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Short communication

A rolling constraint reproduces ground reaction forces and moments in dynamic simulations of walking, running, and crouch gait

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ABSTRACT

Recent advances in computational technology have dramatically increased the use of muscle-driven simulation to study accelerations produced by muscles during gait. Accelerations computed from muscle-driven simulations are sensitive to the model used to represent contact between the foot and ground. A foot-ground contact model must be able to calculate ground reaction forces and moments that are consistent with experimentally measured ground reaction forces and moments. We show here that a rolling constraint can model foot-ground contact and reproduce measured ground reaction forces and moments in an induced acceleration analysis of muscle-driven simulations of walking, running, and crouch gait. We also illustrate that a point constraint and a weld constraint used to model foot-ground contact in previous studies produce inaccurate reaction moments and lead to contradictory interpretations of muscle function. To enable others to use and test these different constraint types (i.e., rolling, point, and weld constraints) we have included them as part of an induced acceleration analysis in OpenSim, a freely-available biomechanics simulation package.

1. Introduction

Muscle-driven simulations of human gait have provided insights into the actions of muscles during walking (e.g., Anderson and Pandy, 2003; Liu et al., 2008), running (e.g., Hamner et al., 2010; Sasaki and Neptune, 2006), and pathological gait (e.g., Peterson et al., 2010; Steele et al., 2010). These studies employ methods, like induced acceleration analysis, which decompose ground reaction forces and moments using foot-ground contact models to examine how muscle forces contribute to accelerations of joints and the body mass center. Results from these studies depend upon the ground contact model (Dorn et al., 2012a; Hamner et al., 2010). It is therefore essential to assess the ability of different contact models to produce accurate ground reactions. Previous studies have compared simulated reaction forces to experimentally measured ground reaction forces (Anderson and Pandy, 2001; Dorn et al., 2012b; Seth and Pandy, 2007). It is also necessary to compare simulated reaction *moments* to measured ground reaction *moments*.

The purpose of this study was to examine the accuracy with which a rolling constraint represents contact between the foot and ground during induced acceleration analyses of walking, running, and crouch gait. Induced acceleration analysis uses a model of foot-ground contact to determine how muscles, gravity, and velocity-related forces contribute to the ground reaction force. To test the accuracy of a rolling constraint we compared ground reaction forces and moments computed in an induced acceleration analysis to experimentally measured ground reaction forces and moments. We also evaluated other constraint-based contact models in an induced acceleration analysis of running to illustrate that these different models produce inaccurate reaction moments and lead to contradictory interpretations of muscle function.

2. Methods

We used simulations of three different gait patterns: walking (Liu et al., 2008), running (Hamner et al., 2010), and crouch gait (Steele et al., 2012) (Fig. 1). Marker trajectories and ground reaction forces and moments were measured while subjects either walked over ground or ran on a treadmill instrumented with force plates. Muscle-driven simulations were generated from these experimental data using OpenSim (Delp et al., 2007). A musculoskeletal model consisting of 92 muscles of the lower extremities and torso was scaled to match each subject's anthropometry using experimentally measured markers placed on anatomical landmarks and calculated joint centers. A corresponding virtual marker set was placed on the model based on these anatomical landmarks. Joint angles were calculated using an inverse kinematics algorithm that minimized the difference between experimental and virtual markers at each time frame (Delp et al., 2007). The computed muscle control algorithm (Thelen et al., 2003) determined muscle excitation patterns required to track measured motion. Details of experimental and simulation methods are included in the primary publications (Hamner et al., 2010; Liu et al., 2008; Steele et al., 2012).

