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INJURY SCIENCE RESEARCH
Proceedings of the Twenty-Eighth International Workshop

Velocity and Level Dependent Facet Joint Kinematics in Low-Speed Rear Impact

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ABSTRACT

This study quantified the kinematics of cervical facet joints as a function of rear-impact acceleration. Six intact human head-neck complexes were prepared and oriented such that the Frankfort plane was horizontal, and the cervico-thoracic disc was rotated to simulate the normal driving position. Retroreflective targets were inserted into the vertebrae for analyzing the temporal kinematics. The specimens were subjected to simulated rear-impact accelerations using a mini-sled apparatus at velocities of 2.1, 4.6, 6.6, 9.3, and 12.4 km/h. Facet joints demonstrated dorsal compression and ventral distraction (local coordinate system). Monotonically increasing variations of peak axial and sliding kinematics occurred with increasing changes in velocity. C5-6 facet joints responded with lower magnitudes of axial and sliding motion at lower input changes in velocity, but higher magnitudes at greater input velocities than the other investigated levels in this study.

INTRODUCTION

Biomechanics of the human head-neck complex in rear crashes has been studied using experimental models. These included static loading of ligamentous columns, spine units, and whole-body specimens [Yoganandan and Pintar, 2000; Winkelstein, et al., 2000]. Although whole-body tests provide data on the kinematics of the head-spine, it is difficult to discern the local motions of the intervertebral joints that contribute to the mechanics of the neck. This is primarily due to the difficulties in resolving the motions with sufficient accuracy as the joints of the spine have minimal dimensions (e.g., facet articulation). Studies using segmented spinal units are incapable of accommodating the curvature and segmental changes of the column [Clark, et al., 1998; Sherk, et al., 1989]. Although these models have attempted to provide answers to questions such as the role of the thoracic spine (from whole-body tests), it is important to delineate local component kinematics (facet joint motions as a function of level). Such evaluations may have implications in the analysis of head-neck kinematics secondary to rear impact as it is well known that motions determine the local integrity of spinal components [Cusick, et al., 1988; Yoganandan, et al., 1990]. The quantification of velocity-dependent kinematics of the innervated components may define tolerance. This study determined the kinematics of the facet joints as a function of velocity.

METHODS

Six unembalmed human cadaver head-neck complexes were used. Prior to head-neck isolation, each specimen was screened for HIV and Hepatitis A, B, and C. The anatomical orientation was as follows:

+x direction = posterior to anterior; +y direction = right to left lateral; +z direction = inferior to superior. To enable rigid mounting of the complex to the minisled apparatus and facilitate proper orientation during testing, each complex was mounted at the first thoracic vertebra in polymehtylmethacrylate (PMMA) and oriented at +25 deg about the y-axis. The skin and muscle were minimally transected on the lateral side to facilitate placement of photo-reflective targets, which were inserted to track relative rigid-body displacements and rotations of the bony elements of the head-neck complex. Two targets were placed along the Frankfort Plane. Targets were placed in the anterior body and superior transverse process of each vertebra. Four targets were placed to outline the facet joints at C4-5, C5-6, and C6-7 levels. In addition, four targets were placed on the PMMA.

All tests were performed using a mini-sled apparatus (Figure 1). The pendulum accelerated in the global x-direction [Yoganandan, et al., 1998]. An energy absorbing material was placed in front of the impacting edge of the pendulum to shape the impact pulse. The input pulse was modeled to mimic the x acceleration at the first thoracic vertebra from our rear impact full-body tests. Modeling criteria were pulse shape and pulse width. Tests were performed to obtain the desired input pulse to the first thoracic vertebra. A 50th percentile Hybrid III dummy head-neck complex was used for these tests. The initial height of the impactor and energy absorbing material on the impactor were altered to obtain the desired input pulses. Input changes in velocity (ΔV) of 2.1, 4.6, 6.6, 9.3, and 12.4 km/h were chosen.

Figure 1. Test setup.

A 2.1 km/h test was performed twice at the start to describe baseline motions and then once between each higher velocity test for diagnosing injury or biomechanical irregularity. Immediately after each test, input pulses were analyzed for consistency between ΔV, pulse width, and peak acceleration. Between tests, the specimen was inspected for injury, which included visual inspection and radiography. If injury was detected, no further tests were done. After the completion of 12.4 km/h tests or diagnosis of injury, a final x-ray was taken. Motion data were obtained at 1000 Hz. The motion of each target was mapped in the sagittal plane. Data were organized into x- and z- positions of each target.

A local coordinate system was established for each facet joint with the positive x-direction along the posterior-anterior direction of the inferior facet joint surface and positive z-direction in the inferior-superior direction perpendicular to the positive x-direction. The local coordinate system was updated at each time step to follow rotation of the lower facet joint surface; the origin always remained at the posterior-inferior target and the positive x-direction through the anterior inferior target. The local and global y- directions remained the same in this transformation, although the local coordinate system origin moved with the posterior inferior joint target. Motions of the targets at the end of the pulse were separated into axial and sliding components. All motions were recorded as the anterior/posterior superior target with respect to the anterior/posterior inferior target. For instance, anterior distraction was obtained by anterior-superior target increasing local z-axis distance from the anterior-inferior target. Positive sliding was defined as the superior target moving in the local positive x-direction with respect to the inferior target. Axial and sliding motions at the three spinal levels were analyzed using linear regression and analysis of variance (ANOVA) techniques. Mean values of anterior and posterior axial and sliding kinematics were evaluated as a function of ΔV. Linear regressions were performed on the data with ΔV as the independent variable and specific facet joint motion as the dependent variable. ANOVA statistics were used to evaluate trends between facet joint motion and either vertebral level or change in velocity.

