Characterization of the 3D Deformation of the Human Rib Cage for the Analysis of Injury Mechanism: An Experimental and Modelling Coupled Approach

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Introduction

1. Frontal impact accidentology
   - The loading of the thorax results mainly in rib fractures that depend on:
     - The crash conditions: velocity, deceleration, ...
     - The restraint system used: airbag, load-limited belt, ....
     - The occupant characteristics: sexe, age, position, posture, ....?

2. Thorax biomechanics
   - Past studies on thorax behavior under antero-posterior loading have:
     - defined its global biomechanical response and
     - conducted to the definition of corridors, injury risk curves, ...

[Kroell et al, Stapp 1971] [Kent et al, Stapp 2004] [Kent et al, 18th ESV Conference 2003]
Introduction

2. Thorax biomechanics
   - It is important to define injury criteria capable to discriminate the different restraint systems and predict accurately the injuries

3. Thorax biomechanics: open issues
   - How the loading sustained by a human thorax leads to injury?
     1) How the 3D deformation of the rib cage is linked to injury?

   2) What are the parameters governing these injury mechanisms?
      - External parameters: Loading conditions, restraint systems, ...
      - Internal parameters: Geometry, material properties, ...

[Kent et al., Stapp 2005]
Introduction

4. Internal parameters

1) The overall geometry of the rib cage (structural characterization)

Thorax geometry

≠ shape

Thorax geometry

≠ rib inclination

Gray (1974) or HUMOS (2001)

Kent et al, Stapp 2005
Introduction

4. Internal parameters
   2) The role of the joints (functional characterization)

5. Objectives of the study
   1) Analyze the effect of the geometry and initial inclination of the ribs on the 3D mechanism of deformation of the rib cage
     => Structural Characterization
   1) Characterize the joints between the ribs and the spine
     => Functional Characterization
Methods

1. Experiments
   - Tests on isolated, denuded and eviscerated rib cages: bones + intercostal muscles
     - Ribcages @ different loading conditions (antero-posterior loading and impact) and different loading velocities
     - Non injurious and injurious tests on same rib cage
     - Measure the 3D motion of the ribs w.r.t the spine
     - Measure/compute the 3D deformation of the ribs
     - Analyze the rib fracture mechanism

2. Numerical simulations
   - Simulation of the tests with personalized FE models:
     - Isolate the effect of geometry from other parameters (material properties, cross section thickness, inertia, ...)
     - Perform parametric study on specific FE model (variation of rib orientation, ...)
     - Simulations of other loading conditions (belt loading, ...)


Experimental Methods

1. Imposed constraints
   - Keep the initial shape of the rib cage including spine curvature
   - Fix rigidly the spine (no relative motion of the vertebrae)
   - Not reduce the costo-vertebral joint range of motion

[Images of experimental setup with markers, accelerometers, and spine fixture]

[Kapandji, 1994]
2. 3D motion recording

- Motion of the ribs were obtained through the motion of 3 triplets of reflective markers, using 4 High speed cameras (2,000 fps)
- and an algorithm of reconstruction (Direct Linear Transformation)
Experimental Methods

3. 3D motion analysis
   - Motion of the triplets were determined at each time step based on rigid body assumption: Rotation and translation were obtained

4. 3D rib deformation
   - Deformation of the ribs were determined from the motion of the markers and an interpolation procedure:
     1) Control points were selected on the initial geometry of the rib and defined an “initial rib line” IRL.

![Diagram of rib deformation and control points](image-url)
Experimental Methods

4. 3D deformation

- Deformation of the ribs were determined from the motion of the markers and an interpolation procedure

  2) The deformation was decomposed into rigid body rotation and deformation in the rib plane obtained by:

  - Means of an interpolation based on the RBF method,
    [Buhmann 2003 Radial Basis Functions: Theory and Implementations., Cambridge Univ. Press]

  - Computing a deformation of the IRL controlled by the coordinates of control points at their initial and at a given state
Experimental Methods

5. Rib rotation

- Angle definition:
  - The orientation of the rib plane defined 2 angles:
    - lateral and
    - frontal

