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3D Dynamic Computer Model of the Head-Neck Complex

Daniel A. Sierra, *Student Member, IEEE,* and John D. Enderle, *Member, IEEE*

Abstract—**A 3D dynamic computer model for the movement of the head is presented that incorporates anatomically correct information about the diverse elements forming the system. The skeleton is considered as a set of interconnected rigid 3D bodies following the Newton-Euler laws of movement. The muscles are modeled using Enderle's linear model. Finally, the soft tissues, namely the ligaments, intervertebral disks, and zigapophysial joints, are modeled using the finite elements approach. The model is intended to study the neural network that controls movement and maintains the balance of the head-neck complex during eye movements.**

Keywords-3D Movement, Eye Movements, Finite Elements, Head-Neck, Quaternions, Neural Control.

I. Introduction

The computer modeling of the head-neck complex has been widely addressed for more than thirty years. Tien and Huston report that the first models developed in the sixties were based on simple pendulum models and evolved to multibody models in the eighties [1]. Most of the interest in modeling the head/neck dynamics arises from the number of deaths related with injury to the head/neck system during vehicle accidents [1]-[3]. In addition, computer models are more versatile and less expensive than physical or biological ones such as dummies, cadavers, or animals. In turn, they impose the challenge to perform a more rigorous validation and are devoted to specific type of analyses [1], [4].

Most modeling of the head/neck system is intended to represent the behavior of the system from an external point of view, *i.e.*, many reports address the modeling of the dynamics of the head/neck in response to external forces, such as those encountered during a car accident or in loading conditions [1], [3]. Other models are intended to study the stability and conditions of the cervical spine to assess the stage of patients with spinal cord injury or related pathologies [5].

In contrast, the model developed here is intended to be an anatomically correct 3D dynamic model of the head/neck complex to study and analyze the neural control of the muscles during eye movements. In consequence, the model incorporates the dynamics of the different constituents of the head/neck, such as the skeleton (head and cervical vertebrae), muscles, and soft tissues (ligaments, intervertebral disks, zygapophysial joints, and uncovertebral clefts). Posterior developments will address the generation of the neural signals controlling the contraction of the head/neck muscles, and in consequence the movement of the entire eye-head-neck system. The model is implemented in Matlab® 7.0 with calls to COMSOL Multiphysics®.

The development of the model complements previous experience in modeling the eye movement in our research group. Since vision is the most important of the senses, the oculomotor system has been the most widely addressed by researchers. Dynamic models for the oculomotor system have been proposed since 1954, with a pioneering work by Westheimer. Enderle and coworkers proposed the updated linear model of the oculomotor muscle, which uses a linear muscle model that has the static and dynamic characteristics of the rectus eye muscle within its operating range [6]-[9].

Understanding of the dynamics and neural control of the eye movements provides interesting insights that uncover the dynamics behind the head and neck movements. In fact, Zangemeister *et al* point out that the head and eye movement models are similar in the sense that both have passive inertias, viscosities, and spring constants with interesting scaling relationships one with another. As a consequence, the head is said to be a viscous inertial load, whereas the eye is a viscous elastic load, which account for the faster movements allowed in the eye [10].

The abstract is organized following the levels of the model. Section II presents the characteristics of the modeling of the skeleton, *i.e.* skull and vertebrae. Section III provides insights about the model of the muscles. Soft tissue modeling is addressed in section IV. Generalities about neural control are in V.

II. Skeleton Modeling

The osseous part of the head/neck system is modeled in a similar way to that in [2] and [3]. The skull and cervical vertebrae are considered as rigid bodies connected by muscles and soft tissues, which exert forces over them. Anatomical data for the skull and cervical vertebrae were taken from [1].

Each rigid body has six degrees of freedom, *i.e.* three translational and three rotational; its dynamics is simulated taking into account the Newton-Euler laws by computing the

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D. A. Sierra is with the Biomedical Engineering Department at University of Connecticut, Storrs, CT 06269 USA, and with the Electrical and Electronic Engineering School at *Universidad Industrial de Santander (Colombia)* (phone: 860-486-0417; fax: 860-486-2500; e-mail: dasierra@ engr.uconn.edu).

