Quantifying Performance of Bipedal Standing with Multi-channel EMG

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Abstract—Recently, spinal cord stimulation has enabled humans with motor complete spinal cord injury (SCI) to independently stand. Quantifying the quality of bipedal standing under spinal stimulation is important for rehabilitation therapies and for new strategies that seek to combine spinal stimulation and rehabilitative robots (such as exoskeletons) in real time feedback. To study the potential for automated electromyography (EMG) analysis in this domain, we evaluated the standing quality of paralyzed patients undergoing electrical spinal cord stimulation using both video and multi-channel surface EMG recordings during spinal stimulation therapy sessions. The quality of standing under different stimulation settings was quantified manually by experienced clinicians. By correlating features of the recorded EMG activity with the expert evaluations of standing, we show that multi-channel EMG recording can provide accurate, fast, and robust estimation for the quality of bipedal standing in spinally stimulated SCI patients. Moreover, our analysis shows that the total number of EMG channels needed to effectively predict standing quality can be significantly reduced while maintaining high estimation accuracy, which provides more flexibility for rehabilitation robotic systems to incorporate EMG recordings. To our knowledge, this paper provides the first study of efficient ways to quantify the performance of bipedal standing of paralyzed patients under spinal stimulation.

I. INTRODUCTION

Spinal Cord Injury (SCI) is a debilitating condition that afflicts ~300,000 people in the U.S., and over 5 million worldwide. Electrical spinal stimulation, using multi-electrode arrays implanted in the epidural space over the lumbosacral spinal cord (as shown in Fig. 1), has recently enabled motor complete paralyzed SCI sufferers to achieve independent weight bearing standing, some weight-assisted stepping, and partial recovery of lost autonomic functions. These preliminary studies have shown that carefully titrated physical therapy must be combined with spinal stimulation to achieve the best functional recovery, and that the stimulating parameters (which combinations of electrodes are activated, as well as their stimulating voltage or current amplitude, and stimulating frequency) which provide the best motor performance can vary substantially across patients. Surface electromyographic (EMG) recordings obtained during training and therapy sessions already play a valuable role in assessing the rate of patient progress under spinal stimulation, as well as the current ad hoc process of optimizing the electrical stimulation therapy for each patient.

This paper presents the first study of surface EMG signals in spinally stimulated SCI patients. A thorough understanding of their properties will benefit many ongoing and future efforts in SCI rehabilitation. We have recently shown how EMG signals can be used with machine learning algorithms to automatically optimize multi-electrode array stimulation parameters [3] in animal models of SCI. Real-time quantification of electrically stimulated standing performance via EMG signals would also enable a feedback signal for the control of rehabilitative robotic devices, such as the Lokomat trainer or exoskeletons, which are coupled with simultaneous spinal stimulation. Recent experiments [6] show that combining both approaches lead to synergistic outcomes.

It should be noted that muscle activity in spinally stimulated standing (SSS) need not be similar to that which would be recorded in healthy human subjects during quiet standing. Comparing to natural standing, SSS has several distinguishing characteristics:

1. SSS is mainly controlled by the activity of the implanted stimulating electrode array, rather than via the action of the patient’s voluntary motor control system.
2. The activity and strength of major muscle groups can be substantially different from the activity and strength under natural healthy standing.
3. Balance is more difficult to achieve in SSS.
4. Common physical measures like center of mass, center of pressure are very dynamic compared to normal standing.

In the human studies, a 16-electrode array (5-6-5 Specify, Medtronic) is implanted for stimulation (Fig. 1). The stimulation is a sequence of electrical pulse trains applied to a set of selected electrodes. The possible stimulus patterns (selected electrodes, their polarity, the pulse amplitude and
width, and the frequency of pulse train) generate a huge space of parameters we can choose from. 12-channel EMG were recorded from key postural muscles while subjects underwent various stimulation patterns.