RESULTS

Figure 2 illustrates mean axial motions of the C5-6 facet joint for the five input velocities. Similar results were obtained at the C4-5 and C6-7 levels. For all three levels (C4-5, C5-6, and C6-7), anterior motions demonstrated distraction, and posterior motions showed compression. Mean axial motions increased with increasing ΔV with the exception of C5-6 anterior and C6-7 posterior motions. In both cases, magnitudes reached a maximum at 6.6 km/h. Sliding motion of the facet joints exhibited increasing motions with increasing ΔV, and is illustrated for the C5-6 level in Figure 3. Similar results were obtained at the C4-5 and C6-7 levels. Motion of the C4-5 joint had lower magnitude than C5-6 and C6-7 joints, which were approximately equal.

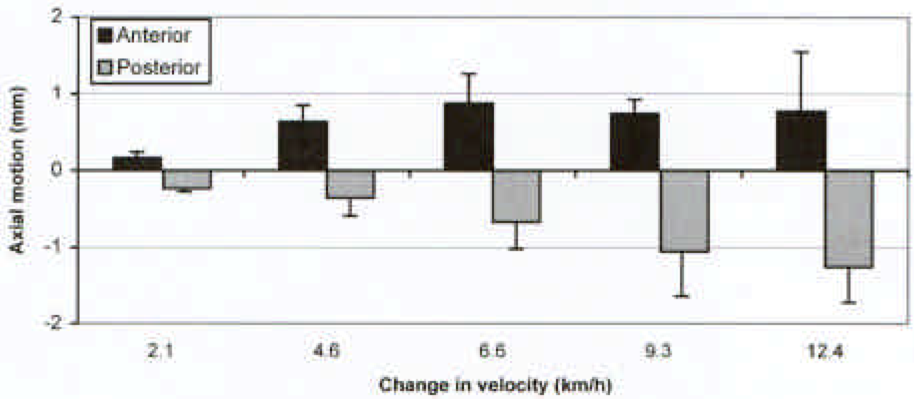

Figure 2. Mean posterior axial motion for C5-6 facet joint.

Regression analyses were performed with input ΔV as the independent variable and motions as dependent variables. Data were split by spinal level. This resulted in R^2 values for each motion component at all three levels. Motions increased linearly with ΔV. All R^2 values were greater than 0.900 with the exception of C5-6 anterior compression and C6-7 anterior and posterior compression. R^2 values of C4-5 and C5-6 compressive motions were greater than C6-7. Sliding motions illustrated greater slope (regression line) than axial motions. This indicates that for the same ΔV, all joints underwent greater displacements in the local x than z direction. Motion of the C5-6 joint was greater than C4-5 and C6-7 joints.

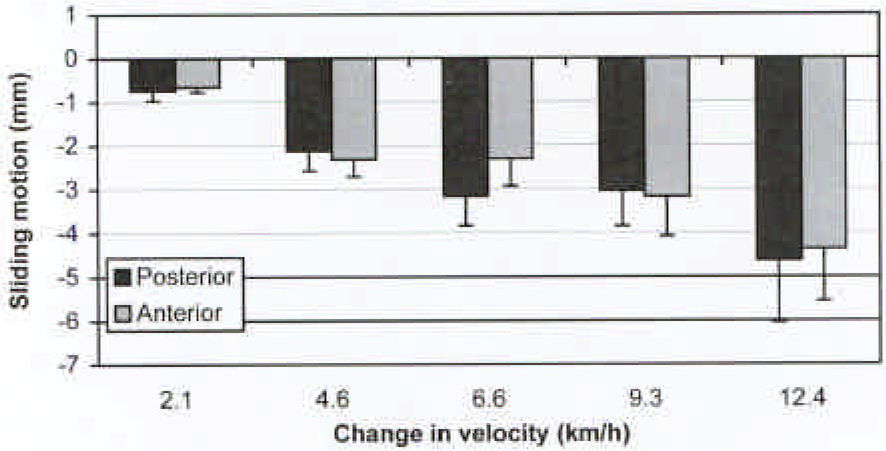

Figure 3. Mean anterior sliding motion for the C5-6 facet joint. Negative siding motion is defined as the superior target moving posterior to the inferior target.

The ANOVA test, conducted to determine the interrelationship between the two factors, spinal level and ΔV on facet joint motions, resulted in a p-value of 0.21. This indicated that the two factors are not interrelated. Therefore, independent ANOVA analyses between facet joint level, facet joint motions, and ΔV were performed. In the analysis of the variability of motions based on level, the independent variable was level and dependent variable was motion. Independent analyses were performed for each of the four motions; i.e., posterior axial and sliding motions, and anterior axial and sliding motions. Data were split by ΔV. With increasing velocity, relative motions of C5-6 (with respect to C4-5 and C6-7) increased for anterior and posterior sliding and posterior axial motion. With increasing velocity, C5-6 anterior axial motions were smaller than C4-5 and C6-7. Results of the ANOVA test with velocity as the independent variable and facet joint motion as the dependent variable indicated that the posterior and anterior sliding motions are significantly affected by ΔV.

ACKNOWLEDGMENTS

This research was supported in part by PHS CDC Grant R49CCR 515433 and VA Medical Research.

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