Pre-Impact Cervical Spine Posture of Human Subjects in Headfirst Free Falls

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I. INTRODUCTION

Headfirst impacts, in which the head collides with a solid object and the cervical spine is compressed by the ensuing torso, can cause cervical spine fractures or dislocations and spinal cord injuries [1-2]. Compressive injuries in the cervical spine vary with the initial conditions present at head contact [3]. Quasi-static human subject tests have shown that the cervical spine posture changes with both inversion and bracing, but these tests lacked the dynamic nature of headfirst impacts [4-5]. The aim of this experiment was to expose human subjects to dynamic headfirst drops and to record their cervical spine posture during the drops. These data will help reveal how pre-impact alignment of the cervical spine affects neck injuries and could ultimately assist in devising interventions to prevent severe cervical spine injuries.

II. METHODS

Eleven healthy human subjects (9F, 2M) were seated and belted (5-point harness, RCI Racers Choice Inc., Tyler, TX) in an automotive racing seat (Kirkey Racing Fabrication INC., St. Andrew's West, ON) that was mounted to a custom-built test rig [6]. University of British Columbia's Clinical Research Ethics Board approved the use of human subjects and subjects gave their written, informed consent. Subjects were inverted in the test rig, elevated about ~1 m, and then released to free fall for 312 ms before decelerating at ~2 g to rest. Before being released, subjects experienced a random fore-period lasting between 5 s and 10 s to reduce their ability to predict the onset of the free fall. Each subject underwent four drops (>15 min. between drops): the first two drops were relaxed (unbraced), wherein their only task was to maintain a horizontal head position; the last two drops were braced, wherein subjects were asked to voluntarily brace for an imminent headfirst impact. No specific instructions were given on how subjects were to perform this bracing manoeuvre. To capture the intervertebral motions of the cervical spine during the drop, sagittal x-rays were acquired using a fluoroscope (OEC 9400, GE, Salt Lake City, UT) attached to the test rig. Images were collected by a high-speed camera (Chronos 1.4, Krontech, Burnaby, BC) at 200 Hz, with the fluoroscope set to 88 kV and 2.8 mA. A bead-array fastened to the subjects' head projected into the fluoroscope field of view and enabled us to determine head angle in the sagittal plane. Image frames at the start of the drop and at 310 ms later (just before the end of the free fall) were manually segmented for each drop. For all visible vertebrae, we calculated the translation (+x = anterior, +z = inferior) and rotation (+y = extension) of the vertebrae between the start and end of the free fall. For the three vertebrae (C3 to C5) that were visible in all trials and all subjects, we calculated the mean and standard errors of the start angle, end angle and change in angle, and then compared these angles between the relaxed and braced conditions using separate general linear mixed models and a significance level of $p \leq 0.05$. Head angles (+y = extension) at the start and end points were measured from the lab horizontal and reported as a sample mean and standard error.

III. INITIAL FINDINGS

All subjects in both the relaxed and braced conditions moved their cervical spine more anteriorly (+x) and inferiorly (+z) during the drop (Fig. 1). While some subjects straightened their cervical spines during the drop, others maintained its initial curvature and instead flexed their whole cervical spine locally about C7. The absolute C3 to C5 angles at the start of the drop were 4.7±1.3° more flexed in the braced condition than in the relaxed condition ($p=0.0005$). At the end of the drop, there was no significant difference in the C3 to C5 angles between the relaxed and braced conditions ($p=0.053$). The change in the C3 to C5 angles were 12.7±2.1° for the relaxed condition and 2.6±0.8° greater for the braced condition ($p=0.0021$). There were no differences between the C3, C4 and C5 vertebrae for the start and end angles ($p>0.19$), but the change in C5 angle was 2.0±1.0° less than the change in the C3 angle ($p=0.042$). In the relaxed condition, head angles were 5.5±1.8° and -2.9±3.0° for drop start and end, respectively, while in the braced condition head angles were -3.5±3.3° and -6.6±4.3°, respectively.

