Effectiveness of Protective Equipment for the Prevention of Sports-Related Concussions in Youth

Stefan M. Duma, Steven Rowson, Joel Stitzel, Ray Daniel, Bryan Cobb, Tyler Young, Brock Strom, Craig McNally, Anna MacAlister, Gunnar Brolinson, Mike Goforth, Mark Rogers, John Shifflett, Alex Powers, Chris Whitlow, Jill Urban, Joseph Maldjian, Elizabeth Davenport

Presented to the Institute of Medicine Committee Sport-Related Concussions in Youth

February 25, 2013 - Washington DC
Financial Disclaimer

- No financial interest in SIMBEX, HITS, or any other helmet related sensor or product

- No financial interest in Riddell, or any helmet manufacturer

- No helmet expert witness consulting

- Speaking fees donated to buy new helmets for youth teams in south-west Virginia.
Funding Sources

National Institutes of Health
  National Inst. Of Child Health & Human Development, R01HD048638

Department of Transportation
  National Highway Traffic Safety Administration

Department of Defense
  US Medical Research and Material Command

Toyota Motor Corporation
  Toyota Central Research and Development Labs
Part 1: Injury Biomechanics Background
   – Reducing injuries in auto-safety by reducing risk

Part 2: Three Fundamental Questions:
   – Is head acceleration correlated to concussion risk?
   – Do helmets differ in their ability to reduce head acceleration?
   – Are there clinical data demonstrating differences in the ability of helmets to reduce concussion risk?

Part 3: Youth Football Study – Preliminary Data
Automobile Analogy
Federal Motor Vehicle Safety Standards (FMVSS) are pass / fail

**FMVSS 208**
Frontal Impact

Fixed Barrier

30 mph

**FMVSS 214**
Side Impact

33.5 mph

20 mph

MDB

33.5 mph

20 mph

MDB
New Car Assessment Program (NCAP)
NHTSA rates safety on 5 star scale

Injury risk to the head, neck, chest, and femur for frontal and side tests
(rollover is ratio calculation)

Overall risk = 5/12 * frontal + 4/12 * side + 3/12 * rollover
New Car Assessment Program (NCAP) NHTSA rates safety on 5 star scale

A star rating is assigned based on the overall risk of serious injury from all tests combined

Overall risk = \( \frac{5}{12} \times \text{frontal} + \frac{4}{12} \times \text{side} + \frac{3}{12} \times \text{rollover} \)
Passenger Car Occupant Fatality and Injury Rates per 100 Million Vehicle Miles Traveled, 1975-2008

~1968 FMVSS 208 (pass/fail)

~1978 NCAP frontal (stars)

44,525
Active Research in all Current and Future Body Regions

We do not know 100% about everything, but know enough to make safety advances.
Active Research in all Current and Future Body Regions

We do not know 100% about everything, but know enough to make safety advances.

- Head injury (HIC)
- Neck injury (Nij)
- Chest compression
- Abdomen
- Pelvis
- Tibia
- Ankle complex

Accelerations → Injury Risk

Femur loads
Concussion Incidence Minimization

3 Strategies:

- Reduce exposure to head impact
  - Rule changes
  - Proper technique

- Reduce concussion risk for remaining head impacts
  - Improve helmet design

Most Effective

Better Equipment

Proper Technique

Rule Changes

Fewest Concussions
Part 2: Three Fundamental Questions:
### Age Definitions

**Generalized Football Values: League Rules May Vary**

<table>
<thead>
<tr>
<th>Age</th>
<th>IOM Youth Definition</th>
<th>Helmet Type:</th>
<th>Level of Play:</th>
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<tr>
<td>5</td>
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<td>6 10 11 13 14</td>
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Is head acceleration correlated with concussion risk?
# Experimental Concussion Research

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Risk of Skull Fracture

HIC\(_{15} = 1000 = 16\%\)

HIC\(_{15} = 700 = 5\%\)

Risk of AIS ≥4 Brain Injury

HIC\(_{15} = 1000 = 17\%\)

HIC\(_{15} = 700 = 4\%\)

(Mertz, 1997)
Hardy: In Situ Brain Strain

Football helmet impacts

Linear and Rotational Accelerations

As accelerations increase, brain pressure and motion increase

Hardy et al (2007)
Experimental Concussion Research

**Cadaver Data**

- 1954 Ford funds WSU

**Animal Data**

- 1961 Gurdjian, Lissner origin of WSTC
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**NFL Data**

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As linear acceleration increases, risk of injury increases.

