Biomechanics of Concussion: Considerations on the Mechanisms of Injury and Reduction of Risk

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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
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   National Highway Traffic Safety Administration

Department of Defense
   US Medical Research and Material Command

Toyota Motor Corporation
   Toyota Central Research and Development Labs
Acceleration-Based Brain Injury

- Inertial Loading (everyday case)
  - From direct head loading
  - From whole body loading
  - Motion of the brain relative to the skull

Acceleration is a metric for characterizing injury risk

- Skull acceleration is indicative of the inertial response of the brain to impact loading
- Skull acceleration doesn’t cause injury, but the pressure and strain response within the brain tissue does
In Situ Brain Biomechanics

- High Speed X-Ray Cadaver Experiments
  - Head impacts at concussive severities
  - Brain response
  - Skull kinematics

- Brain is not “flopping” around
  - 5 to 7 mm of movement
  - Looping pattern

- Acceleration correlated to brain injury mechanisms
  - Strain Response
  - Pressure Response

Acceleration for any point on a rigid body:

\[ \|a_i\| = r_{ai} \cdot \vec{H} + r_{ai} \cdot (\alpha \times \vec{r}) + r_{ai} \cdot (\vec{\omega}_i \times (\vec{\omega}_i \times \vec{r})) \]

**Linear Contribution**

**Rotational Contribution**

Pressure Mechanism

Shearing, Strain - Type Mechanism
Acceleration-Based Head Injury

Injury Risk is a Function of Acceleration Magnitude and Duration

- **Car Crash**: 80+ g, 10+ ms
- **Football**: 50+ g, 15 ms
- **Pillow Fight**: 30+ g, 75+ ms
- **Everyday Activity**: 5+ g, 100+ ms
- **Military Pilot Turning**: 7+ g, 1+ s
Brain Injuries in Football

- 1.6 to 3.8 million sports-related concussions each year in the US

- Increased Occurrence in Collegiate Sports
  - Football has largest total of any sport
  - “Human volunteers” for onset of concussion

- Instrument and observe a high risk population

- Head acceleration data collected from Virginia Tech football players
HIT System Hardware

- 6 accelerometer configuration
- Measures resultant linear acceleration
- Estimates peak rotational acceleration
- Spring-mounted accelerometers
  - Remain in contact with head
Head Acceleration Data Collection

- Helmet instrumentation
  - ‘Real-time’ data transfer 1000 Hz sampling frequency
  - Data acquisition triggers when any accelerometer experiences 10 g
  - 40 ms of data collection
  - Each event is time-stamped and compared to video

○ - instrumented helmet
Head Acceleration Data Collection

- 64 Virginia Tech players instrumented each season
- Data collected for every game and practice
Example Concussive Event
Example Concussive Event

Clinically diagnosed concussion

136 g
6231 rad/s²
# Head Acceleration Data Summary

<table>
<thead>
<tr>
<th></th>
<th>Sub-Concussive</th>
<th>Concussive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Accel.</td>
<td>26 g</td>
<td>105 g</td>
</tr>
<tr>
<td>Rotational Accel.</td>
<td>1137 rad/s²</td>
<td>5022 rad/s²</td>
</tr>
<tr>
<td>Rotational Velocity</td>
<td>5 rad/s</td>
<td>22 rad/s</td>
</tr>
</tbody>
</table>

- Impact duration for impacts were 8-12 ms
- Sub-concussive impact distributions were right-skewed
- Concussive impacts were normally distributed
Linear Acceleration Distributions

PDF

Sub-concussive
Concussive

Peak Head Acceleration (g)
Rotational Acceleration Distributions

![Graph showing rotational acceleration distributions for sub-concussive and concussive cases. The graph includes a PDF axis and a rotational acceleration axis (rad/s²). The sub-concussive distribution is plotted as a solid blue line, while the concussive distribution is plotted as a dashed red line. The distribution for sub-concussive cases peaks higher and is more concentrated at lower values compared to the concussive cases.]
Nominal Concussion Risk Values

