Musculoskeletal Modeling for Hip Replacement Outcome Analyses and Other Applications

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The ability to quantify internal stress distributions within the musculoskeletal system is of particular importance for joint arthroplasty in orthopaedics and subsequent outcome analyses. Musculoskeletal analysis and modeling (MM), which traditionally used rather theoretic algorithms and applications, has now developed to the point that numerically stable and anatomically correct simulations are possible. Importantly, these analyses can now be performed on a patient-specific level. Patient-specific MM considers individualized anatomic features and can incorporate specific movement patterns derived from activities of daily living through motion capture. Whole-joint models consisting of bone, muscle, and joint definitions allow for analysis of joint reaction forces and muscle activation patterns. By taking advantage of increased computational power and more sophisticated modeling techniques, important fundamental and clinical research questions can be addressed.

Recently, MM techniques have been successful in the evaluation of biomechanical outcomes for total hip replacement and resurfacing procedures by several research groups. Focus areas include joint impingement and wear rates, both of which are related to rim (or edge) loading of the acetabular cup. Obviously, implant positioning has a major influence on these parameters. However, patient-specific motion patterns may also have a considerable influence on, for example, wear parameters.[1]

To study these effects, a combined workflow of experimental and numeric methods is typically used. Gait analysis (three-dimensional) and ground reaction forces are used as kinematic and kinetic input parameters to MM. Then generic musculoskeletal models are scaled and adjusted to the patient's anatomy using anthropometric and medical image data. The accuracy of these subject-specific simulations has already surpassed levels that were previously possible. Despite these advancements, MM models, as with all computational simulations, are still subject to sensitivity checks to ensure that accuracy is maintained. Thus, with knowledge of implant position via postoperative scans or intraoperative navigation, hip reaction forces and relative orientations with respect to the acetabular cup can be computed. Then detailed biomechanical analyses of the postoperative loading conditions can be performed—for example, the differences between operated and nonoperated joints can be quantified.[2] Furthermore, this approach can then be combined with simulation at the tissue level through, for example, finite element analysis, to tease out the mechanobiologic effects of surgical intervention.[3] In addition to becoming a standard analysis tool for surgery and postoperative analyses, MM is also set to have an impact on longer-term follow-up issues such as rehabilitation programs, further improving patient care.[4] During hospital stay or in-house rehabilitation programs, patient-specific MM may also be used to draw attention to potentially deleterious aspects of activities of daily living.[5]

There are other fields of orthopaedics in which similar musculoskeletal modeling techniques could be applied. For example, the biomechanical basis for trauma and subsequent tissue degeneration, which is seen in knee joint injury and subsequent posttraumatic osteoarthritis, is an excellent candidate for this approach. In the case of anterior cruciate ligament rupture, whole joint modeling, incorporating bone, muscle, and other joint tissues, would allow for analysis of joint reaction forces at the time of injury, as well as the new equilibrium state following loss of ligamentous restraint. Then, combining these data with finite element analysis could provide insights into the tissue-level changes that occur both within the joint and, particularly, in the adjacent tissues of the subchondral compartment.

As is the case with all computational simulations, experimental validation of these models will be an important consideration. Therefore, procedures and strategies have been developed to validate various elements of musculoskeletal analysis.[6] For example, electromyography is used to compare computed and in vivo muscle activity.[7] However, it still remains a challenge to validate the simulated data against in vivo force data; the use of animal models may prove to be useful in this regard.

Musculoskeletal models may also come to play a role in the prevention of long-term degenerative diseases. With the recent advances in motion-sensing devices, such as those used in the interactive entertainment industry, usually based on accelerometer and optical sensor technology, completely novel methods of disease detection and diagnosis may be possible. If these motion-sensing input devices can be used to generate accurate patient-specific kinematic data, then computational procedures such as those discussed above could be applied to detect early stages of joint degeneration to define optimal medical or surgical management and to optimize postoperative rehabilitation strategies.

MM has now evolved to the point at which accurate patient-specific applications are a realistic option. This approach offers the ability to generate individualized patient-specific models that can quantify changes in joints and tissues following surgery or as a result of injury or disease.

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