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# Neck Vertebral Alignment and Muscle Activation is Affected by Whole Body Inversion

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## ABSTRACT

*Rollover accidents are dynamic and complex events in which head contacts with the roof can cause catastrophic injuries to the neck. To both study and ultimately prevent these injuries, the in vivo neck vertebral alignment and neck muscle activation levels immediately prior to a headfirst impact must be known. To our knowledge there is almost no data of this type available. Therefore, the aim of this study was to explore how occupants react to a headfirst impact scenario, such as a rollover, by altering their neck muscle activation and their neck alignment. The first step to advancing our understanding was to quantify which neck muscles are active and what the spinal posture is in a quasi-static upside-down posture. Six human subjects were tested while seated upright and inverted in a custom built roll apparatus. Vertebral alignment was measured using fluoroscopy and neck muscle activity was recorded using surface and fine-wire electrodes for eight superficial and deep neck muscles. In vivo vertebral alignment and muscle activation levels differed between the upright and inverted conditions. When inverted and relaxed, the neck was more curved and muscle activation was higher than when upright and relaxed. The results of this study provide an in vivo data set of vertebral and muscular response to an inverted configuration which can be used to improve and validate cadaveric and computational models and advance injury prevention strategies.*

## INTRODUCTION

Despite their relative rarity, spinal cord injuries have devastating and costly consequences for individuals and society. Headfirst impacts can result in neck and spinal cord injuries to occupants involved in rollover accidents. A common mechanism of neck injury in a rollover happens when the roof of the car hits the ground and the occupant, who is upside-down, hits the roof with their head (Moffatt et al., 2003; Raddin et al., 2009). It has been proposed that when contacting the roof, the head is stationary relative to the impact surface and the cervical spine is loaded from the momentum of the still-moving torso (Bahling et al., 1995). Previous research suggests that if the force is directed axially through the vertebral bodies of the spinal column, a compression injury results (Maiman et al., 2002). Nightingale et al. demonstrated a mechanism of compressive spine injury using a cadaver head-neck model in a drop tower (Nightingale et al., 1996; Nightingale et al., 1997). This study demonstrated that, when impact occurs near the apex of the head while the neck is perpendicular to the impact plane, there is a greater risk of cervical spine injury. Other researchers have shown that removing the natural curvature of the neck by flexing the spine forward can produce compressive cervical spine injuries (such as burst fractures) (Yoganandan et al., 1990; Pintar et al., 1995). Although there has been a variety of cadaveric research showing that the posture of the head and neck influence the type of injury sustained in a headfirst impact, the actual configuration of the cervical spine immediately before a headfirst impact remains unknown.

*Ex vivo* models of headfirst impact that use cadaver heads and necks generally lack representation of neuromuscular control and postural stability. Many cadaver tests are osteo-ligamentous; others have left the muscle tissue intact (Maiman et al., 1983; Nusholtz et al., 1983) but this only partially represents the passive muscle response. Cables and springs that simulate overall musculature have been used in some impact tests to restrain the head and maintain a particular cervical posture for axial testing (Yoganandan et al., 1990; Pintar et al., 1995). A limited number of axial impact cadaver experiments have attempted to replicate individual muscles by using cables and springs to simulate muscle forces (Saari et al., 2011; Ivancic, 2012), although the selection of muscles and the level of muscle force applied were not based on *in vivo* data relevant to headfirst impact. A limited number of computer simulations have simulated neck muscle activity in headfirst impacts (Hu et al., 2008; Brolin et al., 2009), but the levels of muscle activation and control schemes used here were also not based on human subject data. Nonetheless, Hu et al. have suggested that muscle activation may increase the risk of cervical spine fracture in a rollover setting (Hu et al., 2008).

Our overall goal is to determine the muscular and postural response of the neck immediately prior to a headfirst impact in a rollover crash. The specific objective of this study was to compare the *in vivo* neck vertebral alignment and muscle response during a quasi-static upside-down condition to that of the upright relaxed condition.

