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Dynamic head-neck stabilization and modulation with perturbation bandwidth investigated using a multisegment neuromuscular model

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The human head-neck system requires continuous stabilization in the presence of gravity and trunk motion. We investigated contributions of the vestibulocollic reflex (VCR), the cervicocollic reflex (CCR), and neck muscle co-contraction to head-in-space and head-on-trunk stabilization, and investigated modulation of the stabilization strategy with the frequency content of trunk perturbations and the presence of visual feedback.

We developed a multisegment cervical spine model where reflex gains (VCR and CCR) and neck muscle co-contraction were estimated by fitting the model to the response of young healthy subjects, seated and exposed to anterior-posterior trunk motion, with frequency content from 0.3 up to 1, 2, 4 and 8 Hz, with and without visual feedback.

The VCR contributed to head-in-space stabilization with a strong reduction of head rotation (<8 Hz) and a moderate reduction of head translation (>1 Hz). The CCR contributed to head-on-trunk stabilization with a reduction of head rotation and head translation relative to the trunk (<2 Hz). The CCR also proved essential to stabilize the individual intervertebral joints and prevent neck buckling. Co-contraction was estimated to be of minor relevance. Control strategies employed during low bandwidth perturbations most effectively reduced head rotation and head relative displacement up to 3 Hz while control strategies employed during high bandwidth perturbations reduced head global translation between 1 and 4 Hz. This indicates a shift from minimizing head-on-trunk rotation and translation during low bandwidth perturbations to minimizing head-in-space translation during high bandwidth perturbations. Presence of visual feedback had limited effects suggesting increased usage of vestibular feedback.

1. Introduction

The human head-neck system is a complex and highly flexible biomechanical structure, requiring continuous active stabilization in the presence of gravity. Coordinated feedback control of neck muscle segments is needed to position and stabilize the head in space, and to stabilize the individual neck joints in the presence of trunk motion and other perturbations. These are partly conflicting control objectives. In the presence of dynamic trunk motion, for example while walking or riding in a vehicle, it may be beneficial to minimize head rotation and translation to improve vision and comfort. This can be achieved with a so called head-in-space control strategy using vestibular and visual feedback. In contrast, humans may employ a head-on-trunk control strategy using muscle spindle feedback and co-contraction of antagonist muscles to stiffen the neck and stabilize individual neck joints to prevent neck buckling (collapse) in the presence of gravity.

Experimental studies have demonstrated that muscle spindle and vestibular afferent information contribute to head-neck stabilization through the cervicocollic reflex (CCR) and the vestibulocollic reflex (VCR), respectively (Keshner et al., 1999; Keshner, 2009; Goldberg and Cullen, 2011; Cullen, 2012; Forbes et al., 2013a). This paper investigates the role of the VCR, CCR and co-contraction using an advanced neuromuscular model. An early model captured human response data to sagittal plane torso perturbations with a two-pivot head-neck model (Peng, 1996). The model attributed substantial VCR and CCR contributions to head pitch rotation control, but head translation, which is commonly assumed to be also under VCR and CCR control was not reported. Thus our study aims

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to corroborate previous findings on head rotation control and extend them to head translation to support hypothesis 1: *The VCR contributes to head-in-space stabilization and substantially reduces head rotation and translation in space, while the CCR contributes to head-on-trunk stabilization and substantially reduces head rotation and translation relative to the trunk*.

Local neck deformation like S-shaped bending cannot be (accurately) sensed by the vestibular organ, since it encodes head motion in gravito-inertial coordinates. As a result, muscle length and velocity feedback are expected to be essential for the stabilization of the individual neck joints and to prevent neck buckling (collapse) in the presence of gravity. We therefore define hypothesis 2: *The CCR stabilizes the intervertebral joints and prevents neck buckling*.

Experimental and modelling studies on the extremities and lumbar spine have shown substantial contributions of muscle co-contraction, where simultaneous activation of antagonist muscles creates an "intrinsic resistance" which can be of a similar magnitude as the "reflexive resistance" (Kearney et al., 1997; Mirbagheri et al., 2000; de Vlugt et al., 2006; van Drunen et al., 2013). Keshner (2000) reported effects of neck muscle co-contraction when young (20–40 year) subjects were asked to stiffen their necks, but this effect was absent when subjects performed mental arithmetic or relax tasks. This motivates hypothesis 3: *Co-contraction can contribute to head-on-trunk stabilization, but this contribution will be minor in natural stabilization conditions*.

Experimental studies have shown the ability of the central nervous system (CNS) to modulate neck afferent feedback in response to changing external environments (Goldberg and Peterson, 1986; Gillies et al., 1998; Keshner et al., 1999; Fard et al., 2004; Liang and Chiang, 2008; Reynolds et al., 2008). We demonstrated modulation of neck afferent feedback with the frequency bandwidth of anterior-posterior trunk perturbations (Forbes et al., 2013b), with modest effects of the presence of vision. We tentatively associated this modulation with the attenuation of oscillations, and with a shift from head-on-trunk to head-in-space to stabilization. In line with the experimental data (Forbes et al., 2013b) we define hypothesis 4: *The presence of higher frequencies in the perturbations will induce a shift from head-on-trunk to head-in-space stabilization*. The head-in-space strategy will minimize the seat to head transmission, which can be beneficial for motion comfort (Paddan and Griffin, 1998).

To evaluate the above hypotheses, we developed an advanced neuromuscular model of the human head-neck system. Contributions of VCR, CCR and co-contraction were investigated fitting the model to responses of young healthy subjects exposed to anterior-posterior trunk perturbations with varying bandwidth, during eyes closed and eyes open conditions (Forbes et al., 2013b).

