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Muscle fatigue compensation of the electromyography signal for elbow joint angle estimation using adaptive feature[☆]

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ABSTRACT

The purpose of this study is to develop and evaluate an adaptive feature to compensate the effect of muscle fatigue in the elbow joint angle estimation. In the experiment protocol, subjects are asked to move the elbow in flexion and extension for 15 min. The electromyography (EMG) signal collected from biceps was extracted using the Wilson amplitude (WAMP) and modified WAMP features. A modified WAMP feature consists of the standard WAMP feature and an adaptive threshold; to smooth the features, the Kalman filter was applied. The results prove that muscle fatigue affects the EMG signal. The RMSEs resulting from the standard WAMP feature in the non-fatigue and fatigue conditions are 12.41° ± 5.16° and 18.17° ± 5.53°, respectively. The RMSEs resulting from modified WAMP feature in the non-fatigue and fatigue conditions are 12.63° ± 5.22° and 13.86° ± 4.7°, respectively. This proposed method is able to compensate the effect of muscle fatigue on the elbow joint angle estimation.

1. Introduction

Muscle fatigue is an essential problem in daily life, generated as the human limb performs a repetitive and intense motion. Generally, muscle fatigue is divided into three categories, namely subjective, objective and physiologic [1]. In the physiologic category, the muscle fatigue is commonly measured using the electromyography (EMG) signal, which is a bio-electricity generated from muscle when there is a contraction [2]. The EMG signal can represent a joint angle [3], force [4] of the human limb and muscle fatigue [5,6]. By extracting the EMG signal and using the classifier machines, the EMG signal can be used as a control signal for the exoskeleton, prosthetic devices and teleoperating machines [7]. Generally, those previous studies had a limitation in considering the effect of the muscle fatigue to EMG signal, which was used as a control signal.

The effect of muscle fatigue on EMG signal, while the elbow performs a static or dynamic contraction, has been investigated by previous studies. Yochum et al. investigated the effect of muscle fatigue on the EMG signal using continuous wavelet transform (CWT) under electro-stimulation [8]. Triwiyanto et al. used CWT analysis to assess the effect of muscle fatigue on the spectral parameters

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when the elbow performed a dynamic motion of flexion and extension [5]. The results of those studies revealed that the muscle fatigue affected the EMG parameters (amplitude and frequency) during a dynamic motion in flexion and extension. Gonzales et al. also studied the effect of muscle fatigue on EMG signal during a dynamic motion using mean average voltage, median spectral frequency, Dimitrov spectral index and Choi-William distribution [9]. Karthick et al. analyzed the progression of muscle fatigue during flexion and extension motion using modified B distribution based on time-frequency analysis [10]. However, those studies have not linked the effect of muscle fatigue to the joint angle, force and torque estimation.

In order to obtain the information related to the EMG signal with the joint angle, force and torque, the EMG signal needs to be extracted into the features then used as the input of the classifier machines. Based on the method used to estimate the joint angle, force and torque, the estimation is classified into two categories, specifically machine learning and non-machine learning [7]. In the machine learning method, the estimation is based on the pattern that had been trained into the classifier. In the non-machine learning method, the estimated angle is directly estimated from the EMG features and usually performs an optimization on the features. In the machine learning based method, some previous studies estimated that the elbow joint angle was using an artificial neural network (ANN) [11] and neuro-fuzzy [12]. However, the problem when using the machine learning method to estimate the elbow joint angle is that the machines need to be trained for every subject and every variable change. In fact, it is time consuming to train and apply the machine as a classifier to estimate the elbow joint angle; whereas in non-machine learning, some previous studies used the Hill-type muscle model [13], Kalman filtering [14] and the low pass filtering technique [15] to estimate the elbow joint angle from EMG features. However, those previous studies had not considered the effect of the muscle fatigue on the elbow joint angle estimation. It has been proved in the previous studies that the muscle fatigue affected the EMG spectral parameters (amplitude and frequency) [1,9]. The amplitude of the EMG signal will increase significantly when the subject performs a repetitive and intense motion. This causes the feature of the EMG signal to change; furthermore, the classifier machine or model will fail to recognize the pattern that related to the joint angle, force or torque. Some efforts had been performed to compensate the effect of the muscle fatigue on the estimation. Park et al. proposed to develop a fatigue compensation processor for prosthetic devices by reading the median frequency of the EMG signal and scaling down the amplitude of the EMG signal when the muscle was in the fatigue condition [16]. Na et al. developed a model to consider the time-varying of the EMG signal in the joint force estimation [17] and proposed a muscle twitch model to compensate the effect of muscle fatigue. Thilina et al. proposed a neuro-fuzzy modifier to compensate the effect of muscle fatigue on controlling the upper limb exoskeleton using EMG signal [12]. He used mean power frequency (MPF) feature to detect the progression of the muscle fatigue and modify the neuro-fuzzy parameter. Mostly, previous studies used the frequency domain feature to detect the change of the EMG parameter (amplitude and frequency) when the muscle was in the fatigue condition. However, the feature extraction in frequency domain requires a transformation stage from time to frequency domain, which commonly uses the Fast Fourier Transform (FFT) algorithm.