<table>
<thead>
<tr>
<th>Risk</th>
<th>Linear Acceleration (g)</th>
<th>Rotational Acceleration (rad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>149 g</td>
<td>5167 rad/s²</td>
</tr>
<tr>
<td>25%</td>
<td>171 g</td>
<td>5716 rad/s²</td>
</tr>
<tr>
<td>50%</td>
<td>192 g</td>
<td>6266 rad/s²</td>
</tr>
<tr>
<td>75%</td>
<td>214 g</td>
<td>6815 rad/s²</td>
</tr>
</tbody>
</table>


Head Acceleration Distributions

Helmets modulate energy transferred to the head.

Helmets can be designed to reduce head acceleration.

Concussion risk is lowered.
Basic Helmet Function

- There are two primary components of a helmet to protect from injury
  - Helmet Shell
    - Deflects to distribute force over a larger area
  - Helmet Liner
    - Modulates the energy transferred to the head

Impact response can be tuned to meet design requirements

**Helmets can be designed to reduce concussion risk**

Football helmets used as an example, but other applications
Helmet Comparison: Top Impact from 60 inch Drop Height

Adams A2000 VS Riddell 360

Severity Index

NOCSAE Pass / Fail Threshold

1134

416

Adams A2000 Riddell 360

Peak Acceleration (g)

190

84

Adams A2000 Riddell 360
Let’s Consider Concussion Risk

Which helmet would you choose?

For Identical Impacts:

- Riddell 360
  - 84 g
  - 1% risk of concussion

- Adams A2000
  - 190 g
  - 48% risk of concussion
Football Helmet Evaluations

All head impact data was used to create:

Virginia Tech Helmet Ratings

Combines impact exposure with a risk analysis using real world biomechanical data to assess helmet performance for consumers.
STAR Rating System for Football Helmets

STAR: Summation of Tests for the Analysis of Risk

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

Through a series of drop tests, helmets are evaluated using 2 fundamental concepts:

1. Tests are weighted based on how often they occur
2. Helmets that lower head acceleration reduce risk

\[
\text{Exposure} \times \text{Risk} = \text{Incidence}
\]
Helmet Testing Protocol

Test 4 impact locations:

- Front
- Rear
- Side
- Top

Test 5 impact energies: 12 in, 24 in, 36 in, 48 in, 60 in

Head Impact Exposure

Exposure is defined as a function of drop height and impact location

<table>
<thead>
<tr>
<th></th>
<th>Front</th>
<th>Rear</th>
<th>Side</th>
<th>Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 19 g</td>
<td>164</td>
<td>139</td>
<td>81</td>
<td>63</td>
</tr>
<tr>
<td>12 in</td>
<td>138</td>
<td>165</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>24 in</td>
<td>31</td>
<td>11</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>36 in</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>48 in</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>60 in</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>347</td>
<td>319</td>
<td>163</td>
<td>171</td>
</tr>
</tbody>
</table>

1000 impacts per season
Drop Test Videos

Front Impact – 36 in Drop

Side Impact – 36 in Drop
Linear Acceleration Risk Curve

Exposure x Risk = Incidence

10 Impacts $\times$ 40% Concussion Risk $= 4$ Concussions
# STAR Ratings of Current Helmets

## 5 Stars: Best Available

<table>
<thead>
<tr>
<th>Helmet</th>
<th>STAR Value</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schutt AiR XP Pro VTD</td>
<td>0.207</td>
<td>$199.99</td>
</tr>
<tr>
<td>Schutt Vengeance VTD</td>
<td>0.213</td>
<td>$254.99</td>
</tr>
<tr>
<td>Riddell 360</td>
<td>0.239</td>
<td>$374.95</td>
</tr>
<tr>
<td>Rawlings Quantum Plus</td>
<td>0.245</td>
<td>$259.99</td>
</tr>
<tr>
<td>Rawlings Tachyon</td>
<td>0.262</td>
<td>$299.99</td>
</tr>
<tr>
<td>Xenith EPIC</td>
<td>0.281</td>
<td>$299.95</td>
</tr>
<tr>
<td>Xenith X2</td>
<td>0.284</td>
<td>$235.00</td>
</tr>
<tr>
<td>Xenith X2E</td>
<td>0.285</td>
<td>$235.00</td>
</tr>
<tr>
<td>Riddell Revolution Speed</td>
<td>0.297</td>
<td>$264.99</td>
</tr>
</tbody>
</table>