This work is part of the preliminary study of helping paralyzed patients to stand up via spinal cord stimulation and rehabilitation robotics. In this study, we tested the effectiveness of spinal cord stimulation on a clinically sensory and motor complete participant. It showed that the patient was able to stand over-ground bearing full body-weight without external assistance, only using hands to assist balance. We tested a large number of different stimuli. The qualities of standing are quite different under different stimulating parameters. Currently, the theory on how the muscle activities are supposed to change under spinal stimulation is largely unknown. To our knowledge, this paper is the first attempt to quantify standing performance of SCI patients under epidural stimulation using multi-channel surface EMG. We show that even with a limited number of features and simple linear prediction models, a 12-channel EMG recording can provide accurate, fast and robust estimation for the quality of bipedal standing. We also demonstrate with a Support Vector Machine (SVM) that using a more elaborate feature set can provide fine resolution predictions of standing performance. Moreover, we show through computational analysis that the total number of EMG channels can be significantly reduced while keeping a high accuracy for stand quality estimation. It helps to better understand the motor control mechanisms of SCI patients with spinal cord stimulation. This also suggests the possibility of using EMG to predict standing quality and control robotic prostheses.

II. RELATED WORK

Electrical stimulation can be used in multiple ways to enable or improve motor function in SCI. The data analyzed in this paper is relevant to the process of epidural spinal stimulation for human standing recovery. It has been shown [8] [13] that when properly applied, this type of stimulation can enable paralyzed patients to achieve full weight-bearing standing. The results obtained in this intervention are not derived by direct stimulation of specific postural muscles, but by excitation of natural postural control circuits.

Functional Electrical Stimulation (FES), where electrical currents are applied to the intact peripheral motor nerves of paralyzed muscles to elicit muscle contractions, can provide significant levels of motor function [11]. It is a widely used technique after SCI to enhance muscle strength and movements. EMG signals are used for on-line control of FES [4]. Posture shifting after spinal cord injury using functional neuro-muscular stimulation has been studied in computer simulation [1]. Unlike FES, which has a direct mapping between neuro-muscular stimulation and muscle activity, the mapping between spinal cord stimulation and muscle activity is largely unknown. However, EMG activity is important to the use of both of these electrical stimulation modalities in SCI.

Traditional methods such as time-domain and frequency-domain analyses have been widely utilized in EMG pattern recognition [12] Using EMG to predict movement and control of robotic prostheses has been widely studied, as learning EMG control of a robotic hand [2] or a wrist exoskeleton [9]. EMG signals has also been used to control rehabilitation exoskeleton by paralyzed patients [19], but not under the condition of spinal stimulation.

Biomechanical models are often built to simulate human standing and movement. They range from elegant inverse pendulum models [18], to more complicated musculoskeletal models such as [7], [17], [10]. Biomechanics and motor control of human movement are studied for the understanding of biological mechanisms, the developing of humanoid robots, and the virtual animation of human beings.

Healthy human plans for standing as a single task instead of the coordination of multiple tasks has been considered. The motor control mechanisms of severe SCI patients with spinal cord stimulation is largely unknown.

III. METHODS

A. Human Experiments

A demonstration of the spinally stimulated human stand training experiments with an SCI subject is shown in Fig. 2. The subject practices standing under spinal stimulation using a stand frame for assistance in achieving balance. A specific stimulating pattern is shown in the right part of Fig. 2. Each stimulus is a combination of active electrode selections (red and gray sites), the polarity of the actively selected electrodes (red as anodes and gray as cathodes), and the stimulation amplitude and frequency. Within each experiment, a different stimulus is chosen by an active learning algorithm [16] and applied through the implanted electrode array and its controlling circuitry. Through out the whole experiment, a variety of different stimulating patterns have been tested. The standing quality under stimulation ranged from independent stand to max-assisted standing. Multi-channel EMG signals were recorded and quantitative scores for standing were provided by physicians. A short video in the supplementary materials shows the standing quality under an effective stimulating pattern.

