Exoskeleton Design using Subject-specific Synergy-driven Neuromusculoskeletal Models

Marleny Arones, Josep M. Font-Llagunes, and Benjamin J. Fregly

***Abstract*—Most assistive devices available today are unable to improve gait asymmetries due to the lack of knowledge on how to directly enforce kinematic symmetry in the formulation of cost functions. We designed a cost function to potentially target kinematic symmetry, and observed improvements in gait asymmetries specifically at the hip and ankle.**

I. Introduction

WALKING asymmetry is generally a main concern in gait impairments experienced by amputees, post-stroke patients, and the elderly [1]. Therefore, many rehabilitation programs measure gait asymmetry to evaluate the effectiveness of rehabilitation treatments [2]. While many assistive devices have been proposed to improve gait symmetry, the devices currently available are geared towards reducing metabolic cost, gait training and performance enhancement [3]. This discrepancy may be due to a lack of knowledge on how to directly target kinematic symmetry in design formulation and optimization.

This study predicted the assistive joint moments needed to improve walking asymmetry and thus walking function. An improvement in walking function was quantified by calculating changes in metabolic cost and spatiotemporal symmetry measures.

II. Methods

This study analyzed data from previously collected walking trials from a high functioning male subject suffering from stroke walking dysfunctions. 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 neuromusculoskeletal components were represented using four modeling elements: a kinematic model, an EMG-driven model, a foot-ground contact model, and a motion prediction model using the concept of muscle synergies; see [4] for more details. Originally, the subject-specific neuromusculoskeletal model was calibrated using five muscle synergies per leg. However, this study used the subject-specific neuromusculoskeletal model with two muscle synergies controlling the paretic leg and five muscle synergies controlling the non-paretic leg, which produced a deteriorated walking motion [5].

An optimization was developed within Matlab and GPOPS-II, a direct collocation optimal control software [6], to find ideal joint moment loads that would allow the walking function of the model to improve. The cost function was designed to target kinematic symmetry while allowing minimal changes in the neural commands. To impose kinematic symmetry, the joint angles of the paretic leg were added to the corresponding joint angles of the non-paretic leg, were the goal is to minimize the integral of the continuous summed curves for all six joints (Fig 1). The six joints of interest include: hip flexion, hip adduction, hip rotation, knee flexion, ankle plantarflexion, and ankle inversion.

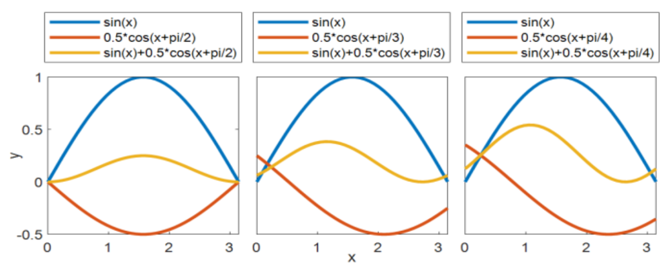

Fig. 1. An example to help visualize the minimization of asymmetry between the red and blue curves occurs when the integral of the summation curve (yellow) is minimized.

The cost of transport (CoT) was calculated using Bhargava's model [7] along with ratios describing spatial and temporal symmetry to determine if the assistive moments resulted in an improved walking motion.

III. Results

The ideal joint moment loads found by the optimizer to minimize kinematic asymmetry improved walking function by decreasing cost of transport and increasing spatial symmetry (Table I). The predicted walking motion showed a decrease in hip hiking, increase in symmetry between paretic and non-paretic hip flexion, decrease in leg circumduction, and correction of the foot drop (Fig 2). Additionally, although the range of motion at the knee did not increase, the timing of the peak knee flexion improved. Despite improvements to most joints of interest, the new walking motion resulted in

M. A. is with the Mechanical Engineering Department at Rice University, Houston, Tx, USA (ma86@rice.edu).

J. F. is with the Mechanical Engineering Department at the Polytechnic University of Catalonia (josep.m.font@upc.edu).

B. F. is with the Mechanical Engineering Department at Rice University, Houston, Tx, USA (fregly@rice.edu).

excessive ankle eversion along with over correction of temporal symmetry.

TABLE I
COST OF TRANSPORT, AND SPATIOTEMPORAL SYMMETRY MEASURES

	CoT	Spatial	Temporal
Original	7.49	0.18	0.44
Assisted	5.67	0.51	0.59

IV. DISCUSSION

This study predicted ideal assistive joint moments needed to improve gait asymmetries along with the cost of transport and spatiotemporal asymmetries. We found that kinematic symmetry may be enforced in the cost function by minimizing the integral of the summed curved between paretic and non-paretic joint angles. The joints of interest for this study included: hip flexion, hip adduction, hip rotation, knee flexion, ankle plantarflexion, and ankle inversion.

The predicted walking motion showed improvements in the common clinical features in hemiparesis walking observed in the two-synergy walking motion. However, it was observed that the temporal symmetry did not improve in the same manner as the cost of transport and spatial symmetry. This finding is consistent with [8] which reported that spatial and temporal symmetry can be targeted independently.

It is important to note that a key limitation of our study is the lack of experimental data as our starting point. Additionally, although the symmetry between the non-paretic and paretic legs was improved for the hip flexion, hip adduction, ankle plantarflexion, future development is needed to improve symmetries in hip rotation, knee flexion and ankle inversion.

