was computed in order to determine the cycles of muscle activity (Figure 3.B). A second-order Butterworth filter with cutoff frequencies of 0.1Hz and 3Hz was employed. The original signal was filtered twice—once in the forward direction and once in the backward direction— filfilt.m routine, in order to guarantee a zero delay between the filtered and original signals. A threshold was set equal to 10% of the maximum value of the filtered signal and used to determine the offset or completion (F) and onset or initiation (I) times of muscle activity. These values were regarded as estimates of the on-off times of muscle activity.

The average between F and the following I defined the center time (T) of the inactivity segment for both, filtered and TK signals. The inactivity segment length was fixed as 400ms. The mean value (M_i) and 15 times the standard deviation (S_i) of the i-th TK segment were used to define the threshold values L_i.

$$L_i = M_i + 15S_i \qquad (2)$$

For simulated EMG, threshold values are computed by the sum of the mean value with three standard-deviations [11]. However, for EMG with very low magnitude of baseline, the use of fifteen standard deviations has been suggested in the literature [12].

Since spurious activity between cycles was present, the median of the threshold values was used for determining the on- and off-times of muscle activity of the corresponding TK signal (Fig. 3.C).

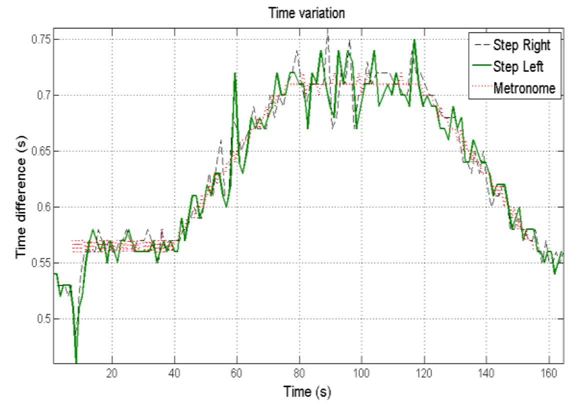
This procedure was used to generate a matrix with the onset and offset times for each muscle. The onset and offset periods were obtained by subtracting consecutive onsets and offsets. In case of muscles that had two activation peaks in one stride only the larger peak was considered here.

III. Results

Here we present the results of the analysis of a representative subject. Fig. 4 shows the metronome frequency variation and the corresponding step times, both left and right during two trials, one with increasing and the other with a decreasing metronome period.

Fig. 4A corresponds to a decrease in beat frequency. Notice that the period increases at small steps of 5 msec and the step time followed "instantaneously" the perturbations or rhythm variations. Fig 4B shows the results from another representative trial with a frequency increase. In this case, the decrease in the time steps are lower than 3 msec but the subject is, again, following the rhythm variation "instantaneously."

A



B

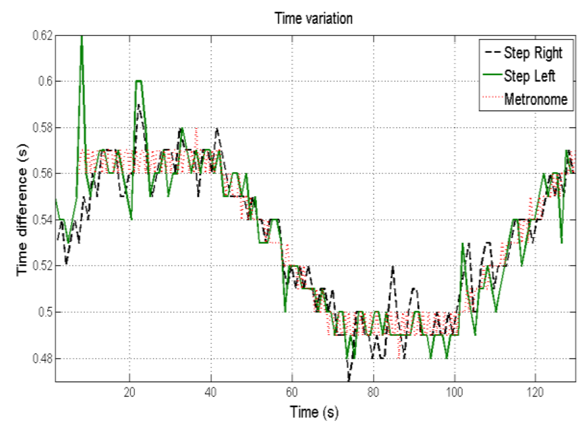


Figure 4. Step Right (solid line), Left (dashed) and Metronome (pointed) period corresponding to two trials with: A. Frequency decrease (increased period) and B. Frequency increase (decreased period).

To assess whether the subject followed the variations in the metronome rhythm, we zoomed in on the region of frequency increase and decrease (Fig. 5). Note that the time resolution of the measurement is 10 msec (100 Hz sampling frequency of the motion capture system).

