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Technique for Chestband Contour Shape-Mapping in Lateral Impact

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Abstract

The chestband transducer permits noninvasive measurement of transverse plane biomechanical response during blunt thorax impact. Although experiments may reveal complex two-dimensional (2D) deformation response to boundary conditions, biomechanical studies have heretofore employed only uniaxial chestband contour quantifying measurements. The present study described and evaluated an algorithm by which source subject-specific contour data may be systematically mapped to a target generalized anthropometry for computational studies of biomechanical response or anthropomorphic test dummy development. Algorithm performance was evaluated using chestband contour datasets from two rigid lateral impact boundary conditions: Flat wall and anterior-oblique wall. Comparing source and target anthropometry contours, peak deflections and deformation-time traces deviated by less than 4%. These results suggest that the algorithm is appropriate for 2D deformation response to lateral impact boundary conditions.

Keywords

Chestband; Lateral impact; Computational methods; Thorax

1. INTRODUCTION

In biomechanical postmortem human subject (PHMS) experiments, the chestband device has permitted measurements of torso deformations throughout impact without invasive instrumentation or parallax error from videographic analysis (Eppinger, 1989). Validated for lateral sled impact experiments using an anthropomorphic test dummy (Pintar et al., 1996), resulting subject-specific chestband contour shapes were post-processed to quantify deflection responses to impact (Kuppa et al., 2003; Pintar et al., 1997; Shaw et al., 2006; Yoganandan et al., 2008). Methodologies by which chest deflections were quantified from the contours have been varied (Fig. 1). For example, deflections were considered to be the maximum change in distance between the spine-sternum axis and three select circumferential points (Pintar et al., 1997), between any two contour location pairings (Shaw et al., 2006), or between the impacted contour aspect and a fixed point on the spine-sternum axis (Yoganandan et al., 2008). Yet, in each methodology the resulting uniaxial deflection

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Conflict of Interest

The authors do not have any conflicts of interest to disclose.

responses may neglect potentially injurious deformations remote from the metric computation site, e.g., narrow-object intrusion in motor vehicle side impact crashes (Pintar et al., 2007). Multidirectional deformation patterns may pose unique injury mechanisms and require multipoint response characterization. Such complex deformations also may be suitable for examination through viscoelastic finite element (FE) methods to characterize visceral response.

Deformations as characterized by chestband contours may be applied to computational models to reproduce subject visceral response. Yet because contours are subject-specific, subject-specific models would be required. Prior human biomechanical FE models for injury evaluation, e.g., HUMOS (Behr et al., 2003), were developed using standard anthropometry measurements and required extensive mesh optimization. Model complexity therefore may prohibit adapting model geometry to experimental test subject anthropometry. Consequently, the present study developed an approach by which subject-specific chestband contours were adapted (mapped) to a standardized anthropometry cross-section for computational examination.

2. METHODS

All data were pre-processed using the RBandPC software (ver. 3.0, Conrad Technologies, Inc., Washington DC, available from the U.S. Department of Transportation) accompanying the chestband transducer (Denton Inc., Farmington Hills, Michigan). Briefly, ASCII chestband data were generated consisting of closed contours for each sample time t . Each contour consisted of i points in approximately 2 mm intervals; each point was expressed within a Cartesian coordinate system defined by user-specified spine and sternum locations (Fig. 2). Origin (O) was defined by the spine. For each contour point i , clockwise circumferential distance (s_i) and Cartesian vector coordinates ($\mathbf{R}_i$) were quantified with respect to O .

Algorithm

The mapping algorithm was developed using MATLAB (MathWorks, Natick, MA). ASCII data were imported from a source chestband contour for all t , and the spine and sternum locations were maintained. Two vectors $\mathbf{X}$ and $\mathbf{Y}$ were defined according to Equations 1 and 2 with respect to: spine centerline (O), sternum centerline ($\mathbf{R}_A$), and points equal to half the circumferential distance between spine and sternum on the left ($\mathbf{R}_L$) and right ($\mathbf{R}_R$) sides (Fig. 3).

