ONLINE CYCLIC MOTION MODELING AND FEEDBACK FOR PHYSICAL TRAINING AND REHABILITATION

Antônio Padilha Lanari Bó *, Roberto de Souza Baptista*,**

* Automation and Robotics Laboratory (LARA), Electrical Engineering Department, Faculty of Technology, University of Brasília, Brasília, Brazil
**DEMAR Project Team, INRIA, Montpellier, France
email: antonio.plb@lara.unb.br

Abstract: When performing cyclic movements during physical training or rehabilitation sessions, executing the exercises improperly may lead to poor results or even in injuries. The main goal of this work is to provide a tool that may help people to increase the correctness of movements based on a real-time visual feedback system. In order to provide an intuitive and effective visual feedback to the user, relevant features of the executed movement are estimated online, hence enabling synchronization of the reference movement with the measured motion in a display. Preliminary evaluation of the method using two reference movements and three different visual aids was performed, indicating satisfactory, but still irregular performance.
Keywords: Cyclic movements, Real-time feedback, Rehabilitation.

Introduction

Every day people engage in physical activities to improve their physical condition or for rehabilitation purposes. However, performing exercises without proper technique can lead to poor results of the exercise program or even result in injuries [1]. For those reasons, to cope with the lack of constant supervision for fitness and/or rehabilitation exercises there is an increasing interest in self-training devices, which provide feedback to the user regarding the quality of the exercise [2]. These devices may also increase user motivation when an adequate interactive interface is available.

In physical rehabilitation following stroke, for instance, a great volume of repetitive exercise is often required, which may be tiresome and difficult to implement due to limited availability of personel for supervised training. In such scenario, one alternative is the use of video games. In [3] a real-time visual feedback system is described and experiments in which the patient’s arm trajectory is displayed along with a predefined ideal trajectory have accelerated motor training.

Nonetheless, besides the importance of cyclic movements for physical training and rehabilitation and the availability of low-cost sensing technology, no effective and intuitive real-time visual feedback system for arbitrary periodic motion is available today. In this scenario, this paper focuses on the development of methods for modeling such movements and estimating online its parameters in order to improve the visual feedback provided to the user. The following section describes the proposed methodology, including a brief discussion of basic concepts. Next, experiments designed to provide preliminary evaluation of the approach are presented. Three subjects participated on an experimental protocol involving two cyclic movements and three different visual aids for correcting the performed motion. Finally, in the last section we present the discussion and our concluding remarks.

Materials and methods

Basic aspects – One straightforward method to improve motor control in cyclic movements is to provide such visual feedback by displaying video sequences of the original motion in a loop during actual movement execution. By using this system, the user would then be required to imitate the recorded motion. However, due to differences in body dimensions, viewpoint, and further issues, this approach may not necessarily lead to satisfactory results. Also, in physical training and rehabilitation it is often not required that the person executes the exercise in the same frequency of the reference motion. However, when using video feedback only, if the user performs the referred motion in a different frequency, the adjustment to synchronize both frequencies must be performed manually previously to the actual exercise.

Another alternative is to present visual feedback to the user in form of quantitative variables that may describe the task of interest, such as depicted in Fig. 1. One clear disadvantage of such approach is that a sensing system is required to measure the performed movement. Nevertheless, by providing visual feedback based on quantitative measurements of linear and/or angular displacements, one may precisely correct her motion to reduce errors with respect to reference movements, as well as provide quantitative performance measures for the therapist.

In order to provide such feedback for the user, one desirable requirement is that both the reference and the performed motion are scaled to the same frequency. Different frequencies may be confusing and increase the required cognitive load, since the signals will often overlap. Thus, it is most recommended that also the phase of both movements are synchronized. If such synchronization is indeed achieved, a more sophisticated interface may then be created, based for instance on an avatar performing the cyclic tasks along with the measured motion.

In order to apply such adjustments on the reference movement, scaling and shifting the signal may be applied. Nonetheless, continuous online tracking of motion frequency and phase may be a difficult task. One possible solution for this problem is based on applying a model for representing periodic signals. Then, estimating the parameters of such model, both frequency and phase may be easily determined.

