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Inter-individual variation in vertebral kinematics affects predictions of neck musculoskeletal models

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ABSTRACT

Experimental studies have found significant variation in cervical intervertebral kinematics (IVK) among healthy subjects, but the effect of this variation on biomechanical properties, such as neck strength, has not been explored. The goal of this study was to quantify variation in model predictions of extension strength, flexion strength and gravitational demand (the ratio of gravitational load from the weight of the head to neck muscle extension strength), due to inter-subject variation in IVK. IVK were measured from sagittal radiographs of 24 subjects (14F, 10M) in five postures: maximal extension, mid-extension, neutral, mid-flexion, and maximal flexion. IVK were defined by the position (anterior-posterior and superior-inferior) of each cervical vertebra with respect to T1 and its angle with respect to horizontal, and fit with a cubic polynomial over the range of motion. The IVK of each subject were scaled and incorporated into musculoskeletal models to create models that were identical in muscle force- and moment-generating properties but had subject-specific kinematics. The effect of inter-subject variation in IVK was quantified using the coefficient of variation (COV), the ratio of the standard deviation to the mean. COV of extension strength ranged from 8% to 15% over the range of motion, but COV of flexion strength was 20–80%. Moreover, the COV of gravitational demand was 80–90%, because the gravitational demand is affected by head position as well as neck strength. These results indicate that including inter-individual variation in models is important for evaluating neck musculoskeletal biomechanical properties.

1. Introduction

In vivo measurement of loads and displacements in the head and neck is very difficult. For this reason musculoskeletal (MS) models have been useful tools for investigating biomechanical phenomena in this system. For example, MS models offer insight into the relationship between joint loads, muscle lengths and tendon forces during whiplash events which may not be replicated experimentally with human subjects (Brolin et al., 2005; Hedenstierna and Halldin, 2008; Stemper et al., 2004; Van Lopik and Acar, 2004; Vasavada et al., 2007). These types of models also have been used to characterize the relationship between computer display heights and gravitational moment due to the weight of the head, muscle moment-generating capacity and other parameters over a range of postures (Straker et al., 2009).

Development of MS models requires several assumptions and simplifications, especially regarding intervertebral kinematics (IVK). IVK may be characterized by the amount of rotation and translation of one vertebra with respect to another, or the amount of rotation and the center of rotation between two vertebrae. In a biomechanical model of the head and neck developed in our lab, the relative motion of each vertebra is assumed to be a pure rotation occurring about a center of rotation fixed in the lower vertebra (Vasavada et al., 1998). Further, the amount of rotation at each intervertebral joint is assumed to be a fixed percentage of the total motion between the skull and T1, and this percentage value does not change over the range of motion. These assumptions make development of head and neck MS models mathematically feasible, but their effects on model estimates are unclear.

Experimental studies have shown considerable variation in IVK among subjects. The distribution of motion among intervertebral segments is found to vary over the range of motion (Anderst et al., 2013b; Wu et al., 2010); for instance, the contributions of the middle cervical levels (C3-C4 and C4-C5) are greater near the neutral posture, but lower cervical levels (C5-C6 and C6-C7) increase their contributions toward the end ranges of motion (Anderst et al., 2013b). In addition, the center of rotation between

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vertebrae is not constant over the range of motion; it moves anteriorly with flexion movements, especially in the upper cervical spine (Anderst et al., 2013a).

Variation in IVK parameters may affect several MS model estimates. Neck strength, equivalently, the moment generating capacity of the neck muscles, is the sum of moments of all muscles. Muscle moment is the product of muscle force and muscle moment arm, both of which are influenced by IVK. Muscle force is affected through the well-known force–length relationship (Gordon et al., 1966), where muscle length is influenced by IVK. Moment arm can be defined using the tendon excursion method (An et al., 1984), as change in muscle length over joint angle, which is also a function of the amount of motion and location of the center of rotation. Therefore, estimates of neck strength may be influenced by IVK variation.

Moreover, the location of the head center of mass with respect to the trunk or cervical intervertebral joints is dependent upon the kinematics of each intervertebral joint linking the head to the trunk. Therefore, the gravitational load on the neck joints due to the weight of the head may vary with IVK. The magnitude of this gravitational load relative to neck strength (i.e., the capacity of the neck muscles to oppose the gravitational load), here referred to as *gravitational demand*, is an important MS model estimate for ergonomic applications (Straker et al., 2009), and this ratio may also be affected by variation in IVK.

The influence of physiological variation on model predictions have been found to be significant in other biomechanical models (Cook et al., 2014), but the influence of physiological variation in IVK parameters has not yet been quantified. The goal of this study was to quantify variation in model estimates of extension strength, flexion strength and gravitational demand (the ratio of gravitational load to muscular capacity) in the sagittal plane due to variation in IVK. Identifying the importance of IVK variation on model estimates is critical for the future application of MS models in evaluating hypotheses related to healthy and pathological functioning of the head and neck.

