Journal of Electromyography and Kinesiology 23 (2013) 182–189

Contents lists available at SciVerse ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Adaptive rehabilitation games

Ouriel Barzilay, Alon Wolf *

Technion IIT, Dept. of Mechanical Engineering, BRML, Haifa 32000, Israel

ARTICLE INFO

Article history:
Received 1 May 2012
Received in revised form 26 August 2012
Accepted 20 September 2012

Keywords:
Adaptive systems
Artificial neural network
Electromyography
Neuromuscular rehabilitation

ABSTRACT

In conventional neuromuscular rehabilitation, patients are required to perform biomechanical exercises to recover their neuromotor abilities. These physiotherapeutic tasks are defined by the physiotherapist, according to his estimate of the patient's pathologic neuromotor function. The definition of the task is mainly qualitative and it is often merely demonstrated to the patient as a gesture to reproduce. Success of the treatment relies then on the accuracy and repetition of the motor training.

We propose a novel approach to neuromotor training by combining the advantages of a virtual reality platform with biofeedback information on the training subject from biometric equipment and with the computational power of artificial neural networks. In a calibration stage, the subject performs motor training on a known task to train the network. Once trained, the tuned network generates a new patient-specific task, based on the definition of the subject's expected performance dictated by the therapist. The system was tested for upper limb rehabilitation on healthy subjects. We measured a 33% improvement in the triceps performance ($p = 0.027$). The novelty of the proposed approach lies in its use of learning systems to the estimation of biological models.

1. Introduction

1.1. Motivation

Rehabilitation consists in the execution of motor tasks designed to help the patient recover maximal movement and organ functionality. The design of these tasks by the physiotherapist is made according to the patient's state and pathology. However, the patient's needs may vary along the rehabilitation sessions and the physiotherapist must adapt his tasks accordingly. This adaptive physiotherapy is very difficult to perform online and relies on the trainer's qualitative interpretation of the subject's performance.

Accurate repetitions of these biomechanical exercises are key points for successful physiotherapeutic treatment. These physical tasks are often strenuous to the patient and the therapy's efficiency largely relies on the subject's motivation, in particular with children who often lack the patience and perseverance necessary for their treatment.

Performing motor training in virtual reality (VR) offers several advantages. The training task can be continuously demonstrated to the subject and act as a virtual teacher. Moreover, the subject can receive in virtual environments (VEs) and with adequate biometric equipment immediate biofeedback on his performance during training. Furthermore, rehabilitation can be performed in the form of interactive games greatly stimulating the subject's motivation during training. This kind of system can additionally provide the physiotherapist with quantitative data on the training session for further investigation. Finally, virtual systems can be augmented with computational models and artificial intelligence.

1.2. Literature review

In the last decades, the use of VR has bloomed in the field of physiotherapy and, at the present time, studies associating VR with rehabilitation are countless. Since the beginning of the 1990's, studies showed scientific evidence that motor skills could be learned in VE (e.g. Goldberg, 1994; Theasby, 1992), replicated into the real world (Rose et al., 1998), and even generalized to certain untrained tasks in the real world (Holden et al., 1999; Holden and Dyar, 2002).

Success of rehabilitation resides in three key concepts: feedback, repetition and motivation (Holden and Dyar, 2002). VE are likely to amend each of these concepts. The technological advancements in both VR and biosensory instrumentation offer the opportunity to provide augmented feedback in real time about one's motor performance. VR systems generally involve specially written software which grants entire control on the provided feedback.

Scientific evidence suggests that learning by imitation leads to the neurophysiologic changes linked to motor rehabilitation (Nudo and Milliken, 1996). VR offers the possibility of producing a *virtual teacher* (Holden et al., 1999), tireless and always available, who may tutor a patient over and over. VR systems can teach and

* Corresponding author. Tel./fax: +972 48292087/5711.
E-mail addresses: barzilay@technion.ac.il (O. Barzilay), alonw@technion.ac.il (A. Wolf).

1050-6411/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jelekin.2012.09.004

correct a subject during practice with real time feedback and, by such, can significantly improve the accuracy of his performance.

Motivation plainly affects performance during rehabilitation (MacLean et al., 2000). With the advancements of graphic hardware and software tools, real-time programs can be shaped as virtual games, in which the measured biomechanical data provide interactive control to the user. Recent examples for this kind of system in the field of entertainment are the Nintendo Wii and Microsoft's Kinect. With this new aspect, motor rehabilitation can be made much more attractive for patients than conventional neuromotor rehabilitation, often repetitive and annoying (e.g. Bryanton et al., 2006).

In summary, VR provides unique tools for rehabilitation that have often been verified to overcome the conventional methods in rehabilitative therapy (Holden, 2005). With the use of VR, the physiotherapist benefits from enhanced control on the rehabilitation session, and the performance and experience of the patient are significantly improved.