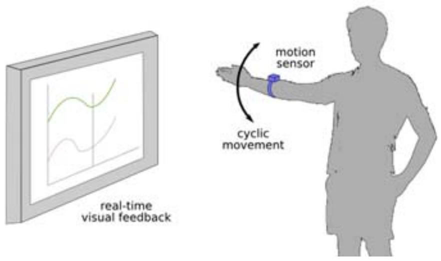

Figure 1. Illustrative example of proposed method, where a human uses real-time feedback for correcting his cyclic movements.

Cyclic motion modeling and online estimation – Different mathematical models can be applied to represent cyclic motions. In our context, it is important to represent the such movements as nonstationary signals, since human motor control limitations produce natural fluctuations. In addition, the selected model must enable straighforward computations of frequency and phase adjustments. In view of those aspects, truncated Fourier series are chosen to represent the cyclic tasks instead of other alternatives, such as Auto-Regressive (AR) models. The adopted periodic model may be represented by

$$s(k) = \sum_{h=1}^{H} \left[a_h \sin\left(h \sum\nolimits_{g=1}^{k} \omega(g) \right) + b_h \cos\left(h \sum\nolimits_{g=1}^{k} \omega(g) \right) \right] + c_0(k) \qquad (1)$$

where ω is the time-varying fundamental frequency, a_h and b_h are the harmonic coefficients, c_0 is the offset value, and H is the number of harmonics, the model order.

For online estimating the parameters of such model, i.e. the fundamental frequency and the corresponding coefficients, a Kalman Filter (KF) is used. The KF is the optimal estimator for linear systems with additive Gaussian noise. Since the adopted system is nonlinear, a modification of the Kalman Filter for such class of problems has been used, the Extended KF. In the EKF, the Kalman equations are applied to the first-order linearization of the nonlinear system around the current state estimate.

Within our EKF framework, the state vector is composed by the model parameters only, which are modeled as random walks. The parameters uncertainties represent then the variability of each parameter. The correction measure on the KF is simply provided by the available sensor. A similar approach has been proposed for pathological tremor estimation in our previous work [4], where more detailed information about the method may be found.

Reference motion adjustment for synchronized feedback– Once the reference movement has been estimated, frequency and phase corrections may be applied based on the measured motion in order to enable synchronized plotting of reference and actual measured motion. For such correction, reliable estimation of the actual performed motion is also required.

Concerning the frequency, since the cyclic movements are modeled as truncated Fourier series, in order to synchronize the frequency of both movements, it is enough to simply replace the reference frequency for the measured frequency, i.e., $\omega_{ref} = \omega_{meas}$. If phase correction is also implemented, a more elaborate procedure is needed. First, the phase between the two movements must be computed. Afterwards, the reference signal must be shifted in order to remove such delay between the cyclic motions. For computing the phase, the cross correlation at each iteration between the measured signal and the simulated signal using the reference motion model is used. Using the estimated delay Δk in samples, the obtained frequency and phase adjustments are used to plot the corrected signal:

$$s_c(k) = \sum_{h=1}^{H} \left[a_h \sin\big(h\omega(k+\Delta k)\big) + b_h \cos\big(h\omega(k+\Delta k)\big) \right] + c_0(k) \qquad (2)$$

Evaluation protocol–Two different one degre-of-freedom reference shoulder movements were applied to evaluate the method. First, a simple uniform oscillatory motion, as illustrated in Figs. 2 and 3, and in the supporting video. Since the movement itself did not resent much complexity, its amplitude was chosen to avoid displacements which could provide straighforward references, such as moving the arm from the waist to full extension, i.e. 90º.

