Machine Learning for Real Time Control of Foot-Drop Correction using Natural Sensors

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Abstract - *The neural signal recorded from the Sural nerve of a 32 year old female participant (five year post stroke with a foot drop) was used to drive a functional electrical stimulation (FES) system for correction of foot drop. The gait events used to control the stimulation patterns (heel strike and foot lift-off) were detected using a machine learning technique operated from a personal computer. The stimulation was applied to the Common Peroneal nerve using an implanted two-channel stimulator and the electroneurogram (ENG) was recorded using an implantable neural amplifier. Both of the implanted devices were operated using telemetry links. The quality of the detection was evaluated during plain gait, pausing, and stair climbing. A functional performance measure of the detection accuracy approached 100% during plain gait, while in other tasks it was still better than 70%.*

Keywords: foot drop, functional electrical stimulation, neural recordings, cuff electrode, adaptive logic networks

1. Introduction

Foot-drop affects hemiplegic patients suffering from varying health conditions; mainly from post-stroke or multiple sclerosis, and some from spinal cord injuries. Several studies have shown that functional electrical stimulation can assist hemiplegic patients by stimulating the Peroneal nerve in the swing phase of the affected leg, which allows the toes to clear the ground by dorsiflexing the foot.

Most of conventional foot-drop correction systems are controlled using a simple external sensor, such as a heel switch. Using a heel switch is not an optimal solution for neither the user or from a control point of view. It has been proposed to use sensors residing within the body in order to produce a more reliable control signal and to produce more users friendly systems (e.g. donning and doffing). As an alternative to implanting sensors, using afferent neural signals recorded from peripheral sensory nerves innervating foot areas has been proposed [1]. This approach can increase the detection performance and solve some of the problems existing with external detection systems, as it will enable the system to be fully implantable.

The purpose of this study is to investigate potential use of machine learning techniques, in particular Adaptive Logic Networks (ALN), and sensory ENG for creating a control signal for FES assisted walking for hemiplegics. ALNs and other machine learning techniques have proved to be useful tools to adapt to different types of sensors for gait event detection [2]. ALN is a type of artificial neural network for supervised learning (i.e. it learns from a set of examples containing input and output values). The learning produces a binary decision tree with linear threshold units in its leaves. This technology is known for its speed of execution, insensitivity to input noise, ability to re-train, and the prospect of easy hardware implementation

In this application, the ALN was trained to detect heel strike and heel lift-off by cloning the function of a heel switch as indicated in Fig. 1.

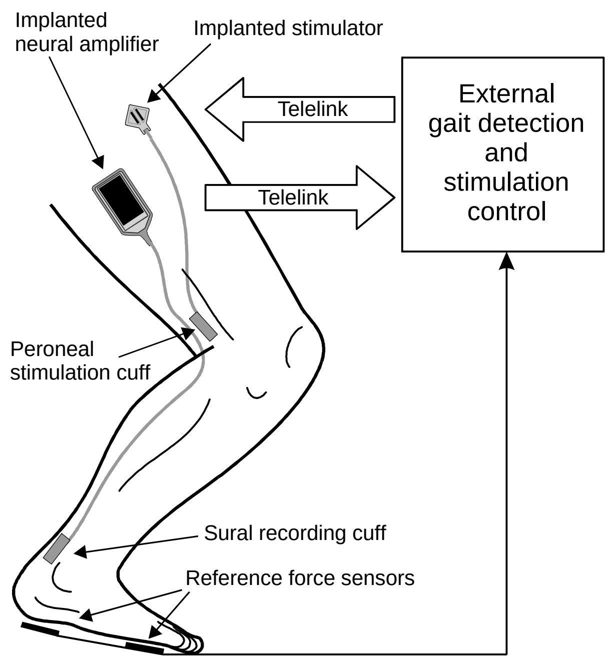

Fig. 1: The setup illustrating the participants left leg with approximate locations of implanted devices. The external unit powers the implanted amplifier and receives the ENG recorded from the Sural nerve cuff, detects gait events using machine learning, and controls stimulation parameters that are relayed to the implanted stimulator.

2. Methods

A 32 year old female participant, five year post stroke with a foot drop, was instrumented with implanted devices for recording sensory neural activity (ENG) and activating the Peroneal nerve for correction of foot drop during gait. A tripolar cuff electrode, 2.8 mm diameter, recording cutaneous activity from the lateral side of the foot sole was inserted on the Sural nerve, through an incision just anterior to the lateral Malleolus. Lead wires were lead subcutaneously across the knee to an implanted neural amplifier located on the lateral side of the upper leg [3]. The implanted amplifier was powered through an external magnetic field, and transmitted the recorded ENG outside the body using frequency modulation. A four channel 12 polar stimulation cuff electrode, 5.8 mm diameter, was inserted on the Common Peroneal nerve through an incision behind the knee. Lead wires were lead subcutaneously to an implanted two-channel stimulator connected to two selected channels in the cuff electrode [4]. An external stimulator controller transmitted pulse width modulated energy bursts to the implanted stimulator selectively for the two channels. The stimulator controller was operated using a digital signal emulating a heel switch, and stimulated the Common Peroneal nerve by ramping up stimulation intensity after a foot lift-off transition, and ramping down the intensity after a heel strike transition. The instrumentation is illustrated in Fig. 1.