As linear and rotational acceleration increase, brain pressure and motion increase.
## Summary of Six Sets of Primate Tests

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<th>Year</th>
<th>Authors</th>
<th>Details</th>
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<tbody>
<tr>
<td>1966</td>
<td>Ommaya, Hirsch</td>
<td>Rotation alone could not cause concussion, needed impact</td>
</tr>
<tr>
<td>1971</td>
<td>Ommaya, Hirsch</td>
<td>Rotation accounts for $\frac{1}{2}$ of brain injury, linear accounts for the other half</td>
</tr>
<tr>
<td>1971</td>
<td>Gennarelli, Ommaya, Thibault</td>
<td>Linear and rotational acceleration relating to concussion</td>
</tr>
<tr>
<td>1972</td>
<td>Gennarelli, Thibault, Ommaya</td>
<td>Rotation related to diffuse brain injury</td>
</tr>
<tr>
<td>1971</td>
<td>Unterharnscheidt</td>
<td>Both linear and rotational acceleration are important for brain injury</td>
</tr>
<tr>
<td>1980</td>
<td>Ono</td>
<td>JARI Human Tolerance Curve</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skull fracture and concussion curves</td>
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<tr>
<td>1981</td>
<td>Gennarelli</td>
<td>Directional dependence of brain injury</td>
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1992 Margulies, Thibault DAI at 16,000 r/s²

1998 Arbogast, and Margulies: properties

2003 Gennarelli: concussion values

2009 Davidsson: DAI
Ommaya: Tolerance to Concussion Scaled from Primates

Animal Data

Rotational Velocity (rad/s)
Rotational Acceleration (rad/s²)
Pulse Duration
Time in ms
100
50
20
10
5
1
Man
Chimpanzee
Rhesus Monkey

4500
100
1,000
10,000
10,000
100,000
1,000,000

(Ommaya, 1985)
Gennarelli: Rotational Acceleration and Concussion

Animal Data

(Gennarelli, 1985; Gennarelli, 2003)
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King: Linear and Rotational Acceleration

53 NFL Cases: 22 injury and 31 Non-injury

Injury Probability vs. Linear Acceleration (m/s\(^2\))

P < 0.0001

Injury Probability vs. Angular Acceleration (rad/s\(^2\))

P < 0.0001

(King, 2003)
Pellman: Linear and Rotational Acceleration

58 NFL Cases: 25 injury and 33 Non-injury

NFL Data

Concussion Injury Risk vs. Linear Acceleration (g) and Rotational Acceleration (rad/s²)

P = 0.0001

(Pellman, 2003)
## Experimental Concussion Research

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2003: Pellman, Viano HIII reconstructions

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Helmet Instrumentation
Two parallel systems during past 10 years

### HIT System
- **6 Accelerometers** mounted normal to the skull
- 3 Linear and Resultant Rotational Accelerations
- ~$1,000/helmet
- Validated by NFL, others

### 6DOF Device (VT)
- **12 Accelerometers** mounted tangential
- 3 Linear and 3 Rotational Accelerations (6DOF)
- ~$10,000/helmet
- Validates HIT System
Cumulative HITS Data Collection

195,000+ impacts recorded at Virginia Tech
2,000,000+ impacts recorded at all institutions

Teams Using the HIT System

- Virginia Tech
- North Carolina
- Oklahoma
- Dartmouth
- Arizona State
- Indiana
- Illinois
- Minnesota

- Wake Forest
- Indiana
- Brown
- Minnesota
- Wake Forest

- 1 High School
- 5 High Schools
- 5 High Schools
- 2 High Schools
- 3 High Schools
- 4 High Schools
- 4 High Schools
- 4 High Schools
- 4 High Schools
- 1 Youth Team
- 5 Youth Teams
Combined Linear and Rotational Risk

Risk Contours

\[ Risk = \frac{1}{1 + e^{(-10.2 + 0.0433a + 0.000873\alpha - 0.00000092a\alpha)}} \]

ROC Curves

AUC = 0.982

HITS Data
63,011 Impacts
244 Concussions

AUC = 0.892

NFL Data
58 Impacts
25 Concussions

(Rowson and Duma, ABME, 2013)
Linear Acceleration Comparison

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<th>NFL Data</th>
<th>Volunteer Data</th>
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<td>25 Concussions</td>
<td>105 Concussions</td>
</tr>
<tr>
<td>98 +/- 27 g</td>
<td>105 +/- 27 g</td>
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- Two very different methodologies, resulting concussion values nearly identical

- Strong evidence in determination of accelerations involving concussions

(Pellman, 2003; Broglio, 2010; Guskiewicz 2007, 2011; Mihalik, 2007; Rowson, 2011)
Rotational Acceleration Comparison

- **Ommaya (1985)**
  - Sagittal Plane
  - 4500 rad/s²
  - 30 rad/s

- **Margulies (1992)**
  - Coronal Plane
  - 16000 rad/s²
  - 46.5 rad/s

- **Davidsson (2009)**
  - Sagittal Plane
  - 10000 rad/s²
  - 19 rad/s

- **NFL**
- **Volunteer**
- **DAI**
## Experimental Concussion Research

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As linear and rotational acceleration increase, brain pressure and motion increase

As linear and rotational accelerations increase, brain injury in primates increases

Linear and rotational accelerations are significantly correlated to concussion risk

Linear and rotational accelerations are significantly correlated to concussion risk

More recent analysis:
- 1985 Ommaya: 4500r/s^2 concussion
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2003: Pellman, Viano HIII reconstructions

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2003 – Present, instrumented high school and college football players
Is head acceleration correlated with concussion risk?

