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Feasible muscle activation ranges based on inverse dynamics analyses of human walking

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ABSTRACT

Although it is possible to produce the same movement using an infinite number of different muscle activation patterns owing to musculoskeletal redundancy, the degree to which observed variations in muscle activity can deviate from optimal solutions computed from biomechanical models is not known. Here, we examined the range of biomechanically permitted activation levels in individual muscles during human walking using a detailed musculoskeletal model and experimentally-measured kinetics and kinematics. Feasible muscle activation ranges define the minimum and maximum possible level of each muscle's activation that satisfy inverse dynamics joint torques assuming that all other muscles can vary their activation as needed. During walking, 73% of the muscles had feasible muscle activation ranges that were greater than 95% of the total muscle activation range over more than 95% of the gait cycle, indicating that, individually, most muscles could be fully active or fully inactive while still satisfying inverse dynamics joint torques. Moreover, the shapes of the feasible muscle activation ranges did not resemble previously-reported muscle activation patterns nor optimal solutions, i.e. static optimization and computed muscle control, that are based on the same biomechanical constraints. Our results demonstrate that joint torque requirements from standard inverse dynamics calculations are insufficient to define the activation of individual muscles during walking in healthy individuals. Identifying feasible muscle activation ranges may be an effective way to evaluate the impact of additional biomechanical and/or neural constraints on possible versus actual muscle activity in both normal and impaired movements.

1. Introduction

Musculoskeletal redundancy (Bernstein, 1967) allows for an infinite number of combinations of muscle activation patterns for performing a task. Current modeling approaches typically handle this redundancy by assuming some optimization criterion, e.g. minimizing muscle stress (Crowninshield and Brand, 1981; Thelen et al., 2003), to select a single muscle activation pattern among many that satisfy biomechanical constraints such as joint torques, joint contact forces (Fregly et al., 2012; Lin et al., 2010; Walter et al., 2014), joint impedance (Franklin and Wolpert, 2011; Hogan, 1984; Mitrovic et al., 2010), etc. The most common biomechanical constraints on muscle activation patterns are based on experimentally-measured kinematics (e.g. joint angles) and kinetics (e.g. ground reaction forces) and found using a single optimization criterion. Such inverse approaches identify optimal solutions that may capture major features of experimentally-measured muscle activation patterns (Thelen and Anderson, 2006; Thelen et al., 2003), but do not inform the extent to which deviations from optimal patterns may also satisfy the biomechanical constraints. While some variations in muscle activity across individuals have been attributed to different body morphology (Buchanan and Shreeve, 1996; Liu et al., 2008; van der Krogt et al., 2012), how much within-individual variations of muscle activity are permitted given these biomechanical constraints has not been well studied. Characterizing all viable deviations in muscle activity from an optimal solution that still satisfy a set of biomechanical constraints would facilitate interpretation of experimental variations in muscle activation patterns as well as how those biomechanical constraints affect not just the optimal solutions, but the set of all possible solutions.

A few attempts to define feasible muscle activation ranges for a given movement have been made previously. These attempts have been limited to matching net joint torques, primarily in isometric tasks, and their results may be highly dependent on model complexity. For example, Kutch and Valero-Cuevas (2011; 2012) demonstrated a limited range of possible muscle activation patterns for finger forces in a 4 degree-of-freedom (DoF) model with 7 muscles, suggesting that biomechanics limit the set of possible muscle activation patterns. Using a simplified planar leg model with 14

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muscles and three DoFs, they demonstrated using computational geometry that removing a single muscle greatly reduces force production capabilities; this approach defines the complete solution space but is limited to 14 muscles. In contrast, we demonstrated very wide feasible muscle activation ranges using a linear programming technique on a model of the cat hindlimb with 7 DoFs and 41 muscles (Sohn et al., 2013). Similarly, Martelli et al. showed wide possible variations in a model of human walking (10 DoFs, 82 muscles), however the Markov Chain Monte Carlo methods they used cannot find explicit limits of activation (Martelli et al., 2015, 2013).

Here, our goal was to identify the feasible muscle activation ranges during a full gait cycle of human walking by extending the methods of Sohn et al. (2013) to a dynamic task. We identified feasible muscle activation ranges during human walking using experimental data (John et al., 2013) and a detailed musculoskeletal model of the human lower extremity with 23 DoF and 92 muscles (Delp et al., 2007; Delp et al., 1990). We extended Sohn's (2013) method such that each time point in the gait cycle was treated as an independent optimization problem (Anderson and Pandy, 2001b), where each muscle's minimum and maximum possible activity level (while allowing all others to vary independently) to satisfy inverse dynamics based net joint torque requirements is identified at each time point. These upper and lower bounds on muscle activation, defining the feasible muscle activation ranges, were then compared to optimal solutions from inverse approaches, i.e., computed muscle control (CMC) (Thelen and Anderson, 2006; Thelen et al., 2003) and static optimization (Anderson and Pandy, 2001b) as well as experimentally recorded electromyographic (EMG) data reported in literature (Perry, 1992; Van der Krogt et al., 2012). Our results show that feasible muscle activation ranges can be applied to standard inverse dynamics solutions using complex musculoskeletal models to identify the degree to which muscle activation level can vary from optimal solutions.