*Note: Helmets dated before 2013 rated as 3 Stars*

## 4 Stars: Very Good

<table>
<thead>
<tr>
<th>Helmet</th>
<th>STAR Value</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG Adult</td>
<td>0.309</td>
<td>$398.00</td>
</tr>
<tr>
<td>Schutt ION 4D</td>
<td>0.327</td>
<td>$244.95</td>
</tr>
<tr>
<td>Rawlings Impulse</td>
<td>0.355</td>
<td>$149.00</td>
</tr>
<tr>
<td>Xenith X1</td>
<td>0.356</td>
<td>$299.99</td>
</tr>
<tr>
<td>Riddell Revolution</td>
<td>0.362</td>
<td>$239.99</td>
</tr>
<tr>
<td>Rawlings Quantum</td>
<td>0.364</td>
<td>$179.99</td>
</tr>
<tr>
<td>Schutt Vengeance</td>
<td>0.365</td>
<td>$254.95</td>
</tr>
<tr>
<td>Riddell Revolution IQ</td>
<td>0.369</td>
<td>$222.99</td>
</tr>
</tbody>
</table>

[www.sbes.vt.edu/helmet](http://www.sbes.vt.edu/helmet)
STAR Ratings of Current Helmets

3 Stars: Good

<table>
<thead>
<tr>
<th>Helmet</th>
<th>STAR Value</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schutt Air XP</td>
<td>0.420</td>
<td>$174.95</td>
</tr>
<tr>
<td>Schutt DNA Pro+</td>
<td>0.450</td>
<td>$194.99</td>
</tr>
<tr>
<td>Schutt Air XP Ultrasil</td>
<td>0.482</td>
<td>$254.95</td>
</tr>
</tbody>
</table>

2 Stars: Adequate

<table>
<thead>
<tr>
<th>Helmet</th>
<th>STAR Value</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schutt Air Advantage</td>
<td>0.578</td>
<td>$159.99</td>
</tr>
</tbody>
</table>

1 Star: Marginal

<table>
<thead>
<tr>
<th>Helmet</th>
<th>STAR Value</th>
<th>Cost</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riddell VSR4</td>
<td>0.791</td>
<td>Not Applicable</td>
<td>Used helmets were tested to provide a reference</td>
</tr>
</tbody>
</table>

NR: Not Recommended

<table>
<thead>
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<th>STAR Value</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adams A2000 Pro Elite</td>
<td>1.700</td>
<td>$199.95</td>
</tr>
</tbody>
</table>

www.sbes.vt.edu/helmet
Publicly Available Data for Consumers

Virginia Tech Helmet Ratings™
Adult Football Helmet Ratings - May 2013

A total of 18 adult football helmet models have been evaluated using the STAR evaluation system and included in the May 2013 Virginia Tech Helmet Ratings™. All helmets included in the ratings have been made available to consumers at the time of publication. Helmets with lower STAR values provide a reduction in concussion risk compared to helmets with higher STAR values. Based on this, the best overall rating of 5 Stars has the lowest STAR value. Group rankings are differentiated by pre-determined thresholds.

