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FORCE-DEPENDENT AND OVER-DETERMINATE KINEMATICS APPLIED TO THE MANDIBLE

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INTRODUCTION

Musculoskeletal modelling (MSM) is commonly applied to estimate muscle, ligament and joint reaction forces that are not possible to measure in a typical clinical setup. In the most frequently applied models, the joints are modelled with idealized constraints such as the temporomandibular joint (TMJ) as a point-on-a-plane [1] (POP) and the knee as a revolute joint [2]. Due to the non-conforming geometries of some joints, the forces can significantly affect the joint kinematics and this is not captured by kinematic constraint-based joint models.

For this reason, recent studies have focused on developing enhanced simulation methods to enable detailed joint models within MSM. Thelen et al. [3] extended Computed Muscle Control (CMC) to co-simulate detailed musculoskeletal dynamics and knee joint mechanics using an Elastic Foundation (EF) joint model. Lin et al [4] introduced a two-level optimization approach to incorporate an EF-based contact knee model into a musculoskeletal model. Andersen et al. [5] introduced the Force-Dependent Kinematics (FDK) method, which has been implemented into the AnyBody Modeling System (AMS, AnyBody Technology, Denmark) and subsequently applied by several research groups to study, among others, the knee [6] and spine [7]. The FDK methodology augments an inverse dynamic analysis method with the possibility of not only computing muscle and joint reaction forces but also joint kinematics, taking into account complex joint geometry and elasticity of the surrounding soft tissues.

Common to these methods is that the gross movement is provided as input to the model and typically estimated using a model with a simplified joint model or no joint model at all based on measured skin marker trajectories, thus disregarding the complex constraint behavior of the real joint.

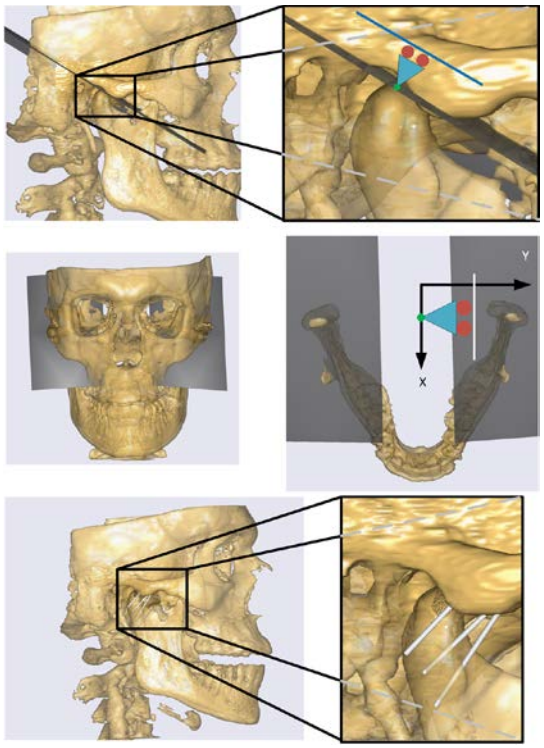

Fig 1: Illustration of the point-on-plane model (top and middle rows) and the FDK model (bottom row).

The purpose of this study was to develop an enhanced FDK approach based on tracking of skin markers in a model with a complex joint influenced, e.g., by EF contact and ligaments. The method was applied to a subject-specific mandible model to estimate joint kinematics and compared to measurements with a custom brace.

METHODS

A cone beam computed tomography (CT) scan (NewTom 5G, QR Verona, Italy) segmented using Mimics (Materialise, Belgium) was applied to develop a subject-specific MSM of a male subject (age 40, mass 70 kg) in the AMS. The model was equipped with 24 Hill-type muscles based on de Zee et al. [1].

Two different models of the TMJ were developed: 1) a POP model [1]. 2) An FDK model, with TMJ ligaments and contacts. (Fig 1).

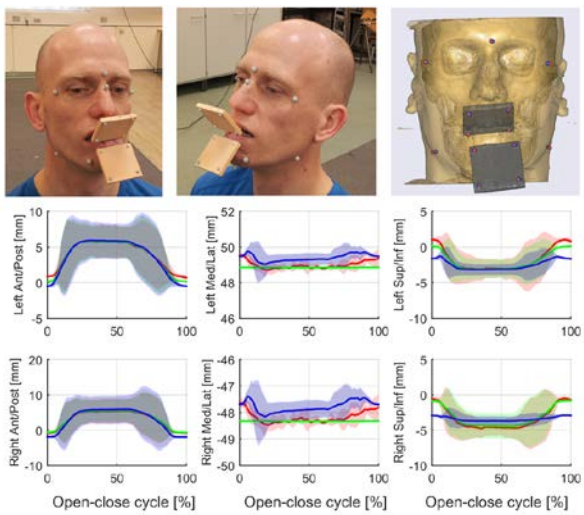

Fig 2: Top row from left to right: the subject wearing the brace during the motion capture session and the musculoskeletal model driven by the measured marker trajectories of the brace. Middle and bottom rows: Predicted left (middle) and right (bottom) joint kinematics during an open-close cycle of the FDK TMJ model (blue), POP TMJ (green) and measured kinematics (red). Shaded areas indicate ±1 standard deviation.

To accurately measure the movement of the mandible relative to the skull, a custom brace was developed based on a dental impression onto which retro-reflective markers were affixed (Fig 2). The trajectories of these markers were tracked by eight infrared high-speed cameras and collected at 100 Hz (Qualysis, Sweden).

While wearing the brace, the subject was instructed to, among others, open and close his mouth repeatedly from which five complete cycles were collected and the markers attached to the brace used as input to the model to drive the three degrees-of-freedom (DOF) not controlled by the TMJ models and to validate the three DOF estimated by the models.

For the POP model, over-determinate kinematics [8] was applied to track the marker trajectories and estimate the joint kinematics.

For the FDK model, the TMJ ligaments were modeled as nonlinear springs and the contact between the TMJ articulating surfaces with an EF model. The movements normal to the POP planes (Fig 1) and the medial/lateral translation were resolved through quasi-static force equilibrium between all acting forces (gravity, inertial forces, muscle forces, contacts and TMJ ligaments) in the model at each time step, whereas the remaining three DOFs were resolved, such that the least square difference between the brace markers and measured markers was minimized by applying an over-determinate kinematics solver [8].

RESULTS AND DISCUSSION

The measured and predicted kinematics of the open-close task are depicted in Fig. 2.

The POP model predicted the movement of the TMJ with a Root-Mean-Square (RMS) error of at most 0.47 mm (Sup/Inf direction) and with a Pearson's correlation coefficient above 0.98 for the Ant/Post and Sup/Inf directions. The Med/Lat direction showed poor correlation (0.14). The FDK model showed comparable results although the RMS errors were slightly higher (at most 1.41 mm) and the correlation coefficients slightly lower (0.85 or higher) for the Ant/Post and Sup/Inf directions but higher than the POP model in the med/lat direction (0.30). The improvements in the Med/Lat direction likely result from allowing the FDK solver to predict this movement whereas the slightly poorer predictions in the two other directions are likely caused by the simplified representation of the TMJ geometry, where especially the contribution of the TMJ disc was omitted.

CONCLUSIONS

In this study, we presented an enhanced FDK method that combines a quasi-static force equilibrium assumption and over-determinate kinematics to estimate muscle, ligament, and joint contact forces, and joint kinematics based on skin marker data and external forces. The method was applied to estimate and validate TMJ joint kinematics against measurements and those of a simpler POP model. The method and model represent a step forward in detailed, subject-specific musculoskeletal modeling and the methodology is applicable to other joints as well.

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