MUSCULOSKELETAL MODELLING: HOW IT BEGAN, WHAT IT OFFERS, AND WHERE IT IS HEADING

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## MOTIVATION

Musculoskeletal diseases in 2004 cost the United States economy more than $849 billion [1] (7.7% of GDP) and places great demands on healthcare systems worldwide. Musculoskeletal modelling and simulation has a tremendous potential to improve patient care and reduce treatment costs by elucidating cause and effect relationships related to neurological and musculoskeletal impairments and by predicting effective surgical and rehabilitation treatments.

## EVOLUTION OF MUSCULOSKELETAL MODELING

Conceptual models of the musculoskeletal system began as early as the 18th century when Newton's equations of motion were formulated by hand to investigate animal limb movement and dynamics [2]. From these roots, musculoskeletal models have evolved rapidly matching the exponential growth in computing capacity. Computers have enabled nonlinear dynamical equations, typical of musculoskeletal models, to be solved numerically without analytical or closed-form solutions. Beginning with the dynamic computer simulations of Chow and Jacobson [3] models have advanced to provide greater insights into human gait with greater ease (Table 1).

**Table 1:** The evolution of dynamic gait simulations.

| | dofs | forces | cpu time(s) |
|---|---|---|---|
| Chow and Jacobson (1976) | 5 | 5 | NA |
| Davy and Audu (1987) | 3 | 9 | NA |
| Yamaguchi and Zajac (1990) | 8 | 10 | NA |
| Anderson and Pandy (2001) | 23 | 64* | 8,000,000 |
| Thelen and Anderson (2006) | 21 | 92† | 1,800 |

* 54 muscles, 10 foot springs; † 92 muscles

Although numerical integration can solve dynamical models with many degrees of freedom and applied forces, formulating representative computerized equations is a nontrivial task. The advent of multibody solvers (e.g., SD/FAST, ADAMS, DADs, SimBody) has allowed non-dynamicists to formulate and solve equations with greater ease. The difficulty, however, remains in describing the geometry and interconnectivity of musculoskeletal systems that do not resemble the idealized shapes found in engineered mechanisms. Muscle paths, for example, are either ignored [3] or painstakingly described according to experimental data sets [4, 5].

## DESCRIPTIVE MUSCULOSKELETAL MODELS

Delp et al. [5] leveraged emerging computer graphics to visualize bones and muscles to enable interactive manipulation of muscle paths and automated calculations of muscle moment-arms and lengths. Graphical models are more easily compared to cadaver and medical imaging data. Software for Interactive Musculoskeletal Modeling (SIMM) was born to bring computer aided design tools, so effective in engineering industries, to the biomechanist. SIMM has enabled the accurate description of joints and muscle paths and provided an environment to test effects of muscle path changes, for example, from a tendon transfer surgery, on the moment generating capacity of muscles.

## INTEGRATING GRAPHICS WITH DYNAMICS

SIMM combined with SD/FAST to formulate the equations of motion, which generated the computer code necessary to solve the equations numerically. Seamlessly integrating graphical and dynamical modelling is one of the features of OpenSim [6].

## COMBINING MODELS WITH MOTION-CAPTURE

Models also allow us to obtain access to internal variables not accessible in experimental studies. Typical motion capture experiments, with trajectories from markers affixed to body segments and force-plate reaction forces, do not provide information about the action of individual muscles. However, by prescribing kinematics and applied loads from measurements, the internal forces/moments can be estimated with a model that satisfies Newton's laws of motion. In most cases, static optimization is employed to decompose joint moments into individual muscle forces. Solving a tracking problem (following motion-capture kinematics) with a dynamic model ensures that Newton's laws are satisfied and enables muscle dynamics to be included.

Models can be deconstructed to determine the acceleration of the whole body due to a single muscle, by applying or perturbing a single muscle force. This process, called a muscle induced acceleration analysis, was used with muscle actuated models of nine subjects walking at four different speeds to determine which muscles contribute to support and progression in unimpaired gait [7]. Recently we have analysed the muscle induced acceleration of a group of children with crouch gait resulting from cerebral palsy. The results present a dichotomy between the positive contribution of gastrocnemius to support (Fig. 1) and its large knee flexion acceleration. The large contributions to support offered by the plantarflexors argues against lengthening the Achilles tendon.

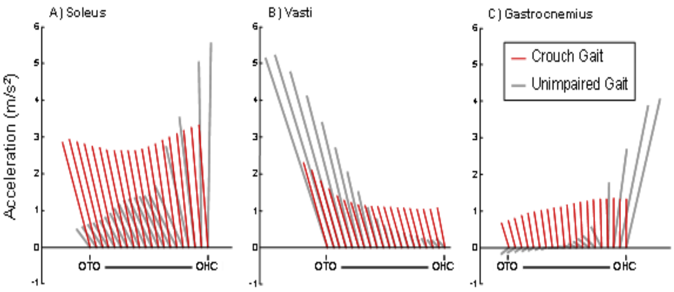


**Figure 1.** Muscle contributions to center-of-mass acceleration in impaired (crouch) and unimpaired gait.

## THE MODEL AS THE HYPOTHESIS

Models are useful for testing hypotheses about form and function. For example, it is assumed that crouched gait is induced or worsened by muscle tightness, resulting in tendon transfer surgeries being the leading form of treatment for crouch gait. However, outcomes from these surgeries are mixed. The question that arises is whether adopting a crouch gait provides advantages that make it favourable to adopt in some cases. We proposed the hypothesis that the crouched posture itself improves the capability of an individual to accelerate their body. To test this hypothesis, we placed a 3D musculoskeletal model with 15 degrees of freedom and 92 muscles into crouched and upright postures during midstance. We then maximized the transverse-plane ground reaction forces by varying muscle forces in the model within physiological ranges.

