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SYNERGY CONTROLS IMPROVE PREDICTION OF KNEE CONTACT FORCES AND MUSCLE EXCITATIONS DURING GAIT

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INTRODUCTION

Knowledge of patient-specific joint contact and muscle forces during activities of daily living could improve the treatment of movement-related disorders (e.g., osteoarthritis, stroke, cerebral palsy, Parkinson's disease). However, it is currently impossible to measure these quantities in vivo under common clinical conditions, and calculation of these quantities using computer models is limited by the redundant nature of human neural control (i.e., more muscles than theoretically necessary to actuate the available degrees of freedom in the skeleton). Walking is a particularly important activity to understand, since loss of mobility is associated with increased morbidity and decreased quality of life [1].

This study investigates whether use of muscle excitation controls constructed from subject-specific muscle synergy information can improve optimization prediction of knee contact forces and muscle excitations during walking. Muscle synergies quantify how a large number of experimental muscle electromyographic (EMG) signals can be reconstructed by linearly mixing a much smaller number of neural commands generated by the nervous system. Our hypothesis was that controlling all muscle excitations with a small set of experimentally calculated neural commands would improve prediction of knee contact forces and leg muscle excitations compared to using independently controlled muscle excitations. The results will be presented at the conference within the broader context of the annual Grand Challenge Competition to Predict In vivo Knee Loads [2], and some unique plans for future competitions will be discussed as well.

METHODS

Waling data used in this study were from the Third Grand Challenge Competition to Predict In Vivo Knee Loads [2]. The subject (female, age 69 yrs, height 167 cm, weight 78.4 kg, neutral leg alignment) received an instrumented knee replacement for primary knee osteo-arthritis. Institutional review board approval and subject informed consent were obtained. The following types of data were collected from the subject: video motion capture from reflective surface markers on the arms, torso, pelvis, thighs, shanks, and feet; ground reaction force and moment from three force plates; surface EMG from 13 hip, knee, and ankle muscles in the implanted leg; and tibial contact force and moment from an instrumented tibial prosthesis. Medial and lateral contact forces were calculated from six-axis tibial load cell data using calibrated regression equations (R2 = 0.99) developed using a deformable contact model of the subject's implant components [3]. A single trial of the subject's normal walking pattern was selected for analysis.

A subject-specific full-leg (pelvis to foot) musculoskeletal model was constructed in OpenSim [3] using full-leg CT scan data collected from the subject. The hip was modeled as a three degree-of-freedom (DOF) ball-and-socket joint, the tibiofemoral and patellofemoral joints as 6 DOF free joints, and the ankle as two non-intersecting pin joints. Muscle origins, insertions, and wrapping surfaces from a published OpenSim model [4] were transferred to the closest anatomic locations on our model after first scaling the published model to match the bone dimensions of our model as closely as possible.

The subject-specific OpenSim model was used to estimate knee contact and leg muscle forces using a novel static optimization approach. Two different categories of optimization problems were formulated, both of which minimized the sum of squares of 44 muscle excitations. The first category (called “Match” cases) tracked 8 experimental inverse dynamics loads (3 at the hip, 3 at the knee – flexion moment, adduction moment, and superior force, and 2 at the ankle) and 13 processed EMG signals. The six-axis knee loads measured by the instrumented implant were applied to the tibia and femur so that tracked inverse dynamic knee loads accounted for contributions from knee contact forces. Thus, the first category matched the experimental medial and lateral knee contact forces and processed EMG signals by design. The second category (called “Predict” cases) tracked 6 experimental inverse dynamics loads (3 at the hip, 1 at the knee – flexion moment only, and 2 at the ankle) with no tracking of EMG data. This category predicted medial and lateral knee contact forces along with processed EMG signals.

Muscle excitation controls for both categories were modeled two ways. The first method (called “Independent”) parameterized each of the 44 muscle excitations independently using B-splines. The second method (called “Synergy”) used non-negative matrix factorization [5] to decompose the 13 mutually dependent processed EMG signals into 6 independent neural command signals with corresponding weights that accounted for 95% of the variability in the original processed EMG signals. For this method, neural commands rather than muscle excitations were parameterized with B-splines, and the corresponding synergy weights were also treated as parameters. In both cases, muscle activation and contraction dynamics were modeled by discretizing the relevant first-order ordinary differential equations describing the EMG-to-activation and activation-to-force processes.

This methodology resulted in four optimization problem formulations: 1) Match/Independent, 2) Match/Synergy, 3) Predict/ Independent, and 4) Predict/Synergy. All four optimization problems were solved using Matlab’s lsqnonlin nonlinear least squares algorithm. In addition to minimizing excitations and tracking experimental inverse dynamic load (and EMG) curves, the cost function minimized changes in activation and contraction dynamics parameter values away from literature values [4].

RESULTS AND DISCUSSION

Both Match cases closely reproduced the experimental inverse dynamics loads (RMS errors <= 16%, R^2 >= 0.93) and EMG signals (average %VAF >= 0.85, average R^2 >= 0.80). Corresponding medial, lateral, and total contact forces were also closely matched (RMS errors <= 75 N, R^2 >= 0.93,). In contrast, for the Predict cases, the Synergy controls better predicted contact forces and muscle excitations than did the Independent controls (Figs. 1 and 2). In particular, Synergy controls predicted knee contact forces better in mid stance (dip near 25% of gait cycle) and over all of swing phase while also predicting contact force peaks better. For both Predict cases, inverse dynamics loads were again closely matched (RMS errors <= 14%, R^2 >= 0.96).

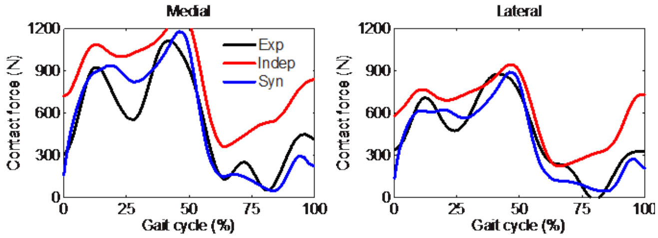

Fig. 1: Comparison between experimental (black) and predicted knee contact forces for Independent controls (red) and Synergy controls (blue).

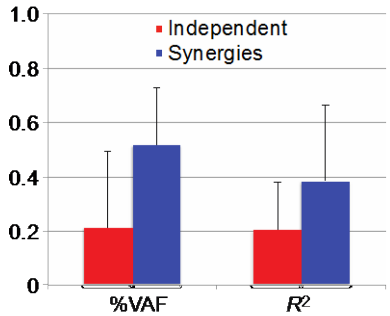

Fig 2: EMG prediction accuracy for Independent controls (red) and Synergy controls (blue).

CONCLUSIONS

By constraining simulated muscle excitation patterns to be constructed from linear combinations of experimentally determined neural commands, we were able to predict knee contact forces (medial, lateral, and total) and leg muscle excitations more accurately than we could using independently controlled muscle excitations. This finding suggests that taking advantage of subject-specific neural constraints exhibited by muscle synergies may lead to more physiologically realistic predictions of internal forces in the human body.

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