CLINICAL INVESTIGATIONS: INSIGHT FROM COMPUTER MODELING AND SIMULATION TECHNIQUES

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BIOMECHANICAL MODELS AND SIMULATIONS

Understanding pathological movement in a clinical setting is extremely difficult because of the highly complex and non-linear characteristics of the neuromusculoskeletal system, the dynamic coupling that allows muscles to accelerate joints and segments they do not span and the presence of biarticular muscles that at times accelerate joints in the opposite direction from their anatomical classification. As a result, the root causes of pathological movement are obscured, making patient assessment difficult and resulting in treatment outcomes that are often unpredictable and likely sub-optimal. However, muscle-actuated forward dynamics simulations offer an extremely useful tool for understanding pathological movement because they allow for the identification of causal relationships between muscle excitation, specific neuromuscular and musculoskeletal properties and movement performance. These simulations include detailed mathematical neuromusculoskeletal models and have become powerful computational tools for identifying muscle coordination principles, diagnosing impaired movement, predicting clinical intervention outcomes, enhancing surgical procedures and identifying injury mechanisms.

Simulation studies have investigated important clinical questions such as how individual muscles: are coordinated to perform a given movement; contribute to joint and tissue loading; expend metabolic energy during movement; function in light of altered intrinsic muscle properties; utilize elastic energy stored in tendons; compensate in response to changes in prosthetic and orthotic design characteristics; and are injured during movement. Simulations can also be extremely useful in asking “what if” questions that cannot be easily answered *in vivo* such as how a particular surgical procedure will influence a muscle moment arm or altered neuromuscular properties influence muscle force and power output. This information can be used to help identify the etiology of movement disorders, make recommendations regarding preoperative surgery planning, design rehabilitation interventions to improve patient outcomes, optimize the design characteristics of orthopedic implants and prosthetic and orthotic components to improve their performance, and design neuroprosthetic systems to restore motor function.

CHALLENGES AND FUTURE DIRECTIONS

One of the primary challenges facing all modeling and simulation approaches, whether simple or complex, is confirming the accuracy of the simulation output. Verifying whether the model is truly predictive of human performance is a formidable challenge since many of the quantities of interest are not measureable, hence the use of the model in the first place. However, carefully designed experimental studies can be used to confirm simulation results and provide impetus for the next generation of further improved models. Similarly, sensitivity analyses can be performed to see how sensitive the model predictions are to specific modeling assumptions. This allows one to systematically define without prejudice the next research needed to improve the model’s success in meeting desired research objectives. Another challenge is that most studies are performed using generic models based on cadaveric data, and therefore analyses are not performed at the individual patient level. Neuromusculoskeletal models that combine data from subject-specific anatomical, physiological and imaging measurements with muscle models that accurately characterize intrinsic muscle force generating properties and neural control elements of the neuromuscular system offer great promise of improving the fidelity of modeling and simulation predictions. Another challenge is to develop a user-friendly modeling and simulation framework that is accessible to the research community (e.g., OpenSim). Current techniques are computationally intensive and require significant programming and mathematical modeling expertise that has limited their impact in research. Despite these challenges, modeling and simulation of human movement is an exceedingly powerful tool that provides a framework for significant advances in patient care and clinical and biomechanical research.