# Characterizing Residual Muscle Properties in Lower Limb Amputees Using High Density EMG Decomposition: A Pilot Study*

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***Abstract*— As research is progressing towards EMG control of lower limb prostheses, it is vital to understand the neurophysiology of the residual muscles in the amputated limb, which has been largely ignored. Therefore, the goal of this study was to characterize the activation patterns (muscle recruitment and motor unit discharge patterns) of the residual muscles of lower limb amputees. One transtibial amputee subject was recruited for this pilot study. The participant wore three high-density EMG electrode pads (8x8 grid with 64 channels) on each limb (a total of six pads) – one on the tibialis anterior (TA), medial gastrocnemius (MG), and lateral gastrocnemius (LG), respectively. The participant was asked to follow a ramping procedure plateauing at 50% of maximum voluntary contraction (MVC) for both the TA and Gastrocnemius muscles. The EMG signals were then decomposed offline; the firing rate and spatial activation patterns of the muscle were analyzed. Results showed slower and more variable firing rate in motor units of residual muscles than those of intact side. In addition, the spatial pattern of muscle activation differed between residual and intact muscles. These results indicate that surface EMG signals recorded from residual muscles present modified signal features from intact shank muscles, which should be considered when implementing myoelectric control schemes.**

## I. Introduction

Powered prostheses have been shown to lower metabolic cost and provide more biomimetic gait patterns [1]. Most of these devices are automated and rely on finite state control, but using the user's input via myoelectric control has shown some promising results [2]. Researchers have investigated using the residual muscles signals and pattern recognition to switch between modes such as standing, walking, and ascending stairs [3]. The EMG signal has also been used to scale the powered push-off assistance [4]. Other researchers have shown the promise to using direct volitional control to modulate the ankle to provide adequate push-off in late stance [5, 6].

Although studies have shown the promise of using an amputee's residual muscles as an input to a controller, very few studies have sought to understand and characterize the EMG signal generated by the residual muscles. When the EMG signal is collected via surface electrodes, the signal is composed of a sum of individual motor unit action potentials (MUAPs). After amputation, the muscle fibers are severed disrupting the control of motor units and distorting the MUAPs [7]. It is then unknown exactly how the residual muscles are recruited to generate force and how the potential nerve reinnervation affects the voluntary activation of the muscles. Sensory feedback is also affected after amputation due to the lack of a distal attachment point. The muscle spindles are unable to sense stretch of the muscle fibers in the same way as an intact muscle would.

One method to investigate the MUAPs is through EMG decomposition. EMG decomposition allows for the separation of the MUAPs from the constituent EMG signals. This information can then be used to investigate reinnervation, motor unit firing rate patterns, and recruitment [8]. When EMG decomposition was first introduced, needle electrodes were inserted into the muscle and localized information about the MUAPs could be attained [9]. Recently, surface electrodes have been used to decompose the EMG signal through 4-pin or 5-pin systems [8, 10] and high-density (HD) electrode arrays [11]. These surface electrodes are advantageous because they are non-invasive and allow for a larger area of muscle of interest to be observed. These recording techniques are coupled with automated decomposition algorithms that allow us to quantify the motor unit control at the population level.

Therefore, the goal of this study is to better understand how muscle fibers are recruited in residual muscles and how the MUAP signal is propagated through the muscle by using HD EMG recording and decomposition techniques. Results from this study will provide more information into the underlying signal being used for prosthesis control. We hypothesize more irregular firing patterns and less organization when compared to intact muscles.

## II. Methods

### A. Participant

One left transtibial amputee subject – male, age 57, weight 127 kg, height 1.88m was recruited for this study. The participant was provided written informed consent for this study approved by the Institutional Review Board at the University of North Carolina at Chapel Hill.

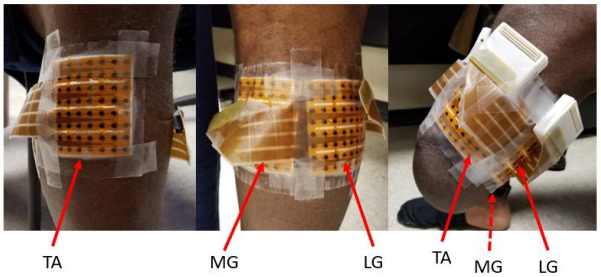


Figure 1. Location of EMG electrods on intact limb front (left), back (middle), and residual limb (right)

