Inverse Dynamics Based Determination of Cervical Spine Loads in Pediatric and Adult Volunteers During Low Speed Frontal Impacts

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ABSTRACT

Little is known about the biomechanical response of children to dynamic loading such as that seen in an automobile crash. Pediatric anthropomorphic test devices (ATD), the tools used to study such response, have been scaled from adult biomechanical data and do not explicitly mimic the response of an actual child. In particular, the developmental changes associated with the cervical spine may limit the accuracy of this scaling process and thus result in a pediatric ATD spine of limited biofidelity that inaccurately positions the ATD head during crash loading. The objective of this study was to use inverse dynamics methods to determine the upper and lower neck forces and moments from the average head and cervical spine trajectory of volunteer subjects in a low speed frontal impact. This data would provide insight into the biomechanical response of the cervical spine of children, particularly the forces generated within the neck. A total of 40 male subjects in four age groups (6-8 years, 9-12 years, 13-15 years, 18-40 years) were tested. Volunteers were restrained in a custom fit three point restraint system and subjected to a 3.1 g frontal impact in a purpose built crash sled. For the purpose of this study, the three-dimensional kinematics data were obtained using reflective spherical markers attached to anatomical landmarks tracked using a 3D motion capture system and the head angular velocity was measured using an angular rate sensor mounted to a bite plate. Forces and moments within the cervical spine were then calculated from the kinematics data using an inverse dynamics approach. These data can then be used to develop a computer model of the cervical spine for crash simulations, as well as recommendations for a physical model for more accurate pediatric ATDs.

INTRODUCTION

Anthropomorphic test devices (ATDs) are used to examine the biomechanical response of humans. This study sought to quantify the biofidelity of the cervical spine response of pediatric ATDs for use in frontal automotive crashes. Adult ATDs were developed using kinematic data from post mortem human subjects (PMHS) in laboratory crash scenarios. Pediatric PMHS are very rare, therefore this same approach is not used to develop pediatric ATDs. Instead, they are scaled versions of adult ATDs. Due to developmental changes that occur in the cervical spine during childhood and puberty, this method may produce an ATD of limited accuracy. To obtain the desired kinematic data, it was decided that the most effective means to do so would be with live volunteers subjected to a mild impact. Because the safety of children is paramount in this study, a crash impulse modeled after that of a bumper car impact was used. Accelerometers were placed on amusement park bumper cars and subjected to various crash scenarios. The greatest impact recorded was from a bumper car running straight into a wall, giving an acceleration pulse of about 5 g's maximum over 30 milliseconds (ms). To err on the side of caution, an acceleration pulse of 3.1 g's over 30 ms was chosen. 40 subjects were tested from 4 age groups, 6-8, 9-12, 13-15, and 18-40 years old.

METHODS

To consistently reproduce the desired acceleration pulse, a purpose built crash sled was fabricated. The sled chassis was constructed of Minitec brand extruded aluminum members. The sled features a low back seat and back support strap to maximize visibility of the spine. A standard three point automotive seatbelt was used to restrain subjects during an impact. The seatbelt was provided by Takata, the project's main sponsor. Shown below is the sled with a Hybrid III 6 year old ATD seated in the prescribed test position (Figure 1). The sled was instrumented with an accelerometer in the direction of sled travel, six axis load cells in the seat and footrest, three seatbelt tension load cells, and an angular rate sensor attached to a bite plate held in the subject's mouth. Data from these sensors was recorded with a TDAS data acquisition system at a sampling rate of 10 kHz. The sled rode on a 20 foot Minitec linear bearing system and was accelerated by a hydro-pneumatic ram. Air pressure in the pneumatic ram provided the force to push the cart, but pneumatics alone produce a mass dependant acceleration. A hydraulic system with a high frequency control valve and linear displacement feedback loop controlled the ram and gave a consistent acceleration pulse regardless of the mass of the sled.

