Does a Unilateral Reduction in Muscle Synergies Lead to Alterations in Gait Post Stroke?

Marleny Arones[1], Carolynn Patten[2] and Benjamin J. Fregly[1]

[1]Department of Mechanical Engineering, Rice University, United States [2]Department of Physical Medicine and Rehabilitation, Rice University, United States
Email: ma86@rice.edu, Web: http://rcnl.rice.edu/

INTRODUCTION

Muscle synergies may provide a helpful avenue for predicting patient function following clinical interventions, such as those arising from neurorehabilitation or orthopedic surgery. Theoretically, muscle synergies reduce the achievable control space making predicted muscle forces and consequently predicted motions more unique. In individual's post stroke, a reduced number of muscle synergies has been associated with a deterioration in walking function [1]. However, whether the degeneration in walking function is a direct result of reduced muscle synergies remains unknown.

Computational walking models coupled with optimal control provide an opportunity to test hypotheses that would otherwise be difficult or impossible to evaluate experimentally. This study aims to study the effect of reducing the complexity of locomotor control of one leg on a subject's walking function. Therefore, we predicted that differences in the number of muscle synergies assigned to one leg would be associated with differences in neuromusculoskeletal quantities.

METHODS

This study analyzed walking data collected previously from a male subject post-stroke. All experimental procedures were approved by the University of Florida Health Science Center Institutional Review Board (IRB-01), and the subject provided written informed consent prior to participation. Motion capture (Vicon Corp), ground reaction (Bertec Corp), and electromyography (EMG) data (Motion Lab Systems) were collected simultaneously from the subject as he walked on a split-belt instrumented treadmill (Bertec Corp) at his self-selected speed.

The subject's neurophysiological and musculoskeletal components were taken into account using OpenSim (v3.3; [2]) and Matlab to develop four different modeling elements: a kinematic model, an EMG-driven calibration model, a foot-ground contact model, and a motion prediction model using the concept of muscle synergies. More specifically, the synergy-driven control model was calibrated using the subject's self-selected speed of 0.5 m/s using five-synergy activations per leg to track the following quantities: ground reaction forces, joint moments, joint angles, and muscle activations; see [3] for details. The subject-specific neuromusculoskeletal model was used to develop two predictions for how the subject would walk after the number of synergies controlling his paretic leg was reduced from the calibrated case of five down to two. In the first optimization, the two paretic leg synergy activations and vectors were free to vary. In the second optimization, the two paretic leg synergy vectors were constrained to be a linear combination of the original five paretic leg synergy vectors. Additionally, deviations of the two paretic leg synergy activations away from a linear combination of the original five paretic leg synergy activations were minimized. During both predictions, the five synergy vectors for the healthy leg were fixed to those found during model calibration. Changes in the five healthy leg synergy activations away from the original five healthy leg synergy activations were also minimized.

The following parameters were analyzed after each prediction optimization: joint angles, joint moments, ground reaction forces and muscle activations. The NRMSE (Normalized Root Mean Square Error) values between the calibration and prediction results were calculated by normalizing each quantity by its range to identify what differences, if any, were observed and where.

RESULTS AND DISCUSSION

When predicting a new walking motion using two unconstrained synergies to control the paretic leg, we found minimal differences compared to walking controlled by five synergies (Fig. 1). There were no large differences between the five- and two-synergy solutions when looking at the joint moments (NRMSE <14%) and ground reaction forces (NRMSE <15%) for both legs. In contrast, predicted muscle activations showed large changes for the paretic leg (NRMSE=33%) but not the non-paretic leg (NRMSE=11.8%) (Table 1). Additionally, the stride length did not exhibit a large change (6.93% error) (Table 2).
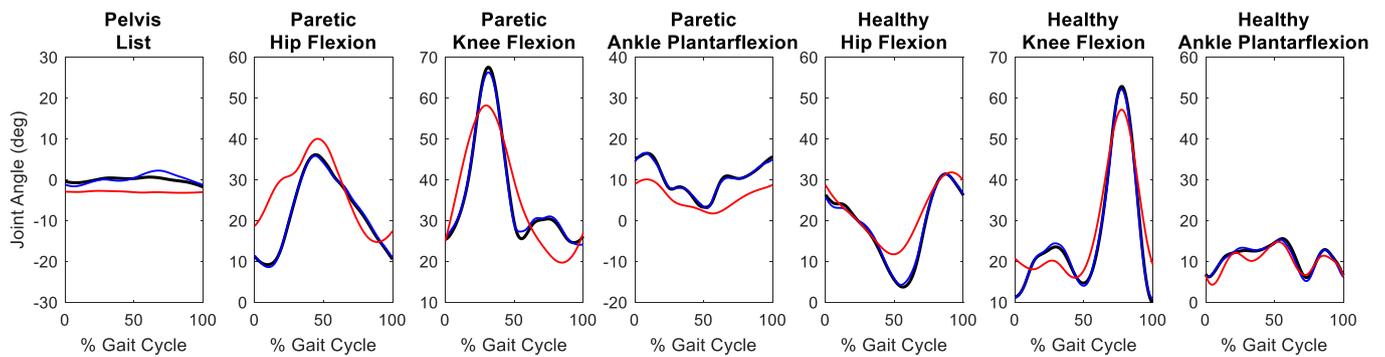
Figure 1| Comparison of joint angles produced between the different control strategies: five synergies (black), two synergies (blue), and two constrained synergies (red).

Table 1| The average NRMSE of the muscle activations, joint moments, and ground reaction forces predicted by the model in comparison to the calibration quantities

	Muscle Activations	Joint Moments	Ground Reaction Forces
Two-synergy prediction unconstrained			
Paretic Leg	0.330	0.135	0.154
Healthy Leg	0.118	0.109	0.118
Two-synergy prediction constrained			
Paretic Leg	3.081	0.411	0.255
Healthy Leg	0.145	0.171	0.139

When predicting a new walking motion using two constrained synergies to control the paretic leg, we found clear differences in joint angles compared to walking controlled by five synergies (Fig. 1). A large difference was also observed for muscle activations (NRMSE = 308.1%) and joint moments (NRMSE = 41.1%) produced by the paretic leg (Table 1). The optimization predicted hip hiking and a foot drop of the paretic leg along with a significant decrease in stride length (29.1% error), which can be directly associated with a degradation of walking performance (Table 2).

Table 2| Comparison of stride length between the calibration and predicted walking motions

	Stride Length (m)
Five-synergy calibration	0.701
Two-synergy prediction unconstrained	0.653
Two-synergy prediction constrained	0.497

Our results support the findings from Clark et al. (2010) [1] who hypothesized that the impairment of locomotor coordination may correspond to the reduction in complexity of locomotor control. Our findings clarify that the reduction in synergies alone does not result in significant deterioration of walking performance. However, a reduction in synergies when constrained to be a linear combination of the original synergies does result in poorer walking performance.

Although our synergy-driven model predicts realistic walking motions, an important limitation of our simulation framework is that there is no enforcement of smoothness when generating muscle activations, which may be the reason why the two-synergy prediction is able to closely reproduce the walking gait generated by that of the five-synergy solution. Since the two constrained synergy model must be created from a linear combination, it doesn't have the same level of freedom to instantaneously vary the muscle activations resulting in the smaller NRMSE of the muscle activations for the two-synergy paretic leg compared to the two constrained synergy error (Table 1).

CONCLUSIONS
Our findings suggest that a less complex neural control structure need not cause impaired walking but rather that walking impairments may be the result of limitations in the formation of the less complex synergies.

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