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### B. Electrode Placement

The participant was asked to remove his prosthetic socket and liner and the skin of the residual limb was gently exfoliated and cleaned using alcohol wipes. Three 8x8 electrode pads with 1cm inter-electrode spacing (OT Bioelettronica, Torino, Italy) were gelled and then applied to cover the tibialis anterior (TA), medial gastrocnemius (MG), and lateral gastrocnemius (LG) muscles (Fig. 1). The pads on the TA, LG, and MG was oriented so that the y-axis corresponded to the proximal-distal direction and the x-axis was along the medial-lateral direction. In the case of the LG and MG pads, the pads were placed adjacent to create an 8x16 pad across the Gastrocnemius. When placing the pads, the muscles were palpated, and the pads were applied to the muscle matching the intact side. After application, signal quality was assessed, and the RMS value of two monopolar channels were chosen (one from the TA and one from the LG) to represent the visual feedback during the trials. These channels were selected because they were free from motion artifact and surrounded by channels with similar signal quality.

### C. Experimental Set-up and Protocol

The subject was seated in a chair with their knee bent at 90˚ and their residual limb remained out of the socket. The max voluntary contraction (MVC) was found for each muscle by asking the participant to contract their muscle as much as possible. Three MVC trials were collected to find an average MVC for both the TA and Gastrocnemius. Visual feedback of the muscle signal was given to encourage a true maximum contraction.

After calibrating the system with the MVC, the participant was asked to follow a trapezoid ramping protocol (Fig. 2). The subject was first asked to relax, ramp up to a steady contraction, hold the contraction for 10 seconds, and then ramp down to zero. The plateau of the ramp was 50% of his MVC. A total of 4 randomized trials were collected - 50% MVC for both the TA and Gastrocnemius with each condition repeated twice. The subject was given rest between trials to reduce the effects of fatigue. This protocol was similar to that used in [10].

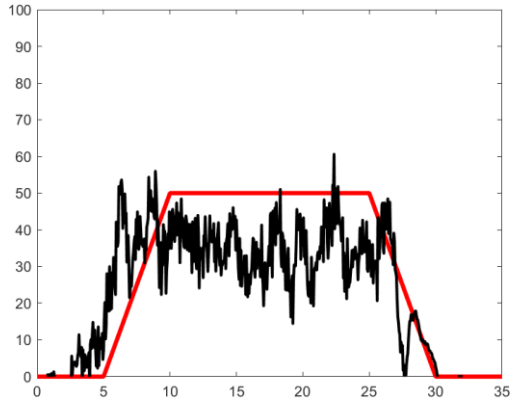


Figure 2. Example of visual feedback provided to subject. The red line is the trapazoid goal and the black line is the RMS of EMG. Note: the plataeu is 15sec, but the subject as told to focus on steady activation for 10sec

After completing all trials with the residual muscles, the same procedure was repeated with the intact muscles. On the intact side, the foot rested on the floor and was allowed to move freely while determining MVC and during the trials to better replicate the state of the residual muscles.

The EMG recordings were collected from EMG USB2+ (OT Bioelettronica, Torino, Italy), sampled at 2048 Hz with a gain of 1000, and band-pass filtered from 10 to 900 Hz.

### D. Data Processing – MUAP Decomposition

After data were collected, the raw EMG signal was decomposed offline using the FastICA method which has been previously verified [12, 13]. Further details about the decomposition algorithm are described in [14, 15]. The coefficient of variation minimization step (the second convergence loop) described in [15] was not used in our current study because large variations in the firing rate were expected in the residual muscle. Motor units were selected using two criteria – firing rate and duplicates. The typical firing rate for motor units is between 5-50 Hz so motor units outside of this range were first excluded. Because the FastICA method tends to converge to the same motor unit multiple times, motor units that were found to be replicas were also removed from the analysis.

### E. Data Processing – Activation Maps

To analyze the activation spatially, the RMS of each monopolar channel of the 8x8 pad was calculated. The RMS was calculated for each trial during the plateau section only – the rest and ramp sections were not included in the average. In the case of the Gastrocnemius, the two pads were combined together to create an 8x16 grid. The activation maps were linearly interpolated six times for better visualization.

## III. RESULTS / DISCUSSION

Results from this study indicate differences in residual muscles compared to intact muscles. Most notably, the location of the activation and firing rate of the motor units was different.

### A. MUAP Decomposition and Firing Rate

Fig. 3 shows the RMS of the EMG signal derived from intact muscles has less variability during the plateau than that collected from the residual side. The participant noted that it was more challenging to maintain a constant contraction level using his residual muscles. This may be due to the lack of sensory feedback and proprioception about the ankle joint or modified high-level control of the muscle.

