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Research Paper

Analysis of surface electromyography signal features on osteomyoplastic transtibial amputees for pattern recognition control architectures

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A B S T R A C T

This paper presents the characterisation of electromyography signals for the purpose of controlling a powered prosthetic ankle using pattern recognition algorithms. The goal is to identify the specific muscles that can be used to guarantee optimal control of a multichannel powered prosthetic ankle. SENIAM and ISEK protocols were used for signal acquisition, processing and reporting. A set of paired surface electrodes were placed above selected muscles on the residual limb. Participants were instructed to perform normal gait. The signals were recorded, labelled and analysed using the Vicon Nexus Motion Capturing System and Noraxon Myomotion System. Signal processing was performed using MR3 Software and further post processing was performed using Matlab. Time and frequency domain features were analysed. The protocol revealed that the tibialis anterior, medial and lateral gastrocnemius muscles actively generate myoelectric signals on the residual limb. A total of 12 time domain and 4 frequency domain features were successfully extracted and used in the analysis. The tibialis anterior muscle was identified as a candidate for classifying dorsiflexion with a mean amplitude of 35.08 μV. The soleus muscle was inaccessible on the amputated leg and as a result only the medial and lateralis gastrocnemius muscles, with 17.40% signal power and 43.73% mean amplitude as compared to the soleus, were available for plantarflexion. There was significant difference ($p < 0.05$) between features from the amputated residual limb and those from the intact normal leg. However, there was no significant difference ($p > 0.05$) between signal features from two different participants. Sagittal plane movements were linearly discriminated with 100% accuracy for tibialis anterior and medial gastrocnemius. However, lateralis gastrocnemius exhibited a 0.0769% classification error as a result of the amputation technique.

1. Introduction

Electromyography (EMG) is a process which involves detection, analysis and use of electromyography signals [1]. These signals have found application in both clinical diagnosis, assistive technology and engineering [2]. In this study the focus is on assistive technology. Lower limb amputees have struggled for long to acquire neural intuitive powered ankle devices so as to aid mobility [3]. As a result this has reduced the confidence the amputees have on the prosthetic limbs. The ankle dorsiflexion and plantarflexion movements are responsible for the proper toe-off and heel-off during normal gait. The propulsive force generated by the ankle enable smooth forward body projection and minimises hip rotation. The natural ankle intuitively adapt to desired gait thereby assisting the body to achieve full range of motion for all anatomical angles such as the hip and the knee. The ankle facilitates the attainment of smooth normal gait, however, the use of stiff mechanical prosthetic ankles presents some difficulties for amputees which may lead to abnormalities within the gait [4]. The poor range of motion and lack of intuitive control of the ankle may result in short term effects such as bruises and long term effects such as lower back-pain.

Therefore there is a need for more a naturally controlled ankle prosthesis and this can be achieved with the use of electromyography signals. Such a technique will present the amputees with intuitive control of the ankle thereby achieving close to natural gait. However, challenges exist on selecting the proper muscles to use and also the poor quality of the electromyography signal available at the amputated limb present challenges on signal processing.

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The *"Standards for reporting EMG Data"* popularly known as the ISEK EMG standards were developed by Dr. Roberto Merlitti [5] and endorsed by International Society of Electrophysiology and Kinesiology (ISEK). They describe how EMG data is recorded, processed, analysed and reported. The standards sufficiently explain the nature of the recording sensors and signal processing. In 1996 the Biomed 2 program by the European Community resulted in the formulation of the *"surface EMG for non-invasive assessment of muscles"* (SENIAM) so as to integrate basic and applied research on surface EMG and to solve key issues with regards to clinical application [6,7]. The SENIAM standards clearly highlighted the locations of electrode placements for surface EMG while the ISEK standards are more aligned to signal processing. Furthermore the SENIAM standards only focus on surface EMG while ISEK takes note of both surface and invasive EMG signals. However the standards complement each other very well. Key issues for both standards are sEMG sensors and sensor placement procedures, sEMG signal processing and surface EMG modelling. Other methods and guides proposed later were merely an extract of the ISEK and SENIAM standards [8].

According to Mercer et al. [9], there is notable variation with regards to electrode placement, inter-electrode distance and determination of landmark morphology during EMG measurement. As a result there is a need to carefully implement SENIAM and ISEK standards when working with amputees as the missing part of the leg provides difficulties on the use of the standard operation procedure. During the recording of EMG signals there are several factors that may lead to the distortion of the signal and these include muscle cross talk, skin impedance and power line interference [10].

