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# Dynamic modeling of SEMG–force relation in the presence of muscle fatigue during isometric contractions

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ABSTRACT

Electromyogram signals contain information for predicting muscle force that can be used in human-machine interaction and medical applications such as the control of prosthetic hands. Different methods exist for estimating the SEMG–force relation. However, muscle dynamic variations during voluntary contractions due to fatigue have been neglected in the identification stage. This would make the models not applicable to normal working conditions. We developed a model based on Laguerre expansion technique, LET, to identify the dynamic SEMG–force relation and investigate the presence of fatigue through kernel analysis. Our proposed data acquisition protocol was used to induce fatigue in the muscles involved in the act of grasping, hence enabling us to study the effects of muscle fatigue. The results of LET in comparison with fast orthogonal search and parallel cascade identification, which were able to accurately identify the desired dynamics, represent an improvement of 15% and 3.8% in prediction fitness, respectively. Moreover, by extracting median frequency (MDF) of the recorded SEMG signals and tracking its changes over time, the existence of muscle fatigue was studied. The results showed that fatigue had an impact on the Brachioradialis muscle. The first and second order kernels of the LET illustrated variations in the time and frequency domains similar to that of MDF for the Brachioradialis muscle corresponding to the fatigue generation process. Employing the proposed model the dynamics of SEMG–force relation can be predicted and its variations due to muscle fatigue can also be investigated.



## 1. Introduction

The relation between muscles' electrical activity and force is of special importance in many applications including gait analysis, orthopedics, rehabilitation, ergonomic design, haptic technology, tele-presence surgery and human-machine interactions [1–26]. Recently, surface EMG (SEMG) has been frequently utilized to estimate muscle force during both voluntary [1–11] and functional electrical stimulation (FES) [8] induced contractions. Muscle force is generated through two mechanisms: muscle activation and muscle contraction dynamics [3]. Activation dynamics refer to the number of active motor units and their specifications which determine the level of muscle activation. The active state is believed to be related to the SEMG amplitude through a first-order dynamic system [3]. The transformation from muscle activation to muscle force is governed by muscle contraction dynamics which is influenced by the mechanical properties of muscles. Parametric and non-parametric models have been employed to accurately obtain SEMG–force relation. Parametric methods use muscle activation dynamics, muscle contraction dynamics and physiological measurements [17,18]; however, non-parametric methods such as fast orthogonal search (FOS) [7,12], parallel cascade identification (PCI) [1,11,33], Laguerre estimation technique (LET) [20,21], artificial neural networks (ANN) [4,5,9,10,32], principle dynamic mode (PDM) analysis [21], Hammerstein models [8] and principal component analysis (PCA) [15] utilize only activation dynamics (SEMG signal).

Efficient modeling of the SEMG–force relation can be a challenging task. The SEMG–force relation is both nonlinear and dynamic. The degree of nonlinearity mainly depends on the muscle fiber composition, contraction history, and force level. Muscle shortening effect and the electromechanical delay (the time delay between SEMG and force onsets) are what produce the dynamic relation

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[2]. A useful SEMG-force model should be able to capture both the dynamic and nonlinear behavior of the system. Toward this endeavor, researchers have included input delays and used nonlinear mapping methods including PCI, ANN, and FOS. The characteristics of the SEMG-force system may vary among different individuals. Other than the aforementioned obstacle, muscle fatigue which may occur in both voluntary and artificially induced contractions can cause drastic changes in the contraction dynamics and the activation ability of a muscle. Muscle fatigue also changes the dynamic SEMG–force relation [22–26]. While studying SEMG signals, fatigue effects appear in both time and frequency domains. Zero crossings (ZCR) of the SEMG signals in the time domain and mean frequency (MNF) and median frequency (MDF) in the frequency domain are commonly utilized for SEMG investigation of fatigue occurrence [23].

In this research, the experimental protocol was designed with the aim of inducing muscle fatigue by voluntary contractions. Our proposed modeling strategy utilized the non-parametric LET to identify the SEMG–force relation. The rationale for this choice was to provide insight to the system dynamics, as opposed to only focusing on the predicted output. We hypothesized that due to the dynamic nature of fatigue, the effects of its occurrence will manifest in the LET linear and nonlinear kernels.

