

# Biomechanical Model of Head and Neck with Motor-Controlled Motion

## Detailed Description of the Work Programme

Our goal is to construct an anatomically consistent biomechanical model that intricately captures the complexities of the head-neck system. This comprehensive model will comprise the base link, seven cervical spine vertebrae (C1-C7), and the head. Each of these components will be treated as a dynamical rigid body, with three rotational degrees of freedom. Furthermore, the model will contain the intervertebral discs and the ligaments, with their elastomechanical properties, alongside the muscles, acting with pushing or pulling forces on their anchoring locations. All of the constituent parts of the model will also have their corresponding masses. The kinematics of the model will be tuned and validated with the data from a mocap system, while the muscular motor control will be determined with the help of the data of the muscular activity measured with EMG sensors. The muscular motor control of the cervical spine will be precisely determined and refined using AI learning algorithms.

### **Task 1: Construction and Evaluation of the Kinematic Model of the Head-Neck System - WORK IN PROGRESS**

At the beginning of our project, the first task will be the construction of a kinematic model of the cervical spine, which will serve as the base model, containing information about the geometrical properties of the cervical vertebrae and the head, i.e. the shapes and positions of the constituent parts of the skeleton, as well as their possible motions.

#### **Task 1.1: Construction of the Cervical Spine Skeleton Model - WORK IN PROGRESS**

In the first step of the first task, the geometries of the cervical vertebrae will be mathematically described and placed in the right positions one relative to the other, as presented in Fig. 1. The shapes and proportions of

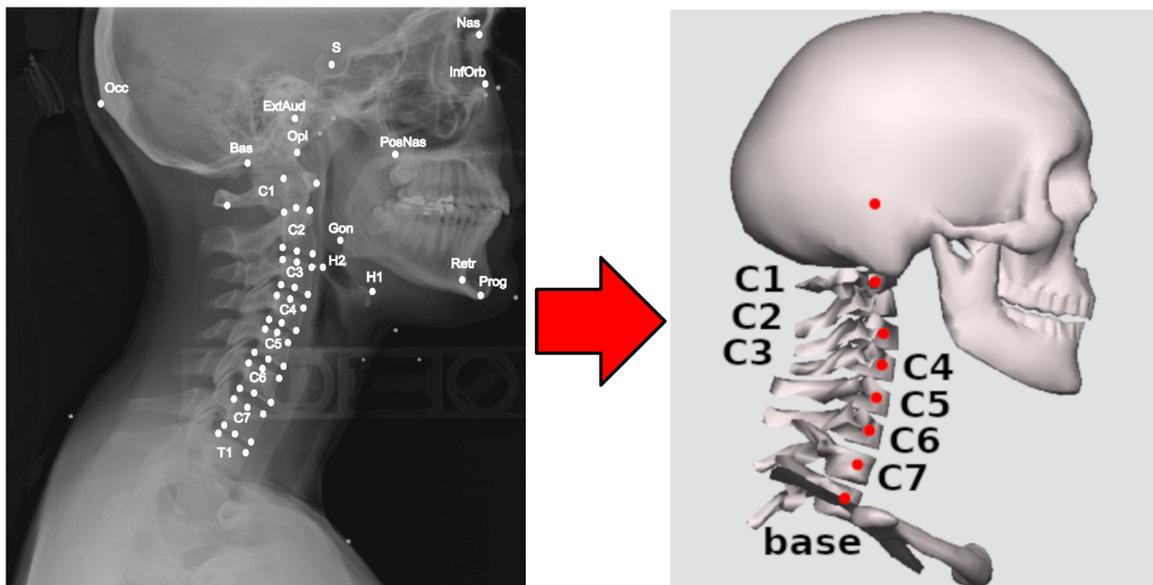


Figure 1: Mathematical model construction from human data. Adapted from [1] and [2].

each cervical vertebra along with the spacings between them were already characterised [3] and the existing data will be used as the first input parameters to the model. The model will allow further scaling of the skeleton

to adjust the model to subjects of different sizes.