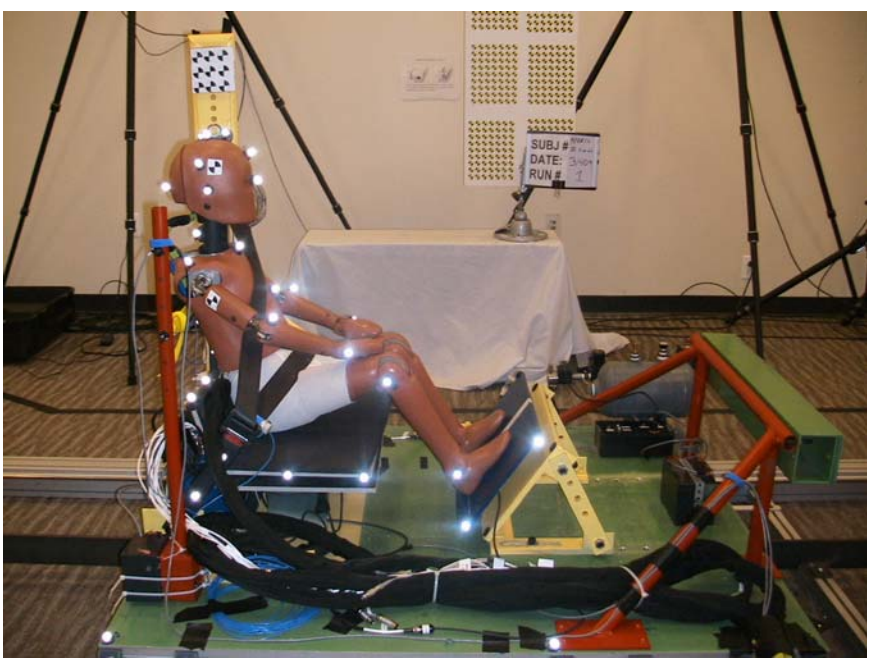

Figure 1: Hybrid III 6 year old seated in the sled.

Kinematic data from the subjects was acquired with an Eagle motion capture system at 100 frames per second. Reflective markers attached to anatomical landmarks were tracked by the eight camera system and imported into 3-D motion analysis software. This kinematic data was used to perform the inverse dynamics calculations to find the forces and moments in the neck.

An inverse dynamics approach similar to that used by Sundararajan et al. was used to calculate the forces at the occipital condyle (OC), the joint between the skull and C1 vertebrae (Sundararajan, 2004). It was assumed that all motion occurred on the Sagital plane (2-D assumption). Inverse dynamics uses the general form of F=MA. Once the accelerations from the motion capture data and mass properties of the head from anthropometric correlations (Jensen 1988) were known, the forces were solved for. This study assumed the center of gravity (CG) of the head was 1.5 cm forward of the external auditory meati (EAM) and on the Frankfort plane. The SAE J211 axis conventions (SAE, 1995) were used as picture below (Figure 2).