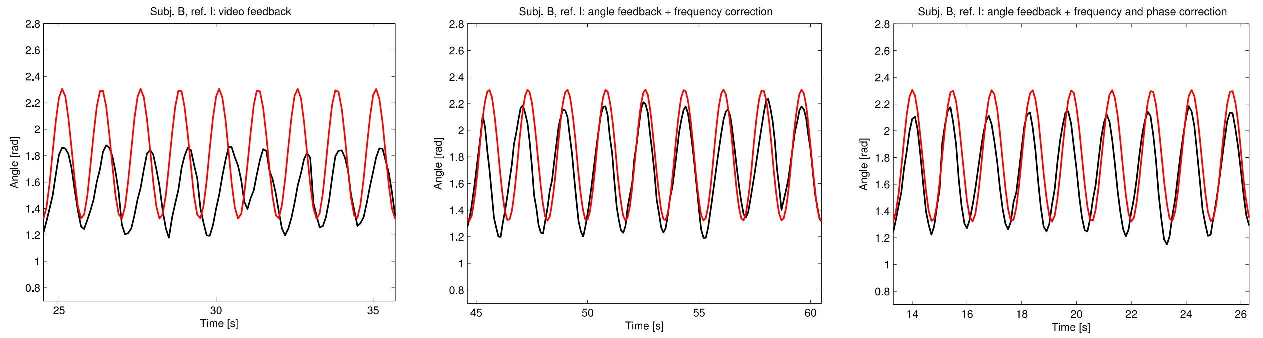

Figure 2. Measured angle (black) from Subject B performing reference movement I (red). From left to right, results from video feedback, angle feedback + frequency correction, and angle feedback + frequency and phase correction, are shown.

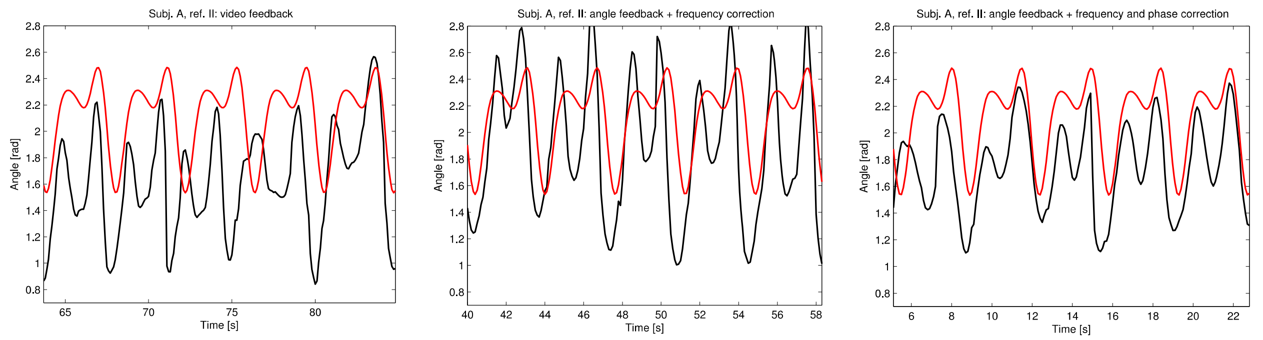

Figure 3. Measured angle (black) from Subject A performing reference movement II (red). From left to right, results from video feedback, angle feedback + frequency correction, and angle feedback + frequency and phase correction, are shown.

Secondly, a more complex motion was performed. It was a biphasic movement with arbitrary composing amplitudes, as illustrated in Fig. 3 and in the supporting video[1]. It is a more challenging task to be learned, as well as a more complex movement to be modeled and estimated by the online estimation algorithm. In both movements, no requirements were established for actually tracking the frequency or phase.

Each movement was described in advance using the recorded video. Next, it was performed using three different visual aids. First, video feedback only was provided. Secondly, feedback from the measured movement and the reference motion were provided, as illustrated in Fig. 1. The reference movement profile was corrected before plotting based on the estimated subject motion. In one approach, only the frequency of the reference movement was synchronized, while next both frequency and phase were adjusted.

Participants and equipments– Three male subjects (age: 34 ± 7 years, height: 178 ± 6 cm, weight: 70 ± 3) participated on the study. None of the subjects participated on the development of the method, nor did any subject had any previous experience on using the setup. Concerning the experimental platform, wireless motion sensors (3-space sensor, Yei Techonology Inc., USA) were applied to estimate the referred angle. Visual feeedback was provided using a computer display.

Results

The experimental data obtained from the trials, as well as each reference movement, are illustrated in Figs. 2 and 3. Furthermore, the performance of subject A performing movement I may be seen in the accompanying video[1].

Finally, due to uncertainties with respect to the functional importance of each type of incorrect motion, it was not feasible to perform a further quantitative evaluation of the results. Indeed, we are unsure if mere delays while executing the corresponding movements should indicate worst performances when compared to small amplitude errors. For instance, that is the result one might expect while using simple error measures (e.g. RMS error). Actually, for most cyclic movements involved in physical training and rehabilitation, changing the phase of motion will not produce much harm, while this may increase the error computed using a fixed-frequency reference movement. For that reason, a table listing quantitative measures of performance for all three subjects is not provided at this point in the research.

