Computers in Biology and Medicine 75 (2016) 243–256

Contents lists available at ScienceDirect

Computers in Biology and Medicine

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

Towards an SEMG-based tele-operated robot for masticatory rehabilitation

Hadi Kalani [a,c], Sahar Moghimi [a,b,d], Alireza Akbarzadeh [a,c,*]

[a] Center of Excellence on Soft Computing and Intelligent Information Processing, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Rayan Center for Neuroscience and Behavior, Ferdowsi University of Mashhad, Mashhad, Iran
[c] Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran
[d] Electrical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran

ARTICLE INFO

Article history:
Received 24 February 2016
Received in revised form
17 May 2016
Accepted 21 May 2016

Keywords:
Clenching movement
SEMG-based control
Rehabilitation robot
Fuzzy impedance control
Fast orthogonal search
Laguerre estimation technique
Artificial neural networks

ABSTRACT

This paper proposes a real-time trajectory generation for a masticatory rehabilitation robot based on surface electromyography (SEMG) signals. We used two Gough-Stewart robots. The first robot was used as a rehabilitation robot while the second robot was developed to model the human jaw system. The legs of the rehabilitation robot were controlled by the SEMG signals of a tele-operator to reproduce the masticatory motion in the human jaw, supposedly mounted on the moving platform, through predicting the location of a reference point. Actual jaw motions and the SEMG signals from the masticatory muscles were recorded and used as output and input, respectively. Three different methods, namely time-delayed neural networks, time delayed fast orthogonal search, and time-delayed Laguerre expansion technique, were employed and compared to predict the kinematic parameters. The optimal model structures as well as the input delays were obtained for each model and each subject through a genetic algorithm. Equations of motion were obtained by the virtual work method. Fuzzy method was employed to develop a fuzzy impedance controller. Moreover, a jaw model was developed to demonstrate the time-varying behavior of the muscle lengths during the rehabilitation process. The three modeling methods were capable of providing reasonably accurate estimations of the kinematic parameters, although the accuracy and training/validation speed of time-delayed fast orthogonal search were higher than those of the other two aforementioned methods. Also, during a simulation study, the fuzzy impedance scheme proved successful in controlling the moving platform for the accurate navigation of the reference point in the desired trajectory. SEMG has been widely used as a control command for prostheses and exoskeleton robots. However, in the current study by employing the proposed rehabilitation robot the complete continuous profile of the clenching motion was reproduced in the sagittal plane.

1. Introduction

Human mastication is a complex process which consists of two movements: clenching and grinding. In clenching the mandible moves only in the sagittal plane, whereas in grinding, it traces a circular path in the frontal plane. Although more than 20 muscles are involved in the process of human mastication, only six of these muscles play the major role [1–4]. For clenching, the Masseter and Temporalis muscles are mostly employed, whereas Pterygoid muscles have the main role in grinding. The movement of human jaw has been investigated by a variety of methods [5–7]. Also, different methods have been utilized for motion classification, e.g. Bayesian classifier [5], artificial neural networks [8–12] and fast orthogonal search (FOS) [13]. Surface electromyography (SEMG) has been used to identify differences in chewing patterns between individuals, and to classify them into groups according to their chewing efficiency [14–18].

The relationship between muscles' electrical activity and body movements is of special importance in many applications including motion classification, control of prosthetic limbs, and tele-operated robots [19–23]. In these applications, use of non-expensive and portable SEMG electrodes is advantageous compared to the use of sensors and cameras which are often very expensive and require massive structures [24]. Generally, SEMG based control is a complex technique which involves detection, processing, and classification for different applications including assistive robots [25,26]. All the SEMG processing methods belong to one of the three main categories: time, frequency, and time-frequency domain processing [19]. Moreover, signal classification is a basic

---

[*] Corresponding author at: Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad 9177948974, Iran.
E-mail address: s.moghimi@um.ac.ir (S. Moghimi).

http://dx.doi.org/10.1016/j.compbiomed.2016.05.014
0010-4825/© 2016 Published by Elsevier Ltd.

step in SEMG based control in a way that accuracy of the control strategy depends highly on the method of classification [27–35]. Robots use different techniques for signal classification, e.g. artificial neural networks [28,29], fuzzy logic [30], neuro-fuzzy methods [27–31] and support vector machines [34,35].

Disorders associated with mastication, e.g. temporomandibular disorders (TMD), craniomandibular disorders (CMD), trismus and edentulous maxilla [36,37], can directly influence many aspects of a patient's life by reducing his/her ability to open the mouth. Different strategies are adopted for the treatment of these disorders. An ordinary manual rehabilitation session often involves difficult maneuvers with force imposed at specific points along a predefined direction of the movement. This method highly depends on the doctor's skills, and may not always be convenient for long-term post-operative physiotherapy [38–47]. Numerical modeling (e.g. finite element method) may provide valuable insight about the stress distribution during the physiotherapy protocol [48,49].