2. Methods

Our method for calculating feasible muscle activation ranges was based on satisfying inverse dynamics joint torque constraints and used a combination of built-in OpenSim analyses with custom Matlab code (Fig. 1). Experimental data in combination with a generic OpenSim model (Scale, Inverse Kinematics, and Inverse Dynamics Tools) were used to calculate movement kinematics and kinetics. Joint torques and muscle parameters extracted from the model were used as inputs to calculate feasible ranges of muscle activation. Our results were compared to solutions from commonly used techniques to calculate optimal muscle activations, specifically static optimization (Anderson and Pandy, 2001b) and CMC (Thelen and Anderson, 2006). We also compared our feasible muscle activation ranges to EMG data from Perry (1992) and van der Krogt et al. (2012).

2.1. Experimental data

We used experimental marker data and ground reaction force data (Fig. 1) of a single subject (male; height, 1.83 m; body mass, 65.9 kg) walking at self-selected speed (1.36 m/s) on an instrumented treadmill. This data is publically available at https://simtk.org/home/muscleprops (John et al., 2013).

2.2. Extraction of model parameters from OpenSim

A generic three-dimensional OpenSim musculoskeletal model of the human lower extremity (gait2392.osim) with 23 DoF and 92 musculotendon actuators (Table 1) was scaled to subject anthropometrics using the Scale Tool. The muscle model parameters extracted for each muscle were: maximum isometric force, optimal fiber length, tendon slack length, pennation angle at optimal fiber length, maximum eccentric force, parallel muscle fiber stiffness, active force-length, passive force-length, and force-velocity shape factors. Joint angles were calculated using the Inverse Kinematics Tool with the scaled model and experimental marker data. Musculotendon lengths and moment arms were extracted from inverse kinematics results. Finally, joint torques were calculated using the Inverse Dynamics Tool with the scaled model, inverse kinematics results, and experimental ground reaction forces.

2.3. Calculating feasible muscle activation ranges

Feasible muscle activation ranges were calculated using custom Matlab code based on a linear mapping between muscle activations ($\bar{a}$) and the joint torques ($\bar{\tau}$) required to produce the task calculated using OpenSim (above):

$$\boldsymbol{R}[\bar{q}(T)] \bullet \boldsymbol{AMF}[\bar{q}(T), \dot{\bar{q}}(T)] \bullet \bar{a}(T) = \bar{\tau}(\mathrm{T}) - \boldsymbol{R}[\bar{q}(T)] \bullet \boldsymbol{PMF}[\bar{q}(T)]$$

where $\boldsymbol{R}$ is the moment arm matrix dependent on joint angle, $\boldsymbol{AMF}$ is the active muscle force contribution, and $\boldsymbol{PMF}$ is the passive muscle force contribution. Both $\boldsymbol{AMF}$ and $\boldsymbol{PMF}$ were computed according to force-length and force-velocity relationships in a Hill-type muscle model (Thelen, 2003) from John et al. (2013). Tendons were assumed to be inelastic (Zajac and Gordon, 1989).

Feasible muscle activation ranges were computed for each muscle at each time point for one complete gait cycle (1.2 s at 72 Hz) and define the upper and lower bounds of each muscle's activation while allowing all other muscles to vary independently. The upper and lower bounds were found using linear programming (linprog.m in Matlab). For each muscle and each time point, the lower (a_M^{LB}) and upper (a_M^{UB}) bounds of muscle activation were identified as follows (Sohn et al., 2013):

a_M^{LB}: Find a^m such that $|\bar{a}|$ is minimized, while

$$\boldsymbol{R}[\bar{q}(T)] \bullet \boldsymbol{AMF}[\bar{q}(T), \dot{\bar{q}}(T)] \bullet \bar{a}(T) = \bar{\tau}(\mathrm{T}) - \boldsymbol{R}[\bar{q}(T)] \bullet \boldsymbol{PMF}[\bar{q}(T)]$$

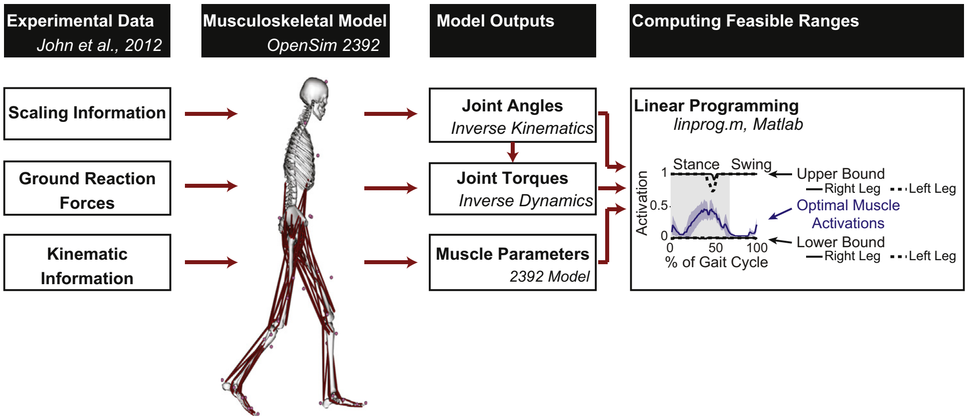

Fig. 1. Schematic of methods used to identify feasible ranges of muscle activation during walking. An OpenSim human lower limb musculoskeletal model with 23 degrees of freedom and 92 muscles (Delp et al. 1990, 2007) was used to perform an inverse dynamics analysis of experimental data from John et al. (2013). Native OpenSim tools (Inverse Kinematics and Inverse Dynamics) were used to calculate joint angles and torques as well as to extract muscle properties necessary to compute muscle force production capabilities (Thelen, 2003; John et al., 2013). Feasible muscle activation ranges were then computed using linear programming (linprog.m) in Matlab. Feasible muscle activation ranges can be compared with optimal or experimental (EMG) muscle activations by superimposing muscle activations onto the feasible ranges.