Discussion

The results illustrated in Figs. 2 and 3 indicate that real-time visual feedback has succeeded in enabling the

[1] The supporting video is available at `https://www.dropbox.com/s/fo4t6znwtddktum/cbeb2014.mpg`.

participating subjects to correctly learn the proposed reference movements. Errors are still observable both in terms of the constant offset position and amplitudes of the composing oscillatory movements. However, particularly considering that the subjects had no prior training on those movements and no prior experience on using the sensing and the visual feedback systems, the obtained results were satisfactory.

Concerning the trials corresponding to movement I, the overall performance was better in comparison with movement II. This was an expected result, since it is a simpler movement in terms of its composing harmonics. Nevertheless, all subjects presented constant offset error using video feedback only, as observed by the mean values on the plots at Fig. 2. Additionally, the errors on the performed amplitudes were lower when using the model-based angle feedback proposed in the paper. Finally, the frequency of movement increased using the proposed method, possibly indicating that the subjects had more confidence on the performed motion.

The tests related to movement II indicate a similar trend, but the overall performance was lower. For those trials, the performance of each subject was considerably more heterogeneous. As a subjective impression, the subjects have expressed both the movement and the visual feedback required higher cognitive effort when compared to movement I.

Although the performance of model-based angle feedback approaches is clearly better, a comparison between providing frequency and frequency + phase corrections may be trickier. For the subject B, both approaches provided similar results for simple and complex movements. For the other subjects, however, the data may lead to inconclusive results. Subject A seemed to perform better using frequency + phase correction. Whenever only frequency adjustment was available, the fact that both oscillatory movements (reference and measured) were mixed on the the display could have confused him. On the other hand, subject C had worse performance when phase correction was also available. As a subjective evaluation, the participant mentioned that the automatic shifting of phase confused him, preventing the achievement of better results and possibly causing a disturbance in the movement phase.

The occurrence of poor results may also be caused by inadequate performance of the estimation methods described in the paper. For instance, if estimating online the parameters of the measured cyclic movement does not correctly function, any frequency or phase adjustments will not be properly displayed. Based on preliminary trials conducted before actual experimentation, we have observed that correcting the reference movement phase led to unstable behavior, particularly if the performed motion was not featuring regular frequency.

Conclusion

In this paper we have proposed and evaluated a methology for providing real-time visual feedback for performing cyclic movements in physical training and rehabilitation. In order to provide an intuitive and effective visual feedback, relevant features of the executed movement, such as frequency and phase, were tracked in real-time, thus synchronizing the reference motion with the measured motion. In order to provide preliminary evaluation of the method, tests were conducted using two reference movements and three different visual aids. Three subjects took part on the trial, and the obtained results are satisfactory.

Our future efforts include further evaluation using more complex movements and a novel protocol to evaluate issues concerning the phase correction instability. Also, we plan on adapting the current implementation to consider multiple degrees of freedom.

Acknowledgements

The authors would like to thank Mitsuhiro Hayashibe (LIRMM/INRIA, France) for constructive discussions related to the paper. Also, we would like to thank the subjects who participated in the study.

References

[1] L. H. Getchell. Exercise Prescription for the Healthy Adult. Journal of Cardiopulmonary Rehabilitation and Prevention, vol. 6, no. 2, pp. 46–51, 1986.

[2] D. Steffen, G. Bleser, M. Weber, D. Stricker, L. Fradet, F. Marin. A personalized exercise trainer for elderly. In: Pervasive Computing Technologies for Healthcare (PervasiveHealth), 2011 5th International Conference on, 2011, pp. 24–31.

[3] M. Holden, A. Dettwiler, T. Dyar, G. Niemann, E. Bizzi. Retraining movement in patients with acquired brain injury using a virtual environment. Studies in Health Technology and Informatics, vol. 81, pp. 192–198, 2001.

[4] A. P. L. Bo, P. Poignet, C. Geny. Pathological tremor and voluntary motion modeling and online estimation for active compensation. IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 19, no. 2, pp. 177–185, 2011.