Ambulation After Incomplete Spinal Cord Injury With EMG-Triggered Functional Electrical Stimulation

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Abstract—Individuals with incomplete spinal cord injury (iSCI) retain some control of the partially paralyzed muscles, necessitating careful integration of functional electrical stimulation (FES) with intact motor function. In this communication, the volitional surface electromyogram (sEMG) from partially paralyzed muscle was used to detect the intent to step in an iSCI volunteer. The classifier was able to trigger the FES-assisted swing phase with a false positive rate less than 1% and true positive rate of 82% for left foot-off (FO) and 83% for right FO over 110 steps taken during three testing sessions spread over a week.

Index Terms—Functional electrical stimulation (FES), spinal cord injury (SCI), electromyogram (EMG), gait event detector.

I. INTRODUCTION

Functional electrical stimulation (FES) provides an opportunity for brace-free ambulation to wheelchair-dependent individuals with spinal cord injuries (SCIs). This report summarizes the development and testing of a new command structure for FES-assisted ambulation that integrates stimulated and voluntary muscle activity in a method suitable for eventual realization in a fully implantable neuroprosthesis for community ambulation after incomplete spinal cord injury (iSCI). Gait event detection is possible with physical sensors such as force sensitive resistors, accelerometers, and gyroscopes [1]–[3]. Biopotentials such as electromyogram (EMG) temporally precedes the generation of force in a muscle and provides an attractive signal for intent detection [3]. Graupe and Kordylewski presented a nonlinear classifier for muscles under voluntary control above the level of the lesion in individuals with motor complete paraplegia [4]. Our study indicates that the surface EMG from partially paralyzed muscles in an individual with motor incomplete injuries can be used by a linear classifier to detect the intent to initiate a step during walking and trigger electrical stimulation.

II. METHODS

A. Subjects

The subject was a 23 years old male with C7 motor and C6 sensory iSCI (ASIA C) who could stand but could not initiate a step. The subject completed six weeks of overground gait training (2-h sessions three times per week) with a physical therapist using an implanted FES system consisting of intramuscular stimulating electrodes inserted bilaterally to activate quadriceps, iliopsoas, tensor fascia latae, and tibialis anterior connected to an eight-channel implanted pulse generator [5], [6]. After discharge from rehabilitation, the subject volunteered for studies related to the myoelectric control of the FES system. Informed consent was obtained from the subject before his participation and the Institutional Review Board of the Louis Stokes Cleveland Department of Veterans Affairs Medical Center approved the study related procedures.

B. Data Acquisition and Processing

The experimental setup for electromyogram (EMG)-triggered FES-assisted walking is shown in Fig. 1. Surface EMG (sEMG) signals were collected from Gluteus Medius (GM), Biceps Femoris (BF), Medial Gastrocnemius (MG), Rectus Femoris (RF), Tibialis Anterior (TA), and Erector Spinae (ES at T9) bilaterally during manually triggered FES-assisted gait following the surface electromyography for the non-invasive assessment of muscles (SENIAM) guidelines [7]. The sEMG signals were preamplified (gain: 100), and low-pass (f_{cut-off} = 1000 Hz) filtered by CED 1902 (Cambridge Electronic Design, Cambridge, U.K.) amplifier (gain: 330 or 990) before being sampled at 2400 Hz (AT-MIO-64F-5, National Instruments, Austin, TX) in the host personal computer. The input channels of CED 1902 were clamped when stimulation pulses were applied to the muscles to prevent stimulation artifact. The implanted FES system delivered electrical pulses at a frequency of 20 Hz to a selected set of muscles [6], [8]. The sampled sEMG was divided into bins of 50-ms duration. In each bin, 30 ms following the start of the stimulation pulse was blanked to remove residual
Fig. 2. LE of ES for training the classifier collected during switch-triggered FES-assisted gait. (a) LE pattern for the class “true” during double support (DS) phase of the gait from contralateral FS to ipsilateral FO. Left DS duration was 1.79 (±0.85) s and right DS duration was 2.23 (±0.69) s. (b) LE pattern for the class “false” during 3-s-long terminal stance.

stimulation artifact and M-wave. The remaining 20 ms of data in each bin was detrended, bandpass filtered (fifth-order zero-lag Butterworth, 20–500 Hz), and rectified. The blanked portion of the sEMG was reconstructed with the average value of the sEMG in the pre- and post-bins [9]. The reconstructed sEMG pattern was then low-pass filtered (fifth-order zero-lag Butterworth, f_{cutoff} = 3 Hz) to get the linear envelope (LE). The LE for each muscle was normalized by its maximum value found during a switch-triggered FES-assisted fast walk trial (one calibration trial for each session).