### **Task 1.2: Implementing the Motion of Each Cervical Vertebra and the Skull - WORK IN PROGRESS**

The second step of the first task of our project will be the determination of possible motions of each vertebra and the skull. The allowed motions will include translational as well as rotational motions of each bone. The motions of each vertebra have already been estimated [3–5] and this data will serve as our first input parameters. Furthermore, the motion of the head-neck system including neck flexion, extension, and left and right components of lateral flexion and rotation have also already been characterised in various research projects [6–11]. These data will be used as the first and rough validation of the obtained flexion and rotation of our head-neck model.

### **Task 1.3: Fine-Tuning of the Cervical Model - WORK IN PROGRESS**

The motion of the modelled cervical spine skeleton will be evaluated and fine-tuned with data from mocap systems available online [12]. In case the online data will not provide all the needed information, additional measurements will be performed with our mocap system [13] located at the CoBoTaT laboratory. The integration of mocap data into the kinematic model ensures a high degree of accuracy, allowing precise motion parameterization that mirrors the real-world movements of the head and neck. With precise mocap data providing the relative positions and motions of the shoulders, back, chest, neck, and head of the healthy subjects, we will determine the angles of rotation and flexion of their cervical system. With further analysis, we will determine the rotations and translations of each vertebra along with the skull to create a cervical model that is capable of simulating realistic motion and is capable to reproduce the measured postures.

### **Task 2: Construction and Evaluation of the Dynamic Model - NOT YET STARTED**

Once the foundational kinematical model will be meticulously crafted and thoroughly evaluated with the mocap data, our focus will shift toward a more intricate phase – the development of the model dynamics. In this advanced stage, we will extend the model with the inclusion of ligaments, intervertebral discs, and all 72 neck muscles, each assigned its unique physical elastomechanical properties. This step is pivotal in enriching the biomechanical model, transforming it from a kinematic into a dynamic and physiologically accurate representation.

#### **Task 2.1: The Inclusion of Intervertebral Discs, Ligaments and Muscles**

To ensure anatomical fidelity, intervertebral discs and ligaments will be positioned at their corresponding locations and endowed with specific properties that mimic their real-world counterparts, encompassing factors such as elasticity, tension, and mechanical response, contributing to a nuanced and realistic representation of the biomechanical model. Some elastomechanical data, although not very consistent, about intervertebral discs and vertebral ligaments already exists [3] and will serve as the first and rough input to our model. Moreover, each muscle will be attached to its corresponding anchoring point where it will act with its pushing or pulling force, controlling the motion of the cervical system. Additionally, masses corresponding to each model element will be incorporated, adding a critical property to the model and enhancing its simulating capabilities.

#### **Task 2.2: The Inclusion of Muscle Forces and AI Learning Algorithms**

For a better understanding of muscular activation, our research will employ data from EMG systems available from online databases and previous studies, such as [14]. If needed, an EMG system with 16 sensors [13], located at our CoBoTaT laboratory, will also be employed. By utilising an array of electrodes, distributed strategically to cover multiple muscles simultaneously, the EMG system that captures and records electrical signals generated by muscle contractions, enables a comprehensive mapping of muscular activity. The EMG signals will not give us only information about the amplitudes of distinctive muscle contractions, but also about the timings of their activation, i.e. their activation times and the duration of their actions, as well as the contraction profiles over the activation times. This empirical data will serve as a crucial input to our model, allowing us to simulate forces obtained from various muscles and find the principles of muscle activation. The inclusion of measured muscle activities in our biomechanical model will enable the construction of a physically accurate dynamical model and provide a comprehensive understanding of the muscle dynamics underlying observed head and neck movements.

