Expert Systems With Applications 90 (2017) 232–240

Contents lists available at ScienceDirect

Expert Systems With Applications

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

Wavelet-derived features as indicators of physiological changes induced by bed rest

Robert Stallard[a,*], Enrico Rejc[b], Karla Conn Welch[a]

[a] Department of Electrical and Computer Engineering, University of Louisville, 2301 S 3rd St., Louisville, Kentucky, 40292, USA
[b] Neuroscience Collaborative Center, 220 Abraham Flexner Way, 15th Floor, Louisville, Kentucky, 40202, USA

ARTICLE INFO

Article history:
Received 9 December 2016
Revised 11 August 2017
Accepted 12 August 2017
Available online 17 August 2017

Keywords:
Wavelets
Classification algorithms
Electromyography

ABSTRACT

Objective: Bed rest studies are employed to simulate microgravity situations as encountered in spaceflight. Current methods of assessing muscle function impairment due to microgravity exposure include techniques such as maximum voluntary contraction assessments using force measurements. Such techniques involve impractical long-feedback loops for applications involving rehabilitation or otherwise detecting physiological changes. Recent studies have made use of the discrete wavelet transform in combination with machine learning methods to classify hand gestures and detect pathologies. In this paper, we demonstrate models capable of discriminating between the before and after bed rest states by extracting features from surface electromyography measurements. *Methods*: A previously conducted and studied bed rest experiment is examined by discrete wavelet transform for tractable feature sets for the purpose of *k*-nearest neighbor and Support Vector Machine classification. Forward feature selection is used with *k*-nearest neighbor or Support Vector Machine selection criteria. Classifiers are evaluated on non-wavelet-derived features for sake of comparison. *Results*: Wavelet-derived features perform well for both classifiers with classification accuracies as high as 95%. Models without wavelet-derived features do not perform as well overall. *Conclusion*: These high-accuracy results are promising for future efforts in neuromuscular monitoring and further investigations with larger sample sizes. *Significance*: Classification algorithms utilizing features derived by wavelet transforms provide a method toward development of short-feedback loop measurements of the physiological effects of prolonged disuse.

1. Introduction

This study demonstrates the use of wavelet-derived features from surface electromyography (sEMG) signals to describe and classify subjects undergoing a 35-day bed rest using the *k*-Nearest Neighbors (k-NN)and Support Vector Machine(SVM) classification schemes. The greater role that this study serves is toward the development of measurement and classification techniques that may shorten an otherwise long feedback loop for rehabilitation or physiological diagnostics. Establishing non-invasive, high resolution, and less time-consuming methods of categorizing or describing an individual's physiological state is also valuable for the development of autonomous diagnostic or rehabilitation systems. Toward these goals, it is necessary to compare measurements made on the same individuals using the same methods but with a larger span of time between the two to mark physiological changes, rather than characterization of sEMG output to mark immediate physiological conditions (e.g., gestures or presence of arthritis). In the present study, we investigate sEMG data taken from the lower limb of subjects performing three different prescribed motions before and after bedrest. We aim to establish the feasibility of classifying physiological conditions in this longitudinal manner and additionally investigate the utility of wavelet-derived features.

Well-controlled trials with careful observations of physiological changes ease the development of methodology for understanding and quantifying the stages of rehabilitation in other areas including exposure to microgravity, recovery from traumatic injury, and rehabilitation of individuals suffering from spinal cord injury. The intent here is to develop analytical tools and capabilities to further identify clinical variables marking physiological changes over time. This particular study's data is sourced from a simulation of microgravity via bed rest, which is known to induce a decline in muscle function due to muscle atrophy, reduction of neural drive and muscle specific force, particularly in the postural muscles of the lower limb (Narici & de Boer, 2011). The ability to observe, predict, and

* Corresponding author.
E-mail addresses: Robert.Stallard@Louisville.edu (R. Stallard), EnricoRejc@KentuckyOneHealth.org (E. Rejc), Karla.Welch@Louisville.edu (K. Conn Welch).

http://dx.doi.org/10.1016/j.eswa.2017.08.024
0957-4174/

mitigate the loss of muscle mass and function is of particular interest to agencies interested in human-based space exploration (Beaty & Carr, 2012; Neal & Shearer, 2012) and organizations interested in quantifying the effects of various neurological or physical disorders, such as muscular dystrophy (Subasi, 2013). Along with analysis of muscle function, prosthetic solutions for amputees is another area of rehabilitation exploring mechanical and signal-based control systems. For example, an FDA-approved prosthetic arm, called "Luke" in reference to Luke Skywalkers bionic arm in Star Wars, has been employed in clinical tests (DoD News, 2013). *Luke* features 10 degrees of freedom for gaining forearm and hand-grasp motions; however, it must be noted that Luke does not rely on residual EMG (surface or otherwise) signals to manipulate the arm, but rather an external foot-based control mechanism. Classifying signals via sEMG represents a means to transition from mechanical prosthetics to signal-based prosthetics. Very recently, a collaboration with Lego's Future Lab has yielded a modular prosthetic that relies on noninvasive surface electrodes measuring myoelectric activity from residual muscle (Wainwright, 2015). Even more recently, a child born without a right forearm was fitted with the *i-limb quantum* produced by Touch Bionics (Davies, 2015). This device is controlled by using simple gestures to activate one of four motions and two grips. These two examples demonstrate proof-of-concept devices using noninvasive means of control and utility in the advancement of sEMG signal processing.