2. Methods

2.1. Subjects and radiographs

Thirty-two subjects with no history of neck pain or prior neck injury were recruited for this study. Approval for this study was obtained from the Institutional Review Board at Washington State University, and all subjects provided informed consent prior to participation in the study. Sagittal radiographs were taken in five postures: maximal extension, mid-extension, neutral, mid-flexion, and maximal flexion as described in a previous study (Zheng et al., 2012). Neutral postures were self-selected by subjects, and maximal postures were voluntarily obtained. Subjects were guided into the mid-extension and mid-flexion postures, which were approximately halfway between the neutral and maximal postures of each subject, as defined by Frankfurt plane angle with respect to the ground. The Frankfurt plane is defined by the line connecting the tragus and the inferior border of the orbital socket.

2.2. Coordinate system and standard motion definitions

The locations of the right and left tragi and inferior borders of the orbits were marked with lead beads (Y-Spots, Beekley Corporation, Bristol, CT) prior to the collection of radiographs. The corners of each cervical vertebral body, the superior corners of T1 and other anatomical landmarks on the skull (external occipital protuberance, basion and opisthion) were digitized in each radiograph.

The origin of the T1 coordinate system was defined as the midpoint of the T1 superior endplate, with the *x* and *y* axes horizontal and vertical, respectively (Fig. 1A). For each bony structure and in each posture, X and Y and angular position were defined with respect to the T1 coordinate system (relative to horizontal). Skull location was defined as the midpoint between the basion and opisthion, and head angle was defined by the vector from the mean tragus location to the mean inferior orbital socket location (Frankfurt plane), relative to horizontal. The location of the C1 vertebra was defined by the midpoint between the posterior and anterior tubercle, and the C1 angle was defined by the vector connecting those two points, relative to horizontal. Coordinate systems for C2-C7 were defined according to International Society of Biomechanics (ISB) recommendations (Wu et al., 2002). Locations of these vertebrae were defined by the geometric center (average of the digitized corner points of the vertebrae). C2-C7 angles were defined by the vector originating at the geometric center and orthogonal to the line formed by the midpoints of the superior and inferior endplates (Fig. 1B), relative to horizontal.

For this analysis, we wanted to include only subjects that exhibited standard cervical spine flexion-extension motion. We defined "standard" motion as that generating a "C" shaped curve of the cervical spine, without excessive protraction or retraction motion. We screened subject data for two criteria. First, motion from one posture to the next was considered "standard" if change in head angle with respect to T1 and ground had the same sign. If this were not the case, e.g., if the head were to flex with respect to T1 and extend with respect to ground, it would suggest substantial motion of the entire trunk, motion of T1 within the trunk frame of reference or a combination of the two. Second, motion over a region was considered "standard" if the center of rotation (CR) of the skull with respect to T1 was between the tragus and the origin of the T1 coordinate system. Head CR location was determined using the Rouleaux method (Panjabi, 1979). For example, in "standard" extension, the CR should be located inferior to the skull so that the head moves back and down while extending. On the other hand, for extension with protraction, the CR is located superior to the skull, and the head moves forward and up while extending. Application of these two criteria resulted in further analysis of data for 24 subjects (14F, 10M; Table 1).

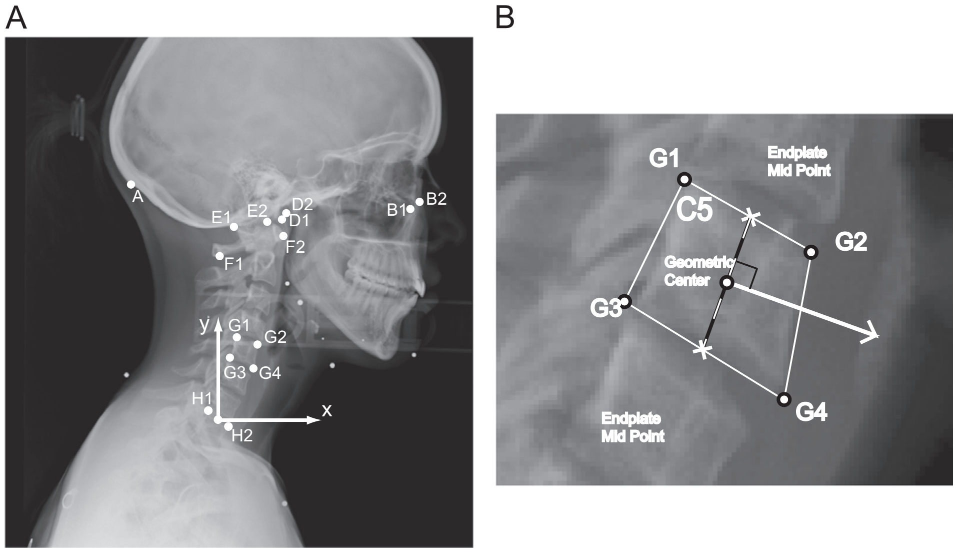

Fig. 1. Identified landmarks and the coordinate systems defined in each radiograph. A. Landmarks include the external occipital protuberance (A), left and right inferior orbital socket (B1, B2), left and right tragus (D1, D2), opisthion (E1) and basion (E2), posterior and anterior tubercles of the C1 vertebrae (F1, F2), vertebral corners (G1-G4), and the corners of the T1 superior endplate (H1,H2). The origin of the T1 coordinate system was defined as the midpoint between H1 and H2, with the *x*-axis horizontal and the *y*-axis vertical. B. Vertebral coordinate system and orientation definition for the C5 vertebra, as an example.