Yes, as shown by the evidence.
Concussions and Head Impact

- Evidence clearly illustrates concussions are caused by head impacts
- Non-head impact related symptoms are very rare and not the primary problem

(Pellman, 2003; Broglio, 2010; Guskiewicz 2007, 2011; Mihalik, 2007; Rowson, 2011)
Do helmets differ in their ability to reduce head acceleration?
NOCSAE
“Drop Test”

Linear acceleration only
NOCSAE headform

Various drop heights

Various directions
Helmet Comparison: Top Impact from 60 inch Drop Height

Severity Index

NOCSAE Pass / Fail Threshold

Adams A2000 Riddell 360

Peak Acceleration (g)

190 84

Adams A2000 Riddell 360
“Linear Impactor” Style Test

HIII Head and Neck

Linear and Rotational Accelerations

Various impact speed and directions
NFL Extensive Helmet Testing

• (Viano, 2006): 10 newer helmets compare against the standard VSR-4
  – Found 6%- 14% reduction in linear acceleration
  – Found 10% - 23% reduction in rotational acceleration

• (Viano, 2011a): 2010 helmets compared to those in the 1970s
  – Linear and rotational accelerations dramatically reduced, variation by helmet type

• (Viano, 2011b): Modern helmet performance
  – 4 of 17 showed significant improvement in reduction of head accelerations
STAR Rating System for Football Helmets

STAR: Summation of Tests for the Analysis of Risk

\[ \text{STAR} = \sum_{L=1}^{4} \left( \sum_{H=1}^{6} E \sum_{R} \right) \]

Combines true impact exposure with an unbiased risk analysis using real world biomechanical data to assess helmet safety for consumers.

(Rowson and Duma, 2011)
# STAR Ratings of Current Helmets

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<th>Helmet</th>
<th>STAR Value</th>
<th>Cost</th>
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<td>5 Stars</td>
<td>Rawlings Quantum</td>
<td>0.364</td>
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<td>Riddell Revolution IQ</td>
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<td>4 Stars</td>
<td>Schutt ION 4D</td>
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<td></td>
<td>Schutt DNA Pro +</td>
<td>0.352</td>
<td>$169.95</td>
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<td>Rawlings Impulse</td>
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<td>Xenith X1</td>
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<td>Riddell Revolution</td>
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<td>Schutt Air XP</td>
<td>0.434</td>
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<td>1 Star</td>
<td>Riddell VSR4</td>
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<tr>
<td>NR</td>
<td>Adams A2000 Pro Elite</td>
<td>1.700</td>
<td>$199.95</td>
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</table>

*5 Stars: Best Available  
4 Stars: Very Good  
3 Stars: Good  
2 Stars: Adequate  
1 Star: Marginal  
NR: Not Recommended*
Do helmets differ in their ability to reduce head acceleration?

Yes, as shown by the evidence.
Are there clinical data demonstrating differences in the ability of helmets to reduce concussion risk?
Compare Two Popular Helmets

Riddell Revolution

Acceleration Metrics:

- NFL: Top group
- VT: 4 STARs (54% risk reduction)

Riddell VSR4

Acceleration Metrics:

- NFL: 2nd Group
- VT: 1 STAR

(Viano, 2011b; Rowson and Duma, 2011)
Clinical Evidence Part 1

Collins et al. (2006)

- Studied over 2141 high school players
- Revolution reduced risk of concussion by 31%
- Peer reviewed, 5 of 6 comments positive ($p = 0.03$)

Primary criticism from Dr. Cantu’s letter

Older VSR4 helmets compared to newer Revolution helmets, and that older helmets test worse than newer

- This is not supported by any evidence: there are no publications or data sets that show older helmets are worse
Clinical Evidence Part 2

• **Rowson and Duma, 2012a**
  • 9 year study of Virginia Tech football players
  • All new helmets
  • Same team physician
  • Controlled for exposure
    All helmets were instrumented with sensors
    153,486 head impacts for 308 players

• Revolution reduced risk of concussion by 85%  
  \( p = 0.03 \)

• Eliminates only previous criticisms of the Collins work
• By accounting for exposure, more accurate comparison of helmet performance
Clinical Evidence Part 3

• Current study, to be published in 2013
  *(Due to IOM copyright, cannot show all details)*

• 13 college teams
  – All instrumented to account for impact exposure
  – All good/new equipment
  – All have very good medical oversight

• Revolution significantly reduces the risk of concussion compared to the VSR4
Are there clinical data demonstrating differences in the ability of helmets to reduce concussion risk?