## 2. Materials and methods

### 2.1. The experimental setup

Ethical approval for the study was granted by the Ferdowsi University of Mashhad. Time-locked SEMG and force signals were recorded during the grasping tasks. The Zemic IP65 dynamometer was used to record hand forces (Fig. 1a). SEMG signals were recorded from the Brachioradialis and the Palmaris Longus muscles using an EAK-945 amplifier. The SENIAM standards were

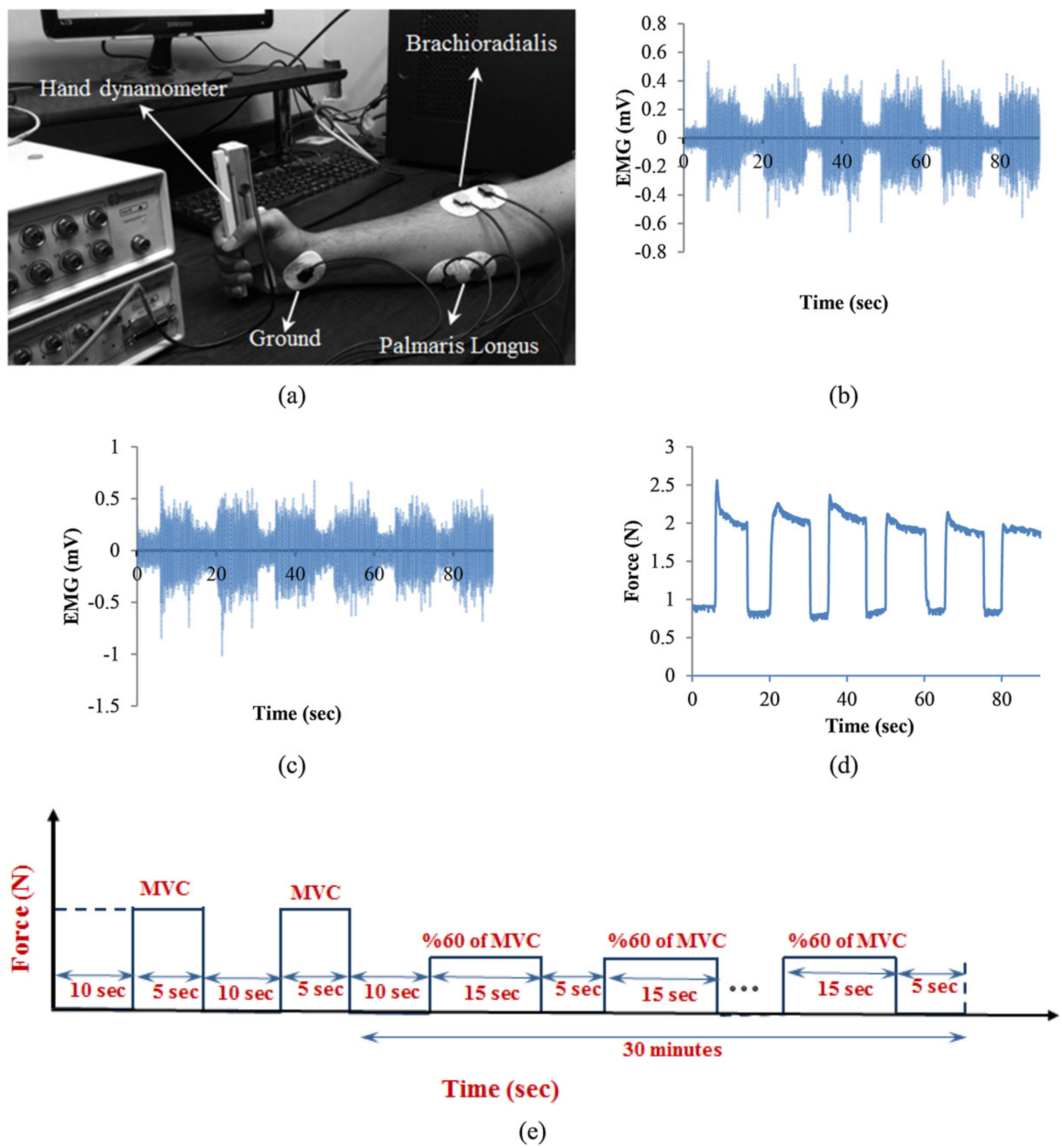


**Fig. 1.** (a) The experimental setup, (b) SEMG signal of the Brachioradialis muscle, (c) SEMG signal of the Palmaris Longus muscle, (d) force signal and (e) schematic of the experimental protocol.