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Lecture

A subject-specific biomechanical control model for the prediction of cervical spine muscle forces

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ABSTRACT

Background: The aim of the present study is to propose a subject-specific biomechanical control model for the estimation of active cervical spine muscle forces.
Methods: The proprioception-based regulation model developed by Pomero et al. (2004) for the lumbar spine was adapted to the cervical spine. The model assumption is that the control strategy drives muscular activation to maintain the spinal joint load below the physiological threshold, thus avoiding excessive intervertebral displacements. Model evaluation was based on the comparison with the results of two reference studies. The effect of the uncertainty on the main model input parameters on the predicted force pattern was assessed. The feasibility of building this subject-specific model was illustrated with a case study of one subject.
Findings: The model muscle force predictions, although independent from EMG recordings, were consistent with the available literature, with mean differences of 20%. Spinal loads generally remained below the physiological thresholds. Moreover, the model behavior was found robust against the uncertainty on the muscle orientation, with a maximum coefficient of variation (CV) of 10%.
Interpretation: After full validation, this model should offer a relevant and efficient tool for the biomechanical and clinical study of the cervical spine, which might improve the understanding of cervical spine disorders.

1. Introduction

Cervical spine musculature plays an important role in maintaining head-neck equilibrium and stability and in preventing intervertebral joint lesions (Lecompte et al., n.d.; Panjabi et al., 1998; Rousseau et al., 2008). Indeed, spinal instability is related to excessive intervertebral displacements, which induces pain. To limit these displacements, the nervous system controls the spinal musculature (Panjabi, 1992a, 1992b; Panjabi et al., 1989). Thus, abnormal muscle behavior may be an explanatory factor of the etiology of neck pain and cervical spine disorders (Alpayci et al., 2016; Cheng et al., 2014; Falla et al., 2007; Fernández-de-las-Peñas et al., 2008). Furthermore, the developmental mechanisms of surgical complications are not yet fully understood, particularly adjacent segment disease (ASD) and proximal junctional kyphosis (PJK), which might induce a secondary compensation at the level of the cervical spine. Abnormal spine loading and muscular dysfunction could be an issue. Therefore, quantifying the spinal muscle force distribution and the corresponding intervertebral joint load in different configurations could provide valuable information for a biomechanical and clinical evaluation of the patient (Choi, 2003; Moroney et al., 1988a). However, multiple muscle systems are difficult to model because of the well-known redundancy problem, i.e. for any given configuration a multitude of muscles can be recruited (Bernstein, 1967), and because of the limitations of the available measurement techniques.

Various models have been developed to face this issue, including mechanistic models using rigid cables simulating the muscles (Kettler et al., 2002), optimization models based on the mathematical optimization of a cost function considering muscle stresses or energy expenditure (Chancey et al., 2003; Han et al., 1995; Moroney et al., 1988a; Stokes and Gardner-Morse, 1995) and EMG-assisted optimization models adopting a direct relationship between muscle or joint forces and EMG data (Cholewicki et al., 1995; Lo Martire et al., 2017). The proprioception-based regulation model, originally developed for the lumbar spine, with the assumption on the core control strategy that muscles prevent spinal joint overloading and limit intervertebral

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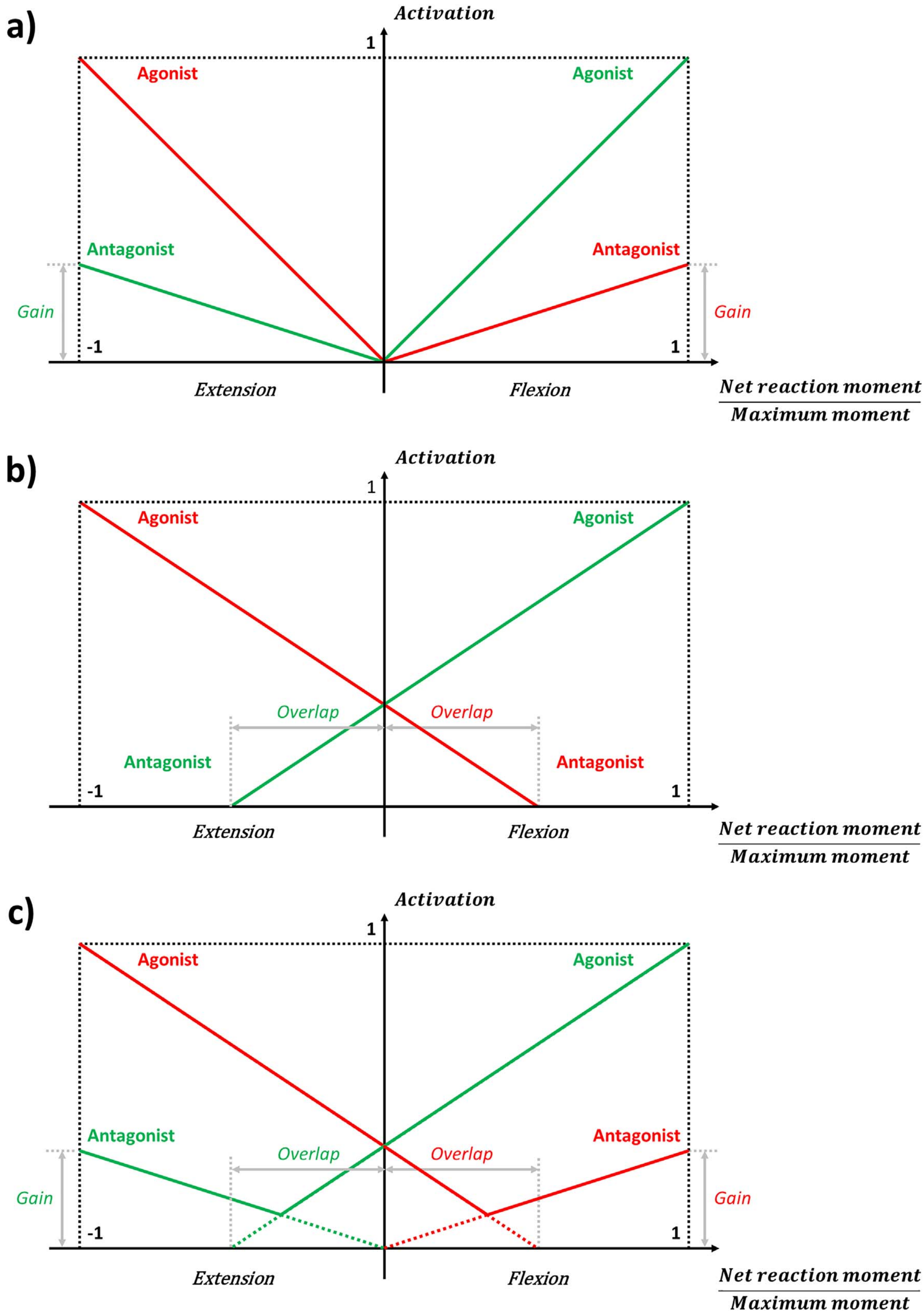

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displacement to protect spine and spinal cord (Panjabi, 1992a; Panjabi et al., 1989), yields physiologically and mechanically consistent results, independently from EMG measurements. This promotes building such a model from clinical image data (Pomero et al., 2004).

The aim of the present study was to propose a subject-specific proprioception-based biomechanical control model to estimate the cervical spine muscle forces. The results reported in two reference studies were used to evaluate the consistency of the model predictions. In order to progress towards the use of this model in a clinical context, the robustness of the model against the uncertainty on the main model