J. D. Enderle is with the Biomedical Engineering Department at University of Connecticut, Storrs, CT 06269 USA (e-mail: jenderle@engr.uconn.edu).

net force and moment [11].

Conventional approaches use Euler/Cardanic angles to express the orientation of the bodies. A number of serious issues have been raised by various authors [11], [12]. In addition to being sequence-dependent and defined in a different way for each joint, parameters used in the model have singularities that affect the computing of angular velocity and angular acceleration vectors. Other authors use quaternions to express the orientation and for computing the kinematics of the bodies [11], [12]. In consequence, the simulation of the skull and cervical vertebrae dynamics makes use of the quaternion algebra to represent orientation. The quaternion algebra was solved using an adaptation of the quaternion toolbox for Matlab® developed by Jay A. St. Pierre [13].

For a given body $\mathbf{M_i}$, the dynamics is computed by Eq. (1), which makes use of the states and variables described in Table 1. In Eq. (1), the derivative of the orientation quaternion is computed using quaternion algebra definitions.

$$\frac{d}{dt}Z_i(t)=\frac{d}{dt}\begin{pmatrix}x_i(t)\\Q_i(t)\\P_i(t)\\L_i(t)\end{pmatrix}=\begin{pmatrix}v_i(t)\\0.5\left(Q_i(t)*\omega(t)\right)\\F_i(t)\\\tau_i(t)\end{pmatrix}\qquad(1)$$

$$\begin{aligned}v_i(t)&=\frac{P_i(t)}{M_i}\\I_i(t)&=R_i(t)I_i^{body}(t)R_i(t)^T\\\omega_i(t)&=I_i^{-1}(t)L_i(t)\end{aligned}\qquad(2)$$

TABLE I
STATES AND VARIABLES USED IN THE MODEL OF A RIGID BODY (VERTEBRA OR SKULL)

Z_i	Complete state vector for rigid body (RB) *i*
x_i	Position of RB *i*
Q_i	Orientation quaternion of RB *i*
P_i	Linear momentum of RB *i*
L_i	Angular momentum of RB *i*
v_i	Linear velocity of RB *i*
ω_i	Angular velocity of RB *i*
F_i	Net force acting upon RB *i*
τ_i	Net moment acting upon RB *i*
M_i	Mass of RB *i*
I_i^{body}	Inertia tensor of RB *i* in local coordinate system
I_i	Inertia tensor of RB *i* in global coordinate system
R_i	Rotation matrix equivalent to quaternion Q_i

III. MUSCLES MODELING

The muscles of the neck generate head movements and help maintain the stability of the cervical spine. Diverse models have been proposed to represent the dynamics of the neck muscles [14]. The model presented here incorporates the Enderle *et al*'s for the rectus eye muscle; individual parameters are estimated for each one of the muscles, parametrized for neck muscles [6]. Anatomical data about the attachment sites and force-generating parameters for the muscles are taken from [14].

Each muscle is modeled as a viscoelastic parallel combination connected to a parallel combination of active state tension generator (F), viscosity element, and length tension elastic element. Each of the elements is linear and their existence is supported with physiological evidence [6].

Figure 1 shows the simplified model of a muscle in connection to an origin body (the floor) and to an insertion body (mass M). The parameters K_{LT}, K_{SE}, B_1, B_2, and F are computed for each one of the muscles of the neck, and incorporated in the simulation.

Considering the basic arrangement in Figure 1, and neglecting the gravity, the dynamic equations for the whole system are:

$$\begin{aligned}&M.\ddot{x}_1=T=B_2(\dot{x}_2-\dot{x}_1)+K_{SE}(x_2-x_1)\qquad(3)\\&B_2(\dot{x}_2-\dot{x}_1)+K_{SE}(x_2-x_1)+B_1(\dot{x}_2)+K_{LT}(x_2)-F=0\end{aligned}$$

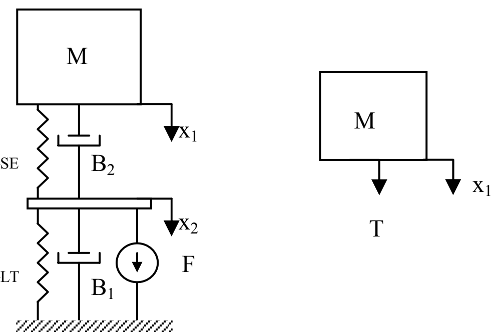

Fig. 1. Linear model for the muscle (left). In this setting, the origin point is the floor and the insertion point is on the mass M, Adapted from [6]. Free body diagram for M with T corresponding to the tension exerted by the muscle (right).