As an amputee sustain a contraction, the amplitude of the surface EMG signal increases as a result of the synchronisation of the activated and newly recruited motor units [11]. However, in some cases this is regarded as symptoms of fatigue [12]. Although the EMG signal is effected by muscle crosstalk, it can easily be described in terms of amplitude, frequency and phase [1]. Therefore the goal is to determine safe operating amplitude levels and at the same time achieve optimum control of the prosthetic ankle. According to Thongpanja et al. [13], the analysis of EMG signals is mainly for muscle fatigue, muscle geometry and muscle force. However, it is muscle force that mainly affects the performance of myoelectric systems since the EMG signal amplitude is proportional to the muscle force. Contrary, for amputees the extent of amputation has an adverse effect on muscle behaviour. The median frequency and the mean power frequency are the most common and reliable indicators of muscle performance [14].

The implementation of pattern recognition based systems for myoelectric control has been extensively investigated and recommendations for non-amputees were made [15,16]. However, challenges still exist for implementation of such robust techniques on amputee related designs [17]. Myoelectric control systems for lower limb prosthetics are often regarded as complex systems due to the nature of the available signals at the residual limb. The pattern recognition system's accuracy and reliability is highly influenced by the classification accuracy which is affected by the quality and nature of signal features. Pattern recognition based systems are complex but reliable control architectures, since they use the signal features instead of signal threshold values. In time domain these features include zero-crossing per second, integrated EMG, mean absolute value and root mean square value [2]. The performance of pattern recognition systems is highly affected by White Gausian Noise (WGN) inherent in the dominant frequency bandwidth [18,2]. The WGN is difficult to eliminate using band pass filtering therefore there is a need to develop a robust feature set that can guarantee optimal classifier performance in the presents of WGN. Since the establishment of the Hudgins features in 1993 [19], efforts had been made to improve the feature set and evaluations were done to develop a grading system for the EMG features. Boostani and Moradi [20] and Phinyomark et al. [21], evaluated the features based on sensitivity to noise, hence the Willison amplitude feature was superior to all the features. However, the analysis was based on simulated noise hence the results differ from online EMG noise interference.

It was hypothesised that the residual limb muscles still contain active myoelectric signals, however, the signal characteristics is affected by the type of amputation. As a result this affects the extent of functionality of the active powered ankle. The objective was to determine the strength of the available myoelectric signals for the purpose of sagittal plane ankle movements.

2. Materials and methods

The methods used for electrode placement, signal acquisition, processing and reporting was strictly based on the SENIAM and ISEK standards. The approved research protocol was an extract from the SENIAM standards with slight modifications to suit for amputees. The SENIAM standards were mainly utilised for electrode selection, selection of muscles and also electrode placement. However, they were not clear on data acquisition and reporting for data acquired from amputee subjects. As a result ISEK standards were used for sampling, filtering and processing of the signals.

2.1. Subjects

The study was conducted under research protocol S16/05/093 approved by Health Research Ethics Committee at Stellenbosch University with regards to experimenting with human beings. The study consisted of two male unilateral transtibial amputees *(left leg amputated)* weighing an average 80 kg and a mean height of 1.75 m. The participants reported independent ambulatory with medium to high daily activities. The participants have been using the passive limb for the past two years. The criteria for inclusion was based on the ability of the participant to effectively use the prosthetic limb inside the laboratory testing environment without the need for assistance. This eliminated the need to train the participants the use of the limb prior to the experiments. Another consideration was for the participant to have a comfortable surface bearing socket which utilises the vacuum system and had no medical history related to the limb injuries or comorbidities that could affect gait, joint angles or electromyography signals. None of the participants had a history of neuromuscular disorders. The experiments were carried out at Stellenbosch University, Central Analytical Facilities, Human Motion Analysis Unit, South Africa. The experimental protocol was explained, hence both orally and in writing to all participants before written consent was obtained.

2.2. Skin preparation and electrode placement

The surface EMG signals were recorded from the soleus, tibialis anterior, gastrocnemius lateralis and the gastrocnemius medialis. Proper skin preparation procedures were performed which included shaving the limb and cleaning with alcohol. The use of alcohol was to reduce signal distortion due to increased skin impedance. The electrodes were then placed on the tibialis anterior, lateral gastrocnemius lateralis and gastrocnemius medialis of the amputated leg. After amputation the soleus could not be accessed, as a result the soleus was not considered on the amputated left leg. As a result soleus muscle was only considered for the normal leg.

Pre-gelled, bipolar Ag/AgCl surface EMG electrodes of 10 mm diameter were used. The electrodes were placed 20 mm apart, longitudinally with respect to the muscle fibre to be measured as recommended by the SENIAM and ISEK standards [6]. The SENIAM and ISEK standards were difficult to apply on the amputated leg