When the signal was decomposed into motor units, 22 motor units were discovered on the intact limb and 17 motor units were found on the residual limb. Looking at Fig. 3, the firing rate is slower in the residual muscles compared to the intact muscles (10.99 Hz vs. 13.10 Hz). Additionally, there is a greater coefficient of variation in the firing rate of the residual muscles compared to intact muscles (37.08% vs. 30.68%). The lower firing rate and greater variability relates to a lower and more unstable excitation command from the brain. Because the signal is weaker and more unstable, additional processing of the raw EMG signal from the residual muscles should be considered when using these

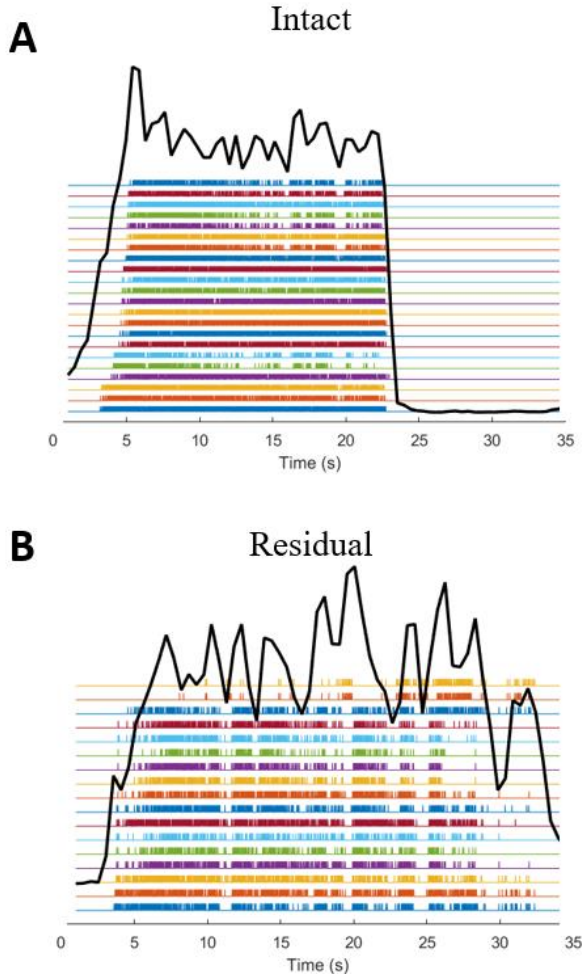


Figure 3. Motor unit decomposition for the Intact (A) and Residual (B) TA muscles for 50% MVC contraction. RMS of EMG is overlayed in black. Each of the colored lines corresponds to individual motor unit spike trains.

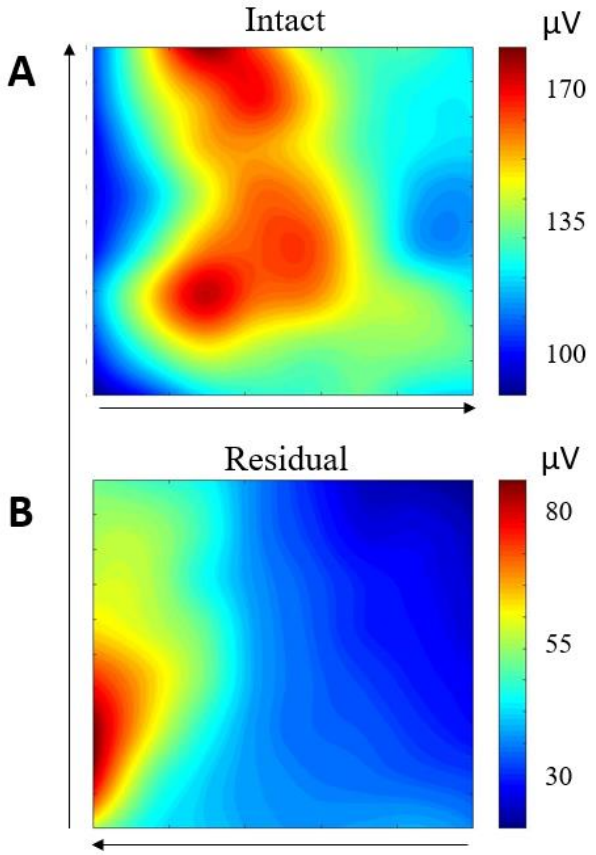


Figure 4. Spatial activation map of EMG activation across 8x8 pad placed on intact (A) and residual (B) TA muscles during 50% MVC contraction. Arrows on the y and x axes points towards the proximal and medial directions, respectively. Note: scales are different

muscles to drive control.