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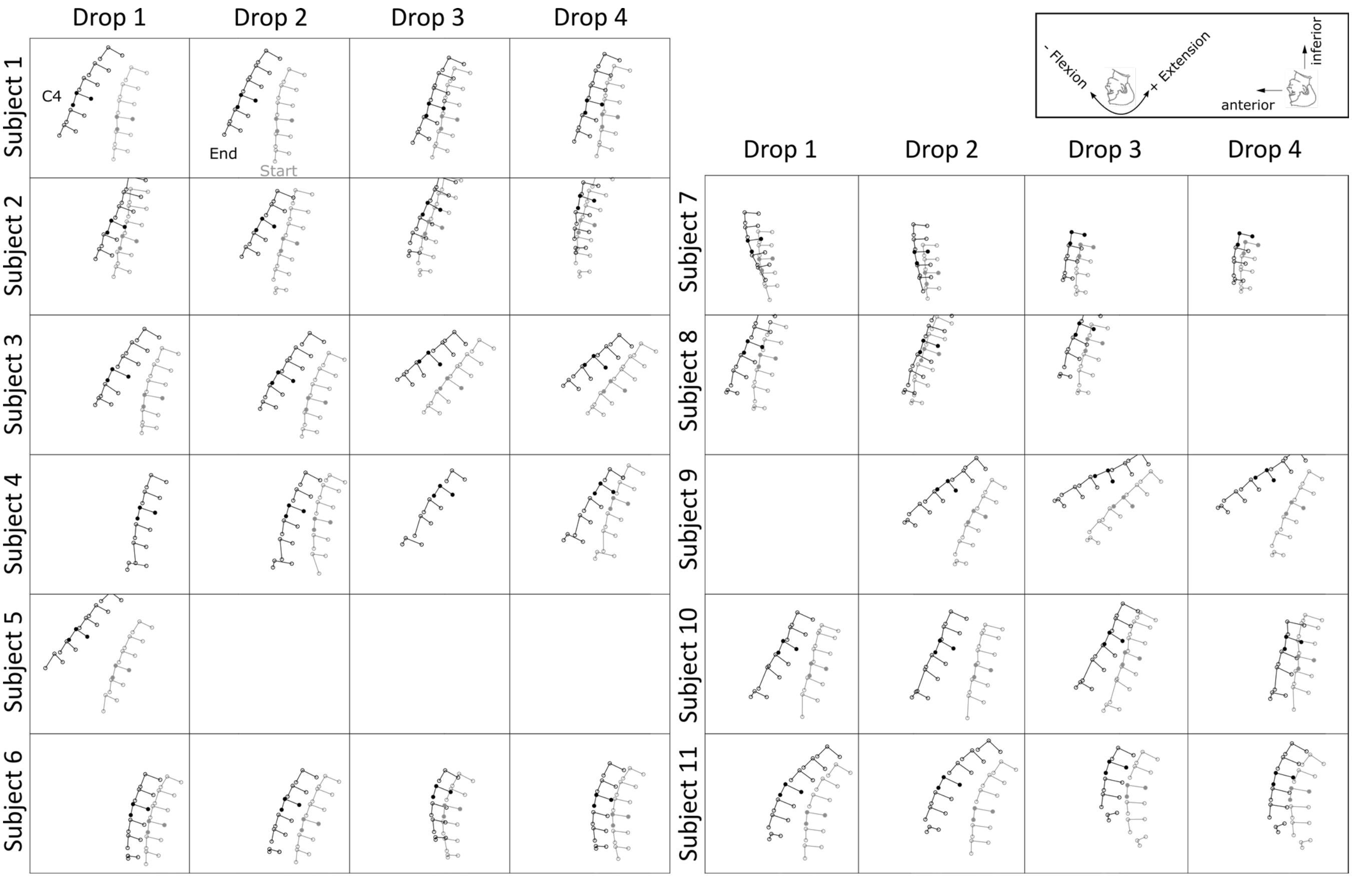

Fig. 1. Vertebral positions of the visible cervical vertebrae at the start (grey) and end (black) of each recorded drop. Hollow circles symbolise the superior-anterior corner and the two inferior corners of each vertebral body. For orientation, the circle markers at the three corners of C4 are filled. Note that the spine is inverted in these images (see the inset at top right for the orientation legend). Empty squares represent missing data.

IV. DISCUSSION

Similar to our initial cohort of four subjects [6], all subjects in both braced and relaxed (unbraced) headfirst drops shifted their cervical spine more anteriorly and inferiorly in response to the inverted free fall. Despite increasing the size of our study group, we observed large variances in the mid cervical spine angles and vertebral translations of the subjects. The range of responses we observed was similar to variances found in Newell *et al.*'s quasi-static experiments [4-5], highlighting the need to account for the range of human neck postures and responses, instead of designing to an average, when developing preventive measures. Our results also demonstrated that pre-drop bracing notably reduced the change in intervertebral flexion angles during the drop, but it did not have a significant effect on the C3 to C5 angles at the end of the drop. This finding suggests that pre-bracing may have a limited effect on the alignment of the cervical spine at the end of a free fall of the duration and magnitude used here. Our flexion angles may have been limited by the restrictions imposed by the 5-point harness, and more variability may exist when typical seat belts are used. The angles and variability we observed may also be influenced by multiple other factors, including an individual's body weight, the interaction between soft tissues and the restrictive racing seat, and the position of the shoulder relative to C7. In summary, our findings suggest that the reflex response to a headfirst drop generates significant motion and repositioning of the cervical spine, and that individuals generally translate their head anteriorly in response to a headfirst free fall.

V. REFERENCES

[1] Bambach, M., *et al.*, *Accid Anal Prev*, 2013. [2] Sekhon, L., *et al.*, *Spine*, 2001. [3] Winkelstein, B., *et al.*, *Med Sci Sports Exerc*, 1997. [4] Newell, R., *et al.*, *J Biomech*, 2013. [5] Newell, R., *et al.*, *Spine*, 2014. [6] Al-Salehi, L., *et al.*, *AAAM*, 2022.