- both were obtained at each time step using the previous methods
Experimental results

1. Lateral rib orientation variation

- Example of one rib cage, Antero-posterior loading,
  Loading velocity: 1.4 m/s

Comparison between rib:
- Rotation varied with the costal level
- Correlation of the rotation with the force-deflection curve
## Experimental results

1. Lateral rib orientation variation
   - Antero-posterior loading

<table>
<thead>
<tr>
<th>Test ID</th>
<th>$V_{\text{max}}$ [m/s]</th>
<th>$\delta \alpha$ [$^\circ$]</th>
<th>Rib 2</th>
<th>Rib 4</th>
<th>Rib 6</th>
<th>Rib 8</th>
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<td>-7.50</td>
<td>-4.77</td>
<td>-4.79</td>
<td>-3.46</td>
</tr>
</tbody>
</table>

Comparison between rib cages
- Magnitude of the rotation ≠ between the rib cages
Experimental results

2. 3D rib deformation
   - Example of one rib cage, Antero-posterior loading, Loading velocity: 1.4 m/s

Comparison between ribs and components:
   - Deformations varied with the costal level
   - Distribution between components varied with costal level
Experimental results

2. 3D rib deformation

- Comparison between the ribs cages
  - The magnitude of deformation and the distribution between the three components are both subject- and costal level-dependent

- Costal level-dependent:
  - Differences between upper ribs and lower ribs deformation
  - Rib rotations varied in function of the costal level

- Subject-dependent:
  - Due to geometry?
  - Due to material properties?
  - Due to joint stiffness?
1. Objectives

- Experiments show some trends to understand the complex mechanism of the 3D deformation of the rib cage
- But important differences between the rib cages were observed than can be explained by several factors:
  - Geometry?
  - Material properties?
  - Joint stiffness?
- To isolate the contribution of the geometry from the other factors, we used personalized FE human body model to simulate the experiments
- The overall rib cage geometry was adapted (i.e. personalized) to the each tested rib cage
- The materials properties of the rib cage (bone, cartilage) and some parameters such as cortical bone thickness were kept identical for all the FE models
- With this methodology, we are able to analyze only the contribution of the shape of the rib cage, i.e. the effect of the “structure” of the rib cage, to its response under a dynamic loading
2. Methods

- The model used was a modified and improved version of the European FE human model HUMOS2, developed on PamCrash®
- Personalization method is based on RBF
- Example of personalized mesh
Finite element analysis

3. Example of simulation results

- As expected, simulations reduced the discrepancies between the subject.
- Geometrical only personalized models have isolated the contribution of the ribcage shape from the other factors such as material properties, cortical bone thickness, ...
1. Rib cage deformation

- The mechanism of the 3D deformation of the rib cage depends on the costal level
- Since past studies demonstrated, for an individual, that material properties do not vary significantly with the costal level

- These differences are due to the geometrical properties of the rib:
  - Connection to the sternum is different for the upper ribs compared to the lower ribs
  - Shape, curvature, inertia, cross section area, thickness of cortical bone of the ribs are different with the costal level within an individual

- But material properties influence strongly the differences between rib cages (inter individual discrepancies)
Discussion

2. Hypothesis on rib cage deformation mechanisms

- Initial rib inclination could influence the deformation of the rib cage
  \[
  \Rightarrow 1) \text{Rib rotation must increase when the initial angle increase} \left[\text{Kent et al. Stapp 2005}\right]
  \]

- In our works:
  - Paired comparison of the initial inclination and of the rotation of the same rib show an increase of the rotation when the initial rib slope increase.
  - However, the correlations were not found statistically significant and it is difficult from the experiments to separate the contribution of the rib orientations to those of the material properties and of the costo-vertebral joint stiffness
  - FE model results show that stiffness of the ribcage are not linked with the amount of rotation of the rib but with the initial slopes of the ribs (not observable from the experiments)
Discussion