5 Stars: Best Available

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4 Stars: Very Good

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Download Printable pdf files:
Linear and Rotational Acceleration
Head Function Publication

Frequently Asked Questions

Additional Research:

www.sbes.vt.edu/helmet
Effect of Helmet Ratings

• **Players**
  • In 2010, 40% of NFL player were in a 1 star helmet
  • In 2010, half of VT football team in 1 star helmet
  • All players in college and most in NFL have switched to better performing helmets

• **Coaches and Parents**
  • Make informed decisions when purchasing new helmets

• **Manufacturers**
  • Design to STAR testing methods to improve helmet performance
  • Rawlings designed Quantum Plus helmet to be 5 stars
Effect of Helmet Ratings

- In 2010, 40% of NFL players were in a 1-star helmet.
- In 2010, half of the VT football team were in 1-star helmets.
- All players in college and most in the NFL have switched to better performing helmets.

### 2013 Football Helmet Rating System

<table>
<thead>
<tr>
<th>Rating</th>
<th>Helmet Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 STAR: BEST AVAILABLE</td>
<td>Riddell 360, K2 X2</td>
</tr>
<tr>
<td>4 STAR: VERY GOOD</td>
<td>SG Adult, Riddell Revolution Speed</td>
</tr>
<tr>
<td>3 STAR: GOOD</td>
<td>Schutt Air XP, Schutt Air Ultralite, Schutt DNA Pro Plus</td>
</tr>
<tr>
<td>2 STAR: ADEQUATE</td>
<td>Schutt Air Advantage</td>
</tr>
<tr>
<td>1 STAR: MARGINAL</td>
<td>Riddell VSR4</td>
</tr>
</tbody>
</table>

Students may wear any football helmet star has been approved by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). If you are uncertain, call whether a particular helmet is being approved by NOCSAE.
On-Field Study of Concussion Rates

- Journal of Neurosurgery (2014)
- Exposure to head impact controlled for
- 1833 players over 5 years
- Data compiled from 8 collegiate football teams:

Can Helmet Design Reduce the Risk of Concussion in Football?

Technical Note

STEVEN ROWSON, PH.D., STEPHEN E. DUGAL, PH.D., RICHARD M. GREENWALD, PH.D., JONATHAN G. BECKWITH, M.S., JEFFREY J. CHU, M.S., KEVIN M. GUCKENWICH, PH.D., JASON P. MIRALKE, PH.D., JOSEPH J. CRUSCO, PH.D., BETHANY J. WILCOX, B.S., THOMAS W. MCALISTER, M.D., ARCHIE C. MCBRIDE, PH.D., STEVEN P. BROGLIO, PH.D., BROCK SCHNEEVEL, M.D., SCOTT ANDERSON, M.D., and P. GUIVER BROGLIONE, D.O. 

School of Biomedical Engineering & Science, Virginia Tech—Wake Forest University, Blacksburg, Virginia; Simonis, Lebanon, New Hampshire; Montana-Geisinger Sport-Related Traumatic Brain Injury Research Center, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina; Department of Orthopedics, Atrium Medical School of Brown University and Rhode Island Hospital, Providence, Rhode Island; Department of Psychiatry, Geisel School of Medicine at Dartmouth, Hanover, New Hampshire; Pediatric Neuropsychological Services, Geisel School of Medicine at Dartmouth, Hanover, New Hampshire; School of Kinesiology, University of Michigan, Ann Arbor, Michigan; Department of Orthopedics and Athletics, University of Oklahoma, Norman, Oklahoma; Department of Neurological Surgery, University of California, San Francisco, California; Outcomes Research, Cleveland Clinic, Cleveland, Ohio; Department of Orthopedics and Athletics, University of Oklahoma, Norman, Oklahoma; Edward F. Coyle College of Osteopathic Medicine, Blacksburg, Virginia.

