

Functional Electrical Stimulation Capability Maps

Eric M. Schearer and Derek N. Wolf

Abstract—We introduce capability maps visualizing the abilities of the arm of a person with a cervical spinal cord injury activated by functional electrical stimulation (FES). We map the arm’s workspace at different wrist positions using a person-specific arm model based on force data gathered during interactions with a robot. We describe four maps: 1) a map of the maximum force the person can produce in one direction, 2) a map of wrist configurations that FES can hold against gravity and other passive forces, 3) a map of the maximum force the person can apply in all directions, and 4) a map of the directions the arm can move with FES. To demonstrate these maps we applied electrical stimulation to nine muscle groups of a person with high tetraplegia, measured the resulting force with a robot attached to the person’s wrist, created a Gaussian process regression model relating the forces to the wrist positions, and used this model to create the four capability maps. The results are 2D images displaying the arm’s force production and movement capabilities for a person with high tetraplegia as a function of wrist position. As these maps predict functional benefits of specific interventions, they can reduce risk in developing new interventions to restore function to people with whole-arm paralysis.

I. INTRODUCTION

The main rehabilitation priority for people with tetraplegia is the restoration of arm and hand function [1]. Arm and hand functions are critical to activities of daily living that allow a person to live independently. These activities include getting dressed, cooking, eating, bathing, and grooming.

Neuroprostheses using FES are a promising avenue to restore arm and hand functions. Neuroprostheses have restored grasping to many people with spinal cord injuries who have volitional control of their shoulders and elbows [2], but success has been limited for people with higher-level spinal cord injuries who do not have volitional control or their shoulders or elbows. Very few FES neuroprostheses have demonstrated control of shoulder, elbow, and hand movements in people with high tetraplegia [3] [4] [5], but these systems are not versatile or robust and have not restored arm and hand function to people with high tetraplegia for everyday use.

It is difficult to predict what functions an FES neuroprosthesis can restore to a specific person with high tetraplegia. First, the number and extent to which muscles are denervated and unresponsive to FES due to lower motor neuron damage [6] [7] is heterogeneous. Further, as reaching motions in-

volve complex coordination of multiple muscles, predicting functional capabilities restored by an FES neuroprosthesis is difficult even if all muscles are innervated and have full strength.

This uncertainty along with surgical risks in implanting a neuroprosthesis greatly limits progress in developing neuroprostheses for people with high tetraplegia. With high uncertainty in functional recovery, a prospective participant is unlikely to risk having a neuroprosthesis implanted. Even after implantation, finding physically achievable movements is challenging [8] and much time and effort can be wasted with an exhaustive trial-and-error search. Knowing a priori what functional capabilities a neuroprosthesis can restore would greatly reduce the barriers preventing the development of neuroprostheses for high tetraplegia.

Computer simulation [9] and lower motor neuron damage screening [10] are insufficient to predict functional recovery. Computer simulations, although they capture muscle interactions across multiple joints, are not person specific and do not represent denervation and atrophy in specific people with high tetraplegia, which is a heterogeneous population [7]. Checking individual muscles for lower motor neuron damage is person-specific but does not predict the achievable workspace, hand forces, or specific functions that might be restored with FES. These screenings can not predict the effects of muscle strengthening, a powered orthosis, or some other intervention to supplement FES. In practice, very few people – those with a plurality of muscles responsive to FES – are deemed suitable neuroprosthesis users. If state-specific shortcomings of FES could be identified for individual persons, many more people could be suitable users of neuroprostheses combining FES and some other intervention.

To ease FES neuroprostheses development for high tetraplegia, we aim to make person-specific predictions of functional capabilities of specific neuroprostheses. These predictions could aid in person-specific muscle selection for a neuroprosthesis and in designing assistive devices to augment FES. We could efficiently plan tests demonstrating physically realizable capabilities for a specific person, rather than wasting time and resources to demonstrate physically impossible movements.

This paper’s objective, which moves toward this aim, is to introduce FES capability maps which predict the reaching capabilities of a person with high tetraplegia using an FES neuroprosthesis. We present the technical details of four types of capability maps 1) maximum force maps, which predict the maximum force a person can exert in one particular direction at each hand position, 2) holdability maps, which predict arm configurations a person can hold with

This work was supported by NIH NINDS grant N01-NS-5-2365, VA grant B2359-C, and NSF grant 1751821.