### *B. Activation maps of EMG Signal*

Fig. 4a shows the average EMG activation for the Intact TA during the 50% activation across the entire pad while Fig. 4b shows the same plot for the Residual TA. Spatially, the residual TA showed a more concentrated activation pattern on the medial edge of the pad. This may be due to the muscle shifting location after amputation due to the loss of a distal attachment point or the reinnervation due to amputation. In addition, the residual activation level was lower in magnitude compared to the intact muscle. As expected, the residual muscles were unable to generate as much voltage compared to the intact muscles.

Interestingly, the intact TA had two prominent activation regions of activation compared to a single activation region as seen in the residual muscle. Previous work related to the upper limb has shown muscles such as the extensor digitorum communis (EDC) have multiple prominent activation regions related to individual finger flexion [16]. Similarly, after targeted muscle reinnervation, HD EMG has shown multiple activation regions corresponding to reinnervated nerves linked to finger flexion, wrist flexion, etc… [12, 17]. The multiple activation regions seen in this study may be due to a similar phenomenon – when dorsi-flexing the ankle, individual toe flexion or ankle inversion/eversion may have occurred resulting in the multiple activation regions. In the residual muscle, only one prominent activation region was observed. This may be attributed to the lack of DOF in the ankle and foot and lack of sensory feedback.

Similar to the TA, the LG and MG muscles on the residual limb had lower activations when compared to intact muscles (Fig. 5). Spatially, the residual muscles have a more even activation pattern across the two residual muscles while the intact muscles have a more defined separation between the two muscles. This could be due to the residual LG and MG shifting post-amputation or due to reinnervation similar to the residual TA.

## IV. LIMITATIONS / FUTURE WORK

Although just one subject participated in this pilot study, results still show differences between the intact and residual muscles. More participants will be tested in the future to make more generalized conclusions about the differences observed in the residual muscle neurophysiology. The information gathered from additional participants will be especially useful because of subject-to-subject variability due to amputation procedure, rehabilitation training, correction surgeries, activity level, and other comorbidities.

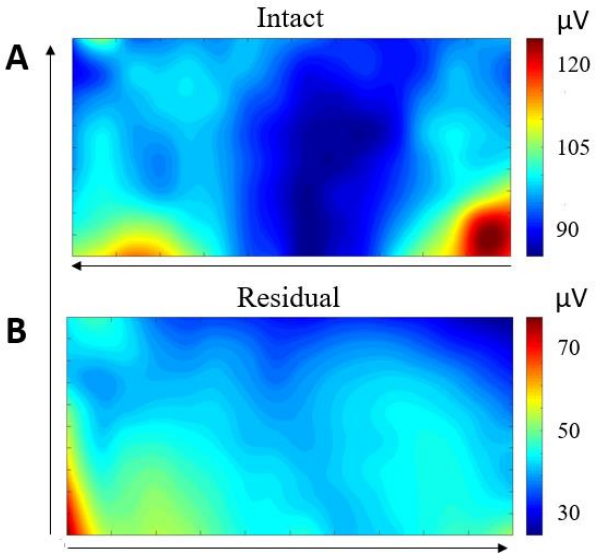


Figure 5. Spatial activation map of EMG activation across 2 8x8 pads placed on intact (A) and residual (B) LG and MG muscles during 50% MVC contraction. The pads are merged together to create a 8x16 grid. Arrows on the y and x axes points towards the proximal and medial directions, respectively. Note: scales are different

As noted earlier, the subject reported difficulty maintaining a steady contraction for 10 seconds especially using his residual muscles, partly due to low firing rate and unstable firing rate patterns. This is important to keep in mind when designing future controllers especially those that utilize EMG signals from the residual muscles.

Future studies will also investigate combining ultrasound imaging with the EMG decomposition. Ultrasound will allow for the fiber orientation, cross-sectional area, and identification of tissues to be extracted to further explain the residual muscles. The imaging data will pair well with the MUAP data to provide a more complete picture of the underlying neurophysiology. Using ultrasound imaging may also allow for better placement of the electrode pads so that the area of interest can be better targeted.

Another future study could also look into mapping the activation zones during different tasks such as toe flexion and ankle inversion/eversion. If this mapping exists on the residual limb, additional DOF could be incorporated into prosthesis control.

## V. Conclusion

Results from this study highlight the need to investigate the neurophysiology of residual muscles due to the increased interests in using EMG signals from the residual muscles for continuous prosthesis control. In this study, we found that the residual muscles not only showed lower activation, but the spatial patterns of activation and firing rate of the individual motors units was different compared to intact muscles. Further efforts are still needed to investigate the muscle recruitment capability of amputees and detailed components of surface EMG signals recorded from residual muscles to enable direct EMG control of prosthetic limbs.

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