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AN INTEGRATED MODELING APPROACH TO STUDY THE INTERACTIONS BETWEEN JOINT CONTACT GEOMETRY, KINEMATICS AND LOADING APPLIED TO THE KNEE

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INTRODUCTION

Knowledge of knee contact forces is important to investigate mechanical factors influencing treatment and progression of osteoarthritis [1]. Non-invasive measurements of contact forces in intact knees are not feasible and therefore, computer simulations are often used as an alternative approach to assess knee joint contact forces [2]. Simulation-based approaches to compute joint loading commonly consist of two phases. In the first phase, a musculoskeletal model with ideal joints (e.g. describing knee kinematics by a hinge) combined with measured kinematics and ground reaction forces is used within an optimization algorithm to compute the contribution of individual muscles to joint torques (muscle redundancy problem). In the second phase, joint contact forces are determined based on the resultant muscle forces using more complex joint models (e.g. geometry-based contact models). However, using a two-phase approach might limit the accuracy of estimated muscle and contact forces. First, in such approaches the relation between joint kinematics and joint loading is not taken into account and hence, joint kinematics are solely determined from the noisy marker trajectories with imposed constraints from the ideal joints rather than the actual joint surface geometry. Therefore, errors in the estimated joint kinematics due to soft tissue artefacts or inaccurate joint definitions will result in errors in resultant joint torques and consequently errors in the estimated muscle and contact forces. In addition, when solving the muscle redundancy problem based on a model with ideal joints, muscle forces are imposed to produce inverse dynamic joint torques along the degrees of freedom (e.g. knee flexion/extension) while the contribution of the muscles to the resultant torques and forces along the other directions (e.g. knee ab-/adduction) is not accounted for.

Therefore, we developed an integrated approach to calculate joint loading while accounting for the interactions between joint contact geometry, kinematics, and muscle and contact forces. To this aim, we use an optimal control approach to compute muscle inputs that drive a forward simulation of movement by tracking experimental marker trajectories based on a musculoskeletal model with geometry-based contact models. Our approach allows us to simultaneously estimate joint kinematics, muscle, and contact forces that are consistent with joint geometry and the measured marker trajectories. Here, we demonstrate our approach by applying it to the knee.

METHODS

Motion capture data including ground reaction forces and marker trajectories recorded from a male adult (72.12 kg, 26 years) during over-ground walking at self-selected speed were used in this study. The gait2392 OpenSim musculoskeletal model [3] of the lower limb was extended with a more detailed 6 degree-of-freedom (DOF) model of the knee. Bone to bone contact between the femoral condyles and the tibia plateau was modelled by Hunt-Crossley contacts between two spheres and a plane (Fig. 1). The knee ligaments (i.e., ACL, PCL, LCL, MCL, and DMCL) were modelled as nonlinear elastic elements [4].

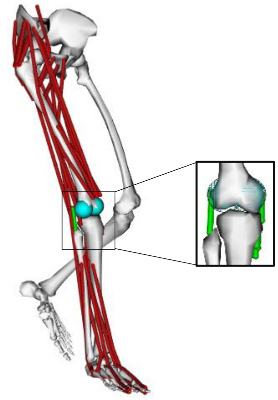

Fig 1: Musculoskeletal model used for the simulation of joint kinematics, muscle, and contact forces.

We computed muscle excitations that minimized a weighted sum of marker errors (difference between experimental and model marker trajectories) and muscle effort (squared muscle activations). This objective function was subject to the muscle and skeletal dynamics that describe the relation between muscle excitations and joint kinematics, from which marker trajectories are derived. Torques along the degrees of freedom in the hip and ankle joints were generated by muscles, while forces and torques along the six degrees of freedom in the knee were generated by ligaments, muscles, and the bone to bone contact.

The resulting dynamic optimization problem was solved using a computationally efficient direct collocation formulation (Fig. 2). The nonlinear programming problem was formulated in CasADi [5] using OpenSim's multibody dynamics library (Simbody) [6] and solved using IPOPT.

RESULTS AND DISCUSSION

Our optimization framework resulted in a realistic prediction of joint contact force (see Fig. 3), reproducing two main characteristics peaks of knee contact force, and with agreement with previously reported knee contact forces based on instrumented prosthesis [7] and computer simulations of joint loading [8].