E. M. Schearer and D. N. Wolf are with the Center for Human Machine Systems, Cleveland State University and the Cleveland Functional Electrical Stimulation Center, Cleveland, OH USA {e.schearer@csuohio.edu, d.n.wolf@vikes.csuohio.edu,}



Fig. 1. Instrumentation for experiments. Pictured is the participant's right arm. Shown in (a) and (b) are the placement of reflective markers for optical tracking, a passive arm support providing supporting force, and the robot that drives the participant's wrist to 27 positions in the participant's workspace. The participant's wrist and distal forearm (c) are in a soft cast that is attached via a magnet to a ball-and-socket joint at the end effector of the HapticMaster robot.

FES, 3) strength maps, which predict the magnitude force a person can exert in all directions at each hand position, and 4) movability maps, which predict the directions a person can move her hand from each hand position. We present how we derive capability maps from experiments with a human participant with high tetraplegia.

II. METHODS

Capability maps are derived from a person-specific model of the arm's response to electrical stimulation. We describe each of the four types of capability maps and how we gather data to learn the person-specific model from which the maps are derived. The four capability maps – the maximum force map, the holdability map, the strength map, and the movability map – are graphical representations of the static capabilities of the arm of a person with high tetraplegia that can be actuated by functional electrical stimulation.

We mapped the capabilities of a single human participant with high tetraplegia who has an implanted neuroprosthesis [11] [12] that can electrically stimulate her paralyzed muscles to move her right arm. The participant sustained a hemisection of the spinal cord at the C1-C2 level from a gunshot wound. She is unable to move her right arm but does have sensation. She experiences hypertonia in some arm muscles. The participant's wheelchair is equipped with a passive arm support to assist against gravity. As is typical of people with high tetraplegia, without this arm support she has essentially zero capability to hold static arm positions even with FES.

In this experiment, the neuroprosthesis stimulated nine muscle groups – triceps, deltoids, latissimus dorsi, serratus anterior, biceps/brachialis, supraspinatus/infraspinatus, rhomboids, lower pectoralis, and upper pectoralis – via nerve cuff [13] and intramuscular [14] electrodes. Stimulation used bi-phasic, charge balanced pulses delivered at 13 Hz. The amplitude of the pulses for each muscle group was chosen to produce as large a force response as possible while not causing the participant to feel pain. The force generated by each muscle group was controlled by varying the pulse-width from 0-250 μ s. Protocols used for this research were approved by the institutional review boards at Cleveland State University (IRB NO. 30213-SCH-HS) and MetroHealth Medical Center (IRB NO. 04-00014).

Data from which to learn models of the response of the participant's arm to electrical stimulation were collected by gathering force and position data as the person's wrist was moved to and held in various static positions by a HapticMaster (Moog FCS) robot while her muscles were stimulated (Fig. 1). The models and identification procedure are described fully in [15] [16]. The robot's force sensor reports the force required to hold the wrist at a given position, and an Optotrak Certus Motion Capture System (Northern Digital, Inc.) determines the position and orientation of the participant's wrist relative to her thorax. The input to the models – called the arm/wrist configuration – is the wrist position in Cartesian space and wrist orientation represented by a quaternion. The models' output is the 3D force applied by the robot to hold the arm/wrist configuration.

In a single experimental session we collected force and arm/wrist configuration data at 27 different wrist positions within the participant's range of motion. At each wrist position we stimulated each of the nine muscle groups, recording the steady-state force exerted by the robot to hold the position along with the arm/wrist configuration. We also recorded the force and arm/wrist configuration when no muscle groups were stimulated. We randomized the order of muscle groups stimulated and wrist positions visited. We completed three sets of stimulating each muscle group at each wrist position according to the time available during the four-hour session.

With the force and arm/wrist configuration data, we used Gaussian process regression to predict forces at the wrist as a function of arm/wrist configuration. Gaussian process regression predicts both the force at the wrist required to hold a configuration when no muscles are stimulated and the forces required to hold a configuration when a specific muscle group is stimulated. The difference between these two predictions is the amount of force a given muscle group can contribute at each configuration.

