INTRODUCTION

Sophisticated biomechanical models offer the clinician a means to answer questions about the diagnosis and treatment of patients which would not otherwise be possible. In particular they can allow the surgeon to predict the outcome of a particular intervention, and to optimise that intervention for a particular patient. In order to meet these goals, a number of criteria must be satisfied. Musculo-skeletal models must be:

- realistic, including all relevant structures;
- interpretable;
- fast;
- user-friendly.

Inverse-dynamic models have often been used in the analysis of biomechanical problems. They generally require only moderate computing power, and have often been used to determine muscle and joint loads. For computer-assisted surgical planning, however, they are not ideal. Firstly, they require assumptions to be made about post-operative kinematics, which are of course unknown, and secondly the output, muscle, joint and ligament forces, are not always easy to relate to patient function. The predictive capability of inverse-dynamic models is thus limited.

Forward-dynamic (FD) biomechanical models, on the other hand, are ideally suited to computer-assisted surgical planning (CASP) in so far as they allow the effects of changes to the musculo-skeletal system to be studied with no a priori knowledge of post-operative kinematics. In addition to removing the need to make assumptions about post-operative kinematics, motions as output allow the results of a simulation to be more easily related to patient function. The disadvantage of forward-dynamic models, though, is that a set of neural inputs is required to drive the model. Conventional FD models optimise these neural inputs, which is computationally very demanding. At each step in the optimisation process, the integration of the whole system must be carried out. For large-scale models, which are essential for realistic modelling, this leads to prohibitively long simulation times (in the order of days or weeks).

An efficient method for the optimisation of FD musculo-skeletal models combining inverse and forward dynamics is described in this study. This method allows the use of large-scale, forward-dynamic biomechanical models in computer-assisted surgical planning and has been applied to the Delft Shoulder and Elbow Model (DSEM).

METHODS

Model Structure

The model to which this algorithm was applied is described in van der Helm (1994). The model is based on the principles of finite element analysis. Each anatomical structure is represented by an appropriate element type. Bones are modelled as rigid bodies, muscles as active trusses (tensile force generating elements) and ligaments as passive trusses (passive elements which can only be loaded in tension). The one exception to this is the conoid ligament which, due to its high stiffness, is modelled as a rigid link. Each node of the finite element model represents an anatomically important structure, such as a joint rotation centre, ligament attachment point or muscle attachment point. Geometrical data for the model are taken from the cadaver studies of Klein-Breteler (1999) and Minekus (1997). In these studies the origins and insertions of the 31 muscles around the shoulder and elbow joints were measured, as well as fibre lengths, sarcomere lengths, tendon lengths, physiological cross-sectional areas (PCSA) and pennation angles.

Optimisation Procedure

Happee and van der Helm (1995) described the combined inverse-/forward-dynamic optimisation (IFDO) method in which muscle dynamics are included in an inverse-dynamic optimisation. The inclusion of muscle dynamics results in an increase in the constraints on the optimisation, preventing sudden, physiologically impossible changes in muscle force.

A muscle model with two state variables is used: contractile element length and activation. Excitation is treated as an input to the muscle model and is taken to be constant over one time-step.

Muscle state variables at time-step \( i-1 \) are integrated using a forward muscle model with minimum (0) and maximum (1) neural inputs to calculate minimum and maximum muscle forces at time-step \( i \). These values form the bounds of the muscle force optimisation. Neural inputs associated with these forces are calculated in a Newton-Raphson iterative process, and subsequently used to drive the FD model from time-step \( i-1 \) to time-step \( i \). An Adams-Moulton routine is used for the integration of the mechanism in the FD model. Differences between the resulting motions of the FD model and the measured motions can be used to correct the calculation of neural inputs at time-step \( i \). This is known as IFDO with controller, or IFDOC, and is shown in Figure 1. The controller is implemented as a corrective moment applied to the generalised coordinates (degrees of freedom). The deviation of the FD model from the desired trajectory is checked at the end of each time-step and a moment in the opposite direction applied to the mechanism during the following time-step, thus bringing the mechanism back towards the required trajectory. The weight factors for the controller were determined empirically.
This results in an optimal set of neural inputs for a given motion. These neural inputs can subsequently be used to drive the model in forward-dynamics mode without the need for further optimisation. Small changes to the geometry of the model can then be made (virtual surgery) and the simulations rerun to examine the effects of these changes on the resulting motions. Changes to the musculoskeletal system which can be simulated are limited to small changes in geometry (e.g. a change in the rotation centre of a joint after arthroplasty) or other changes after which the neural inputs may be assumed unchanged. Together with detailed knowledge of individual patient geometry obtained from imaging studies, this will allow the optimisation of a procedure for a given patient.

By way of illustration, a simulation is presented involving paralysis of serratus anterior. It may be assumed that, at least immediately post-injury, the neural inputs remain unchanged. It should be emphasised here that this simulation is presented purely for the purposes of illustration, and that no conclusions may be drawn at this stage of the model development.

Figure 1: IFDOC scheme

Figure 2. Forces predicted by the FD model during abduction of the humerus
For example, the effects of a displacement of the centre of rotation of the gleno-humeral joint after shoulder arthroplasty could be simulated. Provided the changes remain small, it is assumed that the neural inputs will be the same pre- and post-operatively, as further optimisation is not possible.

The above-mentioned simulation of serratus anterior paralysis also assumes that the neural inputs calculated with a healthy geometry can be applied to the pathological case. This is justified on the grounds that the paralysis occurs suddenly and that the patient would initially attempt to complete the task using familiar patterns of activation. The extent to which the assumption of constant neural activations can be taken remains to be seen, and will be a major part of future validation work. It must also be remembered, of course, that in the case of inverse-dynamic models the assumption that pre- and post-operative kinematics are the same is often made, but is in fact unlikely to be true.

**CONCLUSIONS**

This methodology allows the use of forward-dynamic modelling with large-scale models, opening up many new possibilities. Optimal neural inputs for healthy motions can be generated, and used as the basis for studying pathological anatomy. As the optimisation is carried out in the inverse-dynamic stage, and there is no optimisation during the FD stage, the simulations are relatively fast, compared to the days or weeks mentioned above. Changes to the model can be made (virtual surgery) using an intuitive graphical user interface, and their effect on the predicted motions studied, making the model usable as a Computer-Assisted Surgical Planning tool.

**REFERENCES**


**Figure 1** Activations in certain upper limb muscles predicted by the IFDOC routine during abduction of the humerus.