![Fig. 2. The Standing Experiment under spinal stimulation.](image-url)
The participant is under stable medical condition and has no painful musculoskeletal dysfunction that might interfere with stand training. He has no motor response present in leg muscles during transcranial magnetic stimulation, indicating that there are no strongly active neural pathways connecting cortex and lower limb muscles. No volitional control can be achieved during voluntary movement attempts in leg muscles as measured by EMG activity.

A total of 109 experimental trials were done with the same patient. Each trial lasted around 5 minutes. Within each trial, one stimulating pattern was applied to the 16-channel electrode. The patterns were unchanged within each trial. For a fixed stimulating pattern, the stimulation frequency and amplitude were modulated synergistically in order to find the best values for effective weight-bearing standing. Different stimulating patterns were exploited along the trials in order to find the most effective ones. Specific electrode configuration adjustments were defined to seek improvements of different aspects of motor output. The guideline for parameter-tuning is outlined in our previous literature along with results of previous experiments performed on the same research participant. These constraints together with machine learning algorithms built on top of [15] and [16] were used to determine which electrode configurations, out of those potentially available (~4.3 \times 10^7 combinations of electrodes), were to be examined in order to seek improvements of motor function for standing.

All EMG signals were sampled and recorded at 2000 Hz. Signals from right (R) and left (L) gluteus maximus (GL), medial hamstring (MH), vastus lateralis (VL), tibialis anterior (TA), medial gastrocnemius (MG) and soleus (SOL) were recorded by surface EMG electrodes. These 6 muscle groups are widely known to be activated during standing and walking motion.

The patient performed experimental and training sessions for standing using a custom designed standing frame comprised of horizontal bars anterior and lateral to the individual. These bars were used for upper extremity support and balance assistance as needed. If the knees or hips flexed beyond a safe standing posture, external assistance was provided at the knees to promote extension, and at the hips to promote hip extension and anterior tilt. Facilitation was provided either manually by a trainer or by elastic bungee cords, which were attached between the two vertical bars of the standing apparatus. Mirrors were placed in front of the participant and laterally to him, in order to allow a better perception of the body position via visual feedback, conditioned on the lack of proprioceptive sensory feedback.

Stimulation began while the patient was seated. Then the participant initiated the sit to stand transition by positioning his feet shoulder width apart and shifting his weight forward to begin loading the legs. As shown in Fig. 2, the participant used the horizontal bars of the standing apparatus during the transition phase to balance and to partially pull himself into a standing position. Trainers positioned at the pelvis and knees manually assisted as needed during the sit to stand transition.

During sitting, little or negligible EMG activity of lower limb muscles was induced by epidural stimulation, showing that the weight-bearing related sensory information was needed to generate sufficient EMG patterns to effectively support full weight-bearing standing in spinally stimulated SCI.

Table I illustrates how did the clinicians quantify standing quality. Traditional measurements like center of pressure (COP) and center of mass (COM) cannot characterize the standing for paralyzed patients sufficiently. Typically, spinal cord injured patients do not stand and balance like normal subjects. Since there are no widely accepted quantitative measures for standing quality of paralyzed patients, we developed a 1-10 discrete scoring system. From scores 1 to 5, the standing is not independent but with less and less assistance by bungees or trainers. With limited experimental resources, the max/mod/min level of assistance is a robust measure we could get from experienced assisting therapists. From scores 6 to 10 the standing is independent and full-weight bearing. As the score increases, the standing is more natural, stable and lasts a longer time. After every trial, a score on general standing quality was assigned. Both video and multi-channel EMG were recorded during the experiments.

