# Experimental assessment of a coincident timing motor task of the arm under a passive mechanical perturbation

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Abstract— There are many motor control aspects that must be taken into account for the design and application of rehabilitation robots and exoskeletons. In this respect the outcomes from behavioral motor control studies can provide relevant design criteria. In this context, to verify the level of motor learning and adaptation under the influence of mechanical perturbations, we used a coincident timing task. The task consisted of hitting with the hand a virtual target falling on the screen. The movement was performed in the horizontal plane and consisted of an elbow flexion to reach the real marker on a table. Sixteen volunteers were divided into two groups: 1 - task without perturbation on the hand and, 2 task with a predictable mechanical perturbation on the hand. Data were analyzed by the percentage of correct responses and the tendency of the correct responses. In order to assess the duration as well as the velocity and acceleration of the movement, inertial sensors were used. The results showed a task performance improvement for group 2 when compared to group 1. Furthermore, group 1 showed a trend to delay on correct responses, while the trend in group 2 was to anticipate on correct responses. These results indicate that a predictable mechanical perturbation during learning this coincident timing task can improve the motor learning process and paves the way to further experiments with the use of an upper limb exoskeleton.

# I. INTRODUCTION

Motor learning describes the internal changes in the nervous system that improve the motor skills through repetition, experience and practice of a specific task. These changes result in the acquisition, retention and transfer of motor skills [1]. In the process of learning new skills, motor adaptation can be regarded as a response of the neuro-musculo-skeletal system that adjusts previously known motor strategies to match new goals or changes in the environmental conditions [2]. Motor adaptation involves the ability to transfer previously learned skills to a new context. This process involves motor control modifications in order to react adequately to the new task requirements [3].

It can be considered that there are three modalities of control involved in motor performance. One is predictive (to compensate the high sensory feedback delays), the other is reactive control (despite of the delay, it makes use of the sensory feedback to update the motor commands) and, finally, there is a biomechanical control, which involves modulating the compliance of the limb and the interaction with the environment. These control process are adaptable and can contribute to motor learning [4].

There are several methods to induce motor learning and virtual reality is being increasingly explored in this scenario. Virtual environments can manipulate sensory feedback, e.g. visual and auditory, and can provide adaptive learning algorithms to create individualized paradigms and motor learning [5].

Another method to induce motor learning is based on tasks involving mechanical perturbations, imposing constraints on the movement or modifying the impedance either in the Cartesian or joint space. Then, it is possible to observe the emergence of new motion patterns to perform the task [6-9]. When unexpected perturbations are applied to a certain segment of the human body, the nervous system quickly changes in the response strategy, with the purpose of fulfilling its objective [10]. Current literature is not clear in defining what are the mechanisms involved in this change of strategy, but it is suggested that the intrinsic variability of human movements facilitates motor learning [11]. Some authors have suggested that variance in motor performance can result from a combination of noise and functional properties of the neuro-musculo-skeletal system. This combination might be relevant to adapt to perturbations [12-14].

In this context, Molteni et al. [15] showed that the elastic bands used as perturbations required an additional effort to complete the task. Moreover, it can be noted that the behavioral improvement found in the execution of the task (reduced errors, decreased variability) was not associated to smoother motion patterns [15]. It could be an indication of an increasing neural effort to refine the strategy, despite the improvement in behavioral performance. Therefore, this interpretation would lead to conclude that the neural control effort did not decrease through learning, but rather supported behavioral improvement [15]. These ideas can be considered in the design and applications of rehabilitation robots and exoskeletons.

In the present study it was intended to test if a predictable mechanical perturbation, in this case an elastic force in Cartesian coordinates could help to improve adaptation or learning of a coincident timing task. It was necessary to perform an elbow flexion to hit the target in synchronism with the arrival of a virtual object displayed on the screen, with or without a perturbing elastic force. This study aims to

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assess experimentally influence of mechanical perturbation on the learning of task.