This system has three states that can be expressed as one state equation. However, in order to separate the mass dynamic from the muscle dynamics, the system of equations can be expressed as:

$$\begin{aligned}&Let\quad v_1=\dot{x}_1,\\&M\dot{v}_1=T\qquad(4.A)\end{aligned}$$

....

$$\frac{d}{dt}(x_2)=\left(\frac{-(K_{SE}+K_{LT})}{B_1+B_2}\right)(x_2)+\dots$$

$$\begin{pmatrix}\frac{1}{B_1+B_2} & \frac{K_{SE}}{B_1+B_2} & \frac{B_2}{B_1+B_2}\end{pmatrix}\begin{pmatrix}F\\x_1\\v_1\end{pmatrix}\qquad(4.B)$$

....

$$T=\left(\frac{K_{SE}B_1-K_{LT}B_2}{(B_1+B_2)}\right)(x_2)+\dots$$

$$\begin{pmatrix}\frac{B_2}{(B_1+B_2)} & \frac{-K_{SE}B_1}{(B_1+B_2)} & \frac{-B_1B_2}{(B_1+B_2)}\end{pmatrix}\begin{pmatrix}F\\x_1\\v_1\end{pmatrix}\qquad(4.C)$$

In (4.A), the force exerted over the mass is the tension from the muscle. However, the expression can be expanded to consider a set of muscles and soft tissues exerting forces over the mass M. The total length of the muscle, x_1, and the shortening velocity, v_l, are determined by the dynamics of the mass. In turn, these variables are considered as inputs to 4.B and 4.C.

IV. Soft Tissue Modeling

The soft tissues of the cervical spine consist of a variety of structures connecting and surrounding the osseous elements of the cervical vertebral column [15]. The main categories of soft tissues include the spinal ligaments, intervertebral discs, zygapophysial joints, and uncovertebral clefts. Their general function is to enable and limit movement of the cervical spine. However, these tissues differ in structure and contribute differently to enable and limit the movement. Due to the complexity and non-rigidity of these structures, many authors have chosen to model them by using finite elements approaches [5], [15], [16]. Special characteristics to take into account in the modeling of the soft tissues are presented in the next sections.

A. Ligaments

Ligaments are unaxial structures that resist only tensile or distractive forces. However, depending on their mechanical properties, ligaments can resist tensile forces in a range of directions because of their orientation.

The modeling of the ligaments requires the quantification of their geometry (origin and insertion, length, and cross-sectional area) and material properties (stiffness, force-deflection, stress-strain).

In the case of stiffness or elastic modulus, experiments subjecting the ligament to tensile loading are used. With experimental force-deflection responses, the stress-strain curve can be computed by using the length and cross-sectional area of the ligament. Data presented by Yoganandan and coworkers gives both the geometric characteristics of ligaments and the bilinear modulus of elasticity data [15], [16]. Similarly, the parameters of force, deflection, energy, stiffness, stress, and strain parameters are applicable to (quasi) static tensile loading, *i.e.*, the parameters are valid under day-to-day physiologic types of activity with low rate of loading. With increased rate of loading, the failure force, stiffness, and energy have been reported to increase [15].

Finite element models of the ligaments have included the previously described geometrical and mechanical properties of ligaments. Element idealizations have included spring or cable and membrane types. Spring elements use a force-deflection curve, or stiffness as material property input. Meanwhile, membrane idealization uses a stress-strain curve or modulus of elasticity as the input. Depending on the complexity and need, finite element techniques allow the flexibility to choose linear, non-linear, and/or viscoelastic approaches [15].

B. Intervertebral Discs

Intervertebral discs differ from ligaments in that they respond to or experience multiple load vectors. Under any external loading, with the exception of direct uniaxial tension, discs carry compressive forces in association with other components. In spite of the compressive nature of the loading in the discs, the anatomy of the head and neck imposes moments associated with the compression. During physiologic and traumatic load applications, cervical intervertebral discs respond to a variety of load vectors including compression, bending, and tension.

