FULL BODY INVERSE DYNAMICS SOLUTIONS: AN ERROR ANALYSIS AND A HYBRID APPROACH

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INTRODUCTION

Inverse dynamics is a powerful tool for biomechanical analysis of human movement (Winter 1990), but is subject to various sources of inaccuracy. Otimization-based methods have been developed to improve the precision of inverse dynamics computations (e.g., Kuo 1998; Cahouët et al. 2002). While the efficacy of these methods have been tested using simulated data (Kuo 1998) and real data of symmetric planar motions (Cahouët et al. 2002), they have not been applied to analysis of full-body, asymmetric motions where additional constraints or residual errors may arise. Further, these current methods only consider a partial list of error-contributing factors (e.g., noise-polluted acceleration and force plate data). Many other inverse dynamics input variables such as segmental angle and mass properties can also be subject to significant errors or uncertainties (Desjardins et al.1998; Holden et al. 1997).

In this work, we explore a new approach to inverse dynamics computations applicable for full-body asymmetric movements. Our approach incorporates both motion and ground reaction force measurements, and optimally weighs the top-down and bottom-up solutions based on an analysis of the uncertainties in all possible variables contained in the equations of motion.

METHODS

The entire human body is represented by a 13-segment linkage consisting of the forearms (including the hands), upper-arms, torso, upper-legs, lower-legs, feet, and two weightless links connecting the bi-lateral shoulder and hip joints. The torso segment inter-connects the mid-points of above two links.

Two separate models meeting at the bottom of the torso are constructed. They serve as the bases for two sets of Newton-Euler equations for inverse dynamics solutions, one for the upper body, and one for the lower body which incorporates the ground reaction force measurements. Consequently, there are two different torque estimates at the bottom of the torso, resulting respectively from the "conventional" top-down and bottom-up inverse dynamics solutions. One key constraint in our approach is that the discrepancy between the two estimates should be nullified; i.e., the two torque estimates must be adjusted to a common value. This adjustment leads to a "chain reaction" of changes in the remaining joint torque estimates such that the sum of weighted changes is minimal in a least-squares sense. Additional constraints on the residual errors at the top-most or bottom-most segments are also enforced.

The weights are quantified by the uncertainties in the joint torques: the greater the uncertainty, the greater the amount of adjustment made to the original estimates. Here the uncertainties are determined using an error analysis method (Doeblin 1966):

$$E = \sqrt{\left(\frac{d\tau}{dx_1}\Delta x_1\right)^2 + \left(\frac{d\tau}{dx_2}\Delta x_2\right)^2 + \ldots\ldots + \left(\frac{d\tau}{dx_n}\Delta x_n\right)^2} \qquad (1)$$

where τ is the torque at a given joint; Δx_i are estimated errors associated with the input variables in the equation of motion; and E is the statistical representation of uncertainty (±3σ) in the torque value. The error magnitudes (Δx_i) are synthesized from literature data (Kingma et al. 1996; Schmiedmayer & Kastner 2000; Ganley & Powers 2004) and our own experimental results. The new torque at the bottom of torso is adjusted according to following rule:

$$\tau' = \tau_B + \frac{\tau_T - \tau_B}{E_T^2 + E_B^2} E_B^2 \qquad (2)$$

where τ' is the new torque; τ_T and τ_B are torque estimates resulting from the top-down and bottom-up solutions, respectively; E_T and E_B are the uncertainty estimates obtained from the error analysis. The τ' thus determined is a least-squares solution that minimizes the weighted total of torque changes $\sum \Delta\tau_i^2 / E_i^2$.

To demonstrate the efficacy of the proposed approach, we conducted an experiments in which three males (weight: $82.2 \pm 7.3kg$; height: $180.2 \pm 0.08m$) walked at natural speed with the right foot landing on a force plate (AMTI BP600900). A six-camera Vicon system recorded their movements.

RESULTS AND DISCUSSION

The magnitudes of uncertainties change over time particularly the top-down solution τ_T (Fig. 1). Also revealed is the error-accumulation in the bottom-up direction. Therefore, it is important to weigh the adjustments and do so in a frame-by-frame manner. The grand-average (over time and across subjects) for the discrepancy $\|\tau_T - \tau_B\|$ (Fig. 2) is 9.2 Nm, and for the uncertainty $(E_T^2 + E_B^2)^{1/2}$ as assessed by the error analysis is 15.4 Nm. Both are in the same order of magnitude as error values previously reported (Plamondon et al. 1996), which lends credence to the error analysis performed in this work.

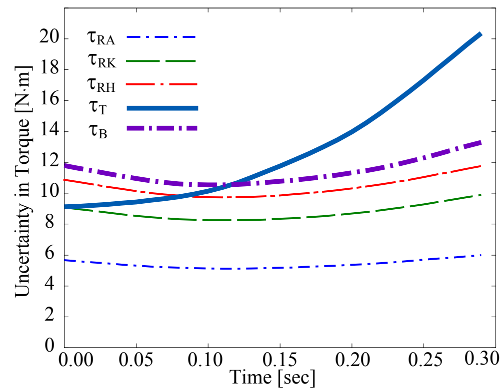

Figure 1: Sample profiles of uncertainties in joint torques during the left-leg-swing phase.

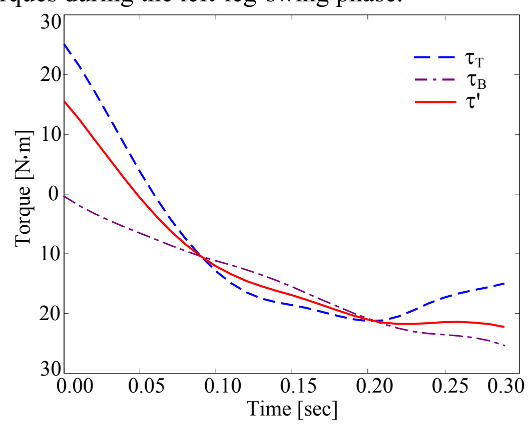

Figure 2: Torques at the bottom of the torso resulting from the top-down, bottom-up, and new approaches.

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