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Short communication

Muscle-induced accelerations at maximum activation to assess individual muscle capacity during movement

Saryn R. Goldberg [a,*], Thomas M. Kepple [b]

[a] Department of Engineering, Hofstra University, 104 Weed Hall, Hempstead, NY 11549 USA
[b] Department of Health, Nutrition, and Exercise Sciences, University of Delaware, Newark, DE, USA

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ABSTRACT

Analyses of muscle-induced accelerations provide insight into how individual muscles contribute to motion. In previous studies, investigators have calculated muscle-induced accelerations on a per unit force basis to assess the potential of individual muscles to contribute to motion. However, because muscle force is a function of muscle activation, length, and shortening velocity, examining induced accelerations per unit force does not take into account how the capacity of individual muscles to produce force changes during movement. Alternatively, calculating a muscle's induced accelerations at maximum activation considers the extent to which the muscle can produce force during movement, as well as the potential of the muscle to accelerate the joints at each instant due to its moment arm(s) and the dynamics of the system. We computed both quantities for the major lower extremity muscles active during the stance phase of normal gait. We found that analyzing the induced accelerations at maximum activation in some cases led to a different interpretation of the muscles' potential actions than analyzing the induced accelerations per unit force. For example, per unit force, gluteus maximus has a very large potential to accelerate the knee during single limb stance, but only a small potential to accelerate the knee at maximum activation due to this muscle operating in suboptimal regions of its force–length–velocity curve during the majority of stance. This new analysis technique will be useful in studying abnormal movement, when altered kinematics may influence the capacity of muscles to accelerate joints due to altered lengths and shortening velocities.

1. Introduction

Understanding how individual muscles contribute to normal (Neptune et al., 2001; Anderson and Pandy, 2003; Riley et al., 2001) and impaired (Higginson et al., 2006) movement is an important area of biomechanical research. An individual muscle's contributions to a motion are commonly quantified by induced accelerations (Zajac and Gordon, 1989). Induced accelerations are typically calculated by applying an individual muscle force or torque to a musculoskeletal model and recording the resulting accelerations of the body segments or joints.

Analyses of induced accelerations per unit muscle force have been used by some researchers to compare the relative potential of muscles to contribute to joint accelerations (Arnold et al., 2005; Kimmel and Schwartz, 2006; Hicks et al., 2008). In this technique, 1 N of force is individually applied by each muscle in a model and the resulting accelerations are compared. These accelerations reflect the influence of muscle geometry and body posture on the potential of each muscle to contribute to the observed movement. However, these values do not take into account the relative capacity of each muscle to produce force due to their differences in physiologic cross-sectional area and their force–length and force–velocity properties during the movement.

An alternative quantity that does take all of these factors into account is a muscle's induced acceleration at maximum activation. In this case, one first calculates the forces and corresponding moments generated by a muscle if it were maximally activated (i.e. activation = 1) throughout the movement. These forces and moments reflect the maximum that this muscle could produce at the lengths and velocities associated with the movement. Second, these force or moment profiles are used to calculate induced accelerations, with the resulting values reflecting the influence of muscle geometry and body posture, as well as the muscle's force-generating capacity. In this study we calculated the muscle-induced accelerations at maximum activation and per unit force for the major lower extremity muscles active during the stance phase of normal gait. We found that analyzing the induced accelerations at maximum activation in some cases led to a different interpretation of a muscle's potential actions than the induced accelerations per unit force. The purpose of this paper is to describe this new analysis technique and to demonstrate its ability to provide new insight.

* Corresponding author. Tel.: +1 516 463 6018; fax: +1 516 463 4939.
E-mail address: eggzszg@hofstra.edu (S.R. Goldberg).

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2. Methods

We collected gait data from a shod, healthy subject (male, 180 cm, 74 kg) walking at a self-selected speed of 1.3 m/s using a marker configuration as described by Holden et al. (1997). Informed consent was obtained for this IRB-approved study. Motion capture and force plate data were sampled at 120 and 1040 Hz, respectively, and filtered at 6 and 20 Hz, respectively. Three trials were collected and a single representative trial was analyzed from right foot-flat to toe-off.

Segment positions and orientations were obtained from the motion capture data and input into a three-dimensional model that included 8-segments and 43 Hill-type musculotendon actuators representing the major lower extremity muscles (Delp et al., 1990). Using SIMM (Musculographics, Inc., Santa Rosa, CA), each muscle was individually given a maximum activation of 1.0 and the resulting joint moments were recorded throughout the motion. Joint moments corresponding to activation levels of 0.75 and 0.5 were also calculated and found to scale with activation within approximately 10%. These joint moments take into account the force-generating capacity of each muscle at the lengths and shortening velocities reached throughout the measured stance phase. SIMM software was also used to output the length of each muscle throughout the motion and from this data, muscle shortening velocities were calculated.

A geometrically identical link model was created using SD/Fast (Parametric Technologies, Needham, MA). For simplicity, this SD/Fast model was moment-driven, containing no muscles, and took as input the joint moments calculated in SIMM that corresponded to maximum activation. The model was positioned according to the measured stance phase joint angles, the joint moments due to each muscle were applied individually, and the resulting joint accelerations were calculated. The model was constrained so that each foot was fixed to the ground during foot-flat. After heel-off, each foot was allowed to rotate about a medial/lateral pin joint passing through the measured center of pressure. This foot–floor interaction model has been found to perform similarly to viscoelastic models of foot–floor contact in induced acceleration analyses (Kepple et al., 2002). The timing of heel-off and foot-flat were determined by examining a plot of the foot angle relative to the ground to identify the period when the angle remained constant and near zero. Data between heel-strike and foot-flat was omitted, both to be comparable to previously published data and due to the high sensitivity of the analysis to foot contact during this period. We performed a similar analysis to compute induced accelerations per unit force as a means of comparison to our maximum activation results and to enable us to compare our results to other published values.