Yes, as shown by the evidence.
5,000,000 Football Players in US

- NFL: 2,000 Players
- College: 100,000 Players
- High School: 1,300,000 Players
- 6 to 13 years old: 3,500,000 Players

70% of football players are between 6 and 13 years old.
Four Youth Publications Pending
(Due to IOM copyright, cannot show all details)

• Head Impact Exposure in Youth Football Part 1: Elementary School Ages 7 to 8 Years and the Effect of Returning Players
• Head Impact Exposure in Youth Football Part 2: Elementary School Ages 9 to 12 Years and the Effect of Practice Structure
• Head Impact Exposure in Youth Football Part 3: Middle School Ages 12 to 14 Years
• Head Impact Exposure in Youth Football Part 4: High School Ages 14 to 18 Years and Cumulative Impact Analysis

Submitted, under review, expected to be published in 4 – 8 weeks.
VT-WFU Youth Study

Head Impact Biomechanics
Game and Practice Data Collection
- Linear and Rotational Head Acceleration Measurements
- FE Modeling for Tissue Response
- Instrumentation transmitted impact data to computer during play
- Helmets were instrumented for each game and practice

Cognitive Testing
- Pediatric ImPACT Testing for 12.5 years old and under
- Adult ImPACT Testing for 12.5 year old and over

Investigating Correlations

Imaging
- Baseline, Injury, and Post-Season
- fMRI:
- MEG:

Age

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<tr>
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6 – 8 Year Olds
- Auburn Mites
- 12 Instrumented Players

9 – 11 Year Olds
- Blacksburg Juniors
- 17 Instrumented Players

12 – 14 Year Olds
- Blacksburg Middle School
- 12 Instrumented Players

9 – 11 Year Olds
- South Fork Jr Pee Wee
- 22 Instrumented Players

10 – 12 Year Olds
- South Fork Pee Wee
- 21 Instrumented Players

15 – 18 Year Olds
- Ronald Wilson Reagan High School
- 40 Instrumented Players
Helmet Instrumentation
Two parallel systems during past 10 years

HIT System
6 Accelerometers mounted normal to the skull
3 Linear and Resultant Rotational Accelerations
~$1,000/helmet
Validated by NFL, others

6DOF Device (VT)
12 Accelerometers mounted tangential
3 Linear and 3 Rotational Accelerations (6DOF)
~$10,000/helmet
Validates HIT System
Data collected wirelessly for every game and practice
Game Impact: 20g – 40g Range
Practice Impact: 50g+ Impact
### Pediatric Head Impact Data

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Teams</th>
<th>Number of Instrumented Players</th>
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<tr>
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<td>6 – 8 Year Olds Auburn Mites 12 Players</td>
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<td>15 – 18 Year Olds Ronald Wilson Reagan High School 40 Players</td>
<td>40</td>
</tr>
</tbody>
</table>

**Players:**
- 19
- 50
- 10
- 40

**Impacts:**
- 3,061
- 11,978
- 3,414
- 16,507

**50th Percentile:**
- 16 g
- 22 g
- 58 g

**95th Percentile:**
- 37 g

**Injuries:**
- 0
- 4
- 2
- 2

**Summary:**
- 119 instrumented players under 18 years old
- 34,960 head impacts recorded
- 8 players sustained concussions
Conclusions

1. Injury biomechanics involves reducing risk
2. Head acceleration is correlated to concussion risk
3. Helmets vary in their ability to reduce head acceleration
4. Helmets that reduce head acceleration result in lower risk of concussion on the field
5. Youth head impact exposure can be high, especially in practices

Much more biomechanical research is needed relative to youth programs in three key areas: regulations, coaching, equipment


Effectiveness of Protective Equipment for the Prevention of Sports-Related Concussions in Youth

Stefan M. Duma, Steven Rowson, Joel Stitzel, Ray Daniel, Bryan Cobb, Tyler Young, Brock Strom, Craig McNally, Anna MacAlister, Gunnar Brolinson, Mike Goforth, Mark Rogers, John Shifflett, Alex Powers, Chris Whitlow, Jill Urban, Joseph Maldjian, Elizabeth Davenport

Presented to the Institute of Medicine Committee Sport-Related Concussions in Youth

February 25, 2013 - Washington DC