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FORCE-DEPENDENT KINEMATICS: A NEW ANALYSIS METHOD FOR NON-CONFORMING JOINTS

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INTRODUCTION

In traditional inverse dynamic analysis of musculoskeletal models [1,2], kinematics and kinetics are treated separately. Kinematic analysis is performed to compute the position, velocity and accelerations of the segments in the model from a description of the joints and the motion. This is formulated through the solution of a set of nonlinear constraint equations. Subsequently, the computed segment positions, velocities and accelerations are substituted into the dynamic equilibrium equations to obtain a set of equations with only unknown reaction and muscle forces. This set of equations is solved through muscle recruitment by assuming a criterion for the distribution of the internal forces between the muscles and the reactions. This approach requires that the joints and motion of the model can be completely described through these constraint equations without consideration of the forces that created the motion. However, several anatomical and prosthetic joints, such as spinal disks, knees and many shoulders are non-conforming to such an extent that the forces significantly influence the detailed joint kinematics and the joint's internal force equilibrium. For instance, in the knee, the internal motions occurring are due to a complex interaction between the muscle actions, cartilage contact mechanics, and soft tissue stiffness and deformations. Forward dynamics approaches have the potential to address these phenomena, but they do not handle complex muscle systems well and often require careful tuning and long computation times to simulate vibrations and damping which in many cases are not very relevant to orthopaedic problems.

To address this problem, we recently developed a new method called Force-Dependent Kinematics (FDK) [3]. The method is used to compute the muscle and reaction forces as well as not-predetermined motion in user-specified directions. In this study, we applied FDK to a simple test problem to model the elbow joint in a 2D model of the arm using contact forces based on two points

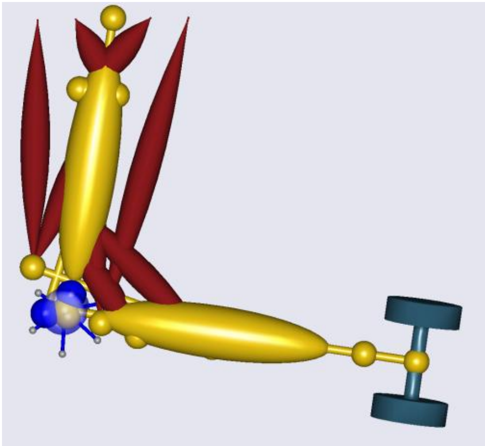

Fig 1: 2D forearm and upper arm model lifting a dumbbell weighing 5 kg. The elbow is modeled using FDK.

in contact with the surface of a cylinder as well as linear springs, mimicking bone contacts as well as ligaments, respectively (Fig. 1).

METHODS

The FDK method is based on an assumption of quasi-static force equilibrium between all the acting forces in the model in the directions in which it is desired to also compute the displacements (denoted α_s). Computationally, α_s is computed by introducing a kinematic driver equation ($\Phi_s(q,t) - \alpha_s = 0$) in a standard inverse dynamic analysis model to obtain a kinematically determinate system for a given α_s. The function $\Phi_s(q,t)$ of the model coordinates, q, and time, t, computes the FDK directions. We assume that the time derivatives of α_s are zero, i.e. we obtain a quasi-static solution. FDK reaction forces, F_s, in the same directions are also introduced. Hereby, the muscle and reaction forces, including the FDK reaction forces, required to balance the model for a given α_s can be computed. The desired FDK displacements bring all the forces in the model in balance, i.e. where the FDK reaction forces are zero. This leads to the computational workflow illustrated in Fig. 2.

