Direct and Inverse Analysis of Human Spine for Helicopter Comfort Assessment

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1 Introduction

The vibrational response of the human body is directly related to unpleasant sensations (discomfort), degradation of efficiency in performing a task and may ultimately lead to health related issues [1, 2, 3]. Thus, proper modeling of the human body response is of critical importance when evaluating both vehicle comfort performance [4] and potential adverse involuntary feedthrough of command inputs [5], especially when, as is the case in rotorcraft, they exhibit an intrinsic propensity to develop a high level of vibrations.

Parameters of the vibratory response of the human body depend on its mechanical properties and geometry, which in turn may depend on anthropometric variables like age, gender, weight and stature. Therefore, the variance of the parameters influencing the response has to be taken into account in the design stage, in order to ensure an adequate level of robustness. Multibody modeling is a viable tool in this context, since it can be viewed as first-principles approach. Starting from the anthropometric parameters, through the geometrical and structural modeling, it supports the extraction of the relevant synthetic parameters evaluating the fitness of a particular design choice to the goal of achieving a greater pilot (or passenger) comfort and/or of reducing the insurgence of possible triggers of adverse interaction phenomena.

2 Human spine multibody model

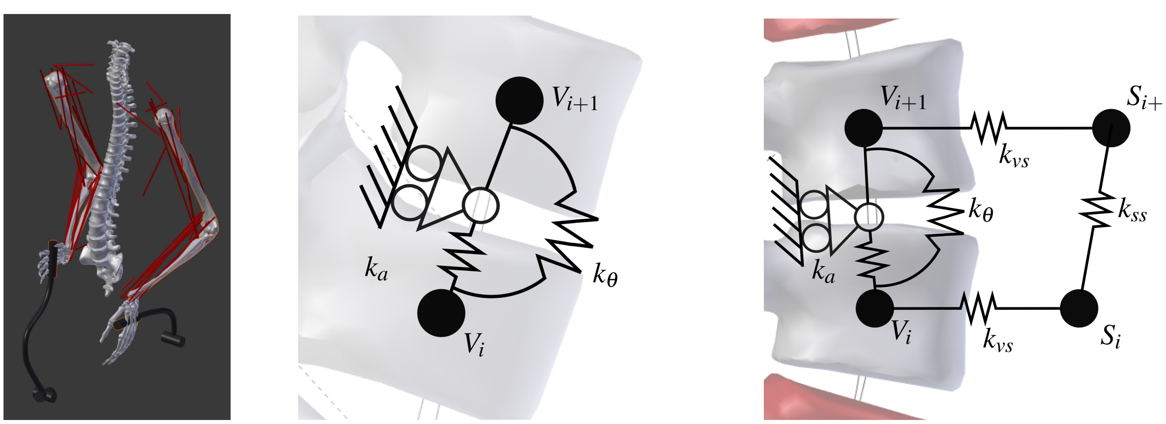

Fig. 1: Algebraic and deformable constraints connecting vertebræ nodes, indicated with V, and visceræ nodes, indicated with S.

This work is specifically focused on the multibody modeling of the human spine. A complete model able to comprehend the spine behaviour in the sagittal plane has been developed in the free general purpose multibody solver MBDyn, aimed at direct and inverse dynamics analyses, and reduced order model extraction.

The model comprises 34 rigid bodies associated with nodes (i.e. entities possessing degrees of freedom) placed in correspondence of vertebræ from S1 to C1, the head, and of 8 visceral masses elastically connected to vertebræ from S1 to T10. Geometry and inertial parameters are adapted to represent a generic subject possessing the desired anthropometric characteristics of age, gender, stature and weight.

When restricted to the sagittal plane, vertebral nodes are connected to each other by algebraic constraints limiting their relative degrees of freedom to sliding along the spine axis and rotation about the lateral axis. When the model is used to perform 3-dimensional simulation, all of the vertebræ nodes relative rotation degrees of freedom are unconstrained, while the translational constraints remain in place.

3 Solution strategies

The spine model has been developed aiming at a high level of generality in its applications. As an encompassing example, in the present work the solution phases needed to extract a reduced order model (ROM) for the evaluation of the upper body vertical vibration response of seated rotorcraft pilot/passengers will be outlined. The general procedure consists in several simulation steps:

1. an underdetermined inverse kinematics analysis that determines the pose of the spine in relation with the imposed position of the head and of the buttocks;
2. an inverse dynamics analysis that estimates the passive muscular intervertebral moments;
3. a direct dynamics analysis aimed at estimating the effect of the active muscular intervertebral moments;
4. an eigenanalysis, directly performed on the system of Differential-Algebraic Equations (DAE) system, to extract the ROM.

To obtain a square problem in the kinematic inversion when solving for the system's positions, a series of static problems are set up, in which *dummy* springs act on the redundant degrees of freedom [6]. The stiffnesses of the springs act as penalty coefficients for the motion of the degrees of freedom they are connected to. Therefore, they can be crafted to minimize the norm of the internal bending moment in the sagittal plane, due to weight.

From the inverse kinematics analysis, the configuration of maximum ergonomy of the spine is obtained. In the subsequent direct analysis, active muscular moments are estimated introducing simple controllers that introduce intervertebral axial forces and bending moments linearly proportional to the difference between the current vertebræ relative positions and the maximum ergonomy configuration.

Once the equilibrium position has been reached, an eigenanalysis is performed to extract a ROM [7] of the spine suitable for vibration analysis in the vertical direction, to be used in linearized, comprehensive rotorcraft vibration analysis [8]. Alternatively, the complete multibody model can be used in direct multibody bioaeroservoelastic analysis of the system [9].

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