<table>
<thead>
<tr>
<th>Score</th>
<th>Descriptions</th>
</tr>
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<tbody>
<tr>
<td>1-2</td>
<td>Assisted by bungees or trainers (max)</td>
</tr>
<tr>
<td>3-4</td>
<td>Assisted by bungees or trainers (mod)</td>
</tr>
<tr>
<td>5</td>
<td>Assisted by bungees or trainers (min)</td>
</tr>
<tr>
<td>6-7</td>
<td>Hip: Not assisted, back arched</td>
</tr>
<tr>
<td></td>
<td>Knee: Not assisted, loss of extension during shifting</td>
</tr>
<tr>
<td>8-10</td>
<td>Hip: Not assisted, back straight</td>
</tr>
<tr>
<td></td>
<td>Knee: Not assisted, extended during shifting</td>
</tr>
</tbody>
</table>

The research participants signed an informed consent for electrode implantation, stimulation, and physiological monitoring studies approved by the University of Louisville and the University of California, Los Angeles Institutional Review Boards. The individuals in this manuscript have also given written informed consent to publish these case details.

B. Standing Model

Fig. 3 shows the musculoskeletal model of the legs and trunk used in this work. It illustrates the locations of the uniarticular muscle tendon units (MTU) and the joints they actuate. The hip joint is extended by the gluteal muscles (GL) and flexed by the hip flexor muscles (HFL), while the knee joint is extended by the vastus lateralis (VL) and flexed by medial hamstring (MH). The tibialis anterior (TA) and the soleus (SOL) generate dorsiflexion and plantarflexion torques at the ankle, respectively. Medial gastrocnemius (MG) is also taken into consideration. The choice of muscles is based on previous clinical experiments and the planar model proposed in [7].

For the control of standing, this model could be redundant subject to the skeletal constraints. A subgroup of muscles...
\{GL, VL, SOL, TA\} might be enough to keep the standing posture stable. We will experimentally evaluate the redundancy of multi-channel EMG signals for predicting standing quality in Section IV.

\begin{center}
\includegraphics[width=0.5\textwidth]{musculo-skeletal_model.png}
\end{center}

Fig. 3. Musculo-skeletal Model.

C. EMG Processing

**Feature Selection.** The 12-channel EMG signal of one experiment is shown in Fig. 4 for a single trial of the experiment. Traditional methods such as time-domain and frequency-domain analyses have been widely utilized in EMG pattern recognition [12], and they have a good capability to track muscular changes. Other methods like Bayesian estimations [14] and linear filtering also achieves good estimations on muscle forces. We first consider simple and robust linear models with one estimator per channel. For each EMG channel, we calculate the mean power within 50 seconds at the early stage of standing and use it as the only feature for that channel. These 12 features were extracted in each trial and used in LDA and linear regression models for simple and robust predictions.

For the multi-class SVM features selection, we drew inspiration from previous works implementing machine learning techniques to predict forces applied at joints using EMG signals for exoskeleton control [9]. A 4th order Auto-Regressive(AR) model was fit to a 250 ms window of each EMG channel and the four coefficients (excluding the bias) were extracted as features. Thus, for 12-channels, a total of 48 features were extracted per observation. By performing 10-fold cross validation on the optimum number of principal components we reduced the training set to the top 19 dimensions which capture 98\% of the variance. Fig. 5. shows the standing scores plotted against the first three principal components of the SVM training set. Even in 3-dimensions we see a high-degree of separability.

**Model Selection.**

As shown in Table I, the data can be coarsely fit into 2 groups: good performances (not assisted, with score > 5) and bad performances (assisted, with score ≤ 5). We apply linear discriminant analysis (LDA) on the 2-class training data and predict whether a new group of EMG signals represents good or bad standing performance. We further train the kernel-SVM model for better accuracy. The SVM is trained to directly predict the standing quality score by translating the problem to a multi-class classification task with 10 classes (scores 1 – 10). Each standing score corresponds to one class. A radial basis function with a scaling factor \( \gamma = 0.79 \) is used for the SVM kernel and a box constraint level of \( C = 11 \) was used to control the number of support vectors.

To show the robustness of EMG signals, we also estimate the standing quality scores by directly applying linear regression on the scores from physicians v.s. 12-dimension power features.