Stretching techniques and jaw-mobilizing devices/robots are available for rehabilitation purposes [38,39]. Studies show that continuous and passive exercise therapy can be effective for pain reduction caused by musculoskeletal deficiencies during jaw movement [38–42]. Recently, robotic systems, including the TheraBite System [42,43], the Dynasplint_Trismus System [47] and the WY (Waseda-Yamanashi) series of robots [44,45], have been employed in clinics for rehabilitation purposes. Generally, the ability of robots to produce repetitive movements and permitting programmable rehabilitation sessions with varying intensity make them helpful tools for conducting effective rehabilitation strategies [41].

In a rehabilitation robot, the volunteer is part of a man-machine system and his/her dynamic model is not as clear and invariant as that of the manipulator [50–57]. Controller design is one of the main complications in employing rehabilitation robots. In this regard, the impedance control scheme was introduced by Hogan [58]. Using this method enables the operator to assign the desired mass/inertia, damping, and stiffness to the robot. The most important feature of impedance control is handling constrained and unconstrained motion [59]. In this method the robot is modeled as a mass, spring, and damper in interaction with human or environment. This type of impedance control is usually called pure impedance control [60] using which external force (applied by human and/or environment) is not controlled. This force can cause serious issues considering the safety of patients. To eliminate this problem, researchers have introduced force tracking impedance control [58–63].

In this study instead of designing a robot that mimics the human masticatory process, we propose a Gough-Stewart robot which is controlled by the SEMG signals of a tele-operator. The robot legs were controlled to reproduce the masticatory process in the human jaw, supposedly mounted on the moving platform, through predicting the location of a reference point (the chin point (CP), placed on the end effector of the rehabilitation robot) using SEMG signals. To the best of our knowledge, this is the first time that a continuous profile of the masticatory motion is predicted and reproduced by a robot. The aforementioned robot was utilized as a rehabilitation robot and equations of motion were obtained by the virtual work method. Fuzzy method was employed to develop a hybrid position/force fuzzy impedance control [62]. Moreover, a jaw model was developed by a general Gough-Stewart parallel robot to demonstrate the time-varying behavior of the muscle lengths of subjects in the rehabilitation process. The proposed approach enables the tele-operator to reproduce the required masticatory motion in the patient's jaw through opening/closing of his mouth to the desired extent.

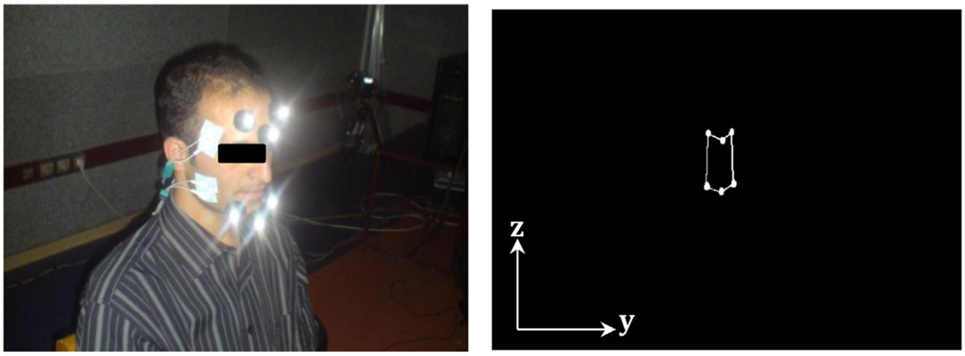
2. Materials and methods

2.1. Experimental setup and procedure

In this work, three kinematic parameters (displacement along the x and z axes and rotation about the y-axis) were predicted using SEMG signals and utilized in the control scheme for reproducing the masticatory trajectory. Seven volunteers (four males) participated in this study. All subjects were well-informed about the procedure and provided written consent to the experimental protocol. In each trial, volunteers were asked to perform a maximum voluntary mandible opening and closing (clenching movement) in the sagittal plane within an interval of five seconds [12]. Three trials were used for training and another three trials were employed for model validation. To record the electrical activity of muscles, an 8-channel SEMG system was employed. For each subject SEMG signals were recorded from four muscles, namely right and left Masseter, and right and left Temporalis muscles (Fig. 1). Recorded raw SEMG signals were passed through a band pass (15–400 Hz) 3rd order Butterworth filter. The resulted signals were rectified and smoothed by a moving average window of size 200. The sampling rate was reduced to 250 Hz. Moreover, to trace the chewing trajectory, Simi Reality Motion System (GmbH, Germany) was employed. The camera output was digitized to 250 frames per second (fps). Frequencies above 7 Hz were removed.

2.2. SEMG-based motion prediction

Different delays of the SEMG signals from the Temporalis and Masseter muscles were used as inputs since it was necessary to consider the delay between muscle activation and limb movements. This delay is variable, depends on several factors including the firing rate dynamics of the muscle, and cannot be neglected [73,74]. This Electromechanical delay has been reported to range from 10 ms to about 100 ms [74–76]. Kinematic variables (i.e.,


[redacted]

(a) (b)

Fig. 1. (a) Marker position and SEMG electrodes on the subject's face. (b) Two-dimensional reconstruction of the marker set.