A simple 2D test model was constructed. The model consisted of the forearm, upperarm, elbow joint, a dumbbell, weighing 5 kg, and seven

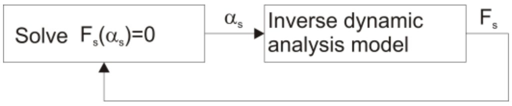

Fig 2: FDK analysis framework. The displacements in the FDK directions (α_S) are computed as the displacements, where no artificial reactions (F_S) are required to balance the model in these directions.

muscle units. The muscles were assumed to be equally strong and with constant strength of 300 N. Three elbow models were tested; a revolute joint and two models with linear contact forces and five linear springs, mimicking bone contacts and ligament actions around the elbow. Contact forces were computed between two points attached to the upper arm (the blue points in Fig. 1) and a cylinder attached to the forearm. The five springs were equally spaced on a circle in the upper arm and they all attached to the same point in the forearm. This point was also used as the center of rotation in the revolute joint.

The model performed a one second lift of the dumbbell by flexing the elbow and shoulder 45^{O} and 30^{O}, respectively, starting with the elbow flexed 90^{O} and the shoulder extended 10^{O}.

RESULTS AND DISCUSSION

When the stiffness in the elbow model was high, the model practically produced the same results as with a revolute joint, i.e. no joint translations and the same muscle forces. However, when the stiffness of both the contact as well as the springs was lowered, the results were significantly different. The detailed motion of the joint was significantly different between the two joint models with high and low stiffness (Fig. 3). The model with high stiffness showed practically no joint translations, similarly to a revolute joint. With low stiffness, however, the simulation results showed translations of up to

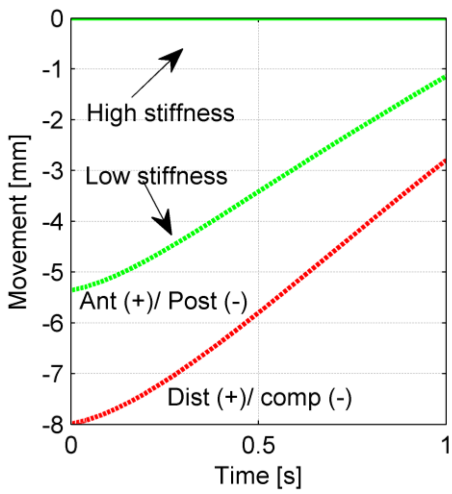

Fig 3: Computed joint translations in the elbow joint. Notice that with high stiffness, the translations are practically zero, whereas with low stiffness, there are some translations in the joint.

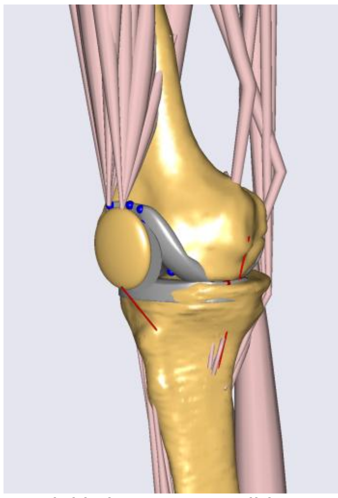

Fig 4: A TKR model is just one possible practical application of the FDK method.

8 mm.

Although the simple arm example illustrated here is not physiological, it demonstrates nicely the features of the FDK method of simultaneously computing the muscle and joint reaction forces, while still allowing modeling of the joints in terms of the force elements. Applications of the method on real problems are under development. For instance, a total knee replacement (TKR) model, an anatomical knee model and modeling of spinal fixation devices are under development. The TKR model is illustrated in Fig. 4 and preliminary results are presented in [3]. The detailed knee mechanics of the TKR model is modeled by the contacts between the implant components and the ligaments.

CONCLUSIONS

While we only demonstrated the FDK methodology on a simple 2D model, the same method works for more complicated 3D models as well. Due to the FDK method's capability to compute both the model motion and internal forces through quasi-static force equilibrium, it opens up new possibilities in detailed modeling of joints in musculoskeletal models. This can be accomplished by creating models directly of the mechanical structures of the joint in terms of force elements, rather than converting the actions of the force elements into kinematic constraint equations. This enables analysis of non-conforming joints under the influence of muscle forces.

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