IV. RESULTS

A. Estimating Standing Qualities

The original 12-channel surface EMG represents 6 muscle groups (GL, VL, MH, TA, MG, SOL) for both legs. For one of the high-quality standing experiments, the EMG waveform is shown in Fig. 4. ‘R GL’ represents right leg muscle GL, etc. The majority of muscles have strong and stationary EMG signals in this case.

We first apply the LDA model with 12-dimension power features as input. The classification of good or bad performances yields to an accuracy at 89.91\%, which is a quite high rate conditioned on the limited number of features and simple LDA model. This classifier is good enough to be used in practice for a fast and robust decision on the quality of standing.

The kernel-SVM model yields 93.9\% classification accuracy on the 10-class discrimination task upon 10-fold cross validation which confirms our belief that EMG signals are accurate predictors of bipedal standing. Moreover, we see that using a more sophisticated model enables us to achieve higher classification accuracy then the linear model even with more classes. From the confusion plot in Fig. 6., we see that most predictions lie within the range of the super diagonals indicating that it is highly unlikely for the SVM to mis-predict a score by a difference greater than 1. The percentages indicate the rate of true positives (white) and false negatives (red). The slots with rates less than 3\% were omitted for succinctness. A standing score of 4 is the most often mis-predicted class due to its similarity with score 5 which can be attributed to the fact that these scores lie on the boundary between the mod and min level of assistance.

To estimate the score for each experiment from EMG features, linear regression is also applied with 12-channel power features as inputs. As shown in Fig. 7, the \( x \)-axis represents true scores and \( y \)-axis measures the estimations by linear regression. The red line represents perfect match \( y = x \). Each dot is represents the true and estimated score of one experiment. The dots would be scattered close to the red line if our estimator is good. Within the 109 experiments, 57.8\% of the estimations are within the region of true score ±1. And 93.6\% of the estimations are within the region of true score ±2. Also 98.2\% of the estimations are within the region of true score ±3. The standard deviation of estimating errors is 1.19, which is quite small comparing to the 1-10 scoring range.
B. Reducing EMG Channels

Although more channels provide better estimation in general, in practice we may not have the access to as many channels for all experiments. Also, fewer channels makes experiments efficient in time and budget. We investigate the possibility to reduce the number of EMG channels while keeping a high accuracy rate.

To choose the optimal $k \in \{1, 2, 3, 4, 5, 6\}$ sub-groups of muscles from the existing 6 muscle groups, we evaluate the classification/regression performance of the total $\binom{6}{k}$ muscle combinations. The optimal combination of muscle groups for each $k$ is shown in Table II. The single best muscle group for prediction is soleus (SOL).

Notice, this reduction process is different from principal component analysis (PCA) which reduces the feature space by picking the top independent components. Our approach aims at achieving good classification/regression by using fewer number of EMG channels. The chosen EMG channels
TABLE III
THE ACCURACIES WITH REDUCING CHANNELS

<table>
<thead>
<tr>
<th>Channels v.s. Accuracies</th>
<th>LDA(2-class)</th>
<th>SVM(10-class)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL, VL, MH, TA, MG, SOL</td>
<td>89.91%</td>
<td>93.9%</td>
</tr>
<tr>
<td>VL, MH, TA, MG, SOL</td>
<td>88.91%</td>
<td>93.6%</td>
</tr>
<tr>
<td>VL, TA, MG, SOL</td>
<td>88.07%</td>
<td>93.0%</td>
</tr>
<tr>
<td>VL, MH, SOL</td>
<td>87.16%</td>
<td>92.7%</td>
</tr>
<tr>
<td>VL, SOL</td>
<td>87.16%</td>
<td>89.5%</td>
</tr>
<tr>
<td>SOL</td>
<td>80.73%</td>
<td>63.5%</td>
</tr>
</tbody>
</table>

The performances of reducing EMG channels were experimentally evaluated, which confirms that the 12-channel EMG signals are highly redundant for predicting standing quality. We show the optimal combinations with high accuracy and this performance can be maintained at a high level even with quite few channels. This fact is contradicting to our initial assumption of multiple muscle group coordination and no dominant component. However, we still believe that better estimation for the standing quality requires recording from larger number of muscle groups.

