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Improving joint torque calculations: Optimization-based inverse dynamics to reduce the effect of motion errors

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Abstract

The accuracy of joint torques calculated from inverse dynamics methods is strongly dependent upon errors in body segment motion profiles, which arise from two sources of noise: the motion capture system and movement artifacts of skin-mounted markers. The current study presents a method to increase the accuracy of estimated joint torques through the optimization of the angular position data used to describe these segment motions. To compute these angular data, we formulated a constrained nonlinear optimization problem with a cost function that minimizes the difference between the known ground reaction forces (GRFs) and the GRF calculated via a top-down inverse dynamics solution. To evaluate this approach, we constructed idealized error-free reference movements (of squatting and lifting) that produced a set of known "true" motions and associated true joint torques and GRF. To simulate real-world inaccuracies in motion data, these true motions were perturbed by artificial noise. We then applied our approach to these noise-induced data to determine optimized motions and related joint torques. To evaluate the efficacy of the optimization approach compared to traditional (bottom-up or top-down) inverse dynamics approaches, we computed the root mean square error (RMSE) values of joint torques derived from each approach relative to the expected true joint torques. Compared to traditional approaches, the optimization approach reduced the RMSE by 54% to 79%. Average reduction due to our method was 65%; previous methods only achieved an overall reduction of 30%. These results suggest that significant improvement in the accuracy of joint torque calculations can be achieved using this approach.

Keywords: Inverse dynamics; Optimization; Joint moments; Error reduction

1. Introduction

Inverse dynamics is a method commonly used in the biomechanical analysis of human movement to calculate the net torque (or muscle moment) due to the contraction of muscles spanning each joint. This method uses kinematic, kinetic, and anthropometric information as input to solve the Newton–Euler equations of motion for each body segment (Winter, 2005).

Despite the widespread use of the inverse dynamics method, researchers recognize that it is error prone. The literature suggests that the main sources of error are: (1) inaccuracy in movement coordinate data, (2) estimations of body segment parameters, (3) errors related to force plate measurements, and (4) identification of joint center of rotation locations (e.g., Bell et al., 1990; Kuo, 1998; Schwartz and Rozumalski, 2005; Riemer et al., in press). Inaccuracy in movement coordinate data affects the calculation of the motions of individual body segments (i.e., segment angles and accelerations). This inaccuracy is caused by two types of errors: (a) error in marker location due to inherent motion capture system noise (Richards, 1999) and (b) relative motion between skin-mounted markers and the underlying bone (a.k.a. skin movement artifact) (Cappozzo et al., 1996; Fuller et al., 1997; Holden et al., 1997). We have found that these various inaccuracies can result in uncertainties of estimated joint torques ranging from 6% to 232% of the peak torque (Riemer et al., in press).

Two approaches have traditionally been used for inverse dynamics computations. The first requires only kinematic

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and anthropometric data to calculate joint torques. This process, often referred to as the top-down approach, typically starts at the (unloaded) distal segment of the upper extremity(ies) and proceeds downward such that dynamic equilibrium conditions are satisfied for each successive segment. The top-down approach, however, is quite sensitive to the propagation of inaccuracies, including those affecting acceleration data (Cahouet et al., 2002); thus, this method is not typically used to compute both proximal and distal (e.g., upper and lower extremity) joint torques simultaneously. The second method tends to improve torque estimates for the lower extremity and reduce acceleration effects by adding kinetic data, typically ground reaction forces (GRFs) for locomotor tasks. This method, often called the bottom-up approach, starts at the distal segment of one or both lower extremities and proceeds upward through the body. By incorporating GRF measurements, boundary conditions are defined for the bottommost segment. These added conditions result in redundant information since there are now more equilibrium equations than system unknowns. Some research groups have suggested that these conditions result in an over-determined system (Vaughan et al., 1982; Kuo, 1998; Cahouet et al., 2002). As a consequence, due to errors such as those mentioned above, these traditional methods can result in residual forces and torques on the most-distal segment.