We hypothesized that the mechanical perturbations increase and/or facilitate motor learning of a coincident timing task. The reason would be the need to pay more attention in view of the additional sensory feedback both exteroceptive (contact forces) and proprioceptive (muscle spindles or Golgi tendon organs) provided by the perturbing force. It must be taken into account that interaction forces are important in feedback control [6]. Therefore, providing an external force can improve the execution of the task. Moreover, it is also possible that mechanical perturbations improve the smoothness and allow the emergence of a less variable pattern of movement.

In this context, we expected more errors on the first phase of the task and reduction of errors in the next phase after stabilization of the strategy of the motion under the perturbing elastic force applied at the hand.

### II. MATERIALS AND METHODS

The experimental protocol was approved by the Ethical Committee of the University Hospital of the University of São Paulo. All participants agreed voluntarily to participate in the experiment and signed an informed consent before participating.

## A. Instrument

A custom computer program was used in this study in which images of the real world were captured by a webcam and the virtual 3D objects (falling cubes) were represented superimposed to the real world, creating a mixed environment for the subject. The program presented the falling cubes and recognized a marker placed on the table as the target in the real world that must be reached by the subject to perform the coincident timing task. The software was developed in the Department of Electronic Systems Engineering. Coincident timing was based on the Basin Anticipation Timer of Lafayette Instrument used in a study by Fonseca et al. [8].

The program generated a text file with the results from the task on each block: if the trial was correct (within  $\pm 200$  ms of the target timing) or incorrect as well as the time deviation with respect to the correct time.

The virtual coincident timing task consisted on ten cubes displayed simultaneously on the computer screen within the real environment registered by the webcam. These ten cubes started to turn on (green light) in sequence, as if they were falling, until the last cube, which is the virtual target and coincident with the real target detected by a marker, is reached (Fig. 1).

## B. Procedure

Sixteen volunteers (ten males and six females) participated in this study, divided randomly into two groups with eight subjects each group. Group 1: Task without perturbation dynamic change; Group 2: Task with a mechanical perturbation applied by means of an elastic band attached to the hand of the subject. The elastic band was a one of commonly used in physical therapy (Carci model

tubing beige strong 80cm). The participant ages ranged between 18 and 40 years. For both groups, the task of the participants consisted of moving the hand to obstruct the webcam to hit the target.

During the Acquisition phase, all groups started performing 28 attempts divided in 4 blocks with 7 attempts each block (at slower speed -1.78 m/s) of the coincident timing task and, after five minutes, they performed seven more repetitions for the Transfer phase. In this case the same task was performed while the cubes were falling with a faster speed -2.02 m/s. Both velocities have been validated in a previous study [8]. Acquisition phase refers to training the task, usually characterized by several repetitions. Transfer phase refers to perform the same task performed before on the acquisition phase, but with some parameter changed. In this case, the velocity of cubes that appeared was increased.



Figure 1: Experimental setup: A) elastic band; B) angle 140° elbow flexion; C) target; D) webcam; E) screen with the coincident timing task.

The subjects performed the task in a quiet environment in front of the computer screen, a table with markers, adjustable chair, supervised by an evaluator responsible for the instructions. In order to perform the task, the chair was adjusted according to the height of the individual, as well as the footrest, in such a way that it would be properly positioned in order to view the beginning and ending of the virtual cubes. Before starting the task, the experimenter explained in detail and demonstrated how to perform the task three times.

The subject was instructed to place the right hand on the table, on a mark determined by the evaluator (90° shoulder flexion and 140° elbow flexion, measured by a goniometer). The arm was supported by the table with elbow and shoulder placed at the same height. The horizontal point-to-point arm movements were performed by the upper limb with two degrees of freedom elbow and shoulder. When the first cube turned on (green light), the participant had to follow the sequence of in order to reach the marker (real target) and cover it with the hand, obstructing the webcam image exactly when the last cube, (virtual target), turned on. The participant received an auditory feedback, in which different sound signals indicate either hit in time or error.

