Respirator Models to Analyze Sensor Placement and Fit

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Kathryn Butler
Building and Fire Research Laboratory
National Institute of Standards and Technology
kathryn.butler@nist.gov
DHS Projects on Respirator Modeling

Characterizing Respirator Fit for Real Faces and Masks

Respirator Sensor Placement for Accurate Readings

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Fire Fighter Respiratory Protection

• Respirators must protect against many hazards
  – Particulates, chemical and biological toxins
  – Lack a priori knowledge of threats

• Wide range of situations
  – Normal and high stress
  – Short duration: fire suppression
  – Long duration: salvage and search and rescue

• Issues
  – Imperfect fit
  – Leaks
  – Heavy breathing and coughing
Issues

Imperfect fit
- Annual fit test - good enough?
- Variation over time
  (Month-to-month, wearing-to-wearing, minute-to-minute?)
- What are the consequences?

Leaks
- Do they happen?
- Under what conditions?
- Occasional? Individual?

Sensor for real-time monitoring
- Good idea? State of technology?
- Where would it be placed?
Computational Models

• Can test variety of situations
  — Breathing pattern
  — Leak geometries
  — External environments
  — Contact between face and mask

• Visualization of results
  — Velocity
  — Pressure
  — Particle traces
  — Gas concentrations

 1st step: Need to define the complex geometry of a person wearing respirator
Head Geometry
3D Scanner

3D scanner

3D point cloud

Smoothed, holes filled

Mouth open
Mask Geometry
3D Scanner

3D point cloud

Smoothed, holes filled
Mask Geometry
Mechanical Drawings
Mask Geometry
CAD
Combining face and mask
- the easy way doesn’t work
How can we characterize fit and discomfort for a given individual and a respirator?

Computationally push respirator onto face, taking into account

- Material properties of respirator
- Material properties of skin over bone

Contact pressures indicate regions of potential leaks or discomfort

How good is a rigid 3D scan for predicting fit?
How difficult would it be to customize the seal?

Piccione and Moyer, 1997
Project: CHARACTERIZING RESPIRATOR FIT FOR REAL FACES AND MASKS (K. Butler, M. Smith)

Issue: Importance of fit and comfort for respiratory protection
- Emergency responders can overbreathe respirator at high work rates. Without a good fit, respiratory protection is compromised and leaks can occur.
- Emergency responders are willing to discard protective equipment when they believe it impedes their ability to do their jobs. Comfort is critical to wearability, especially during long operations.
- The use of rigid 3D head scans or physical headforms for testing and sizing respirators do not take properties of skin and bone into account.

Purpose
- To enhance respirator fit and sizing procedures by improved knowledge of the relationship between human and respirator features and respirator effectiveness

Approach
- Characterize the relationships between respirator fit, respirator discomfort, and the geometry of faces and respirators using the actual material properties of rubber or silicone seals and skin over bone
Technical Approach

- Prepare 3D representations of respirator masks and human heads
- Push flexible mask onto face computationally for multiple pairings, plotting stresses on the contact surface to find locations of possible leaks and fit comfort
  - Rigid face
  - Skin over rigid face
  - Skin over rigid bone from medical scans
- Animate face and determine position or motion of jaw most likely to result in a leak
- Assess sensitivity to mask positioning, material properties, and design factors.
- Assess ability of fixed 3D head scan to evaluate goodness of fit in comparison with actual material properties of face. Recommend improvements in respirator sizing procedures and changes to standards.
Variety of respirators and faces
Respirator Seal Geometry

CAD

Full seal

Single seal
Technical Approach

Finite Element Method (FEM)
Contact problem
Jingzhou Yang - Texas Tech University

Apply 2.5 N (5 N) force to each strap
2.5N on each strap
Pressures on Face

2.5N on each strap
Pressures on Respirator

5 N on each strap
Pressures on face

5 N on each strap
What are the possibilities for real-time respirator monitoring?

- Where are the best positions for monitoring flow, pressure, gas concentrations?
- How is the flow affected by a leak?
- What breathing resistance does the user experience?
Project: RESPIRATOR SENSOR PLACEMENT FOR ACCURATE READING (K. Butler, M. Nyden, R. Bryant)

Issue: Real-time monitoring
- Monitoring of conditions inside a respirator would provide immediate warning of a leak. The emergency worker could then be removed from a dangerous situation.
- For readings that accurately and rapidly reflect the respiratory intake of emergency worker, the sensor must be placed in a region that sees the flow but is not disturbed during respirator use.

Purpose
- To evaluate the need and potential sensor technologies for real-time monitoring of emergency responder respiratory intake, and to provide criteria and recommendations for placement of sensors in respirator masks

Approach
- Determine locations within a respirator mask that are suitable for placement of a sensor for real-time monitoring of respiratory intake, using computational methods validated by experiment
Technical Approach

- Conduct a workshop to discuss the need and potential solutions for real-time monitoring of emergency responder respiratory intake.
- Prepare 3D representations of actual heads and half and full facepiece respirator masks, and define the region of flow between facepiece and face.
- Solve for the flow field and pressure field for multiple head-mask combinations, low and high work rates, and a variety of leaks
- Validate the model against experiment
- Determine criteria and potential locations for sensors to perform real-time monitoring of breathing intake, and incorporate results into a standard for monitoring device placement
Workshop
Real-Time Monitoring of Total Inward Leakage of Respiratory Equipment Used by Emergency Responders
1 May 2009

- ~25 attendees
  - Firefighters, researchers (sensors and respirators), manufacturers, standards committee representatives
- Addressed the critical issues
  - What is the need?
    - Potential uses: Is there a leak? Can the respirator be removed?
      - Data collection, physiological monitoring
    - Possible approaches: outside or inside mask, mounted on gear, multiple measurements
  - What sensor technologies are available?
    - Measure gas species, particulates, pressure
  - What challenges must be met?
    - Confounding factors, unknown environment, trust of users
Prepare the Geometry
Interior Flow Model

Breathing (at rest):

\[ V_T = 0.5 \text{ L} \]
\[ f = 15 \text{ breaths/min} \]
Mesh – Refined where needed

Mesh boundaries first, then interior
→ 350,000 cells
Gas Flow within Half Mask - Exhalation

Velocity

Pressure

Streamlines
Gas Flow within Half Mask - Inhalation

Velocity

Pressure

Streamlines
Gas Flow for Normal Breathing

$V_T = 0.5 \text{ L}$
$f = 15 \text{ breaths/min}$
Comparison of Pressures

Normal Breathing

\[ V_T = 0.5 \text{ L} \]
\[ f = 15 \text{ breaths/min} \]
\[ P \text{ range} \sim -0.2 \text{ to } +0.5 \text{ Pa} \]

Under Work Load

\[ V_T = 1 \text{ L} \]
\[ f = 30 \text{ breaths/min} \]
\[ P \text{ range} \sim -3 \text{ to } +7 \text{ Pa} \]
Thank you