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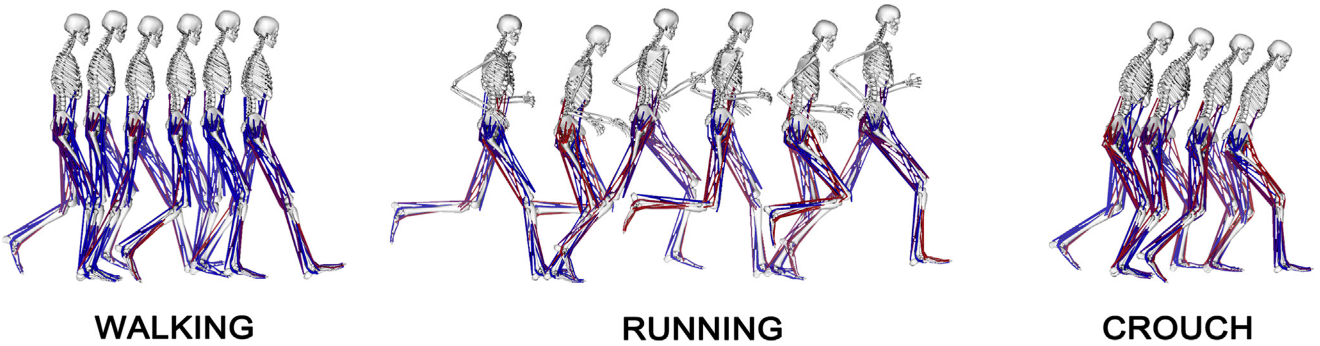

Fig. 1. Simulations of a walking gait cycle, a running gait cycle, and a crouch gait cycle. The simulations shown are of a representative subject from each study. Each set of simulations (i.e., walking, running, crouch) consisted of data from three subjects; all were analyzed using the rolling constraint to model ground contact during an induced acceleration analysis. Each simulation used a scaled musculoskeletal model with the lower extremities and torso driven by 92 musculotendon actuators.

An induced acceleration analysis was used to compute reaction forces and moments of a constraint between the foot and ground due to the forces acting on the musculoskeletal model: muscle forces, gravity, and forces due to velocity effects (i.e., Coriolis and centripetal forces). The resultant constraint reaction force and moment were calculated by summing the constraint reactions due to each force acting on the musculoskeletal model. This calculated sum was then compared to the experimentally measured ground reaction force and moment to assess accuracy.

We calculated accelerations due to forces acting on the musculoskeletal model using equations of motion for a constrained, rigid body system with muscles (Sherman et al., 2011):

$$[M]\ddot{q} + [C]^T\lambda = [R]F_m + F_g + F_v \quad (1)$$

$$[C]\ddot{q} = b \quad (2)$$

where M is the mass matrix, q is a vector of generalized coordinates (e.g., joint angles), C is the constraint matrix, λ reprsents generalized constraint reaction forces, F_m represents muscle forces, F_g represents gravitational forces, F_v represents forces due to velocity effects, R is the matrix of muscle moment arms, and b is a vector containing position and velocity terms (i.e., q and $\dot{q}$) of the constraint equations (i.e., Eqs. (3)–(6)) expressed in terms of generalized accelerations, $\ddot{q}$. The constraint matrix C maps generalized constraint reaction forces λ to generalized forces. Generalized constraint reaction forces λ and generalized accelerations $\ddot{q}$ are solved simultaneously.

To model contact between the foot and the ground, we implemented a rolling constraint (Fig. 2; ROLL) that generates a fore-aft, vertical, and mediolateral reaction force and a vertical reaction moment. With a constraint-based contact model, constraint equations are included in the equations of motion and reactions are computed at each time step. Contact models utilizing spring-dampers (e.g., Anderson and Pandy, 2001; Neptune et al., 2000) require equations of motion to be integrated forward in time to calculate contact forces. Constraint-based models eliminate the computational cost of forward integrations and sensitivity of results due to differing integration time windows.

The rolling constraint combines four individual constraints: a unilateral non-penetrating constraint (Eq. (3); i.e., foot cannot penetrate ground but can be lifted) and a pure rolling constraint (Kane, 1961) (Eqs. (4)–(6)), which includes two no-slip constraints (i.e., limits fore-aft and mediolateral foot translations) and a no-twist constraint about the axis normal to ground (i.e., limits vertical rotations). Each constraint is applied at the measured center of pressure.