In the initial simulations, the musculoskeletal model will be simplified by grouping the muscles to act jointly within their corresponding group. The groups of muscles will be divided into deep, intermediate and superficial muscles, as shown in Fig. 2. With the refinement of the model dynamics and the attribution of separate roles to each muscle group, the roles of individual muscles within their corresponding group will be elucidated. At this point the muscle groups will be further divided into individual muscles present in the human cervical region

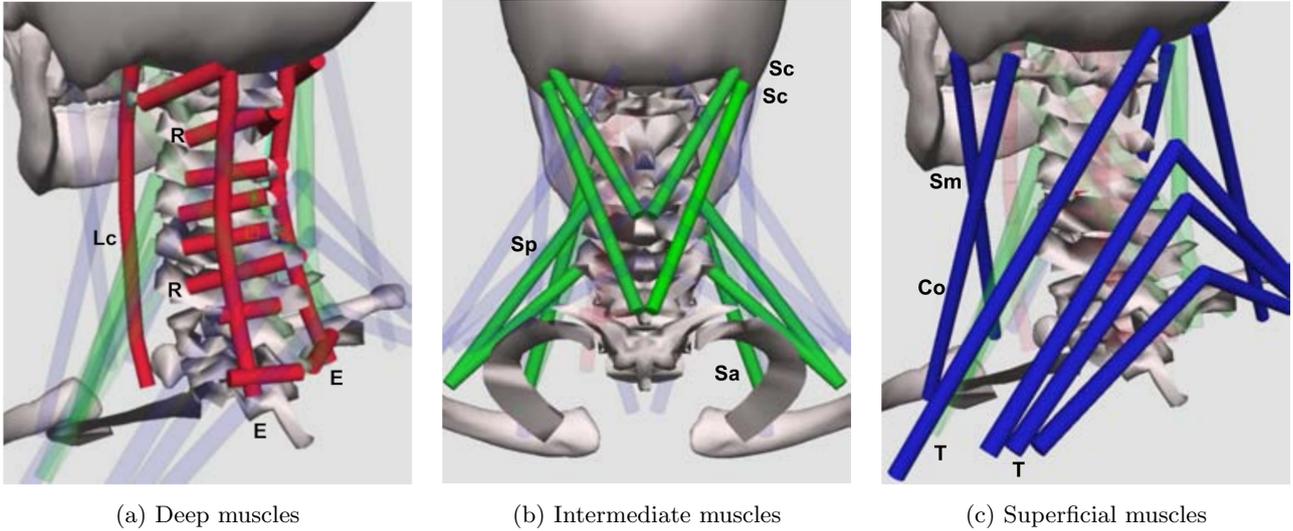


Figure 2: Musculoskeletal model of the cervical system. The muscles are divided into the deep muscle layer shown in red, the intermediate muscle layer shown in green, and the superficial muscle layer shown in blue. Source: [2].

and the attribution of force generation to each muscle separately will take place.

The introduction of machine learning algorithms marks a significant stride in our research methodology. These algorithms will be harnessed to simulate the intricate challenges associated with neck-muscle actuator motor control. By the utilisation of machine learning algorithms, we aim not only to simulate the complex and yet not-understood muscle activation that leads to the observed head and neck motion but also to determine the precise values of the elastomechanical parameters of the intervertebral discs and ligaments. This integrative approach, blending machine learning algorithms with experimental head-neck pose and motion data, along with muscle activity measurements, will help us create a precise dynamic representation of the musculoskeletal system and offer insights into the intricate muscle activity. By calibrating our model with real-world data, we aim to achieve a high degree of accuracy and reliability in explaining the actual forces and tensions within the head-neck system.

### Task 3: Model Predictions - NOT YET STARTED

The last task of the proposed project will take place after the dynamic model will be created. At this point, the elastomechanical properties of the intervertebral discs and the ligaments will be determined, mirroring the physiological intricacies of the cervical spine, while the muscular motor control dynamics will be tuned to reproduce the observed motion. The biomechanical model will in this stage be calibrated and ready to simulate different muscle activations to generate various head-neck movements and obtain diverse cervical postures.

Upon achieving a precise and calibrated state for our biomechanical model, we will exploit its capabilities to calculate the motion of the head-neck system under varying conditions. In particular, we will explore scenarios where either individual muscles or specific groups of muscles are activated. This tailored approach mirrors the conditions observed in cervical dystonia, where abnormal muscle activation is the reason for the manifestation of unusual head-neck motions and tremors.