$$\mathbf{X} = \mathbf{R}_A - \mathbf{O} = \mathbf{R}_A \quad (1)$$

$$\mathbf{Y} = \mathbf{R}_R - \mathbf{R}_L \quad (2)$$

A new origin (O') was defined by the intersection of $\mathbf{X}$ and $\mathbf{Y}$. Vector $\mathbf{Q}_i$ then defined the location of contour point i with respect to O' . Arbitrary coordinates q_1 and q_2 , defined according to Equations 3 and 4, expressed point i with respect to the axes defined by $\mathbf{X}$ and $\mathbf{Y}$.

$$q_{1,i} = \mathbf{Q}_i \cdot \mathbf{X} \quad (3)$$

$$q_{2,i} = \mathbf{Q}_i \cdot \mathbf{Y} \quad (4)$$

Parameters $q_{1,i}$ and $q_{2,i}$ represented a new spatial definition for point i . These parameters were then expressed with respect to contour circumference s , generating two uniaxial functions to describe the overall shape of the contour (Fig. 4a). Yet, each contour circumference was subject-specific with the sternum falling at a unique distance from the spine. Therefore a normalized contour circumference was defined with respect to the spine ($s_P' = 0$), sternum ($s_A' = 0.5$), total circumference ($s' = 1.0$), and the half-distance between spine and sternum on the left ($s_L' = 0.25$) and right ($s_R' = 0.75$) side (Fig. 4b). Recall that the sets q_1 and q_2 represent the band shape at a specific sample time t . The shape change over the entire time duration was considered by normalizing each set of q_1 and q_2 with respect to q_1 and q_2 values at $t = 0$ (Eqs. 5 and 6). Final normalized datasets consisted of dimensionless u_1 and u_2 coordinates, unique for each sample time, with respect to dimensionless circumference s' (Fig. 4c).

$$u_1 = \frac{q_{1,t=t_1}}{q_{1,t=0}} \quad (5)$$

$$u_2 = \frac{q_{2,t=t_1}}{q_{2,t=0}} \quad (6)$$

These dimensionless datasets permit source contour deformations to be mapped to a target geometry with unique initial dimensions and n discrete contour points. This was accomplished by first repeating for the target geometry the computational process to obtain undeformed $q_{1,n}$ and $q_{2,n}$ with respect to s_n' (Fig. 4b). This corresponded to $t = 0$ for the target geometry. The MATLAB 'interp1' function was employed to interpolate using cubic splines the normalized parameters $u_{1,i}$ and $u_{2,i}$ from the source contour to the desired points n along the target contour circumference s_n' (Fig. 5). Following interpolation, the source deformations were mapped to the target geometry for all t according to Equations 7 and 8.

$$q_{1,n,t=t_1} = q_{1,n,t=0} \cdot u_{1,n,t=t_1} \quad (7)$$

$$q_{2,n,t=t_1} = q_{2,n,t=0} \cdot u_{2,n,t=t_1} \quad (8)$$

Final deformations of the target geometry were obtained by plotting (q_1, q_2) datasets for all t on stationary $\mathbf{X}$ and $\mathbf{Y}$ axes.

Evaluation

Two source contour datasets were selected from 11 PMHS experiments (Kuppa et al., 2003; Yoganandan et al., 2008) to evaluate algorithm suitability. These experiments employed PMHS positioned in a normal vehicle seated posture and subjected to a lateral sled impact at $\Delta V = 6.7$ m/s in one of two boundary conditions: flat rigid wall or 20–30° anterior-oblique wall. A target geometry was developed from the external contour of the torso at the T11 vertebral level of the Visible Male from the US-NIH Visible Human Project (Spitzer et al., 1996). This target contour was discretized into 192 nodes for future use with a FE model.

Geometric measurements for the target contour as well as the selected experimental source chestband contours are shown in Table 1.

Algorithm validity was evaluated with qualitative and quantitative comparisons. Qualitatively, resulting contours were examined for similarity in appearance. For quantitative comparisons, deflections were computed between the contour perimeter and the chestband origin as defined by intersecting axes. After being normalized to total chest breadth in accordance with accepted biomechanical injury metrics (Pintar et al., 1997), deflections were compared along similar angles (θ) with respect to the anterior direction (Fig. 3). Peak deflections with respect to θ as well as deflection-time traces were examined.