One inertial sensor (VN100, VectorNav, USA) was attached in the dorsum of the right hand to measure angular velocity and acceleration of the hand during task execution.

# C. Data analysis

With respect to the data analysis, in order to verify the occurrence of motor learning, two parameters were taken into account: (a) the correct hits were those that occurred within 200 ms of the exact time when the last cube turned on (between -200ms and 200ms); (b) measures of correct hits were used to analyze the performance.

The measure of correct attempts was the time difference between the arrival time of the last cube and the time at which the sensor was actually obstructed with the hand. We analyzed the percentage of correct responses and the directional tendency, that is, if the response had a tendency to anticipate or delay to complete the task.

In each trial, response time was recorded by the custom computer program. Each repetition has duration 4500 ms, considered hit if the subject touches the mark in the range of 4300-4700 ms. Along with incorrect responses, response times of less than 200 ms or more than 200 ms were discarded, we worked on from the successes. Mean was calculated for each subject for each block of a given experimental condition. Lastly, an error rate was calculated to assess the number of incorrect versus correct responses in each block and experimental condition.

The data were analyzed in blocks with seven attempts and Matlab (The Mathworks, Inc) was used along with Excel data analysis tools (Microsoft Corp. USA).

In order to capture the data from the inertial sensors the Matlab toolbox provided by VectorNav was used. A custom program was made to obtain the total duration of the movement (difference between onset and end) as well as the time duration to the peak angle that corresponded to the instant when the target was hit. These data were analyzed statistically in order to assess the differences between groups.

# III. RESULTS

Fig. 2 shows the percentage of correct responses along the task (acquisition and transfer phase) for both groups.



Figure 2: Percentage of correct responses along the task comparing both groups; B1, B2, B3 and B4 refer to acquisition phase; T refers to transfer phase.

The directional tendency of correct responses is shown in Fig. 3 for group 1 and Fig. 4 for group 2. Group 1 showed a clearly directional tendency to delay on responses, while the group 2 showed the opposite, with directional tendency of anticipation of the responses.



Figure 3. Directional tendency on correct responses for group 1 (without perturbation).



Figure 4. Directional tendency on correct responses for group 2 (predictable mechanical perturbation).

The motion trajectories showed a consistent pattern with a peak in the forearm angle that corresponded to the target

hit. With respect to the total movement duration and the time duration to peak angle, the time between the movement initiation and the maximum angle, none of these parameters had significant results after non-parametric tests. Intersubject variability was larger than the condition difference, suggesting the need to increase the number of subjects.

However, both variables showed a clear trend to decrease with practice (Fig. 5). In addition, there was a trend to have a lower movement duration when the task was performed under mechanical perturbation.



Figure 5. Block mean time duration of the movement to the angle peak duration. The mean and the confidence intervals for each block (bl1-bl4) and the Transfer (T) task. The line with circles represents the group 2 (predictable mechanical perturbation) while the line with squares represents the group 1 (no perturbation).

### IV. DISCUSSION

The goal of this study was to investigate if a mechanical perturbation during learning of a coincident timing task resulted in a task performance improvement when compared with the same task without mechanical perturbation.

In the present study, we first hypothesized that the group that practiced the task under a force using an elastic band applied on the movement of arm (group 2) would show an improvement in the motor learning or adaptation. This improvement would be reflected in a lower number of errors during the Transfer phase of the task. This hypothesis was confirmed, because the rate of correct responses for this group were increasing during the experiment and resulted in less errors during the Transfer phase.

These results can be explained by the need of a temporal organization taking into account the external forces applied on the hand that difficult task execution. The clear results about the performance from this group suggest a consistent planning to adapt the motion pattern to hit the target on time [8].

The mechanisms of learning may be more related to the ones observed in recent studies [16,17] on which amplification of the visual error from the task, rather than physically perturbing the motion produce faster adaptation to a novel environment.