Based on these muscle force production predictions throughout the participant's workspace, we derive the maximum force, holdability, strength, and movability at each arm/wrist configuration. The maximum force map (Fig. 2A) plots the maximum force in any particular direction that a person can apply at the wrist when stimulating the person's

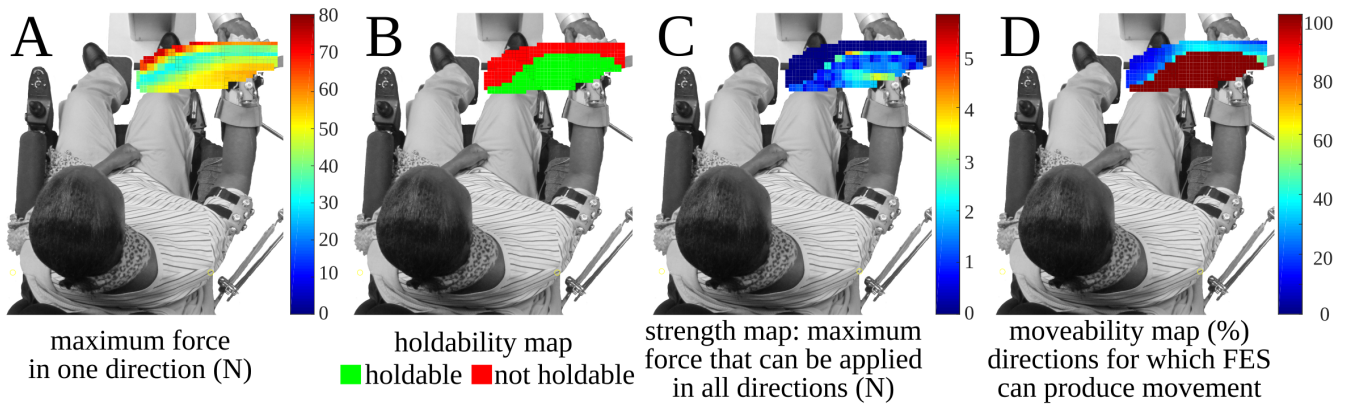


Fig. 2. Cross sections of capability maps: maximum force in Newtons (A), holdability (B), strength in Newtons (C), and movability in % of directions (D) of a participant with high tetraplegia and an implanted FES neuroprosthesis. These horizontal cross sections are shown from above approximately 2 cm below shoulder height. These maps are a snapshot of the person’s capabilities on a particular day.

muscles. The holdability map (Fig. 2B) indicates which wrist positions are achievable given the force required to hold that position and the forces that the muscles are able to produce. If it is possible to move a person’s wrist to a particular position and the person’s muscles are capable of producing the forces required to hold that wrist position, that wrist position is holdable (green in Fig. 2B), otherwise, that wrist position is not holdable (red in Fig. 2B). The strength map (Fig. 2C) plots the magnitude force that the person’s arm can apply at the wrist in all directions via FES. The movability map (Fig. 2D) is a plot of the fraction of directions for which the muscles can produce force for a given wrist position. We call this the movability map because we assume that applying a static force in a given direction is analogous to producing a movement in that direction. Capability maps are shown in 2D slices of a 3D grid with 6 mm discretization.

III. RESULTS

We present the capability maps of the arm of a person with a high cervical spinal cord injury. These maps represent the ability of the participant’s FES neuroprosthesis to produce force and motion at different places in her hand’s workspace.

The maximum force map (Fig. 2A) displays the maximum force the person can apply with FES in a single direction. In general the person cannot apply this maximum magnitude force in other directions. The highest magnitude forces – 70-80 N – are on the boundary of her reachable workspace (red in Fig. 2A). These maximum forces are inward toward her body (direction not shown) as both her arm support and her biceps/brachialis muscle group pull her hand inward. Maximum forces in the area of her workspace that are holdable (green in Fig. 2B) are 50-60 N. These forces (yellow in Fig. 2A) are generally outward as her triceps muscle group is strong relative to other muscle groups.

The holdability map (Fig. 2B) displays green if the participant’s muscles can produce enough force to hold the arm/wrist configuration against the passive stiffness of her arm and the arm support. Otherwise it displays red. Besides vertical support, the arm support tends to pull the hand toward a central equilibrium location in the horizontal plane.

This person has a limited volume of holdable positions, namely those closer to the participant and to the right. The participant is unable to overcome the inward pull of the arm support for the more distal arm/wrist configurations. Her pectoralis muscles are unable to produce enough force to hold positions further to the participant’s left.

The strength map (Fig. 2C) displays the largest force that the person can apply in all directions. Note that the person has zero strength (dark blue in Fig. 2C) for non-holdable arm positions (red in Fig. 2B). This is because she can not produce a force in all directions at these arm/wrist configurations. At holdable arm/wrist configurations her strength in all directions is only 2-4 N, much smaller than the maximum force in a single direction.