# METHODS

## Subject Group

The subject group consisted of 6 asymptomatic subjects (3 females and 3 males) with an average (± standard deviation) age of 33 ± 7 years (Table 1). Subjects gave their informed consent, and the University of British Columbia's Clinical Research Ethics Board approved the study.

The subjects were secured in a seat with a 5-point harness and held statically in both an upright and inverted position (Figure 1). Subjects were instructed to relax in both upright and inverted positions. For both configurations, vertebral alignment was measured using fluoroscopy, and neck muscle activity was recorded using surface and fine-wire electrodes for eight superficial and deep neck muscles. Fluoroscopy images and EMG signals were analyzed using Matlab (R2010b, MathWorks Inc., Natick, MA).

Table 1: Mean (standard deviation) values for the subject group anthropometric data

| Subject Group Anthropometric Data | |
|---|---|
| Height (cm) | 173.7 (8.1) |
| Weight (kg) | 69.0 (10.3) |
| Neck circumference (cm) | 34.6 (4.1) |
| Head circumference (cm) | 57.2 (3.0) |

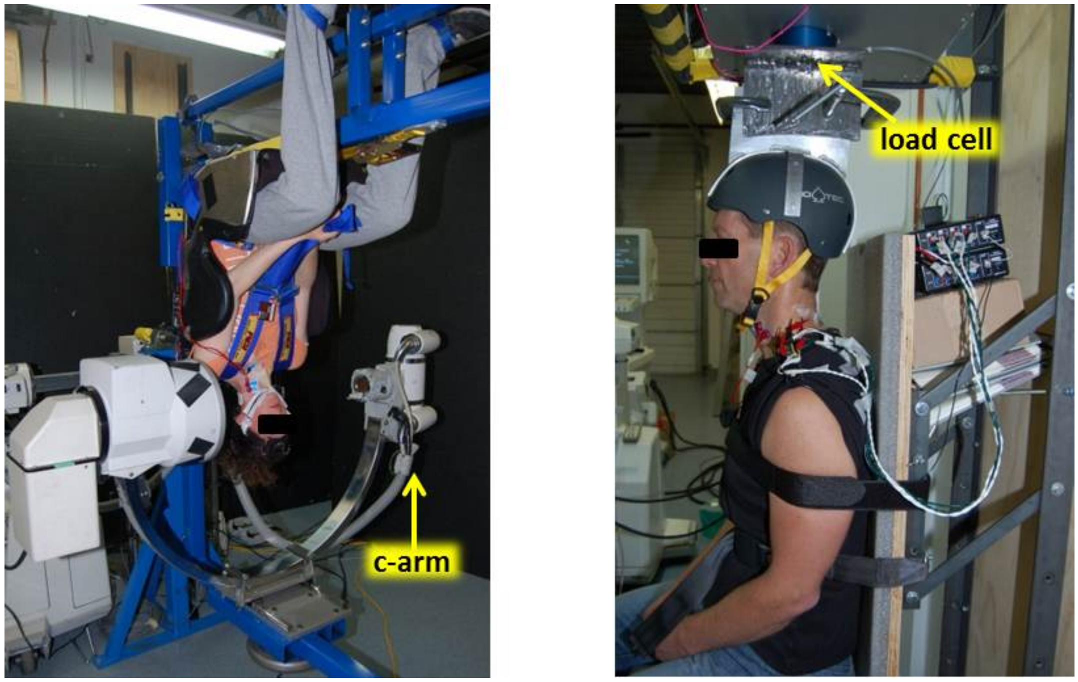
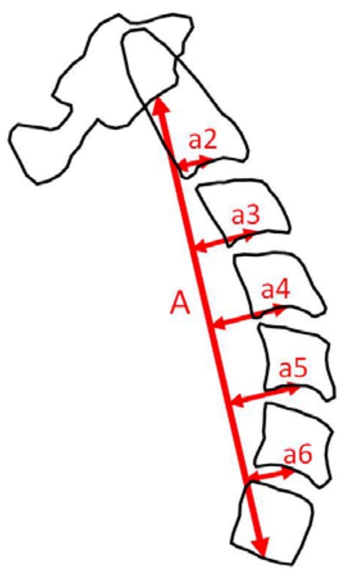



Figure 1: Left: Subject secured in the inversion device. Right: Subject performing MVC tasks while wearing a helmet attached to a load cell.




$$\text{C.C.I.} = \frac{100 \times (a2 + a3 + a4 + a5 + a6)}{A}$$

Figure 2: The Cervical Curvature Index (CCI) adapted from Takeshita et al. (2001). Lower values correspond to more aligned spinal postures.