A recent model of motor adaptation [18,19] suggests that the CNS (central nervous system) corrects the motion, either increasing or decreasing muscle activation, based on muscle stretch or shortening in the previous movement. The CNS integrates the sensory information from visual and proprioceptive sources and learns to associate sensory patterns with motor actions. Additional sensory information about the success or failure of the task would help to establish the correct motor patterns to reach the target on time. Sensory integration is part of the CNS internal representation of movement, where associations are developed between a motor command and the resulting motion [6]. The group 2 (predictable mechanical perturbation) showed a trend to anticipate the responses. This can be explained by the internal representation in the CNS that may take the form of a forward model of limb dynamics. The motor command can be used to predict the expected motion and the associated sensory feedback [7,9]. Therefore, the elastic band attached to the hand requires that the subject adapts the forward model of the limb. This suggests an increased neural effort to refining the strategy that resulted in the improvement of behavioral performance.

This interpretation is consistent with Molteni et al. [15], that showed in their research that the statement that neural effort did not decrease trough conditions, but rather supported behavioral improvement.

The percentage of correct responses for group 2 was growing along the task, except blocks 2 and 3 that maintained the same values) for the group 2 (predictable mechanical perturbation). Differences between expected and actual afference might then be used to refine the motor command during learning, allowing improvement of performance [6]. The organization of control within each of those principal strategies likely represents a transformation of the movement trajectory and frequency into different control modalities, each representing a context-dependent application of modular control for motion with the shoulder and elbow [20].

Probably, the repetition of the same task created some dispersion between trials and with a possible accommodation of the movement. Therefore, the repetition of the trials was not generating any learning or adaptation. It can be noted that this explanation is consistent with the observations made by the participants themselves who performed the task.

Our results demonstrated that the internal model allowed compensation for the force field and the subjects performed better when performing the task under a predictable elastic force. The group 2 (predictable mechanical perturbation) presented better levels of adaptation and learning than group 1 (without perturbation). It can be concluded that training a task under predictable mechanical perturbations was more effective to promote adaptation and learning when compared with tasks without mechanical perturbations.

It can be argued that this result is mainly due to the effect on the attention of the subject. In this respect, it would be recommended to include more challenging conditions during the execution of repetitive tasks, for instance, in rehabilitation environments. The inclusion of perturbing forces during the task execution could be implemented in a rehabilitation robot either an end-point manipulator or an exoskeleton. These results pave the way to further studies on coincident timing tasks involving different types of perturbations for the design of rehabilitation exoskeletons. Further experiments incorporating these concepts are being carried out with a 1 dof exoskeleton already developed in this group [21].

