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Implementation of neck active musculature using an enhanced hill type model for spine kinematics measurement

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1. Introduction

The mechanisms of the cervical spine injuries during whiplash are complex phenomena that can be elucidated using finite element models (FEMs). Muscle activation plays a decisive role in the stiffening of the head-neck behavior during these impacts. Although several FEM of neck musculature have been developed using a traditional Hill type contraction model, Günther et al. (2007) demonstrated their inability to effectively dampen oscillations during high dynamic loading, leading to numerical instabilities. Consequently, they developed an enhanced Hill type model (EHTM) that includes a separate behavior of the muscle fiber contraction unit and tendon zone. This study aims to implement and validate a finite element model of head neck musculature using the EHTM to better understand the muscular influence on injury risk during whiplash.

2. Methods

2.1 Head neck finite element model

The T1-Head portion of the Spine Model for Safety and Surgery (SM2S) was used in this study (Tuchtan et al., 2015). The C0-T1 vertebrae and head geometry were derived from a high-resolution CT-scan reconstruction of a healthy 50th-percentile male. The head and vertebrae were considered rigid. Deformable structures such as intervertebral discs and ligaments were respectively modelled using a hyper elastic Mooney-Rivlin material law and multi-curve viscoelastic stress-strain law. The FEM was developed on the HyperWorks 2022 software platform (Altair Engineering ®, Troy MI, USA) and simulations were run on OpenRadioss ® solver.

2.2 Neck musculature implementation

The neck musculature model includes: superior and inferior trapezius, splenius cervicis and capitis, semispinalis, sternocleidomastoid, longus capitis, longus colli, scalenus and rectus capitis. A total of 114 1D spring elements were used to model the 10 muscles groups chosen for this study. Sites of insertion and origin, as well as physiological parameters of contraction were extracted from the dataset provided by Borst et al. (2011). The Enhanced Hill Type Model of contraction comprises two distinct mechanical segments. Each muscle fiber unit includes a contractile element (CE), modeling cross-bridge force generation, and a parallel elastic element (PEE), representing passive muscle tissue response. The series tendon unit consists of a serial elastic element (SEE) and an adaptive serial damping element (SDE), unlike the constant damping used in traditional Hill models.

2.3 NBDL validation data

The Naval Biodynamics Laboratory (NBDL) dataset is widely used to validate the behaviour of FEMs that include neck musculature. The experimentation protocol consists of sled impact tests on volunteer subjects exposed to accelerations ranging from 2G to 15G in

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rear, frontal and lateral direction (Ewing et al., 1976). In this study, accelerations measured at the T1 level during a 2G frontal acceleration were applied to the model. Head kinematics in translation and rotation were assessed for three different musculatures configurations: no muscle (NM), passive muscles (PM) and activated muscles (AM). The muscle activation scheme was chosen according to Siegmund et al. (2007) electromyographic data, i.e. activation of the flexors occurs after a 25 ms reflex delay followed by the extensors at t = 50 ms.

3. Results and discussion

The global shape of the head anterior displacement relative to T1 is in good agreement with the experimental data (Fig. 1. (a)). The maximum value of displacement in both the no-muscle and passive muscle setups falls within the two-standard-deviation corridor but remains below the experimental result. This may be due to differences in cervical spine posture between the model and the subjects. Mean velocity results (computed on the 110–150 ms linear zone) are consistent with experimental data, indicating a correct response of the model in this region. However, a consistent time shift is observed across all configurations, which may be attributed to the initial pre-stresses that are not represented in the model. Regarding head rotation (Fig. 1. (b)), all model responses fall within the one standard deviation corridor. A reduction of head rotation is observed in the simulation results, likely due to contact between the skull and the C2 vertebra. These findings clearly indicate a stiffening effect of the muscles on the cervical structure. Neck musculature reduces the maximum anterior displacement by 5% with passive muscles and 19% with active muscles, compared to the no-muscle condition. A noticeable effect of the anterior muscles appears after 180 ms of simulation, during head tilting, as they reduce the maximum head flexion by 6% with passive muscles and 18% with active musculature compared to the no-muscle condition.

4. Conclusions

The developed head-neck FEM musculature outlines the significant impact of contraction on spine-head complex kinematics. For now, only 2G accelerations have been used to assess the model's bio fidelity. Future studies should explore responses under higher dynamic conditions and various impact directions. Furthermore, alternative patterns of muscle activation should be investigated. The EHTM supports several types of activation method. Recent studies (Martynenko et al., 2023) showed improved kinematic predictions using PID controller or reflex-based controllers, approaches that warrant further testing.

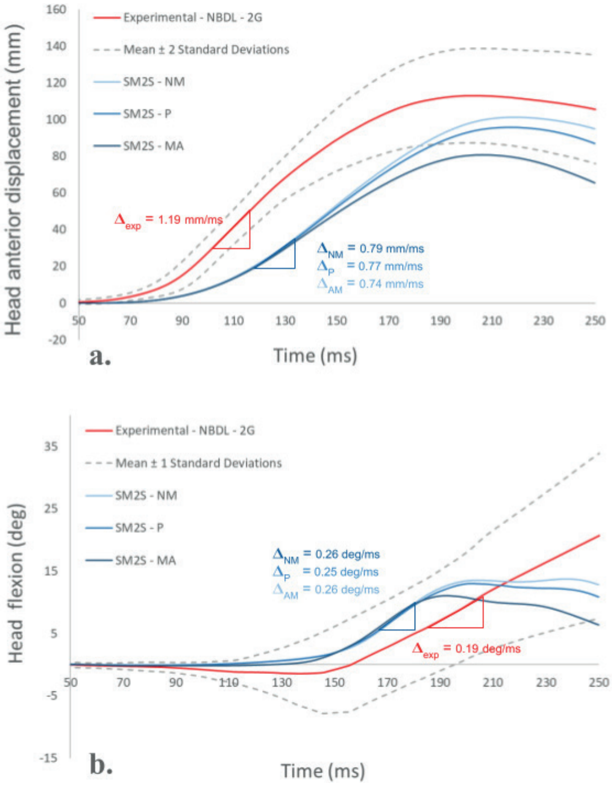

Figure 1. Comparison of Head center of gravity displacement relative to T1 (a) and rotation in sagittal plane (b).

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Conflict of Interest Statement

None.

Contributor Roles

AA: Software, Conceptualization, Methodology, Writing original draft; MHB: Supervision, Funding acquisition, Methodology, Writing-review & editing; EW: Supervision, Funding acquisition, Conceptualization, Methodology, Writing-review & editing.

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