During experiments the participant was carrying a hardware processing unit containing filters for minimizing EMG and noise pickup in the ENG signal, bin integrators, and stimulation artifact elimination circuits. The bin integrated (RBI) ENG and signals from two force transducers (force sensitive resistors) were lead to a personal computer through a long cable, allowing the participant to move freely. Stimulator control signals were lead to the participant for full control of the stimulation.

In the control software running on the computer, the RBI ENG was acquired at 100 bins (samples) per second and was further low pass filtered and an 11 dimensional input domain was created by extracting features from the data using several history points. The input domain was used for either training or evaluating the gait event detection algorithms. A target signal meant for training and calculating performance measures was derived from the two force transducers located under the foot sole. All signal processing and feature extracting parameters were optimized for optimal performance.

The software was operated in either training mode or evaluation mode. When in training mode, the stimulation was controlled by the target signal to ensure proper stimulation timing while neural data was recorded. After 15-20 gait cycles, the ALN gait event detector was trained to be able to create a control signal similar to the target signal from the input domain. When in evaluation mode, the stimulation was controlled by the output from the ALN gait event detector while the target signal was used for later calculation of performance measures.

In the detector algorithms a hysteresis threshold was applied to create a binary signal representing either stance or swing phase since the output from the ALN is decimal by nature. To eliminate minor errors in the binary ALN output, we applied restriction rules. We have shown previously that adaptive restriction rules trained on the training data set and evaluated during the real-time use can eliminate critical errors of the control system within certain limitations [5]. In this study we have introduced adaptive restriction rules based on simple fuzzy logic, which gives more flexible error correction and a shorter delay than the restriction rules previously reported on.

In order to investigate the performance and accuracy of the detection, four different tasks were defined to reflect everyday use of a foot drop stimulator; normal gait, normal gait with 5 second stops, walking on stairs, combination of normal gait with 5 second stops and walking on stairs. The participant was performing a task once, equivalent to 15-20 gait cycles, with the software in training mode. After completed training the task would be repeated with twice the number of gait cycles with the software in evaluation mode, evaluating the ALN detector just trained. This was repeated for all tasks twice a week over a period of time to test the day-to-day stability of the detection system. Occasionally ALN detectors previously trained were also evaluated to test the generalization performance of the system. Only preliminary results are reported here as experiments are still in progress.

Two groups of performance measures were utilized to assess the performance of the detection accuracy. Firstly, the percentage of correctly detected samples in the ALN output was calculated. The average delay in the restriction rules and the percentage of correctly detected samples on the restriction rules output taking the delay into account were also calculated. These measures give an impression of the overall performance, from a technical point of view. Secondly, a functional performance was calculated. A window defined around every gait event detected in the target signal, ranging from 100 msec before to 150 msec after the transition, characterized a detected event from the restriction rules output as being correctly timed if inside the window, and incorrectly timed if outside the window. The functional performance referred to the percentage of detected events being correctly timed, and was calculated separately for heel strike and foot lift-off. The number of extra or missing detections was also calculated as percentages of the total number of expected events, and referred to as inclusion and exclusion errors. The specifications of the window characterizing correctly timed transitions were selected to give a functional performance close to 100% for normal gait. This was done, not as an attempt to specify what would be sufficiently precise to control stimulation, but rather as an indication of the accuracy of the detection system in general.