C. Classifier Development

The training data were collected over a month to capture day-to-day variability. The processed LEs for the sEMG from each muscle were divided into two classes: the class “true” was comprised of LEs during double-support prior to foot-off (FO, 150 patterns) and the class “false” consisted of the LE during terminal stance (150 patterns) based on the occurrence of foot strike (FS) and FO as determined from the insole foot-switch data. A minimum set of uncorrelated patterns (PC) were then found using principal component analysis such that their linear combinations accounted for most of the variance in the mean-adjusted data set constructed with the LE patterns from both the “true” and “false” classes (total 300 patterns) [10]. The orthogonal rotations (MATLAB™ “varimax”) was applied to minimize the number of factors (i.e., PC after rotation) and increase the loading on fewer factors that are features for the classes “true” and “false.” The loadings on the features normalized by the square root of the sum of the squared loadings created separate clusters of points for the classes in the feature space. For intent detection, the classifier estimated the feature loadings for the LE of a candidate sEMG (i.e., case “true”). The feature loading was estimated for each feature from the dot product between the feature and the mean-adjusted LE of the candidate sEMG. The Euclidean
distance between the point in the feature space represented by the normalized loading and the centroid of the cluster “true” was used to detect the intent. The receiver operating characteristics (ROCs) curve showed the tradeoff between selectivity (i.e., false positive rate) and sensitivity (i.e., true positive rate) with the test data as the threshold (for the Euclidean distance) was varied. A statistic, discriminability index (DI < 1) was computed from the area under the ROC curve to select the best muscle having the highest DI.
D. Online Testing of the sEMG Classifier During FES-Assisted Ambulation

The sEMG classifier was integrated with the FES system for real-time operation in an xPC-targetTM (The MathWorks Inc., Natick, MA) to trigger preprogrammed stimulation patterns for walker-aided ambulation. The first FES-assisted step had to be triggered manually from the “stand” state using a start switch after which the subsequent steps were triggered by the classifier. The classifier started scanning the LE of the selected muscle after the end of the FES-assisted swing phase of the contralateral limb. For safety, the FES system returned to the “stand” state when the classifier failed to trigger the next step within a fixed duration decided by the subject (≥3 s). The subject used a switch to manually stop the FES system if it triggered a step when none was intended (false positive). If the FES controller stopped and failed to trigger an intended step (false negative) then the subject was able to override the FES system to manually trigger the step, after which the classifier would resume operation. During each trial, the subject tried to reach a self-selected steady gait from the “stand” position. The online performance of the classifier was evaluated over three sessions (three days) evenly spread over a week.

III. RESULTS

A. Muscle Selection for the Classifier

The left (L) and the right (R) side muscles in the descending order of their DI were ES (L:0.87, R:0.88), MG (L:0.82, R:0.85), GM (L:0.78, R:0.77), RF (L:0.71, R:0.70), TA (L:0.64, R:0.68), and BF (L:0.56, R:0.54). The selected muscle ES was free from muscle spasms but the distal muscles MG and TA exhibited significant muscle spasms. The LE pattern of ES that was used to train the classifier (N = 150) is shown in Fig. 2.

The first three principal components ranked by their eigenvalues accounted for more than 85% of the variance. The clusters in the feature space are shown in Fig. 3(a), the extracted features are shown in Fig. 3(b), and the ROC curve is shown in Fig. 3(c). The left and the right FO classifier predicted the FO 1.13 (±0.46) s and 0.95 (±0.35) s ahead of the event, respectively.

B. Online Testing of the Classifier

One false positive occurred for the right leg during terminal stance at the first session of testing, when more than 60 steps were taken. The user learned to convert the terminal step into a short step and then anticipation of the event, respectively.

The user retains direct control over the trigger by modulating his/her volitional EMG from muscles required to successfully complete the movement, giving the appearance of being “automatic.” The user of the sEMG-triggered FES system exercises the volitional muscle function in conjunction with the stimulation. This enhances the coordination between the voluntary and stimulated muscles and may have long-term benefits [11]. The potential exists to make the classifier adaptive by online training using the misclassified EMG patterns, thus having it learn to accommodate for fatigue and other time-varying factors that may influence long-term performance. The subject preferred the “automatic” EMG-based triggering of the steps and was able to achieve a steady, fluid gait with the system. Our future goals include surgical installation of an implanted stimulator–telemeter that acquires EMG information from implanted electrodes and transmits it to a wearable external control unit (ECU) that implements the classifier, which will run in the wearable ECU and generates the required commands to deliver appropriately timed stimulation (see Fig. 1). It is postulated that iSCI subjects with good volitional modulation of EMG but reduced hand and finger function will prefer the “automatic” EMG-triggered FES-system due to reduced dependence on manual switches for long-term community ambulation.

IV. DISCUSSION

The sEMG-triggered FES-assisted ambulation was successfully implemented and evaluated in the laboratory by an iSCI subject. The false positives were successfully reduced to 1%, minimizing the likelihood of potentially more disruptive event of initiating a step unexpectedly. The user retains direct control over the trigger by modulating his/her volitional EMG from muscles required to successfully complete the movement, giving the appearance of being “automatic.” The user of the sEMG-triggered FES system exercises the volitional muscle function in conjunction with the stimulation. This enhances the coordination between the voluntary and stimulated muscles and may have long-term benefits [11]. The potential exists to make the classifier adaptive by online training using the misclassified EMG patterns, thus having it learn to accommodate for fatigue and other time-varying factors that may influence long-term performance. The subject preferred the “automatic” EMG-based triggering of the steps and was able to achieve a steady, fluid gait with the system. Our future goals include surgical installation of an implanted stimulator–telemeter that acquires EMG information from implanted electrodes and transmits it to a wearable external control unit (ECU) that implements the classifier, which will run in the wearable ECU and generates the required commands to deliver appropriately timed stimulation (see Fig. 1). It is postulated that iSCI subjects with good volitional modulation of EMG but reduced hand and finger function will prefer the “automatic” EMG-triggered FES-system due to reduced dependence on manual switches for long-term community ambulation.

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