The movability map (Fig. 2D) displays the percentage of 3D directions for which the participant’s muscles can produce force and hence motion. The participant can produce force in all directions (dark red in Fig. 2D) for holdable arm/wrist configurations (green in Fig. 2C) except those on the boundary of the holdable region. At non-holdable arm/wrist configurations movability is less than 100% – around 40% near the boundary of the holdable region. At these non-holdable configurations, the participant can produce forces toward the holdable configurations.

Note that the individual capability maps are interrelated. Arm/wrist configurations that are holdable have non-zero strength and 100% movability. Arm/wrist configurations that are not holdable have zero strength and movability less than 100%. The strength map continuously quantifies force production capability at holdable configurations. The movability map continuously quantifies capabilities at non-holdable configurations. The maximum force map communicates force production capabilities that are available in one direction rather than all directions.

IV. DISCUSSION

We presented the concept of capability maps and demonstrated their derivation and display for a person with high tetraplegia who uses an FES neuroprosthesis to produce arm movements. Capability maps show the ability of that person’s

shoulder and arm muscles to produce forces at the wrist at each location in the person's workspace. This allows us to determine in which directions a combination of muscles can produce movement, how large a force the muscles can produce, and whether the muscles can overcome passive forces to hold an arm/wrist configuration.

The work we presented is a limited first demonstration of capability maps. The work was done with a single participant who has a rather small range of motion due to hypertonia. We intend to further develop capability maps with more human participants with high tetraplegia who have a wider range of capabilities. We will validate capability maps by using an FES controller to produce forces in each direction at different arm/wrist configurations and comparing these actual forces to those predicted by the capability maps.

The idea of examining the effects of specific muscle groups on capability is not new, as researchers have previously developed similar theory [17], used computer models to identify important muscle groups for standing posture [18] and more recently for arm movements [9]. The innovation in the work presented in this paper is that we can map the capabilities of specific people rather than of computer or theoretical models.

In our current research we use capability maps to plan experiments in the development of FES controllers to produce functional reaching movements. Capability maps tell us which arm/wrist configurations to target and which to avoid on a given day of experiments. They also suggest that we might adjust the stiffness of the person's arm support to expand the arm/wrist configurations at which the person can produce significant force. The output of a complex combination of muscle actions changes from day to day with the condition of the person with the spinal cord injury. Being able to predict these outputs saves significant time we previously spent on experiments with goals that were impossible given a person's muscles on a given day.

We intend capability maps to become a powerful tool in predicting outcomes of different interventions at a very early stage in the rehabilitation of people with high tetraplegia. Currently it is very difficult to predict the outcome of an intervention at an early stage. This discourages clinicians and engineers from trying interventions that can have the largest functional impact but come with significant risk such as a surgically implanted neuroprosthesis. Capability maps could also guide the selection of a combination of interventions (e.g. a powered orthosis and FES) that together restore significant function. Further development of capability maps may allow for actually predicting future functional outcome measures such as the Capabilities of Upper Extremity Test [19] that result from a specific intervention.