A disadvantage of extracting the muscle fatigue from EMG signal using frequency domain is that the computation is high cost [12] and causes an unacceptable time delay in the development of a real-time system. Therefore, a new proposed method is needed to obtain the muscle fatigue information in time domain. Based on the time domain feature, some previous studies used root mean square (RMS) to detect the effect of muscle fatigue on the EMG signal [18,19]. Furthermore, in conjunction with the elbow joint angle estimation based on EMG signal, a previous study [3] has proven that the Wilson Amplitude (WAMP) feature was one of the features with a better performance in estimating the elbow joint angle than the others. However, the weakness of the standard WAMP feature is that the feature is unable to compensate the effect of muscle fatigue since it uses a real constant value for the threshold parameter. Since the EMG amplitude increases significantly due to the effect of muscle fatigue, then the threshold value of the standard WAMP feature needs to be dynamically following the EMG amplitude. In this study, in order for the WAMP feature to compensate the effect of muscle fatigue, the RMS feature was placed as a dynamic threshold and as a parameter of the WAMP feature. In doing this, when the muscle fatigue influenced the EMG signal, the threshold would adaptively change to follow the amplitude of the EMG signal. In addition to the lowpass filter, the Kalman filter had also been used to smooth the results of the features extraction process due to the simple calculation and low computation cost. A previous study [14] has investigated the optimum parameters values of the measurement noise (R) and process noise (Q) to obtain the best performance of the elbow joint angle estimation. Therefore, in this study, the Kalman filter with those optimum parameters was used to smooth the estimation.

To overcome the limitation and the weakness of the previous studies, the objective of this study is to develop an adaptive feature to compensate the effect of muscle fatigue on the elbow joint angle estimation using the EMG signal. This adaptive feature consists of the time domain feature (WAMP), which is used to extract the EMG signal in relation to the elbow joint angle and an RMS processor, which is used to calculate the time-varying of the EMG amplitude due to the effect of muscle fatigue. The special aims of this study are: (1) to evaluate the performance of the proposed method and the standard method when the muscle is in the non-fatigue and fatigue condition, (2) to examine the significant difference of RMSE using single factor ANOVA between the standard method and the proposed method. The main contribution of this paper is to develop a new adaptive feature based on time domain feature, which is able to detect the change of the EMG amplitude due to the effect of muscle fatigue, so that it can minimize the effect of muscle fatigue on the elbow joint angle estimation. Another contribution is that the estimation of the elbow joint angle is performed only from single muscle (biceps), which differs from the previous studies. Previous studies used from 2 to 4 muscles to estimate the elbow joint angle [11,13,15].

This paper is organized as follows: section II explains the participants, experiment protocol, data processing and statistical analysis; section III shows the results of the study including the performance values and the statistical analysis results; section IV compares the result of this study and other studies and section IV summarizes the study.