## Fluoroscopy

A fluoroscopic C-arm (OEC 9400, GE) was used to image the cervical vertebra. One image was analyzed from each fluoroscopic video and was synchronized with the EMG recordings. The motions of the vertebrae were tracked in the fluoroscopy images using an automatic tracking algorithm. Briefly, the gradient of the image was taken, and normalized cross-correlation was used to find the location of the vertebra in the fluoroscopic image (Cerciello et al., 2011). This allowed the angle and displacement of each vertebral body to be determined. The Cervical Curvature Index (CCI), adapted from Takeshita et al. (2001), was defined as the perpendicular distance of vertebrae C2-C6 from a line joining the mid-inferior points of C1 and C7 (Figure 2). These distances were normalized to the length of the line from C1 to C7 and multiplied by 100. The CCI provided a measure of overall neck curvature, where a higher number indicates a larger curvature.

## Electromyography

EMG activity was measured using both indwelling and surface electrodes. Surface electrodes were placed on the skin superficial to the left sternohyoid (STH) muscle (Siegmund et al., 2007). In order to measure neck muscle activity of the deep neck muscles, indwelling fine-wire electrodes were inserted into the left sternocleidomastoid (SCM), trapezius (Trap), levator scapulae (LS), splenius capitis (SPL), semispinalis capitis (SsCap), semispinalis cervicis (SsCerv), and multifidus (MultC4) muscles (Siegmund et al., 2007). The indwelling electrodes consisted of pairs of PFA-Coated Stainless Steel 0.0055" diameter wire (A-M Systems, Inc., Sequim, WA) with 1 mm exposed wire and 2-3 mm inter-electrode spacing. The wires were inserted with ultrasound guidance to a point near the center of each muscle belly at the C4/5 level. Since the cross-section of the trapezius muscle was typically only a few millimeters thick at the C4/C5 level, wires for this muscle were inserted near C5/C6. The fine-wire signals were amplified and band-pass filtered at 50-1000Hz and the surface signals were amplified and band-pass filtered at 30-1000Hz. The RMS of the muscle activity was calculated for a 500ms window; this window was centered on the fluoroscopic image of interest. Each muscle's activation was normalized to the activation elicited for that muscle in a maximum voluntary contraction (MVC).

For the MVCs, seated subjects were secured to a rigid backboard while wearing a skateboard helmet. The helmet was attached to a 6-axis load cell (45E15A-U760, JR3, Inc., Woodland, CA) directly above the subject's head (Figure 1). Maximal voluntary contractions were performed isometrically in the neutral head posture in the following 7 directions: flexion, extension, left lateral bending, two 45 degree oblique combinations (of flexion/left lateral bending and extension/left lateral bending), and clockwise and anti-clockwise axial rotations. Each contraction was repeated twice, and trials were three seconds in length. The EMG signals were amplified and band-pass filtered as before. A 500ms window in which the maximum force was exerted was identified; the RMS for each muscle's EMG was calculated in this 500ms window. The maximum RMS value for each muscle, regardless of direction, was used for EMG normalization.

# RESULTS

The subject group had an average CCI of 21.2 when they were upright and relaxed (Figure 3). When subjects were inverted and told to relax, the average CCI increased to 40.7. All subjects increased their CCI when inverted, although there was a high inter-subject variability in both conditions.

While upright and relaxed, the subject group had minimal muscle activity ranging from a group mean response of 0.4%MVC (SPL and MultC4) to 1.0%MVC (LS) with little variability in the subject responses (Figure 4). When the subjects were inverted and relaxed, there was increased activity: the mean muscle response was 10.4 times higher in the inverted condition. This increase was most pronounced in the deep neck muscles, SsCap, SsCerv, and MultC4, which increased to 14.4%MVC, 4.5%MVC, and 11.6%MVC, respectively. As with neck curvature, there was a large inter-subject variability in the EMG data. In the inverted condition, the standard deviation was as high as 19.4%MVC in the multifidus and 36.5%MVC for trapezius.