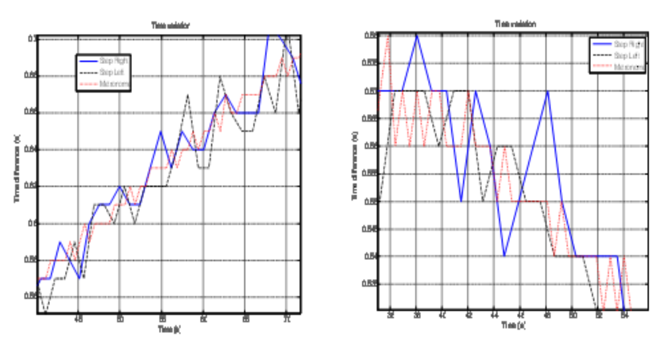
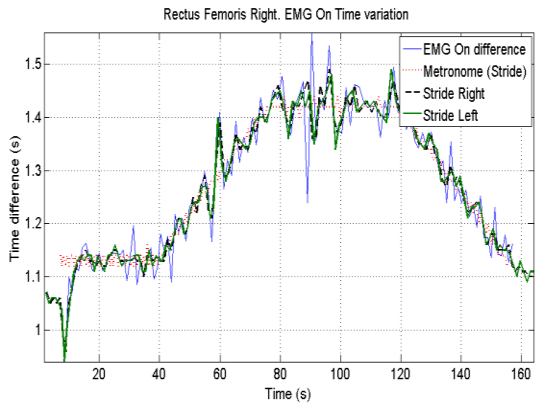


Figure 5. Step Right (solid line), Left (dashed) and Metronome (pointed) period corresponding to two trials with: A. Frequency decrease (increased period) and B. Frequency increase (decreased period). Data presented during the interval of variation.

We assessed the onsets and offsets of each muscle activation burst and compared them with the metronome and the stride period that doubled that of the metronome as it was considering consecutive heel strikes of the same leg.

A



B

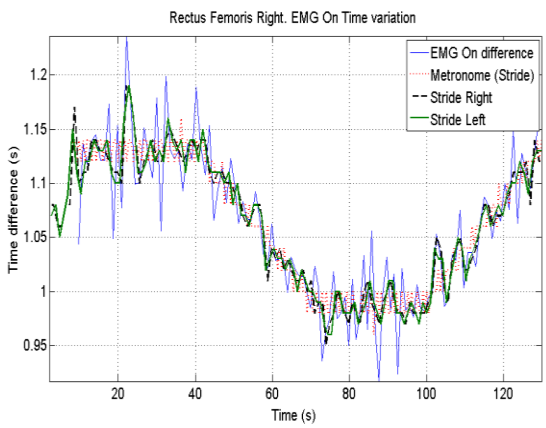


Figure 6. Onset periods of the Right Rectus Femoris (solid thin line), Stride periods of the Right (dashed) Left (solid thick) and Metronome (pointed). These data correspond to two trials with: A. Frequency decrease (increased period) and B. Frequency increase (decreased period).

It must be remarked in Fig. 6 that the onset of the RF follows "instantaneously" the variation in rhythm.

IV. DISCUSSION

The goal of this study was to investigate whether healthy young subjects reacted to subtle implicit perturbations in the metronome rhythm. More specifically, we examined how the changes in the rhythm were integrated in the task execution. The results show that the gait period is completely "entrained" with the metronome rhythm and even for small variations in the cueing, the subject followed "instantaneously" these variations.

It is very unlikely that the subject consciously perceived changes in the period consisting of less than 10 msec. For large cumulative changes, though, they realized that they had to adapt their step length as they were perceiving that their position on the treadmill band was changing.

These results support the idea of a cortical loop in a hypothetical Central Pattern Generator of gait that has been proposed by several authors [13-16].

These results also support the need to further assess the use of an auditory pacemaker in combination with movement therapy in general and robotic therapies, in particular to enhance recovery after stroke or Parkinson's disease [7, 8, 17, 18]. We are presently investigating the possibility of employing this pacemaker to stimulate changes in the rhythm and symmetry and to obtain quantitative measures to help in the assessment of these results. In addition, we are investigating the use of a metronome as a biomarker to assess responders versus non-responders. It is hypothesized that patients who can follow small variations in rhythm, as healthy people do, would have a better rehabilitation outcome.

ACKNOWLEDGMENT

The Authors thank M. Ishizawa and N. Lescura for their help during the gait measurements. A.F.C. thanks the CNPq (311659/2012-8). R.S.S thanks the CNPq for a PIBIT grant.