This redundancy has been used to reduce error effects through optimization methods, which based their cost function upon minimizing these residuals. These optimization methods adjust specific input parameters in the top-down calculations until optimal values are found that minimize the difference between the known ground reaction measurements and those predicted through the top-down calculation.

These optimization methods have been used to (i) determine an optimal set of body segment parameters (Vaughan et al., 1982), (ii) reduce the effect of noise in measured data (i.e., GRF measurements and segment motion) (Kuo, 1998), and (iii) calculate optimal segment accelerations in order to improve joint torque calculations (Cahouet et al., 2002). Vaughan et al. (1982) and Cahouet et al. (2002) assumed that minimizing a cost function is sufficient for improving results; however, their cost functions did not contain information on the joint torques, and therefore it is possible to minimize their cost functions but also increase error in the joint torques. Kuo (1998) overcame this situation by suggesting an additional success criterion, which stated that the difference between the optimized and simulation-based reference or "true" joint torque value should be less than the traditional (non-optimized) inverse dynamics solution. Cappozzo (2002) and Mazza and Cappozzo (2004) recently proposed a method that used GRF data to compute optimal solutions for joint angular motion. Their motivation was to find a technique that used only GRF data to estimate joint motion.

These studies, though, were not designed to eliminate the effect of characteristic error in the motion profiles. Previously, it was found that inaccuracy in estimated segment angular position (and associated acceleration) is the main contributor to uncertainty in joint torque solutions (Leardini et al., 2005; Riemer et al., in press). Therefore, an optimization method that could reduce errors in movement data and account for both motion capture system noise and skin movement artifact should provide the greatest improvement. This paper extends these past studies by describing an optimization problem to find optimal angular position data to reduce error in estimated joint torques.

2. Method

The goal of this work was to develop a method to increase the accuracy of estimated joint torques through the optimization of angular position data used to describe body segment motions. Specifically, we formulated a constrained nonlinear optimization problem with a cost function that minimized the difference between the known GRFs and the GRF calculated via a top-down inverse dynamics approach. We evaluated the efficacy of this approach by examining simple planar reference motions of three- or four-segment systems (Fig. 1). More specifically, we constructed two reference motions (squatting with arms crossed and lifting with straight arms) that generated a set of error-free test data. We refer to these data as the true segment angle profiles, joint coordinates, joint torques, and GRF. Artificial noise was then added to the true motion data to mimic real-world data. These noisy data were then used to compute joint torques via our optimization approach and traditional (bottom-up and top-down) approaches. Relative to the true values, results from optimized segment angle profiles and related joint torques were then compared to results derived from the traditional non-optimized approaches.

2.1. Optimization formulation

The general formulation for the optimization problem was

$$\begin{aligned} &\min \quad z(v) \\ &\text{s.t.} \quad \begin{cases} c_k(v) = 0, & k \in E, \\ c_k(v) \geqslant 0, & k \in I, \end{cases} \end{aligned} \tag{1}$$

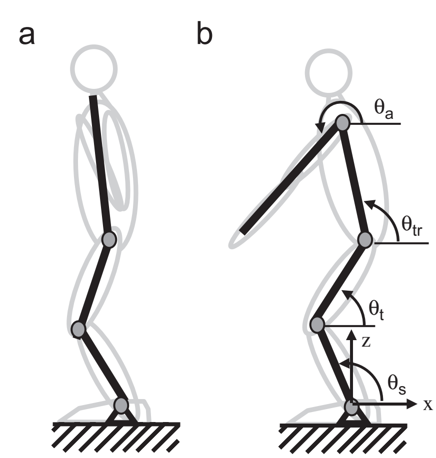

Fig. 1. Squatting (a) and lifting (b) motions were represented by three- and four-segment models, respectively. Segment angles for the shank (θ_s), thigh (θ_t), torso (θ_{tr}), and arm (θ_a) were defined as shown.