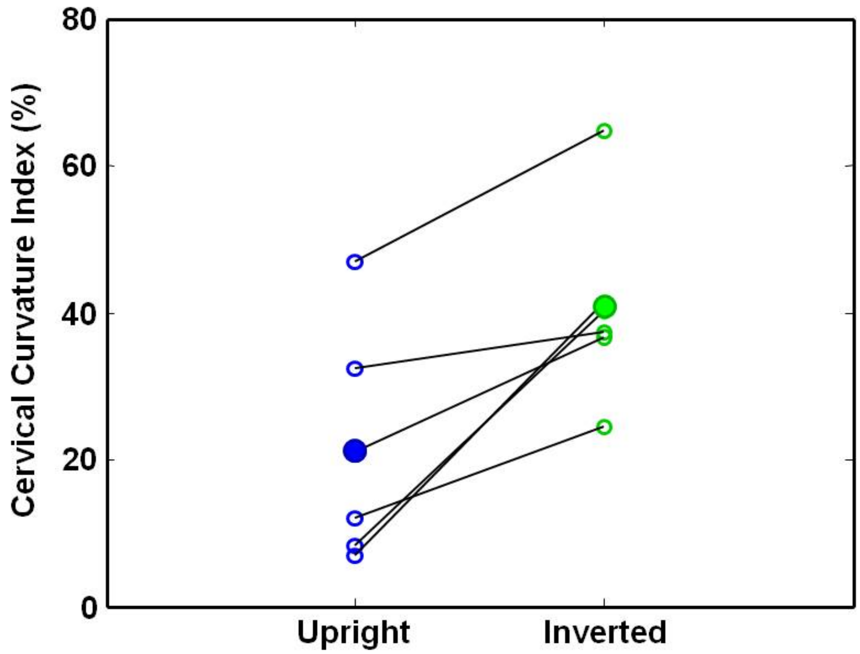



Figure 3: Average (solid circles) and each subject's (open circles) curvature index for both conditions: upright-relaxed (blue), inverted-relaxed (green)

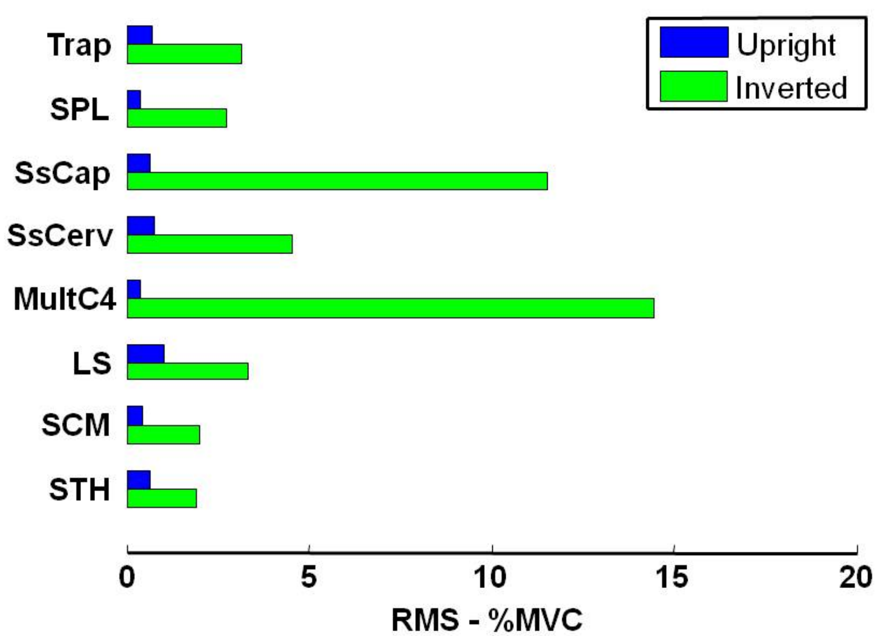



Figure 4: Average EMG activity for 8 neck muscles normalized to %MVC for all subjects: upright-relaxed (blue) and inverted-relaxed (green).

