RoboSpine: Simulating Cervical Vertebrae Motion Using Elementary Contact Pairs

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Abstract

The reconstruction of inter-vertebral motion of the human cervical spine, although basically understood, still poses many open problems. This is so because pairs of vertebrae undergo in general six-dimensional motion relative to one another, but display a high degree of coupling between gross translational and rotational degrees-of-freedom due to restraints imposed by ligaments and muscles and the compliant nature of the inter-vertebral discs [4]. Described in this paper is the mathematical modelling of a vertebrae pair using multibody methods and impact analysis techniques with elementary contact geometry for the facet joints. The results are compared with existing approaches and with experimental data, showing a good agreement with the latter and an efficiency boost compared to existing approaches by a factor of 350. The investigations are focused on the vertebrae pair C5–C6 but can be easily extended to other vertebrae.

Madymo Model

MADYMO is a world-wide standard for occupant safety analysis. It was chosen in the present context for creating a reference computer model of the kinematic, static and dynamic intervertebral interactions. The facet joints were specified as `Ellipsoid-Ellipsoid Contact Interactions`. The visco-elastic behavior of the intervertebral disc was implemented by connecting the origins of the vertebra body reference systems through `Point-Restraints` for the translational part and `Cardan Restraints` for the rotational part, and supplying appropriate stiffness parameters for the ensuing relative degrees of freedom. Furthermore, six ligaments of type `Kelvin Element` were attached to the vertebrae. Data for the model parameters were employed according to [1]. The determination of static equilibrium poses of the vertebrae pair requires the computation of dynamics for the movable vertebra C5 until oscillations are damped out.

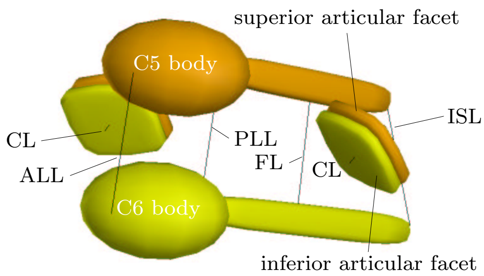

Figure 1: C5–C6 Madymo ellipsoid model

MOBILE Model

As an alternative approach, an object-oriented model of the vertebrae pair was implemented using the multibody program library MOBILE [2]. For the unilateral constraints of the facet joints, a class `MoRegImpCircleCircle` representing the contact of two cylinder faces, either in edge-edge, edge-face, or face-face (flat) contact was implemented and included in the MOBILE library. Contact is hereby regarded as a non-smooth state transition, with appropriate state event objects "firing" when a state transition takes place. This restarts the integrator with appropriate initial conditions, making the simulation more efficient than without stop conditions. State transition from flat contact to the other two types of contact and vice-versa is computed using a novel blending function, which avoids zig-zagging of state transitions for the nearby flat case. All other components, i.e., ligaments, the intervertebral disc, and stiffnesses of the facet joints, were modelled as in the MADYMO reference model. Static equilibrium poses were computed using the built-in object `MoStaticEquilibriumFinder` of MOBILE, which works with a Newton-Raphson algorithm. This rendered a highly efficient code that made it possible to move the vertebrae pair online in quasistatic analysis, using appropriate software sliders which change the system parameters interactively.

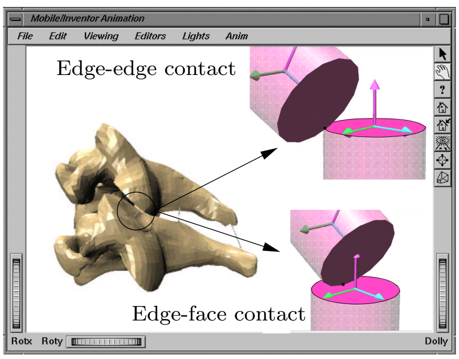

Figure 2: C5–C6 MOBILE model.

Model Validation

Both vertebrae pair models developed with the MADYMO package and the MOBILE library were compared and validated with the experimental results reported by Moroney [3] and the computer simulation performed by de Jager [1]. The simulations compute the translational and rotational deflections from the reference position of vertebra C5 to the new state of equilibrium for nine loading conditions corresponding to application of a single force (20 N) or moment (1.8 Nm) in direction of each elementary motion of C5. In this setting, the numerical values shown in Fig. 3 were obtained. Hereby, the following test loads were computed: anterior shear (AS), posterior shear (PS) for x-translation, lateral shear (LS) for y-translation, tension (TNS) and compression (CMP) for z-translation, lateral bending (LB) for x-rotation, flexion (FLX) and extension (EXT) for y-rotation, and axial rotation (AR) for z-rotation. As it can be seen, a good agreement between the experimental data and the computer models could be achieved. In particular, the simplified MOBILE model renders results that are not more inaccurate than the complex MADYMO model. However, the MOBILE model runs faster than the MADYMO model by a factor of 350. This allows one to compute the motion of a vertebrae pair in real-time simulation environments, in contrast to the MADYMO model, which can be used only in offline applications.

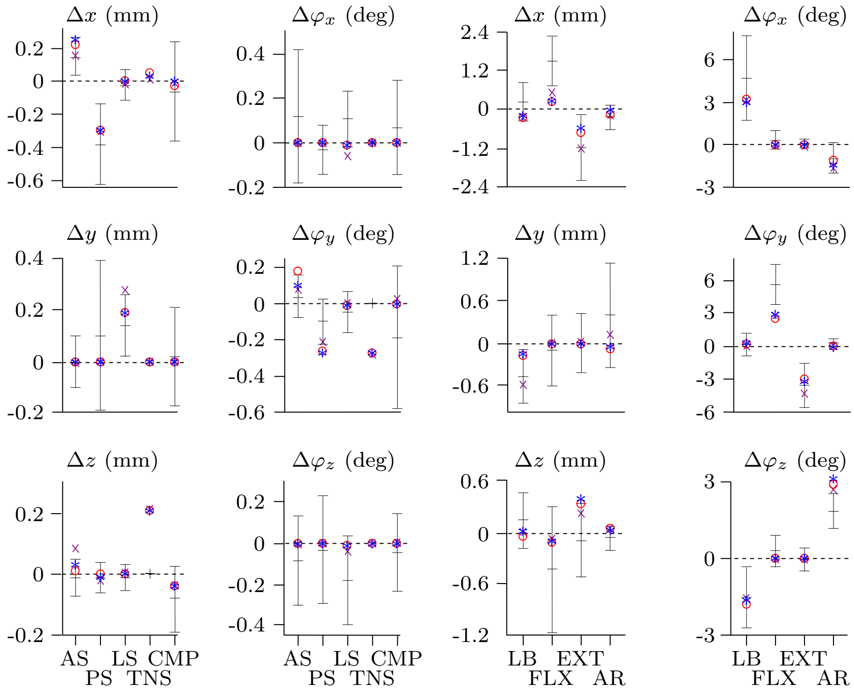

Figure 3: Model comparison of main and coupled displacements: MOBILE: ∘, MADYMO: ∗, de Jager [1]: × with experimental results of Moroney [3]: + (average± SD).

Conclusions

A novel modelling technique for quasistatic analysis of the motion of a vertebrae pair is presented, which makes use of elementary contact mechanics for rendering the physical effects within the facet joints. The resulting model is more efficient than Ellipsoid-Ellipsoid restraints commonly found in the literature by a factor of 350, while rendering results of comparable accuracy.

Acknowledgments

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