REFERENCES

[1] G. Rosati, A. Rodà, F. Avanzini, and S. Masiero, "On the role of auditory feedback in robot-assisted movement training after stroke: review of the literature," *Comput Intell Neurosci,* vol. 2013, p. 586138, 2013.
[2] S. J. Kim and H. I. Krebs, "Effects of implicit visual feedback distortion on human gait," *Exp Brain Res,* vol. 218, pp. 495-502, May 2012.
[3] C. Chisari, F. Bertolucci, V. Monaco, M. Venturi, C. Simonella, S. Micera, *et al.*, "Robot-assisted gait training improves motor performances and modifies Motor Unit firing in post-stroke patients," *Eur J Phys Rehabil Med,* Jan 30 2014.
[4] A. Duschau-Wicke, A. Caprez, and R. Riener, "Patient-cooperative control increases active participation of individuals with SCI during robot-aided gait training," *J Neuroeng Rehabil,* vol. 7, p. 43, 2010.
[5] D. Zanotto, G. Rosati, S. Spagnol, P. Stegall, and S. K. Agrawal, "Effects of complementary auditory feedback in robot-assisted lower extremity motor adaptation," *IEEE Trans Neural Syst Rehabil Eng,* vol. 21, pp. 775-86, Sep 2013.
[6] S. K. Banala, S. H. Kim, S. K. Agrawal, and J. P. Scholz, "Robot assisted gait training with active leg exoskeleton (ALEX)," *IEEE Trans Neural Syst Rehabil Eng,* vol. 17, pp. 2-8, Feb 2009.
[7] M. Roerdink, C. J. Lamoth, J. van Kordelaar, P. Elich, M. Konijnenbelt, G. Kwakkel, *et al.*, "Rhythm perturbations in acoustically paced treadmill walking after stroke," *Neurorehabil Neural Repair,* vol. 23, pp. 668-78, Sep 2009.
[8] R. Secoli, M. H. Milot, G. Rosati, and D. J. Reinkensmeyer, "Effect of visual distraction and auditory feedback on patient effort during robot-assisted movement training after stroke," *J Neuroeng Rehabil,* vol. 8, p. 21, 2011.
[9] J. Hermie, J. H. Hermens, B. Frericks, R. Merletti, D. Stegeman, J. Blok, *et al.*, "Seniam Book 8. Results of the SENIAM project. European Recommendations for Surface ElectroMyoGraphy. ," ed: Roessingh Research and Development b.v., 1999.
[10] A. Forner Cordero, H. Koopman, and F. van der Helm, "Multiple-step strategies to recover from stumbling perturbations," *Gait & Posture,* vol. 18, pp. 47-59, AUG 2003 2003.
[11] X. Li, P. Zhou, and A. S. Aruin, "Teager-Kaiser energy operation of surface EMG improves muscle activity onset detection," *Ann Biomed Eng,* vol. 35, pp. 1532-8, Sep 2007.
[12] S. Solnik, P. Rider, K. Steinweg, P. DeVita, and T. Hortobágyi, "Teager-Kaiser energy operator signal conditioning improves EMG onset detection," *Eur J Appl Physiol,* vol. 110, pp. 489-98, Oct 2010.
[13] R. Yuste, J. N. MacLean, J. Smith, and A. Lansner, "The cortex as a central pattern generator," *Nat Rev Neurosci,* vol. 6, pp. 477-83, Jun 2005.

[14] J. T. Gwin, K. Gramann, S. Makeig, and D. P. Ferris, "Electrocortical activity is coupled to gait cycle phase during treadmill walking," *Neuroimage,* vol. 54, pp. 1289-96, Jan 2011.

[15] M. MacKay-Lyons, "Central pattern generation of locomotion: a review of the evidence," *Phys Ther,* vol. 82, pp. 69-83, Jan 2002.

[16] K. Takakusaki, "Neurophysiology of gait: from the spinal cord to the frontal lobe," *Mov Disord,* vol. 28, pp. 1483-91, Sep 15 2013.

[17] K. Sacco, F. Cauda, F. D'Agata, S. Duca, M. Zettin, R. Virgilio*, et al.*, "A combined robotic and cognitive training for locomotor rehabilitation: evidences of cerebral functional reorganization in two chronic traumatic brain injured patients," *Front Hum Neurosci,* vol. 5, p. 146, 2011.

[18] J. M. Hausdorff, J. Lowenthal, T. Herman, L. Gruendlinger, C. Peretz, and N. Giladi, "Rhythmic auditory stimulation modulates gait variability in Parkinson's disease," *Eur J Neurosci,* vol. 26, pp. 2369-75, Oct 2007.