There are multiple ways to improve the accuracy of the predictions. We have already demonstrated that using more elaborate features with a SVM allows us to achieve high prediction accuracy even for the multi-class problem. Including even more features from raw EMG signals and using finer picked/tuned models is one venue for improvement. As mentioned in Section I, the activity and strength of major muscle groups can be very different from the activity and strength under natural standing. Usually, it contains an early response strongly modulated by the electrical stimulation and a late response which is more like the EMG patterns from healthy subjects. Separating these two stages for feature extraction should also improve the predictability. Under a budget constraint on the number of channels, asymmetric placement of EMG sensors on left and right legs could also improve the accuracy assuming the stimulation effects equally for the two sides. We could also consider adding more physical measurements for prediction conditioned on the experimental environments.

In general, our estimators can provide reliable scores on the quality of patient standing when experienced physicians are not available during experiments.

B. Sensor Placement Efficiency

We have shown the optimal EMG channel combination subject to a budget constraint on the number of channels. What if we have more EMG sensors to place? Previous research [5] suggested that the prime muscle targets should be a set of $8 \times 2$ muscles supports 42% of the standing postures. Coactivation of an extra $4 \times 2$ muscles increased the percentage of feasible postures to 71%. We can sample hands to assist balance. We demonstrate a musculo-skeletal model containing the major muscle groups that are involved in stable standing and use it to explain the feasibility of reducing EMG channels.

V. CONCLUSIONS AND DISCUSSIONS

A. Predictions

In this paper, we show that multi-channel EMG recording can provide accurate, fast and robust estimation for the quality of bipedal standing under spinal stimulation. We tested the effectiveness of spinal cord stimulation on a clinically sensory and motor complete participant. It showed that the patient was able to stand over-ground bearing full body-weight without any external assistance, using their muscle groups.

Table III shows the optimal classification results with different number of muscle groups (channels) with 2-class LDA classification and 10-class SVM classification. For both models, the accuracy is slowly decreasing as the number of chosen muscle groups ($k$) decreases from $k = 6$ to $k = 2$. A quite high accuracy of 87.16% (for LDA, and 89.5% for SVM) is maintained even at $k = 2$. The muscle groups vastus lateralis (VL) and soleus (SOL) are the optimal combination for $k = 2$. One of them (SOL) is ankle flexor and the other (VL) is knee extensor as shown in 3. The accuracies drop significantly from $k = 2$ to $k = 1$. This makes sense since at least 2 actuators are needed to control the 2 degrees of freedom. As a 2-class classification, LDA keeps a higher accuracy rate than SVM at $k = 1$.

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The performances of reducing EMG channels were experimentally evaluated, which confirms that the 12-channel EMG signals are highly redundant for predicting standing quality. We show the optimal combinations with high accuracy and this performance can be maintained at a high level even with quite few channels. This fact is contradicting to our initial assumption of multiple muscle group coordination and no dominant component. However, we still believe that better estimation for the standing quality requires recording from larger number of muscle groups.

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from this larger space and it may reduce to a better group of 12 channels than the current 12 channels.

C. Combining with Exoskeleton

A large group of people including spinal cord injured patients often need rehabilitation robotic systems to provide functional gait therapies or assist their standing and moving. Current assistive standing systems rarely takes feedback other than direct force measurements from users. The automatic approach to quantify the quality of bipedal standing by EMG could provide estimation of standing quality to the assistive systems for better standing control. More efficient gait therapies and movement control could be achieved by incorporating EMG measures into the rehabilitation robotic systems.

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