## Discussion of Results

A common mechanism of neck injury in a rollover is when the occupant's head impacts the roof of the car, typically while they are upside-down. Despite this condition, previous axial impact cadaveric testing protocols have frequently used cadavers in an upright configuration (Maiman et al., 1983; Yoganandan et al., 1990; Pintar et al., 1995), in a prone/supine position (Nusholtz et al., 1981; Alem et al., 1984), or an inverted configuration but with the neck positioned in an anatomically upright, neutral posture (Nusholtz et al., 1983; Nightingale et al., 1997). In addition, several recent neuromuscular models have been based on, and validated with, data from the upright neutral posture. For example, Halldin et al. (2000) proposed, and modeled computationally, a car roof mechanism that may reduce the compressive neck load in a rollover accident. Our data suggests that an individual's postural response when upside-down is not the same as when upright.

In general, the role of musculature has largely been neglected in cadaver tests (McElhaney et al., 1983; Nightingale et al., 1997; Carter et al., 2000) and computational models (Yang, 1998; Camacho et al., 1999; Halldin et al., 2000) that have been used to replicate axial impact injury or study injury prevention strategies. The general assumption has been that there would be little to no active muscle response prior to impact since injury occurs before muscles could be actively recruited. However, this study suggests that by simply inverting an occupant, even if relaxed, there is an increase in muscle activity. The center of gravity of the head is slightly anterior to the occipital condyles (Yoganandan et al., 2009), which, when inverted, pulls the head and neck into extension and increases the neck curvature. To pull the head forward to its neutral posture likely requires increased muscle activity. Further work is being conducted to measure the muscle activation required to pull the head forward and the subsequent changes in the spinal posture. Nonetheless, the current findings suggest that it may be important to include neck muscles in headfirst injury models; since even the inverted relaxed posture was associated with an increase in muscle activity in the present study.

Axial impact cadaveric tests have been performed with a range of head and neck postures in order to study the effects of posture on injury mechanisms; yet, there is no general consensus as to what the posture actually is before a headfirst impact. This information is critical for designing and testing neck injury prevention devices, such as rollover roof protection mechanisms or specific roof linings. Not only have we shown that the average subject's inverted posture is not the same as their upright posture, we have also shown that there is large variability in subject responses. This may mean that when conducting experiments or modeling these types of injuries, a variety of neck postures need to be studied. Previous cadaver research has suggested that even small changes in the eccentricity of the spine or the loading vector, on the order of ±1cm, can change the mechanism of injury (McElhaney et al., 1983; Pintar et al., 1995). The range of postures seen in our subjects suggests that testing a limited number of conditions (i.e. only one curvature) may not simulate the response of different people. The neck is mechanically complex: it interacts with the head through the unique C1 and C2 vertebrae, and comprises seven vertebrae and over 23 pairs of muscles. There was also a wide range of initial neck postures amongst individuals in the upright resting posture. Therefore, it is likely there would be different individual responses of the neck in real injurious scenarios.

Relaxing while inverted may not simulate the reaction of occupants involved in a rollover environment. Further work is being conducted to measure the *in vivo* neck response when inverted and looking forward and when inverted with the neck muscles tensed. To extend these findings to a rollover collision scenario and capture a more realistic reaction, further work is also needed to confirm these findings in a dynamic rollover simulation.

## CONCLUSIONS

The aim of this study was to determine whether the inverted relaxed neck posture and muscle activity is different than that of an upright relaxed state. When inverted and relaxed, the muscle activation was about 10 times higher and the cervical curvature index was almost double what they were when upright and relaxed. The increase of neck muscle activation was greater in the deep muscles of the neck. These data suggest that the *in vivo* response to being inverted is not the same as upright. Although further experiments are needed to confirm these findings in dynamic rollover conditions, they show that prior head-first injury models may not have used initial conditions relevant to a rollover collision.

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