#### Task 3.1: The Evaluation of the Kinematics of the Cervical Model

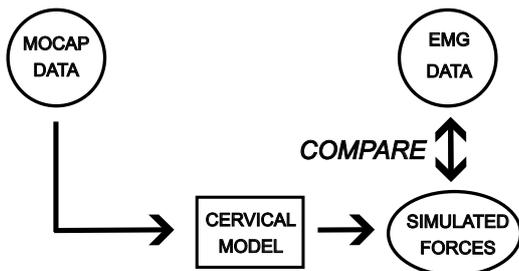


Figure 3: A schematic representation of the evaluation of the kinematics of the cervical model.

To evaluate the predicting capabilities of the created cervical model, measured mocap and EMG data will be employed and compared to the obtained simulation results. Initially, the kinematics of our cervical model will be evaluated. To do so, the mocap data of the head-neck pose and motion will be given as the input parameters to our model. Employing AI learning algorithms, the model will determine which muscles need to be active and what are the contraction forces needed for the reproduction of the given motion and posture. The modelled muscle activation will finally be compared to the EMG data of the neck muscles to validate if the simulated muscle activity coincides with the

measured neck muscle activity. This way we will reproduce the activation of the neck muscles of healthy individuals performing various movements. The evaluation of the kinematics of the cervical model is schematically depicted in Fig. 3

### Task 3.2: The Evaluation of the Dynamics of the Cervical Model

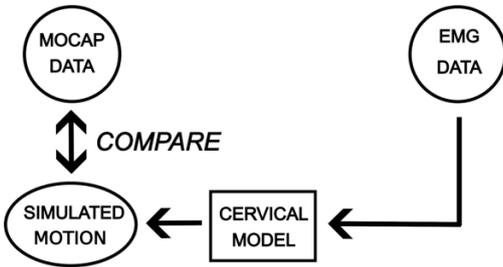


Figure 4: A schematic representation of the evaluation of the dynamics of the cervical model.

In the second step of the evaluation, the dynamics of the cervical model will be investigated. For this purpose, the EMG data of the neck muscles will be given as input parameters to our model. Utilising AI learning algorithms, the model will employ the measured muscular activities to obtain head-neck motion and posture. The simulated cervical posture will finally be compared to the mocap data to evaluate the predictions of our model. This way an inverse evaluation as the one performed in Task 3.1, schematically depicted in Fig. 4, will be performed.

After performing the validation, our biomechanical model will serve as a valuable tool for the detailed analysis and interpretation of unusual head-neck motions and tremors. By systematically activating single muscles, specific groups of muscles, and mutually opposed agonist and antagonist neck muscles, we will be able to replicate and understand different head-neck move-

ments and postures, including unusual motions and postures, occurring at the diverse manifestations of cervical dystonia. This is why this analytical approach holds the potential to uncover patterns, triggers, and contributing factors to abnormal movements, paving the way for a more profound comprehension of cervical dystonia.

Moreover, the human head-neck region contains 72 muscles and therefore this is a redundant system, which means that the activation of different muscles or groups of muscles can lead to the same cervical movement. To explain certain motions, the activation of various combinations of muscles and muscle groups will be investigated. The exploration of different modalities that lead to a certain posture will include for example the minimisation of total consumed energy or the minimisation of the maximal activity of individual muscles.

However, the advantages of our model will not lie only in its capacity to simulate the overall posture and movements of the head and neck but also in the nuanced aspects of musculoskeletal stiffness and tension. By integrating information about the activation of distinct muscles or specific groups of muscles, our model will allow for a dynamic exploration of how these muscles interact and contribute to the overall stiffness or tension within the system. This comprehensive analysis opens avenues for elucidating the intricate biomechanics underlying a diverse array of head-neck diseases.

Through this multifaceted research strategy, we aspire not only to advance our understanding of cervical biomechanics but also to lay the groundwork for more precise diagnostics and tailored interventions in the domain of neurological disorders affecting the head and neck muscles, which will pave the floor for personalised treatment strategies for individuals not only with cervical dystonia but any other cervical disease or injury and for physiotherapists and sports coaches to prescribe rehabilitation programs and exercises to target specific cervical muscles.

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