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The envelope of motion of the cervical spine and its influence on the maximum torque generating capability of the neck muscles

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ABSTRACT

The posture of the head and neck is critical for predicting and assessing the risk of injury during high accelerations, such as those arising during motor accidents or in collision sports. Current knowledge suggests that the head's range-of-motion (ROM) and the torque-generating capability of neck muscles are both dependent and affected by head posture. A deeper understanding of the relationship between head posture, ROM and maximum torque-generating capability of neck muscles may help assess the risk of injury and develop means to reduce such risks. The aim of this study was to use a previously-validated device, known as Neck Flexibility Tester, to quantify the effects of head's posture on the available ROM and torque-generating capability of neck muscles.

Ten young asymptomatic volunteers were enrolled in the study. The tri-axial orientation of the subjects' head was controlled via the Neck Flexibility Tester device. The head ROM was measured for each flexed, extended, axially rotated, and laterally bent head's orientation and compared to that in unconstrained neutral posture. Similarly, the torque applied about the three anatomical axes during Isometric Maximum Voluntary Contraction (IMVC) of the neck muscles was measured in six head's postures and compared to that in fully-constrained neutral posture.

The further from neutral the neck posture was the larger the decrease in ROM and IMVC. Head extension and combined two-plane rotations postures, such as extension with lateral bending, produced the largest decreases in ROM and IMVC, thus suggesting that these postures pose the highest potential risk for injury.

1. Introduction

Trauma of the cervical spine is common in motor vehicle accidents (Nahum and Melvin, 2002; Siegmund et al., 2005; White and Panjabi, 1978; Whiting and Zernicke, 1998) and in contact sports such as American football (Banerjee et al., 2004; Mueller, 1998; Mueller and Cantu, 2008; Proctor and Cantu, 2000; Torg et al., 2002). Most of the injuries occur when forces acting on the neck exceed the combined resistance of muscle, soft tissue, and bones and deform the neck beyond its physiologic Range of Motion (ROM). The excessive loads may be caused by inertial forces that develop during vehicular accidents (King, 2000; Maher, 2000; Manoogian et al., 2006; Yoganandan et al., 2001; Yoganandan et al., 2000) or from impact forces applied to a football player's helmet during collisions (Brolinson et al., 2006; Viano and Pellman, 2005; Viano et al., 2007). The cervical spine can be injured by forces that cause excessive motion about any of its major axes (lateral bending (α), flexion–extension (β), and axial rotation (γ), Fig. 1) (White and Panjabi, 1978; Whiting and Zernicke, 1998) but may be most susceptible to injury when forces are applied in multiple directions. For example, flexion combined with axial compression can lead to compression fractures of the vertebrae (Torg et al., 1977; Torg, 1985, 1997; Torg et al., 2002; Torg et al., 1979a, 1979b) while extension combined with either axial rotation or lateral bending can result in cervical cord neurapraxia, also known as "stinger" or "burner" (Castro, 2003; Kuhlman and McKeag, 1999).

A combination of passive and active mechanisms act to protect the cervical spine against injury. Passive protection is provided by the tissues that surround the cervical spine, including ligaments,

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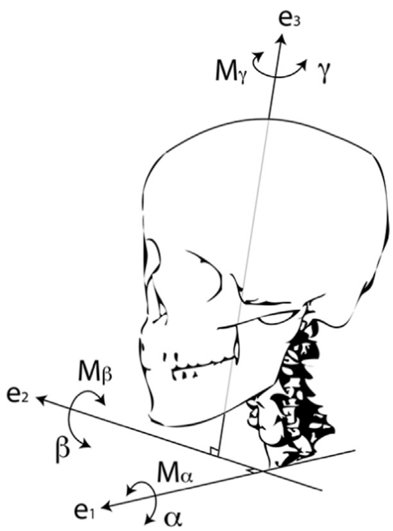

Fig. 1. Anatomical coordinate system for describing rotations, ROM, and IMVC of the cervical spine. Here: α and M_α are respectively the rotation and torque around the lateral bending axis e_1 (fixed to base of the cervical spine, oriented anteriorly and aligned with C7-T1 junction); β and M_β are the rotation and torque around the flexion/extension floating axis e_2 (perpendicular to e_1 and to e_3); γ and M_γ are the rotation and torque around the axial rotation axis e_3 (fixed to the head and oriented perpendicular to the Frankfurt horizontal plane).

bones, discs, and connective tissues. These tissues provide the spine with its stiffness characteristics (McClure et al., 1998; McGill et al., 1994) and dictate the spine's ROM (Castro et al., 2000; Ferrario et al., 2002; Fielding, 1956; Lind et al., 1989; Lynch-Caris et al., 2006; Roozmon et al., 1993). The neck's stiffness and ROM in the major anatomical planes have been found to vary with age, gender (Castro et al., 2000; Dvorak et al., 1992; Lansade et al., 2009; McClure et al., 1998; Sforza et al., 2002; Trott et al., 1996), posture (McClure et al., 1998; Panjabi et al., 1993) and the presence of pathological conditions (Antonaci et al., 2002; Heikkila and Wenngren, 1998; Hilibrand et al., 2006; Hino et al., 1999; Puglisi et al., 2004). However, no quantitative data are available to describe the relationship between lateral bending ROM and neck's orientation in flexion, extension, or axial rotation. It is expected that posture of the cervical spine away from neutral will produce deformations in soft tissues such as ligaments, intervertebral discs, and tendons that will reduce the out-of-plane ROM and thus will increase the risk of injury.