2. Hypothesis on rib cage deformation mechanisms
   - Initial rib inclination could influence the deformation of the rib cage
     \[ \rightarrow 2) \text{Rib deformation in its plane must decrease when the initial angle increase [Kent et al. Stapp 2005]} \]
   - In our works:
     - In our experiments: Paired comparison of the initial inclination and of the deformation of the rib in its plane does not show any significant correlations or trends
     - But FE simulation show a trend, that tends to confirm the previous assumption #2)
     - Nevertheless many factors, other than the initial rib inclination, interacted in the deformation of the ribcage
     - And the initial rib angle can not solely explain the mechanism of rib cage injury
Discussion

3. Influence of geometrical factors

- We searched correlations between the mechanical responses of the rib cage:
  - stiffness,
  - rib rotations and
  - deformations

in function of different geometrical parameters:
  - axillary thickness,
  - initial angle of the ribs,
  - and the Centroid Size [Gayzik et al 2008 J Biomechanics]

- Correlation were found for stiffness with:
  - the initial angle of the rib 4 ($R^2=0.87$, $p=0.065$) and Rib 6 ($R^2=0.95$, $p=0.026$)

- No significant correlation ($p > 0.1$) were found for deformations
  - but axillary thickness correlated with deformation in the rib plane
  - CS correlated slightly the rib plane deformations
Discussion

3. Influence of geometrical factors

- No significant correlation ($p > 0.1$, $R^2 < 0.3$) were found for rib rotations, with
  - CS and
  - axillary thickness

- However, a relation was determined with the mean value of the rib slopes and the rib rotations

- The database (both tests and simulations) should be extended to confirm or reject these tendencies
- and to determine the influence of the different parameters of factors on the deformation of the rib cage
Discussion

4. Costo–vertebral joints characterization

- One of these other factors is the costo-vertebral joint.
  Our assumption is that the stiffness of this joint controlled the motion of the ribs during loading and can influence the response of the thorax.

- To characterize this joint:
  - we defined an axis of rotation between the vertebra and the rib: the Finite Helical Axis FHA
  - obtained from the kinematics of the markers close to the costo-vertebral joint between two positions: initial and at time t.
4. Costo–vertebral joints characterization

- We found that the axis orientation is not consistent with physiological axis
- The orientation of the FHA changed during the loading
  => move downward around x-axis and forward around y-axis
Discussion

4. Costo–vertebral joints characterization

- The orientation of the axis changed with the costal level

Example: variation of the axis orientation at 30 mm of deflection:

<table>
<thead>
<tr>
<th>Plane</th>
<th>Rib 2 vs. Rib 4</th>
<th>Rib 2 vs. Rib 6</th>
<th>Rib 2 vs. Rib 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transversal</td>
<td>18.25°</td>
<td>17.02°</td>
<td>29.63°</td>
</tr>
<tr>
<td>Frontal</td>
<td>16.50°</td>
<td>21.73°</td>
<td>38.51°</td>
</tr>
<tr>
<td>Sagittal</td>
<td>24.75°</td>
<td>25.53°</td>
<td>26.58°</td>
</tr>
</tbody>
</table>
Discussion

5. Simulation of other loading conditions

- Simulation of load belt tests [Univ. of Virginia data]
- Influence of rib orientation on the strain distribution (related to rib fracture)
Conclusion

- We develop a method to measure and compute
  - the relative motion of the ribs with respect to the vertebra
  - and the 3D deformation of the rib cage

- This allows us to describe the mechanisms of deformation of the ribcage including both rotation and deformation of the ribs up to rib fractures

- We determine a Functional Helical Axis to characterize the costo-vertebral joints under dynamic loading conditions

- We demonstrate the ability to generate FE models of the rib cage from a relatively small sample size of anatomical points
Conclusion

- We develop a combined experimental-computational framework that can be used for subject-specific FE modeling of the thorax

- The steps of the proposed methodology are:
  - To use the strategy for obtaining personalized geometries of the thorax FE models
  - To examine and validate the response of the numerical model of the thorax by comparison with well-control experimental tests and
  - To test the sensitivity of the FE model to changes of intrinsic parameters such as size, shape, orientation of the ribs, or material properties, etc.

Hence, with this methodology, the numerical human model is used to perform ‘virtual experiment’ programs
Acknowledgments

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  www.thorax-project.eu

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