Constraint name	Equation	Constraint condition(s)	
Vertical, unilateral, non-penetrating	$\rho_Y(q) \geq 0$	$\hat{F}_Y > F_{threshold}$	(3)
Fore-aft no slip	$v_X(q,\dot{q}) = 0$	non-penetrating condition and $\hat{F}_Y\mu_{friction} > \sqrt{F_X^2 + F_Z^2}$	(4)
Mediolateral no slip	$v_Z(q,\dot{q}) = 0$	non-penetrating condition and $\hat{F}_Y\mu_{friction} > \sqrt{F_X^2 + F_Z^2}$	(5)
Vertical no-twist	$\omega_Y(q,\dot{q}) = 0$	no slip condition and $r_{contact}\mu_{friction}\,\hat{F}_Y > M_Y$	(6)

In Eqs. (3)–(6), ρ_Y is the vertical position of the foot, v_X and v_Z are the fore-aft and mediolateral foot velocities, respectively, and ω_Y is the foot's vertical angular velocity, all with respect to ground. $\hat{F}_Y$ is the measured vertical ground reaction force, F_x and F_z are the simulated fore-aft and mediolateral constraint reaction forces, respectively, and M_Y is the simulated vertical constraint reaction moment. The constraint equations are differentiated to provide constraints on the system accelerations, $\ddot{q}$ (Eq. (2)).

Specified parameters were used to determine when each constraint was active (i.e., turn on/off each constraint) based on constraint conditions in Eqs. (3)–(6). If conditions were met, each constraint was applied to the foot at the measured center of pressure, allowing direct comparison of simulated constraint reactions and measured ground reactions. In the constraint conditions, $F_{threshold}$ is a threshold (5 N) for the vertical reaction force used to determine when the non-penetrating constraint is active (Eq. (3)), $\mu_{friction}$ is a friction coefficient (0.65) used to determine when the no-slip constraints are active (Eqs. (4)-(5)), and $r_{contact}$ is a contact radius (0.01 m) representing the size of the contact area between foot and ground and is used to determine a threshold for the reaction moment (Eq. (6)). Parameter values were determined by varying each parameter within a range of physically realistic values (i.e., $0\ \text{N} < F_{threshold} < 50\ \text{N}$; $0.01 < \mu_{friction} < 1$ and $0.001\ \text{m} < r_{contact} < 0.1\ \text{m}$) and selecting values that provided appropriate timing for heel strike and toe-off. Parameters only affected when the constraints were active and varying parameters had no effect on the magnitude of reaction forces and moments calculated with the constraints. The accuracy of the rolling constraint was assessed by calculating root-mean square (RMS) difference between each component of measured ground reactions and simulated constraint reactions, averaged from the three subjects in each study.

To examine how different constraint-based contact models affect interpretation of muscle function, we conducted a case study using running simulations in which we quantified how different constraints affect muscle contributions to mass center accelerations calculated by induced acceleration analysis. We examined running as it produces larger, more rapidly changing ground reaction forces than walking. We compared the rolling constraint with two constraint-based contact models used in previous studies: a point constraint (Fig. 2; POINT) and a weld constraint (Fig. 2; WELD). The point constraint does not allow the foot to translate in any direction (i.e., fore-aft, mediolateral, or vertical), while it allows the foot to rotate about all three axes (e.g., Kepple et al., 1997). Thus, a point constraint applied at the center of pressure generates reaction force in all directions (i.e., F_x, F_y, and F_z), but cannot generate any reaction moment (i.e., M_x, M_y, and M_z). The weld constraint does not allow the foot to translate or rotate (e.g., Anderson and Pandy, 2001) and can thus generate reaction forces and moments in all directions. By comparison, the rolling constraint limits foot translation in all directions while only limiting rotation about the vertical axis, thus generating reaction forces in all directions but only a vertical reaction moment. Each constraint (ROLL, POINT, and WELD) was applied in the same induced acceleration analysis framework, allowing for direct comparison between simulated constraint reactions and measured ground reactions. The point and weld constraints were turned on when the vertical ground reaction force exceeds a specified threshold (i.e., $\hat{F}_Y > F_{threshold}$). Accuracy of each constraint type was assessed by calculating RMS difference between each component of average simulated constraint reactions and average measured ground reactions. We also calculated average contributions of soleus and vasti to fore-aft and upward mass center accelerations during stance, as these represent important muscle groups for braking and propulsion (Hamner et al., 2010; Liu et al., 2008; Neptune et al., 2008).

3. Results

The rolling constraint produced reaction forces and moments similar to ground reaction forces and moments measured about the center of pressure for walking, running and crouch gait (Fig. 3). In each case, muscles of the lower extremities and torso, gravity,