REDUCING RESIDUAL FORCES AND MOMENTS IN A THREE-DIMENSIONAL SIMULATION OF RUNNING

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INTRODUCTION

Understanding the actions of muscles during running is a challenging problem because important variables, such as muscle forces, are generally not measurable. To gain insight into muscle actions we are creating three-dimensional simulations of running that track experimentally measured running dynamics and allow estimation of muscle forces and the motions they produce. Unfortunately, due to experimental errors and modeling assumptions, such as lumping arms into a rigid trunk segment, dynamic inconsistencies between experimental kinematics and ground reaction force arise (Kuo, 1998). To resolve dynamic inconsistencies an additional force and moment (called residuals) must be applied to a model such that the sum of the residuals and the ground reactions equal the mass-acceleration products of the body segments. To improve the dynamic consistency of forward dynamic simulations, Delp et al. (2007) developed a residual reduction algorithm (RRA). By slightly adjusting body segment mass distributions and experimental kinematics, residuals applied to the model can be significantly reduced. The purpose of this study is to investigate the performance of RRA in reducing the residuals in a three-dimensional simulation of running.

METHODS AND PROCEDURES

Data were collected on an adult male subject (height 1.83 m, mass 65.9 kg) running at 3.9 m/s on a Bertec split-belt instrumented treadmill (Fig. 1). A 6-camera Motion Analysis system recorded the positions of markers placed according to a modified Cleveland Clinic marker set. A three-dimensional 10-segment, 23 degree-of-freedom musculoskeletal model (Thelen and Anderson, 2006) with 92 muscles was scaled to match the anthropometry of the subject. An inverse kinematics problem was solved using weighted least squares optimization to determine experimental kinematics (e.g., joint angles) that minimized the error between experimental markers and markers on the model. A forward simulation of a running gait cycle that reduced residuals and tracked the experimental kinematics was then created using OpenSim (Delp et al., 2007).

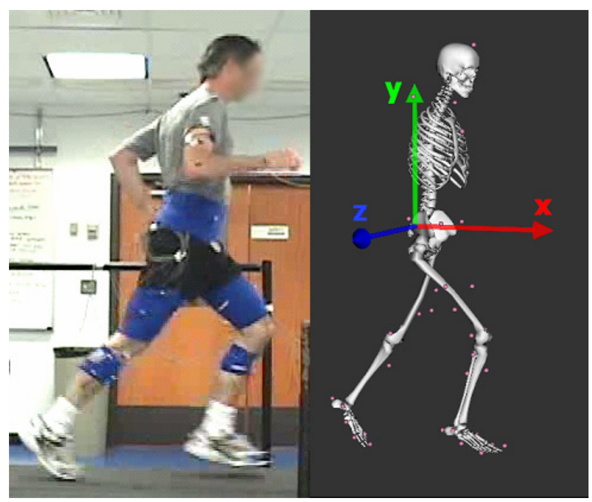

Figure 1. A three-dimensional simulation of running generated from motion capture data. Coordinate axes are shown for reference.

To investigate the performance of RRA, joint moments and residuals were calculated before and after use of RRA. In both cases, residuals were applied to the mass center of the pelvis segment. To reduce the residuals, RRA adjusted the torso mass center, the total mass, and the experimental kinematics.

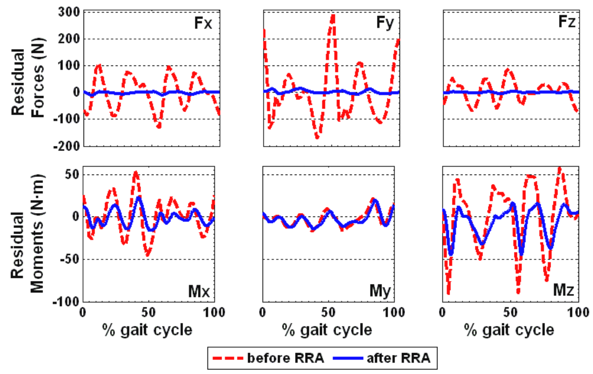

Figure 2. Residual forces and moments calculated before (dashed line) and after (solid line) RRA.

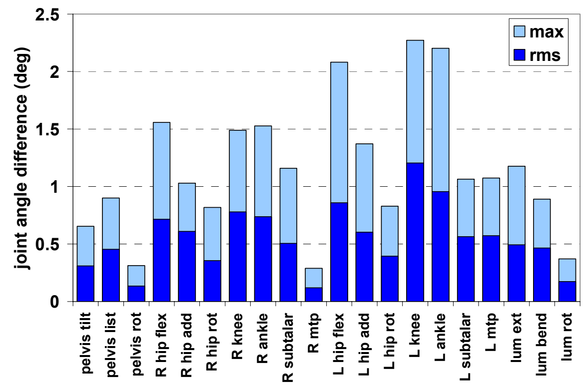

Figure 3. Maximum and RMS differences in kinematics (i.e., joint angles) before and after RRA.

RESULTS & DISCUSSION

Applying RRA substantially reduced the residuals. Prior to RRA, the residual forces were large. For example, F_y, the vertical force applied to the pelvis, was as large as 300 N. After application of RRA, the amplitudes of the forces applied to the pelvis were less than 15 N (Fig. 2, top row). RRA reduced M_x and M_z, the residual moments in the frontal and sagittal planes, by about 50%. In contrast, RRA did not appreciably reduce M_y, the moment in the transverse plane, perhaps reflecting that arm swing was not accounted for in the model. The maximum value of M_y (19.8 N·m) is similar to measured peak transverse moments due to arm swing (14.5 N·m; Cavanagh, 1990).

Our experimentally measured hip, knee, and ankle joint kinematics and moments were consistent with literature data (Winter, 1983; Swanson and Caldwell, 2000). The simulation tracked the experimentally measured joint angles to within 2.5º (Fig. 3). Maximum changes in pelvis translation were 9 mm in the anterior-posterior and superior-inferior directions, and 12 mm in the medial-lateral direction. The torso mass was adjusted 0.14 kg and its mass center was moved less than 1 mm.

Moments at the knee and ankle were not appreciably altered by RRA, but changes in back joint moments were as large as 20%. This suggests that residual reduction may not be important when estimating forces generated by ankle and knee muscles. However, reducing residuals may be important for estimating forces generated by hip and torso muscles. Future work will use the altered kinematics and mass properties from RRA to create three-dimensional muscle-actuated forward simulations of running to investigate the action of muscles.

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