REFERENCES

- [1] K. D. Anderson, "Targeting recovery: Priorities of the spinal cord-injured population," *Journal of Neurotrauma*, vol. 21, no. 10, pp. 1371–1383, 2004.
- [2] P. H. Peckham, M. W. Keith, K. L. Kilgore, J. H. Grill, K. S. Wuolle, G. B. Thrope, P. Gorman, J. Hobby, M. Mulcahey, S. Carroll *et al.*, "Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study," *Archives of physical medicine and rehabilitation*, vol. 82, no. 10, pp. 1380–1388, 2001.
- [3] A. B. Ajiboye, F. R. Willett, D. R. Young, W. D. Memberg, B. A. Murphy, J. P. Miller, B. L. Walter, J. A. Sweet, H. A. Hoyer, M. W. Keith *et al.*, "Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: a proof-of-concept demonstration," *The Lancet*, vol. 389, no. 10081, pp. 1821–1830, 2017.
- [4] W. D. Memberg, K. H. Polasek, R. L. Hart, A. M. Bryden, K. L. Kilgore, G. A. Nemunaitis, H. A. Hoyer, M. W. Keith, and R. F. Kirsch, "Implanted neuroprosthesis for restoring arm and hand function in people with high level tetraplegia," *Archives of Physical Medicine and Rehabilitation*, vol. 95, no. 6, pp. 1201–1211, 2014.
- [5] A. Pedrocchi, S. Ferrante, E. Ambrosini, M. Gandolla, C. Casellato, T. Schauer, C. Klauer, J. Pascual, C. Vidaurre, M. Gföhler *et al.*, "MUNDUS project: MULTimodal Neuroprosthesis for daily Upper limb Support," *Journal of NeuroEngineering and Rehabilitation*, vol. 10, no. 1, pp. 1–20, 2013.
- [6] P. Peckham, J. Mortimer, and E. Marsolais, "Upper and lower motor neuron lesions in the upper extremity muscles of tetraplegics," *Spinal Cord*, vol. 14, no. 2, pp. 115–121, 1976.
- [7] M. Mulcahey, B. Smith, and R. Betz, "Evaluation of the lower motor neuron integrity of upper extremity muscles in high level spinal cord injury," *Spinal Cord*, vol. 37, no. 8, p. 585, 1999.
- [8] E. M. Scheerer, Y. Liao, E. J. Perreault, M. C. Tresch, W. D. Memberg, R. F. Kirsch, and K. M. Lynch, "Evaluation of a semiparametric model for high-dimensional FES control," in *7th International IEEE EMBS Conference on Neural Engineering*, 2015, pp. 304–307.
- [9] D. Blana, J. G. Hincapié, E. K. Chadwick, and R. F. Kirsch, "Selection of muscle and nerve-cuff electrodes for neuroprostheses using customizable musculoskeletal model," *Journal of Rehabilitation Research & Development*, vol. 50, no. 3, pp. 395–408, 2013.
- [10] A. M. Bryden, H. A. Hoyer, M. W. Keith, M. Mejia, K. L. Kilgore, and G. A. Nemunaitis, "Upper extremity assessment in tetraplegia: the importance of differentiating between upper and lower motor neuron paralysis," *Archives of physical medicine and rehabilitation*, vol. 97, no. 6, pp. S97–S104, 2016.
- [11] B. Smith, Z. Tang, M. W. Johnson, S. Pourmehdi, M. M. Gazdik, J. R. Buckett, and P. H. Peckham, "An externally powered, multichannel, implantable stimulator-telemeter for control of paralyzed muscle," *IEEE Transactions on Biomedical Engineering*, vol. 45, no. 4, pp. 463–475, 1998.
- [12] R. L. Hart, N. Bhadra, F. W. Montague, K. L. Kilgore, and P. H. Peckham, "Design and testing of an advanced implantable neuroprosthesis with myoelectric control," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 19, no. 1, pp. 45–53, 2011.
- [13] G. G. Naples and J. T. Mortimer, "A spiral nerve cuff electrode for peripheral nerve stimulation," *IEEE Transactions on Biomedical Engineering*, vol. 35, no. 11, pp. 905–916, 1988.
- [14] W. D. Memberg, P. H. Peckham, and M. W. Keith, "A surgically-implanted intramuscular electrode for and implantable neuromuscular stimulation system," *IEEE Transactions on Rehabilitation Engineering*, vol. 2, no. 2, pp. 80–91, 1994.
- [15] E. M. Scheerer, Y. Liao, E. J. Perreault, M. C. Tresch, W. D. Memberg, R. F. Kirsch, and K. M. Lynch, "Semiparametric identification of human arm dynamics for flexible control of a functional electrical stimulation neuroprosthesis," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 12, pp. 1405–1415, 2016.
- [16] D. N. Wolf and E. M. Scheerer, "Holding static arm configurations with functional electrical stimulation: A case study," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 10, pp. 2044–2052, 2018.
- [17] F. J. Valero-Cuevas, "A mathematical approach to the mechanical capabilities of limbs and fingers," in *Progress in motor control*. Springer, 2009, pp. 619–633.
- [18] A. D. Kuo and F. E. Zajac, "A biomechanical analysis of muscle strength as a limiting factor in standing posture," *Journal of Biomechanics*, vol. 26, pp. 137–150, 1993.
- [19] R. J. Marino, J. A. Shea, and M. G. Stineman, "The capabilities of upper extremity instrument: reliability and validity of a measure of functional limitation in tetraplegia," *Archives of physical medicine and rehabilitation*, vol. 79, no. 12, pp. 1512–1521, 1998.