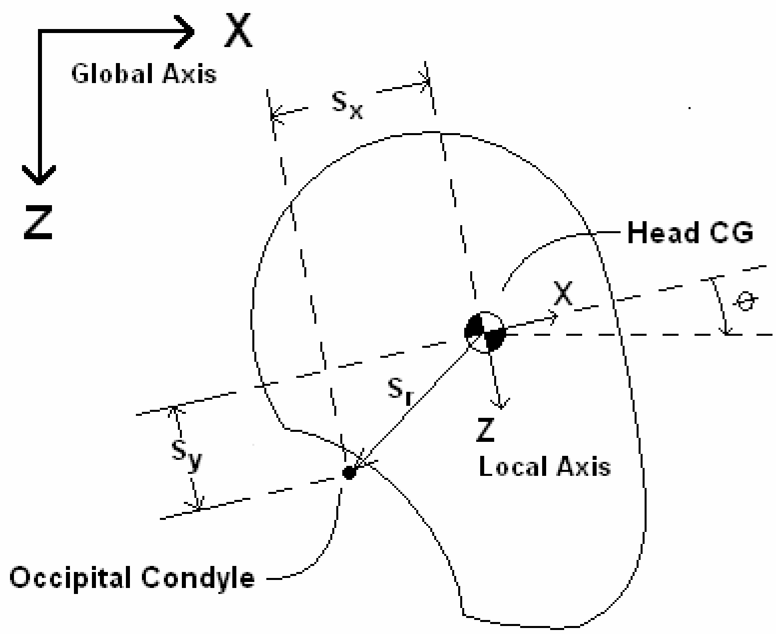

Figure 2: Axis conventions and CG and OC location

The acceleration of the head CG alone was not sufficient to calculate the forces at the OC. The acceleration was first rotated to keep the local X axis on the Frankfort plane, next the acceleration was transformed to the OC location using the five term acceleration equation.

$$a = \ddot{r} + \ddot{s}_r + (\alpha \times s_r) + (2\omega \times \dot{s}_r) + (\omega \times (\omega \times s_r))$$

Where:

$\ddot{r}$ is the Head CG acceleration

s_r is the distance vector from the head CG to the Occipital Condyle (OC)

$\dot{s}_r$ and $\ddot{s}_r$ are the velocity and acceleration respectively between the head CG and OC. Both are zero in this case ω and α are the angular velocity and angular acceleration of the head

Using the non-zero terms, the acceleration of the head CG translated to the OC is $a = \ddot{r} + (\alpha \times s_r) + (\omega \times (\omega \times s_r))$. Forces were found by multiplying the accelerations by the head mass and adding the proper component of the head weight. To clarify, the total force in the X direction was

$$F_x = m_{head}(a_x \cdot \cos\theta + a_y \cdot \sin\theta - g \cdot \sin\theta + \alpha \cdot s_y + \omega^2 \cdot s_x)$$

RESULTS

To validate the calculations, a Hybrid III 50% male ATD was used in the sled and the reactions in the upper neck load cell were measured and compared to the calculated loads. Plots comparing the forces in the X and Z directions as well as the moment about the Y axis are pictured below (Figure 3).

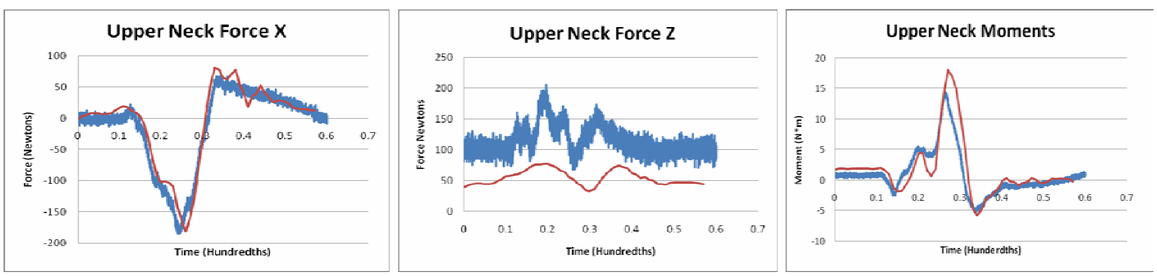

Figure 3: The red line is calculated from motion analysis and the blue is measured from the ATD upper neck load cell

The inverse dynamics process was used to calculated loads in the neck of a Hybrid III 6 year old ATD, and at the OC of subjects in each age range.

CONCLUSIONS

The plot for the Force in the Z direction did not match the collected and calculated data, this was believed to be caused by a calibration error. Although the vertical positions were skewed, the trends were still similar, the difference was assumed to be a simple biasing error.

This method proved to be an effective way of assessing the forces and moments in the neck of both Adults and children. This study may affect the design of the next generation of pediatric ATDs.

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