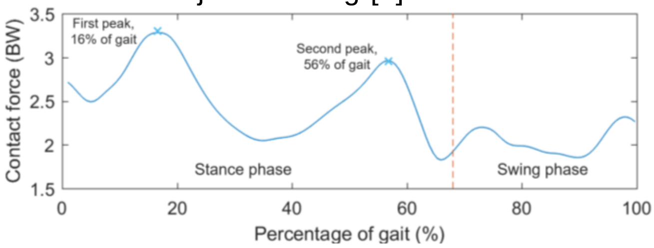

Fig 3: Predicted contact force for one gait cycle.

Joint kinematics estimated with the integrated approach was consistent with joint geometry (Fig. 4). Secondary knee joint kinematics estimated with the integrated approach differed from kinematics estimated based on marker trajectories without accounting for constraints imposed by joint surface geometry using Opensim's Inverse Kinematics (IK) tool. (Fig. 4). Here, we demonstrated the feasibility of an integrated approach to compute kinematics and loading. We will explore the use of more detailed surface geometries and validate our integrated approach using measured instrumented knee contact forces provided by "Grand Challenge Competition to predict in vivo Knee Loads [7].

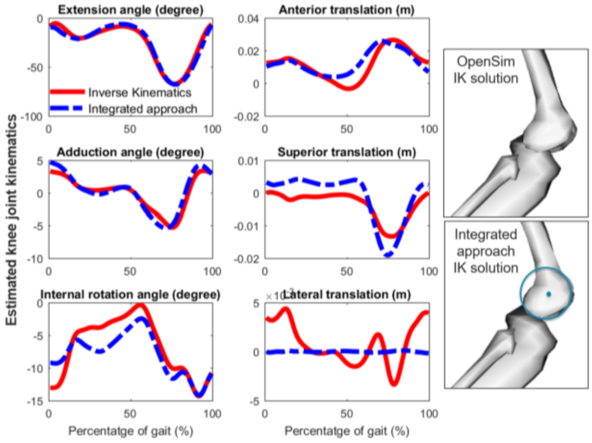

Fig 4: Estimated knee joint kinematics

CONCLUSIONS

Our forward dynamic simulations based on a musculoskeletal model that was extended with a complex knee joint contact model generated dynamically consistent estimations of kinematics, kinetics, muscle and contact forces. The developed method is not only important to understand the role of mechanical loading in OA, but also has the potential to facilitate the design of joint prostheses through *in silico* assessment of the effect of joint surface geometry on kinematics and loading. Our integrated approach can also be applied to other joints whose motion is largely determined by soft tissue forces such as the thumb and shoulder.

REFERENCES

1. Maly SJ, et al. *Curr Opin Rheumatol, Res* **20(5)**: 547-52, 2008.
2. Lin YC, et al. *J Biomech,* **43(5)**: 945-52, 2010.
3. Delp SL, et al. *IEEE Trans Biomed Eng,* **54**: 1940-1950, 1990.
4. Xu H, et al. *Comput Methods Biomech Biomed Engin,* **18(11)**:1217-1224, 2015.
5. Andersson JAE, et al. *MPC,* 1–36, 2018.
6. Sherman MA, et al. *Procedia IUTAM*, **2**: 241-61, 2011.
7. Fregly BJ et al. *J Orthop Res,* **30(4)**: 503-513, 2012.
8. D'Lima DD et al. *Proc Inst Mech Eng*, **226(2)**: 95–102, 2012.

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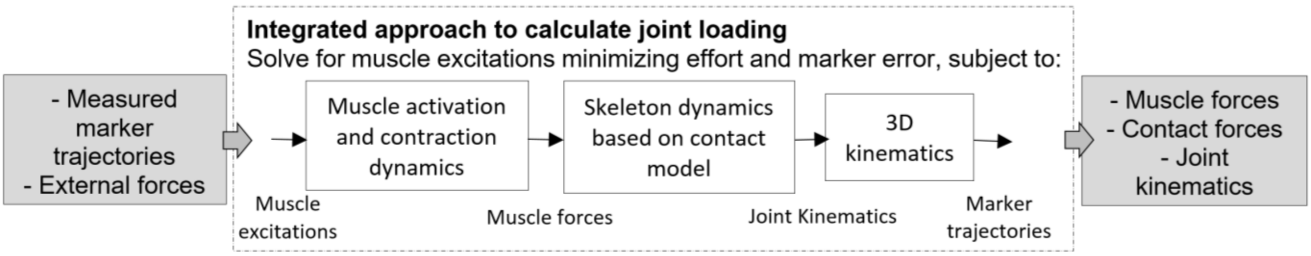

Fig 2: Schematic representation of the integrated approach