Active protection of the cervical spine is provided by surrounding musculature. The strength of these muscles has been studied mainly through measurements of Isometric Maximum Voluntary Contraction (IMVC). Most studies quantified IMVC in flexion and extension only (Barton and Hayes, 1996; Garces et al., 2002; Jordan et al., 1999; Mayoux-Benhamou and Revel, 1993; Rezasoltani et al., 2005). Few studies quantified IMVC in other directions, such as lateral bending and axial rotation (Chiu et al., 2002; Chiu and Sing, 2002; Seng et al., 2002; Van Wyk et al., 2010; Vasavada et al., 2001; Vasavada et al., 2002), and the effect of cervical spine posture on IMVC has only been studied in flexion/extension and lateral bending (Garces et al., 2002; Harms-Ringdahl and Schüldt, 1989; Jordan et al., 1999; Van Wyk et al., 2010). The authors found no information on the effect of neck posture on IMVC in axial rotation. Furthermore, no information was found on the effect of neck posture away from neutral on the IMVC in out-of-plane directions. For example, the effect of an axially rotated neck on the IMVC in flexion is unknown. It is expected that posture of the cervical spine away from neutral will reduce the maximal force generating capacity of neck musculature and thus will increase the risk of injury.

In light of the above discussion, it is expected that both the ROM and the IMVC at a given neck posture decrease as the distance from this neck's posture to the neutral neck posture increases. This further suggests that the risk for a cervical spine injury resulting from large external forces depends on the posture of the neck at the time of loading. For example, a football player who is hit on the head frontally while the head is turned, or a driver whose head is turned to the side while being hit from behind by another vehicle are both critical situations where the cervical spine is at higher risk of injury due to the out-of-neutral posture at the time of impact. Subsequently, the goal of this study is to quantitatively describe the dependence of the cervical spine's ROM and IMVC on neck posture. This has the potential to provide valuable information for establishing safety guidelines and for the design of improved neck protective devices and safety equipment for athletic activities and for motor vehicles.

2. Methods

2.1. Subjects

Ten young asymptomatic volunteers consisting of six males and four females (age 25 ± 4.9 years) with no history of neck or shoulder pathology participated in the study. The testing protocol was approved by Drexel University's Institutional Review Board. All subjects provided written informed consent after the testing procedure was explained. General anthropometric data, consisting of age, height, weight, Body Mass Index (BMI), head circumference, neck circumference, and neck length, were recorded from each subject (Table 1). Preliminary tests showed that the chosen population size was sufficient to achieve a statistical power of at least 0.8 at 0.05 level of significance.

2.2. Instrumentation

The main characteristics evaluated in this study, passive ROM and IMVC, were defined and measured relative to an anatomical coordinate system (Grood and Suntay, 1983) recommended by the International Society of Biomechanics (Wu et al., 2002) and adapted to the cervical spine (McClure et al., 1998) (Fig. 1). These were measured using a six-degree-of-freedom validated instrumented linkage, referred to as the Neck Flexibility Tester (NFT, Fig. 2). Details of this device have been provided previously (McClure et al., 1998). The NFT measured the subject's ROM via rotational sensors and IMVC via torque sensors at any neck posture (McClure et al., 1998). Each rotational axis could be moved and locked in position so that a subjects' head could be positioned, oriented and fixed anywhere within the subject's physiological envelope of motion. In this study, neck motion and posture are defined as the motion or posture of the head with respect to the base of the cervical spine (first thoracic vertebra). Data from the sensors (position and torque) were collected through an A/D converter at a sampling rate of 20 Hz.

2.3. Testing procedure

After explaining the testing protocol to the subject, he/she was seated in the NFT chair with his/her torso fixed to the chair via Velcro straps. The NFT linkage was attached to the subject's head via a lightweight helmet. The axes of the NFT were aligned to the subject's head and base of the cervical spine, as described earlier, while maintaining a neutral posture (McClure et al., 1998). Neutral posture

Table 1
Anthropometric data for the 10 tested subjects (mean ± SD). Head circumference was measured just above the ears level. Neck circumference was measured around the laryngeal prominence. Neck length was measured by palpation from the occipital condyle to the midpoint of the line between the C7 spinous process and the T1 spinous process, referred to as the C7-T1 point.

	Male	Female	All
Age (years)	25.8 ± 4.9	24.5 ± 0.6	25.2 ± 3.2
Height (cm)	173.5 ± 8.7	167.6 ± 9.0	171.1 ± 8.9
Weight (kg)	69.3 ± 10.6	67.3 ± 15.5	68.5 ± 12.6
BMI (kg/m^2)	22.9 ± 2.7	23.6 ± 2.8	23.2 ± 2.7
Head circumference (mm)	569.6 ± 15.4	570.0 ± 7.1	570.0 ± 12.1
Neck circumference (mm)	365.8 ± 16.2	342.0 ± 37.7	356.0 ± 24.8
Neck length (mm)	150.8 ± 25.3	127.7 ± 14.9	141.6 ± 21.1