Among the relevant geometric characteristics of the intervertebral discs are their height at mid-depth, the ratio of anterior to posterior height, and cross-sectional areas of the nucleus pulposus and entire disc as a function of spinal level. For modeling, force-displacement properties, stiffness, and stress-strain (elastic modulus) are required. These material properties are needed in more than one mode because of the multi-modal behavior of the disc. Most of the experimental studies have addressed the gross response of the disc under this mode to determine parameters such as microfailure load, stiffness in the most linear, physiologic range, and energy absorption characteristics. Because of the differences in the constituents of the discs are noticeable, experiments to determine their individual characteristics are performed. The Young's modulus of elasticity for the annulus ground substance range from 3.4 to 4.7 MPa, while for the annulus fibers, a linear Young's modulus of 450 to 500 MPa is routinely chosen [15].

A number of approaches have been used for the simulation of the discs. For example, a composite, single-entity definition incorporating the Young's modulus of elasticity in compression and tension has been used. This model, which uses solid finite elements, does not differentiate between the properties of the nucleus, annulus ground substance, and fibers. In other more complex approaches, the nucleus is modeled using incompressible fluid elements, or using solid elements with a Poisson's ratio close to 0.5. In the case of the annulus component, fibers have been simulated using reinforced bar or cable elements and ground substance with solid elements [15].

C. Zigapophyseal Joints

Like the intervertebal disc, zigapophyseal joints respond to multiple load vectors, helping them in the resistance of compressive forces. These joints provide a complementary role to the intervertebral discs. Because of the oblique orientation of the facet processes, the external load is resisted by normal and shear forces in the joint. These joints are fundamental for the stabilization of other tissues in the region of the neck and act to limit the torsion of the disc.

Geometrical properties of interest are the length and cross-sectional area. For modeling purposes, the gap between the opposing cartilages is filled with synovial fluid. The simulation using finite elements requires the definition of the material properties of the synovial fluid, synovial membrane, articular cartilage, and fibrous capsule. The linear Young's modulus of elasticity for articular cartilage and synovial membrane has been determined by using stress-strain curves. The synovial fluid definition uses fluid density [15].

Finite element simulations of the zygapophysial joint include facet bone, capsular ligament, and air gap between the two cartilages. While facet bone is modeled as a solid element, the capsular ligament is modeled as explained above. The space between the two cartilages is defined using sliding or contact gap elements. The synovial fluid is modeled using fluid elements, and synovial membrane using membrane elements.

D. *Uncovertebral Clefts*

The clefts, which are not formed at birth, are located in the vertebral body-disc-vertebral body medium, from C2 to T1 and extend to meet in the midline to produce a fissure across the back of the disc. The clefts allow for a large degree of movement between the vertebral bodies and through the intervertebral disc. The clefts enable the disc to accommodate the coupling of lateral bending and axial rotation that is governed by the zygapophysial joints [15].

Geometrical data of interest to model the clefts are the anteroposterior length, medial-lateral depth, and superior-inferior height of each cleft. For the modeling, the clefts have been addressed with analog approaches to those used for the zygapophysial joints, involving gap elements.

V. Neural Control Modeling

The control of the head and neck movements during tasks involving eye positioning involves diverse autonomic and semi-autonomic responses. Physiological evidence indicates that saccades are controlled through a parallel- distributed network involving the cortex, cerebellum, and brain stem. To direct the eyes toward a target, one possible neurosensory control mechanism for the head and eye movements is a time optimal controller [9], [17]. This system includes sensory inputs from the visual, auditory, and vestibular subsystems. The sensory information is integrated by the neural control mechanism to generate the driving signals for the diverse muscles [8], [17].

VI. Conclusions

The modeling of the head-neck complex for eye movements implies an adequate knowledge of the different structures forming part of the anatomy. A wealth of information for the modeling of the cervical structures is available. On the other hand, the oculomotor system modeling provides interesting insights to be expanded to other anatomical subsystems.

The development of the model in an open computing environment allows the exploration of the dynamics of the system. Finally, having an anatomically correct 3D model of the head-neck complex allows the uncovering of the neural pathways coordinating the eye movement and stability of the whole complex.

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