The study of human motion and motor control has been the source for the development of dynamic, kinetic and mechanical models used in medicine, motion capture (Stanney et al., 1999), robotics (Krakauer, 2006) and neuroscience (Wren and Pentland, 1998). The existence of internal models (neural processes that simulate the response of the motor system to estimate the outcome of a motor command) for motor control and trajectory planning has also been investigated during the last years with respect to cognitive science and neurophysiology, and they have been applied to motor system identification (Pollard et al., 2002). Nevertheless, in our study we adopted an approach radically different from the methods commonly found in the literature: instead of elaborating a sophisticated model of the patient, we relied on the ability of artificial neural networks to estimate unknown models from known inputs and outputs.

In this research, we introduce a novel approach able to improve neuromuscular training in VR by means of artificial intelligence systems. Artificial neural networks (ANNs) are trained to learn from observation of the patient's performance and subsequently produce new patient-specific virtual physiotherapeutic tasks. During a training session, the subject is exposed via a head-mounted display unit to these virtual tasks which demonstrate to him the movements to perform. By means of a 3D motion capture system and electromyographic (EMG) sensors, the system constantly tracks the kinematics of the subject and his muscles activation. From these data, an ANN is trained to respond to the subject's biofeedback information, having the desired muscles activation and motions as references. Once trained, the network generates a new trajectory as a biomechanical exercise, according to the previous performance of the subject.

This system allows the physiotherapist to plan the expected neuromuscular performance instead of designing the physiotherapeutic exercise leading to it. He may decide which muscles to focus on and which functional pattern is expected to be executed. Since the system is tuned per patient and per session, the generated exercise is specific to the patient's pathology and to the stage he is at within his rehabilitation program.

2. Methods

The purpose of the system is to generate a virtual rehabilitation task adaptively to one's current motor performance and to the desired motor performance prescribed by the physiotherapist. The system should thus receive a performance to produce an adequate exercise. Conversely, a subject performing motor training can be seen as producing a motor performance on a given exercise. This automated task generator is thus actually based on the estimation of the inverse model of the subject (Fig. 1).

We hypothesize that the inverse model of a patient can be estimated with a neural network specifically trained and tuned to the patient's performance. Furthermore, we hypothesize that executing a patient-specific physiotherapeutic exercise will result in a better kinematic and electromyographic performance.

2.1. Experimental setup

Subject kinematics was recorded with Vicon™ motion capture system, which tracks anatomical landmarks marked by reflectors. In parallel, we used a wireless Aurion™ surface EMG ZeroWire system to collect electrical signals of the subject's target muscles. Both kinematics and EMG data were simultaneously collected by the Vicon system. The markers were placed on the limb to reeducate and on the head-mounted display unit in order to track the subject's head movements and accordingly modify the display of the virtual environment (Fig. 2). The processing and analysis of the data was performed in real time in the custom C++ application running on the workstation. In addition to the input data preprocessing, the software agent manages the graphic user interface, the estimation of the inverse model of the subject and the rehabilitation task generation. The subject was equipped with an eMagin™ 3DVisor Z800 head-mounted display from which he received the audiovisual feedback.

The kinematic recordings allow reproducing in the virtual environment a replica of the subject's hand. In each of the developed platforms (Fig. 3), the rehabilitative task was encoded in an interactive game controlled by the subject's arm. The user received in real time augmented feedback on his performance during training. For instance, in the virtual ball tracking application (Fig. 3), the user was constantly notified on the distance to the target with the color of a second ball on the virtual arm, a varying musical background volume and shadows on the ground.

2.2. Experiment workflow

In a first step, the subjects practiced motor training on a known exercise displayed as the trajectory of a virtual ball which he must follow with his pointing finger. At this stage, the subject is instructed to find a standing spot from where the entire exercise can be executed and to keep his feet steady during the training session. This exercise has been designed such that most of the reeducation workspace, in front of the patient and at the reach of his hand, is covered. This exercise, along with the corresponding performance of the subject, composes the training set on which the network is taught and customized to the subject. Once the network converges, we obtain an estimation of the inverse model of the subject. In parallel, the physiotherapist conceives, based on his

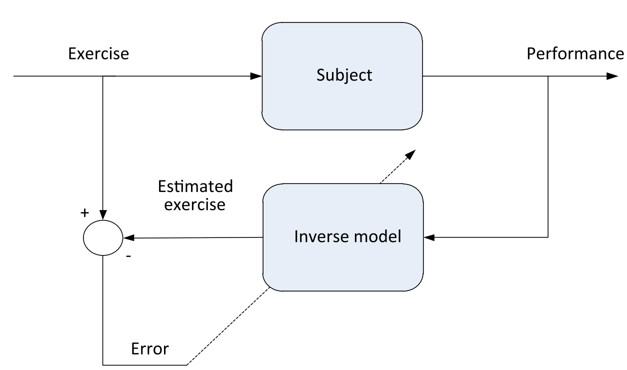

Fig. 1. Estimation of the subject's inverse model.