2. Background

In the recent decade, a substantial body of work has been published concerning a variety of methods for the use of sEMG signals as a means to control prosthetic devices (Boostani & Moradi, 2003; Lamounier, Soares, Andrade, & Carrijo, 2002; Liu & Luo, 2008; Oskoei & Huosheng Hu, 2008) and diagnose physiological disorders (Nair, French, Laroche, & Thomas, 2009; Zuo, Wang, Liu, & Chen, 2013). Phinyomark et al. have made use of features derived from the Discrete Wavelet Transform (DWT) for the purpose of classifying hand gestures (Phinyomark, Limsakul, & Phukpattaranont, 2011; Phinyomark, Phukpattaranont, & Limsakul, 2012). Additionally, statistical comparisons were performed for a several wavelets, features, and algorithms (Phinyomark et al., 2013) and have demonstrated classification accuracy of greater than 98% with six different hand gestures. Karlik (2014) has reviewed studies utilizing both wavelet methods and time-series modeling to extract features for the purpose of prosthetic-related classification with upper classification accuracies ranging from 90% to 98% for time-series methods and 92% to 98% percent with wavelet methods. While their performances are comparable, the DWT is preferred here due to its unique properties including the ability to process the signal in both frequency and time domains while providing a "zoomed-in" view across a range of frequency bins without distortion. These reviewed studies report on a number of features to be examined when analyzing sEMG signals with a focus on classification of hand-based gestures by utilizing an array of features measured from lower limb muscles, across time before and after bed rest, in an effort to identify changes due to physical deconditioning, rather than instantaneous movements.

Work has also been done in utilizing features derived from sEMG signals to determine whether or not an individual has a disorder such as arthritis. Nair et al. (2009) employ time-based features and test eight algorithms to classify between healthy subjects, subjects with rheumatoid arthritis, and subjects with osteoarthritis. Nair et al. emphasize that the purpose of these classification schemes is to provide insight into muscle behavior in order to improve rehabilitation. sEMG recordings of six muscle groups within each leg of the patient are performed while the subject is in gait (walking). Utilizing both neural nets and kernel methods, they demonstrate up to 97% accuracy for the three-class problem.

One method of evaluating overall neuromuscular changes due to prolonged disuse includes a statistical evaluation of changes in lower limbs' power and force output. A complementary study analyzed the effects of bed rest in comparison to power output recorded during explosive extensions of the lower limbs (Rejc et al., 2014). The study supports its conclusions that muscle atrophy was mitigated by a moderate caloric diet restriction that significantly reduced the body fat gained throughout 35 days of bed rest; however, this positive outcome was not sufficient for reducing the loss of maximal explosive power of the lower limbs. This finding indicates the possibility that the neural component played an important role in determining power output during lower limbs extension, which is a relatively complex movement involving three joints and the interaction of uni- and multi-articulate muscle-tendon units.

In this study, we aim to demonstrate the use of direct electrophysiological measurements - the surface electromyogram (sEMG) - to discriminate between two physiological states, pre- and post-bed rest that might otherwise be done by comparing morphological characteristics or force output measurements. This effort aligns with similar efforts at algorithmic classification of instantaneous states as previously described, by exploring the similar problem of classification along a time-dimension. Additionally, we demonstrate the additional classification yield obtained when employing wavelet-derived features.

3. Methodology

The data analyzed in this study were collected from 10 healthy male subjects who underwent 35 days of bed rest under a moderate caloric diet restriction (1.2 times their resting energy requirement). Physical characteristics of the subjects are reported by Rejc et al. (2014). Before and after bed rest, the subjects performed non-fatiguing, isometric, maximal voluntary contractions of knee extensors, knee flexors, and plantar flexors with the right (dominant) lower limb. Force output and sEMG from the gastrocnemius medialis (GM), rectus femoris (RF), vastus lateralis (VL), and bicep femoris (BF) were sampled at 1 kHz using an EMG100C BIOPAC Systems, Inc. amplifier connected to an MP100 BIOPAC data acquisition system. The experimental setup is described in detail by Rejc, Lazzer, Antonutto, Isola, and di Prampero (2010). Briefly, the isometric contractions were performed by the subjects seated on either a special chair (knee flexion and extension) or sledge ergometer (plantar flexion). Two maximal voluntary contractions of 4–5 s under each isometric effort were performed. To prevent fatigue, after each contraction the subject rested for 2 min.

sEMG signal data was digitally pre-processed by applying a Hilbert transform to the sEMG signal envelope (obtained via zero-phase, 5th order butterworth filter with a low-pass corner frequency of 10 Hz) and determining the starting and ending moments of the signal, ultimately selecting the active portion of the sEMG signal. This selection was then extracted from the original signal, rectified and high-pass filtered with corner frequency of 10 Hz to remove any motion artifacts (De Luca, Donald Gilmore, Kuznetsov, & Roy, 2010). The active signal time is obtained by examining the signal from the primary muscle driving the movement (e.g., VL drives the knee extension). See Fig. 1.

The present study analyzes wavelet-derived features for classifying physiological changes indicative of prolonged disuse. The DWT is used to extract compact approximations of the original signal by decomposing it into coefficients corresponding to high and low frequencies (or detailed and approximate coefficients, respectively)Daubechies (1992), commonly referred to as a wavelet decimation. Chosen features are moving average (MAV),