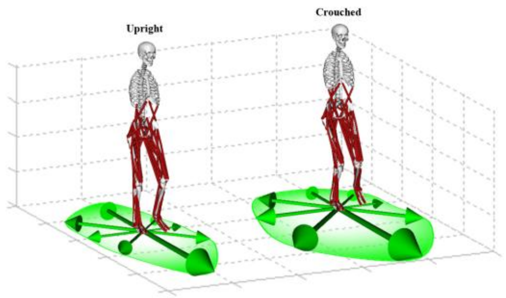


**Figure 2.** Maximum midstance ground reaction forces generated in the transverse plane from the musculoskeletal model in unimpaired (upright, left) and crouched (right) gait.

The crouched posture, on average, generated 24% larger maximum ground reaction forces during midstance compared with an upright posture (Figure 2). Therefore, one potential benefit of adopting a crouched posture is the increased mechanical advantage of muscles to accelerate the center-of-mass both forward and medio-laterally as was hypothesized. This may help to compensate for balance and other deficiencies resulting from cerebral palsy.

## PREDICTING OUTCOME FROM SIMULATION

By far the most powerful aspect of dynamical models is the ability to ask “what if” questions and the potential to predict outcome. This requires a high degree of confidence in the model to represent both the mechanical and neurological conditions of the patient, which can be very difficult considering the complexity of the central nervous system. In some cases we can assume an ideal behaviour to test the best case scenarios. For example, stiff-knee gait, which is characterized by diminished knee flexion during the swing phase, is a common symptom of spastic cerebral palsy. Many stiff-knee patients exhibit excessive knee extension moments prior to swing which has been attributed to rectus femoris (RF) muscle activity [8]. We asked whether abnormal RF excitation prior to swing or during swing has a greater influence on peak knee flexion by ideally eliminating RF excitation during pre-swing and early swing (Figure 3b).

We generated preoperative subject-specific simulations of ten cerebral palsy patients who exhibited stiff-knee gait and underwent RF transfer by tracking subject motion capture data with scaled models. The simulated effects on peak knee flexion were compared for each subject, by eliminating excitation prior to and during swing. Peak knee flexion was influenced more by abnormal RF excitations prior to swing compared to those during swing, (Figure 3c). Therefore, pre-swing RF activity is a stronger indication for RF transfer than the traditional focus on activity during swing.

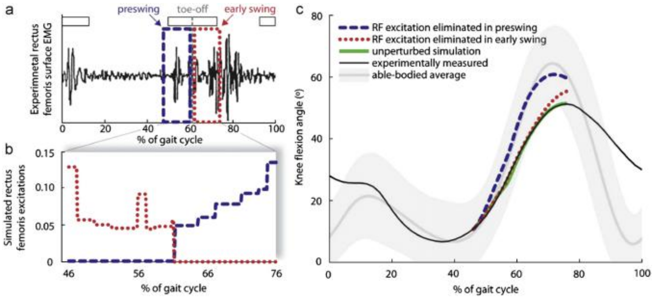


**Figure 3.** Increase in peak knee flexion when rectus femoris activity was separately eliminated during pre-swing and early swing. (a) Surface EMG. (b) Eliminated muscle activities. (c) Simulated knee flexion angles.

## CHALLENGES AND FUTURE VISION

Subject-specific simulation is a powerful tool for identifying the biomechanical causes of movement abnormalities and has the potential to improve treatment planning. However, simulations have yet to deliver on this promise. Joint and muscle path descriptions have improved significantly in the last two decades, but important challenges remain. First, the body’s acceleration is a consequence of the resulting ground reaction force; thus, it is imperative that contact modelling be incorporated for analysing locomotion. Second, to investigate the effects of model changes, we must be able to synthesize the excitation (controls) to muscles that would reproduce human behaviour. This is a daunting challenge given the complexity of the human central nervous system. Fortunately, detailed musculoskeletal models can serve as the platform for developing theories of motor control.

We envision a future in which simulations maximize treatment efficacy, limit undesired consequences and reduce costs. To accomplish this will require the scientific and clinical community to contribute and refine musculoskeletal models and their analyses. Towards this end OpenSim [8] was introduced to provide a free and open musculoskeletal modelling and simulation environment that combines the efficient formulation and solution of system dynamics with high fidelity graphics and analysis tools. It is our hope that OpenSim will act as a catalyst to promote model exchange and ignite modelling innovation to be shared by all.


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