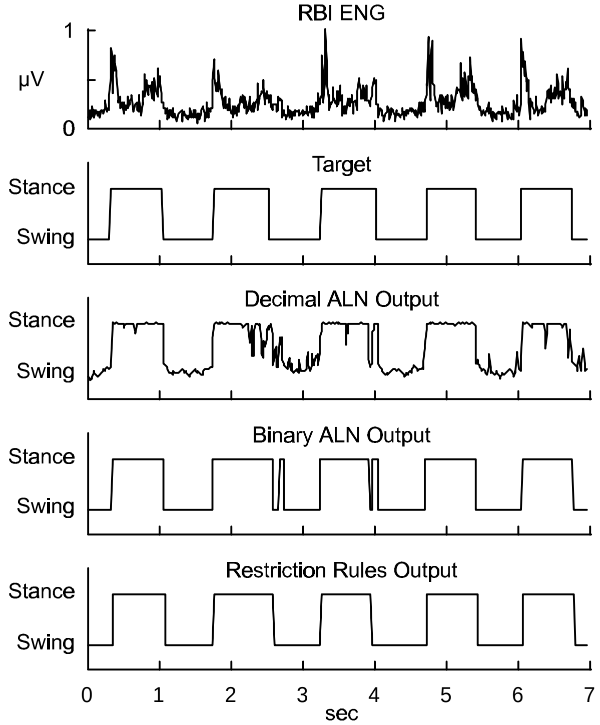

Fig. 2. Data example from a typical evaluation session during normal gait. Top two plots are the raw RBI ENG and the target signal as acquired by the software. Next two plots are the ALN output before and after hysteresis threshold. Bottom plot is the restriction rules output that controls the stimulator.

3. Results

The results presented are based on 6 sessions of plain walking, 4 sessions of walking with stops, and 2 sessions of each staircase climbing and the combined task. Each session consisted of 40-50 gait cycles for all tasks except for staircase climbing, which consisted of about 20-25 gait cycles. Each ALN detector evaluated were trained on a separate data set recorded on the same day. The data presented were recorded on three different days, 309 to 316 days after implanting the cuff electrode.

Fig,. 2. illustrates an example of data from an evaluation session during plain walking. The data example was chosen to reflect typical errors and performance of the detection system. It can be seen that the restriction rules eliminate the two errors by selecting one of two detections rapidly following each other.

As can be seen from Fig. 3, the detection accuracy is highest for plain gait and staircase climbing. For all tasks, applying adaptive restriction rules increased the performance zero to two percent and introduced a 20-30 msec delay on average. From Fig. 4 it can be observed that the detection of heel strike for most task is more precise than the detection of foot lift-off. Note that a performance less than 100% does not indicate that the event was not detected, but only that the event was detected outside the specified time frame. Tasks with an exclusion error larger than zero has missing detections, while inclusion errors false indicate detections of non-existing events.

Preliminary results from studying the generalization

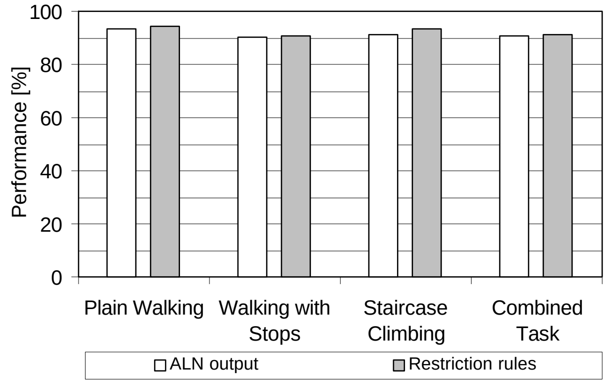

Fig. 3. Performance measured for the binary ALN output and the output of the restriction rules, calculated for each of the four tasks investigated as the percentage of correctly detected samples compared to the recorded target signal (100 Hz sample rate).

properties of the detection system indicate that even an ALN detector trained up to 36 days earlier show no significant reduction in detection performance. This is an important finding since it indicates that the detection system is stable over time, even if not trained recently. This finding is also supported by the day-to-day performance of the detection.

4. Discussion and Conclusion

The foot-drop restoration system is a relatively simple system, but involves many of the principal problems encountered by more complex FES systems. It is also a system that has the potential for success, based on the number of patients who could benefit from an improved system. It is anticipated that the research results will be generally applicable to other types of FES systems and that the potential success of a simple system will facilitate development of more complex systems as well.

We conclude from our work that ALN in conjunction with the signal derived from natural sensors provide a stable control signal for FES assisted walking. This method may very well be suited for the next generation of foot-drop correction units.

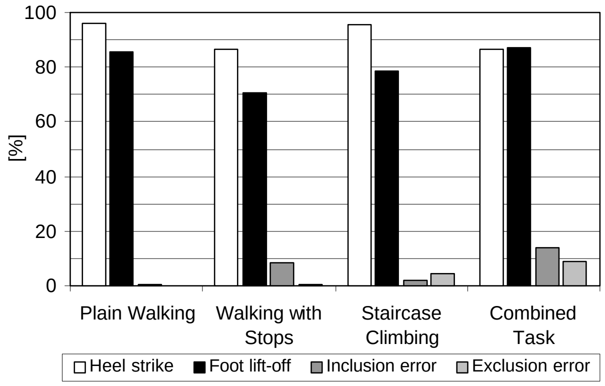

Fig. 4. Functional performance and error measures for the four tasks investigated. The data is based on the same sessions as in Fig. 3.

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