V. CONCLUSION

In conclusion, our preliminary findings may shed light on the formulation of a cost function to implement kinematic symmetry to improve the cost of transport and spatial asymmetry measures. Our findings could potentially lead to a paradigm shift in the design of assistive devices for neurologically-influenced walking impairments.

ACKNOWLEDGMENT

Funding provided by the Cancer Prevention and Research Institute of Texas Grant RR170026, and NSF Graduate Research Fellowship

REFERENCES

[1] E. T. Hsiao-Wecksler, J. D. Polk, K. S. Rosengren, J. J. Sosnoff, and S. Hong, "A review of new analytic techniques for quantifying symmetry in locomotion," *Symmetry (Basel).*, vol. 2, no. 2, pp. 1135–1155, 2010.

[2] S. Hesse, C. Werner, A. Bardeleben, and H. Barbeau, "Body weight-supported treadmill training after stroke," *Curr. Atheroscler. Rep.*, vol. 3, no. 4, pp. 287–294, 2001.

[3] P. Malcolm, S. Galle, P. Van den Berghe, and D. De Clercq, "Exoskeleton assistance symmetry matters: unilateral assistance reduces metabolic cost, but relatively less than bilateral assistance," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 74, 2018.

[4] A. J. Meyer, I. Eskinazi, J. N. Jackson, A. V. Rao, C. Patten, and B. J. Fregly, "Muscle synergies facilitate computational predict ion of subject-specific walking motions," *Front. Bioeng. Biotechnol.*, vol. 4, no. October, 2016.

[5] M. Arones, C. Patten, and B. J. Fregly, "XVII International Symposium on Computer Simulation in Biomechanics July 28th–30th 2019, Alberta, Canada Does a Unilateral Reduction in Muscle Synergies Lead to Alterations in Gait Post Stroke?"

[6] A. V. Patterson, M. A.; Rao, "GPOPS-II: a MATLAB software for solving multiple-phase optimal control problems using hp-adaptive gaussian quadrature collocation methods and sparse nonlinear programming.," *ACM Trans. Math. Softw.*, vol. 1, no. 41, pp. 1–37, 2014.

[7] L. J. Bhargava, M. G. Pandy, and F. C. Anderson, "A phenomenological model for estimating metabolic energy consumption in muscle contraction," *J. Biomech.*, vol. 37, no. 1, pp. 81–88, 2004.

[8] L. A. Malone and A. J. Bastian, "Thinking about walking: Effects of conscious correction versus distraction on locomotor adaptation," *J. Neurophysiol.*, vol. 103, no. 4, pp. 1954–1962, Apr. 2010.

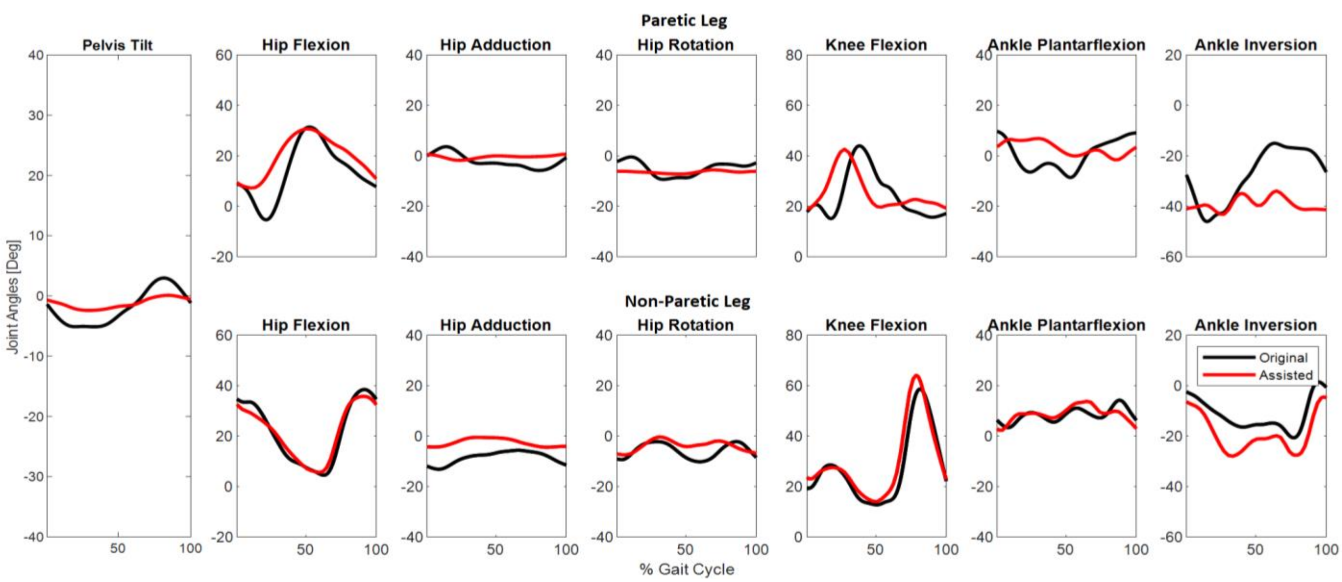

Fig. 2. Comparison between the original(black) and assisted(red) walking motions.