3. Results

Analyzing which muscles had the most potential to accelerate the hip and knee at maximum activation led to a different interpretation than the results calculated per unit muscle force. The most striking difference was seen in gluteus maximus

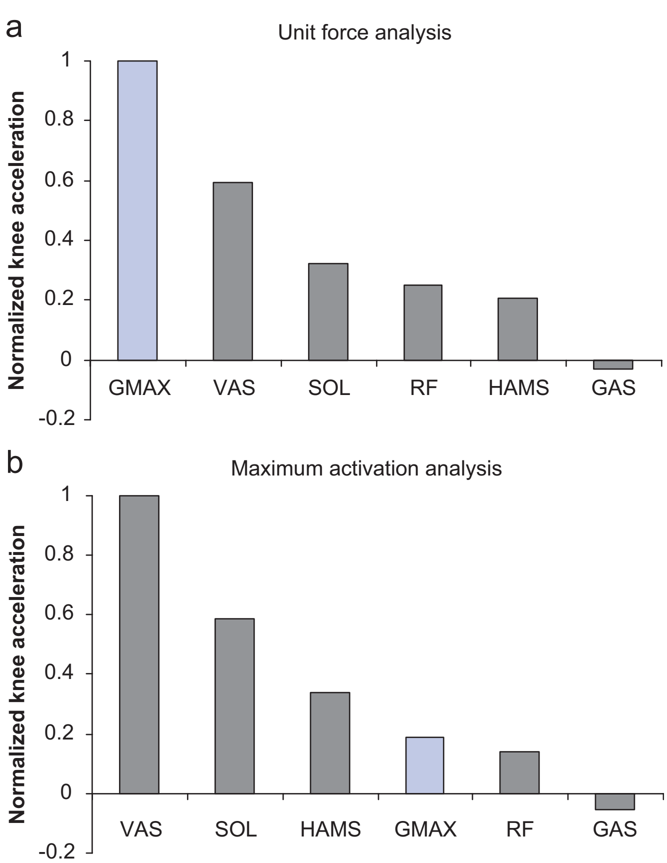

Fig. 1. Scaled knee accelerations (a) per unit muscle force and (b) at maximum muscle activation averaged from foot-flat to toe-off due to selected muscles (GMAX = gluteus maximus; HAMS = combination of biceps femoris long head, semimembranosis, and semitendinosis; VAS = vasti; SOL = soleus; GAS = gastrocnemius; RF = rectus femoris). Values have been scaled by the peak value. (The pre-scaled values for the average induced acceleration per unit muscle force (not shown) due to the most influential muscles, as well as their relative rank order, matched closely with similar data presented by Arnold et al. (2005).) Note that the relative ranking of GMAX decreases for the maximum activation analysis as compared to the unit force analysis.

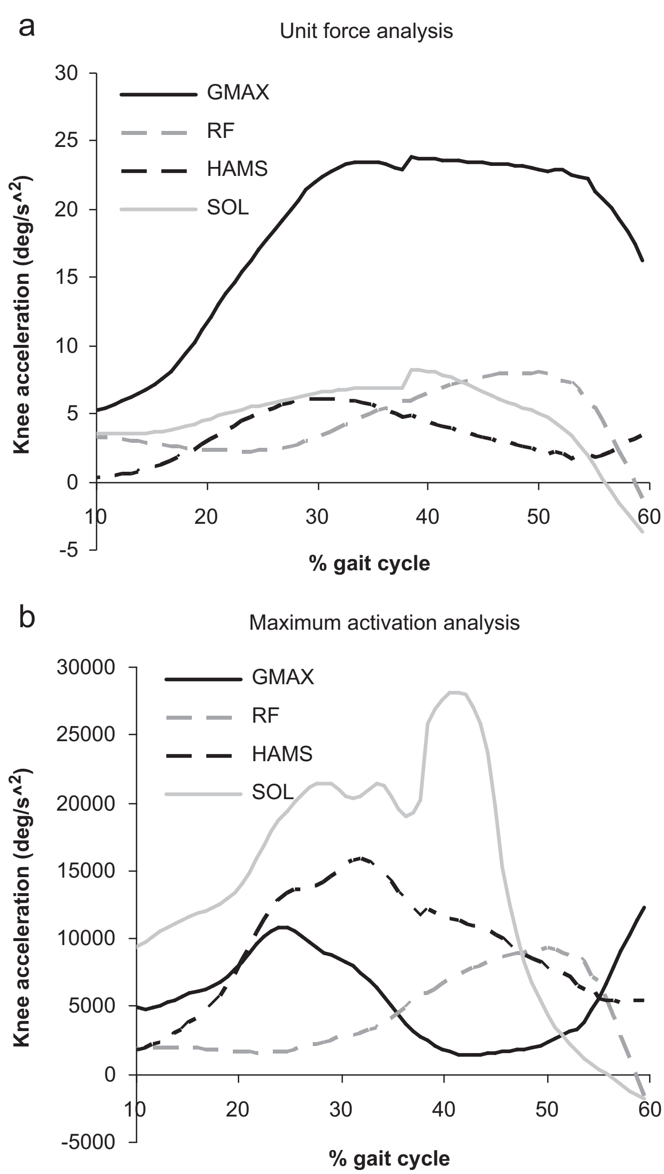

Fig. 2. Knee accelerations (a) per unit muscle force and (b) at maximum muscle activation during stance for selected muscles. Note that the shape of the curves for RF, HAMS, and SOL is fairly consistent between the two analysis techniques, while the shape of the curve for GMAX changes. This suggests that GMAX was the muscle whose capacity to accelerate the knee was most affected by its force–length–velocity properties during the movement.