2. Methods

Neuromuscular neck models presented in the literature range from 1-pivot models (Peng, 1996; Peng et al., 1997; Peng et al., 1999; Fard et al., 2003; Rahmatalla and Liu, 2012; Wang and Rahmatalla, 2013) to detailed multisegment models (van Ee et al., 2000; Wittek et al., 2000; Yoganandan et al., 2002; Chancey et al., 2003; Stemper et al., 2004; Brolin et al., 2008; Hedenstierna, 2008; Almeida et al., 2009; Meijer et al., 2013; Östh et al., 2016). To study stabilization of the individual intervertebral joints, a multisegment model is needed. Chancey et al. (2003) presented a multisegment neck model and used optimization to generate balanced activations of 23 muscle pairs representing relaxed and maximally tensed initial states, minimising intervertebral motion while exposing the model to gravity for 100 ms. However we found no proof that any existing multisegment neck model stabilizes the individual joints in the presence of gravity with prolonged dynamic perturbations. The VCR and CCR can separately control head rotation and translation, but we are not aware of any model including such separate feedback loops.

In order to address the above limitations, a three-dimensional (3D) multisegment nonlinear neck model (de Jager, 1996; van der Horst, 2002; de Bruijn et al., 2015) was extended with a new control model (Fig. 1).

2.1. Biomechanical head-neck model

The model contains nine rigid bodies representing the head, seven cervical vertebrae (C1–C7), and the first thoracic vertebra (T1). The head mass is 4.69 kg and the total neck mass is 1.63 kg (van der Horst, 2002). The 8 intervertebral joints allow 3D rotational and translational motion, resulting in a total of 48 degrees of freedom (DOF). Centers of rotation are not imposed and joint motion is governed by non-linear models of the passive structures. Intervertebral discs, ligaments

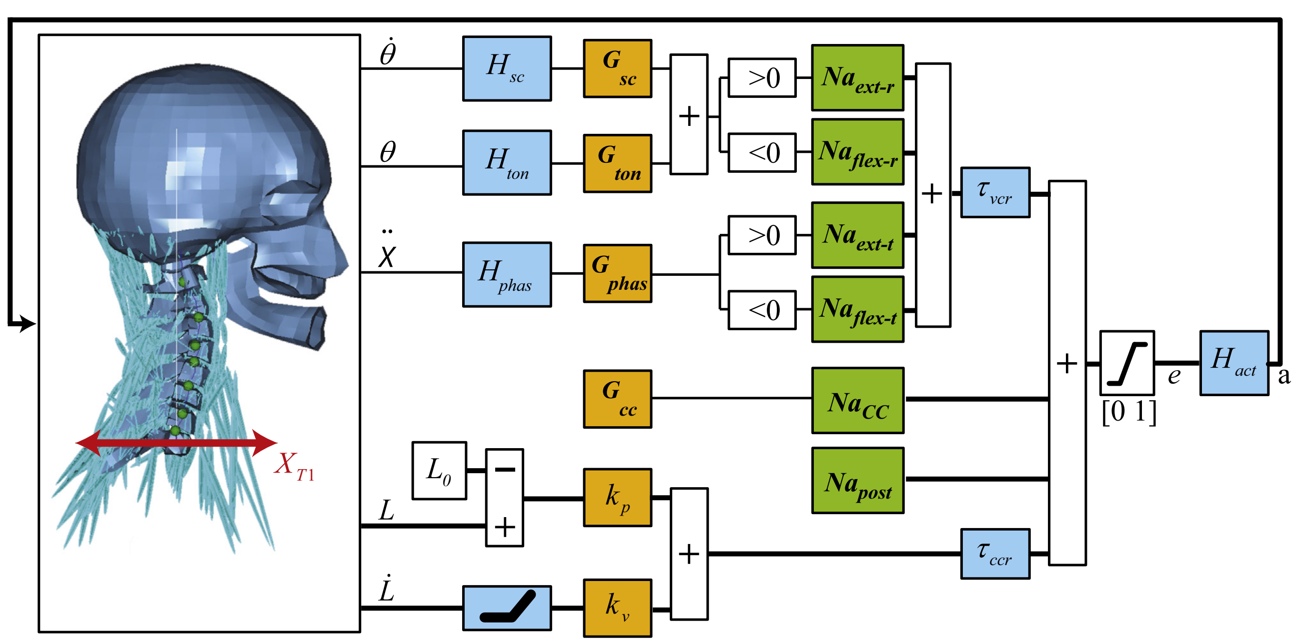

Fig. 1. Neural control model. Blue blocks contain sensory and muscle activation dynamics and delays, orange blocks contain the feedback sensitivity (gain) and co-contraction parameters. Green blocks are muscle synergy vectors converting scalar control signals to an appropriate activation of multiple muscle segments for flexion (Na_{flex-r} for rotation, Na_{flex-t} for translation), extension (Na_{ext-r} for rotation, Na_{ext-t} for translation), co-contraction (Na_{cc}) and postural activity counteracting gravity (Na_{post}). The VCR provides feedback of head angular velocity $\dot{\theta}$, angle θ, and acceleration $\ddot{X}$ with sensor dynamics H_{sc}, H_{ton}, H_{phas}, and feedback sensitivity parameters G_{sc}, G_{ton}, G_{phas}. The CCR provides feedback of muscle contractile element (CE) length L with sensitivity parameter k_p and velocity $\dot{L}$ with sensitivity parameter k_v where muscle CE reference length L_0 represents the desired posture. Neural pathway delays are defined for VCR (τ_{vcr}) and CCR (τ_{ccr}). H_{act} captures muscular activation dynamics transforming neural excitation (e) into muscle active state (a). X_{T1} is the applied mechanical perturbation being translation of the base of the neck. Thick lines indicate multiple signals for all 258 muscle segments.