A Knee Exoskeleton Harvesting Different Energy Levels Changes Muscle Forces during Gait: Revealing Muscle Contributions to Metabolic Cost of Movement

Andrew J. Miller1, Raziel Riemer2, Jeffrey A. Reinbolt1
1Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, Tennessee, USA
2Department of Industrial Engineering and Management, Ben-Gurion University of the Negev, Beer-Sheva, Israel
Email: ajm.miller96@gmail.com

Summary

It was proposed that muscle force is related to metabolic cost of gait [1]. A knee exoskeleton, harvesting different amounts of energy, modulates the metabolic costs, during gait. We used musculoskeletal modelling and simulation to estimate muscle forces changes due to the energy harvesting levels. Mean muscle forces over the gait cycle were significantly different (p<0.01) at most exoskeleton energy harvesting levels; moreover, the muscle force changes account for the observed metabolic cost changes over different energy harvesting levels.

Introduction

Metabolic cost of gait is determined by the muscular force generated to overcome gravity; however, individual muscle contributions to the metabolic cost remain unknown [1,2]. By using an energy harvesting exoskeleton during gait, metabolic cost changes as the amount of energy harvested changes [3]. The purpose of this study was to determine muscle force contributions to metabolic cost by investigating the changes resulting from harvesting energy at the knee with an exoskeleton that modulates the metabolic costs during gait. We hypothesized that muscle forces estimated during gait using different energy harvesting levels will have different means over the gait cycle. Furthermore, our goal was to determine which muscle forces contributed most to the observed changes in metabolic cost during gait using the exoskeleton energy harvester. A better understanding of muscle force contributions to metabolic cost is necessary to refine exoskeleton design for targeted interactions with humans.

Methods

Experimental data was collected for one healthy subject (male, 32 yr, 180 cm, 85 kg) walking with a knee energy harvesting exoskeleton on both legs [4]. The subject walked on an instrumented treadmill for 7 minutes (v = 1.3 m/s) at six different conditions: mechanically disconnected (wearing the device as a dead weight, 0% harvesting) and five harvesting levels (15%, 22.5%, 30%, 37.5% and 50%), each one representing a level of resistance torque applied onto the knee joint. Kinematics were collected using ten cameras (Oqus, Qualisys, Sweden), ground reaction forces (GRFs) with an instrumented treadmill (FIT, Bertec Corporation, Columbus, OH, US), and metabolic rates via oxygen consumption (Quark, Cosmed, Italy). The GRFs were filtered using a second-order Butterworth low-pass filter with a cut-off frequency of 35Hz, and motion data were filtered using a cut-off frequency of 6Hz.

To estimate muscle forces using an OpenSim-MATLAB API, we scaled a musculoskeletal model (23 degrees of freedom and 92 muscle-tendon actuators) to match the subject and performed inverse kinematics to determine the model's generalized coordinate values that match the marker data. We applied torque from the exoskeleton energy harvester to each femur and tibia and then performed static optimization (minimizing the sum of muscle activations squared) to resolve the net joint moments and determine individual muscle forces. We evaluated our hypothesis regarding muscle force differences by performing a balanced one-way ANOVA followed by multiple comparisons of muscle force means across different energy harvesting levels. We also computed the relative contributions of individual muscle forces to the overall means and compared these muscle forces to the observed metabolic cost.

Results and Discussion

Muscle forces were significantly different (p<0.01), on average, across several of the energy harvesting levels (Figure 1). There were 16 muscles contributing to roughly half of the mean muscle force and accounting for the observed metabolic cost changes at each device setting.

Figure 1: Significant differences (*, p<0.01) in mean muscle forces highlighting the 16 major contributors to the metabolic costs during gait using a knee exoskeleton harvesting energy at different levels.

Conclusion

An exoskeleton harvesting energy at the knee changes the muscle forces during gait consistent with observed changes in metabolic cost. Relationships between muscle forces and metabolic cost of movement will potentially improve exoskeleton design for rehabilitation and other applications.

References