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#### V. References

- R.A. Schimidt and T.D. Lee, "Motor control and learning: a behavioral emphasis Champaign" (Book style), IL: Human Kinetics, 1999.
- [2] K.M. Newell and R. Ranganathan, "Some Contemporary Issues in Motor Learning," *Progress in Motor Control*, D. Sternard, Ed. New York: Springer, 2009, pp. 395-404.
- [3] J.W. Krakauer, P. Mazzoni, A. Ghazizadeh, R. Ravindran, and R. Shadmehr, "Generalization of motor learning depends on the history of prior action", *PLoS Biol*, vol. 4, no. 10, p. E316, Oct. 2006.
- [4] D.M. Wolpert, J. Diedrichsen, J. Randall Flanagan, "Principle of sensorimotor learning," *Nature Reviews Neuroscience*, vol. 12, 2011, pp.739-751.
- [5] L.M. Straker, A.C. Campbell, L.M. Jensen, D.R. Metcalf, A.J. Smith, R.A. Abbott, C.M. Pollock, and J.P. Piek, "Rationale, design and methods for a randomised and controlled trial of the impact of virtual reality games on motor competence, physical activity, and mental health in children with developmental coordination disorder", *BMC Public Health*, vol. 11, pp. 654, Aug 18, 2001.
- [6] F.C. Huang, R.B. Gillespie, and A.D. Kuo, "Human adaptation of nteraction forces in visuo-motor coordination," in *IEEE Transactions* on Neural Systems and Rehabilitation Engineering, vol. 14, no. 3, pp. 390-397, Sep. 2006.
- [7] R. Johansson and K. Cole, "Sensory-motor coordination during grasping and manipulative actions," *Current Opinion Neurobiol.*, vol. 2, pp. 815-823, Dec. 1992.
- [8] FS. Fonseca, RN. Benda, VLS. Profeta, H. Ugrinowitsch, "Extensive practice improves adaptation to unpredictable perturbations in a sequential coincident timing task", *Neuroscience Letters*, vol. 517, pp. 123-127, 2012.
- [9] B. Metha and S. Schaal, "Forward models in visuomotor control," J. Neurophysiol., vol. 88, no. 2, pp. 942-953, 2002.
- [10] N. Bernstein, "*The Coordination and Regulation of Movements*" (Book style). Oxford: Pergamon Press, 1967.
- [11] EJ. Manoel, KJ. Connolly, "Variability and development of skilled actions", *International Journal of Psychophysiology*, vol. 19, pp. 129-147, 1995.
- [12] KM. Newell, KM. Deutsch, JJ. SosnoffG, G. Mayer-Kress, "Variability in motor output as Noise: A defaut and erroneous proposition," in *Movement System Variability*, K. Davids, S. Bennet, KM. Newell, Eds. Champaign, IL: Human Kinects, 2006, pp. 3-23
- [13] J. Hamill, REA. Van Emmerik, BC. Heiderscheit, L. Li, "A dynamical system approach to lower extremity running injuries," *Clin. Biomechan.*, vol. 14, pp. 297-308, 1999.
- [14] JF. Yang, JP. Scholz, ML. Latash, "The role of kinematic redundancy in adaptation of reaching," *Exp. Brain Res.*, vol. 176, no. 1, pp. 54-69, 2007.
- [15] E. Molteni, V. Cimolin, E. Preatoni, R. Rodano, M. Galli, AM. Bianchi, "Towards a biomarker of motor adaptation: Integration of kinematic and neural factors," in *IEEE Transactions on Neural*

Systems and Rehabilitation Engineering, vol. 20, no. 3, pp.258-267, 2012.

- [16] W. Yejun, P. Bajaj, R. Scheidt, and J. Patton, "Visual error augmentation for enhancing motor learning and rehabilitative relearning," in *Proc. 9th Int. Conf. Rehabil. Robot. 2005 (ICORR* 2005), 2005, pp.505–510.
- [17] B. R. Brewer, R. Klatzky, and Y. Matsuoka, "Visual feedback distortion in a robotic environment for hand rehabilitation," *Brain Res. Bull.*, vol.75, pp. 804–813, Apr. 15, 2008.
- [18] D. W. Franklin, E. Burdet, P. T. Keng, R. Osu, C. M. Chew, T. E. Milner, and M. Kawato, "CNS learns stable accurate and efficiente movements using a simple algorithm," *J. Neurosci.*, vol. 28, pp.11165–11173, 2008.
- [19] K. Tee, D. Franklin, M. Kawato, T. Milner, and E. Burdet, "Concurrent adaptation of force and impedance in the redundant muscle system," *Biol. Cybern.*, vol. 102, pp. 31–44, 2010.
- [20] O. Levin, A. Forner-Cordero, Y. Li, M. Ouamer, and S. P. Swinnen, "Evidence for adaptive shoulder-elbow control in cyclical movements with different amplitudes, frequencies, and orientations", *Journal of Motor Behavior*, vol. 40, no. 6, pp.499-515, 2008.
- [21] A.B.W. Miranda, A.Y. Yasutomi, C. Souit, and A. Forner-Cordero, "Bioinspired mechanical design of an upper limb exoskeleton for rehabilitation and motor control assessment," in *The Fourth IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp.1776-1781, 2012.