3. RESULTS

A qualitative comparison between the source (PMHS) and target (FE) geometries is shown in Figure 6. For each boundary condition, localized deformation shapes and magnitudes were consistent between the subject-specific source contours and the standardized target geometry. Figure 7 depicts quantitative deflection analyses corresponding to the two boundary conditions. Peak normalized deflections expressed with respect to θ deviated a maximum of 2.3% or 3.8% of peak overall deflections for the flat rigid or oblique wall boundary conditions, respectively. Deflection-time traces were also compared at $\theta = 90^\circ$ and 70° for these respective boundary conditions; location of time trace measurement is indicated by broken lines in Figure 7. Examining the flat rigid and oblique boundary conditions, peak deflections on the deflection-time trace deviated by a maximum of 3.7% and 2.2%.

4. DISCUSSION

Chestband deformation patterns in 2D were mapped between two moderately-dissimilar anthropometries. Initial (undeformed) chestband contours are subject-specific due to external torso dimensions, e.g., depth and breadth (Table 1). Although thoracic sections in the transverse plane may be approximated by an ellipse, test subject contours are not always symmetrical. Moreover, previous geometric or mass scaling relationships, e.g., Equal-Stress / Equal-Velocity (Eppinger et al., 1984), are not applicable to planar deformation patterns for normalization between test subjects. Therefore this methodology represents a novel approach by which planar contour deformations may be translated between anthropometries and is useful for computational models and for anthropomorphic test dummy development and biofidelity assessments.

The boundary conditions evaluated in this study represent lateral impact scenarios with variable directions of thoracic deformation. Because crash occupants sustain chest loading from a diverse set of vehicle interior components (Nirula and Pintar, 2008), side impact crashes may not represent flat pure lateral contact. Therefore the present study employed chestband data from both flat rigid wall and oblique wall sled tests. Contrasted with flat rigid wall, obliquely mounted wall boundary conditions induced deflections of greater magnitude and more anterior with respect to subject anatomy (Yoganandan et al., 2008). The mapping algorithm was shown suitable in these boundary conditions, demonstrating the robust nature of this computational approach.

The algorithm evaluated in this study is appropriate for moderately-dissimilar geometries under these boundary conditions. Specifically, subject-specific source contours and resulting target contours were elliptical in appearance with major and minor axes oriented similarly. Intuitively, large anatomical variances such as those between species may require algorithm refinement or an automated assessment of initial geometric similarity. Further, the chestband

contour deformations account for external deformations only and do not consider variations to underlying anatomical structures or their resulting deformation responses. For example, imaging studies have suggested wide variances in visceral anatomy within the human population despite external height and weight similarity (Geraghty et al., 2004). Therefore future work should examine the relationship between visceral anatomy and visceral response when external deformations remain unchanged.

Research Highlights

1. Chestband contours represent subject-specific deformation patterns in the transverse plane.
2. A shape-mapping algorithm was developed to apply contours to a standardized anthropometry.
3. Qualitative and quantitative evaluation found the algorithm suitable for lateral impacts.

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Figure 1.
Deflection calculation methods for chestband contours from PMHS lateral impacts.

Figure 2.
Contour data generated by RBandPC for contour point i .

Figure 3.
Contour axes definition used to obtain q_1 and q_2 with respect to X and Y.

Figure 4.

Parameters along exemplar chestband circumference: (a) q_1 and q_2 with respect to subject-specific circumference, (b) q_1 and q_2 with respect to normalized circumference, and (c) undeformed and deformed u_2 with respect to normalized circumference.

Figure 5.
Normalized parameter u_2 before and after interpolation from source points i to target points n .

Figure 6. Exemplar contours from source PMHS chestbands (left) and from target FE geometry (right) for sled impacts with two boundary conditions: (a) flat rigid wall and (b) oblique wall.

Figure 7.
Quantitative comparison between Source and target contour deflection measurements:
Overall peak normalized deflections (left) and deflection-time traces (right) for (a) flat rigid wall and (b) oblique wall.

Table 1

Chestband contour geometry

Contour	Boundary Condition	# Discrete points	Depth (mm)	Breadth (mm)	Circumference (mm)
Source 1	Flat rigid	312	257	302	902
Source 2	Oblique	522	289	375	1086
Target	-	192	278	348	1034