Of all sports, football accounts for the highest incidence of concussions in the United States; due to the large number of athletes participating and the nature of the sport. While there is general agreement that concussion incidence can be reduced through rule changes and teaching proper tackling technique, there remains debate as to whether helmet design may also reduce the incidence of concussion. A retrospective analysis was performed of head impact data collected from 1833 collegiate football players that were instrumented with helmet-mounted accelerometer arrays for games and practices. Data were collected between 2007 and 2010 from eight collegiate teams: Virginia Tech, University of North Carolina, University of Oklahoma, Dartmouth College, Brown University, University of Minnesota, Indiana University, and University of Illinois. Concussion rates were compared between players wearing Riddell VSR4 and Riddell Revolution helmets, while controlling for the head impact exposure of each player. A total of 2,281,444 head impacts were recorded from which 64 concussions were diagnosed. The relative risk of sustaining a concussion in a Revolution helmet compared to a VSR4 helmet was 44.1% (95% CI: 38.1% - 50.1%). When controlling for each player's exposure to head impact, a significant difference was found between concussion rates for players in VSR4 and Revolution helmets ($X^2 = 4.68$, $P = 0.0305$). This study illustrates that differences in the ability to reduce concussion risk exist between helmet models in football. Although helmet design may prevent all concussions from occurring in football, evidence illustrates that it can reduce the incidence of this injury.

KEY WORDS: brain injury • sports • concussion incidence • football • exposure • prevention

SPORTS-RELATED concussions were once thought to only result in transient symptoms and neurocognitive impairment. However, recent research has suggested potential links between repetitive concussions and neurodegenerative processes in some athletes. This work has led to the increased awareness and media attention on the possible long-term effects of sports-related concussions. Of all sports, football accounts for the highest incidence of concussion in the United States due to the large number of athletes participating and the nature of the sport.
Can Helmet Design Reduce the Risk of Concussion in Football?

Technical Note

Steven Rowson, Ph.D., 1 Stefan M. Duma, Ph.D., 1 Richard M. Greenwald, Ph.D., 2 Jonathan G. Beckwith, M.S., 2 Jeffrey J. Chu, M.S., 2 Kevin M. Guskiewicz, Ph.D., 3 Jason P. Mihalik, Ph.D., 3 Joseph J. Crisco, Ph.D., 4 Bethany J. Wilcox, B.S., 4 Thomas W. McAllister, M.D., 5 Arthur C. Maerlender, Ph.D., 6 Steven P. Broglio, Ph.D., 7 Brock Schnebel, M.D., 8 Scott Anderson, A.T.C., 9 and P. Gunnar Brolinson, D.O., 10

Riddell Revolution reduces risk of concussion by 53.9% compared to Riddell VSR4 (p = 0.03)
Various studies show differences between helmets in ability to reduce concussion risk with Revolution

<table>
<thead>
<tr>
<th>Helmet</th>
<th>STAR Value</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.362</td>
<td></td>
</tr>
<tr>
<td>Riddell VSR4</td>
<td>0.791</td>
<td></td>
</tr>
</tbody>
</table>

Exposure Controlled On-Field Study: 53.9%
Laboratory-Based STAR Evaluation: 54.2%

Laboratory and clinical agreement on ability to reduce concussion risk
What About Rotational Acceleration?

- Pure rotational impacts do not occur
  - Helmets are smooth, round
  - Helmets do not catch and rotate the head, like animal tests did

- Linear component of the impact drives the rotational component

- Rotational acceleration is highly correlated to linear acceleration

If linear acceleration is reduced by a helmet, rotational acceleration is also reduced

Combined Probability of Concussion

- Linear Acceleration (g)
- Rotational Acceleration (rad/s/s)

Probability Levels:
- 90%
- 75%
- 50%
- 25%
- 10%
- 5%
- 1%
- 0.1%
- 0.01%
- 0.001%
- 0.0001%
Can All Concussion Be Prevented?

• No, any player in any sport can sustain a head injury with even the very best head protection
  • Individual tolerances
  • Genetic predispositions
  • Extrinsic factors

• Helmets don’t cover entire head
  • Only reduce risk for impacts to covered regions

• Until there are more advanced materials, helmets are limited by padding size and thickness

Not all concussions can be prevented with helmets, but concussion risk and incidence can be minimized
Concussion Incidence Minimization

3 Strategies:

- Rule Changes
- Proper Technique
- Better Equipment

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

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

Fewest Concussions
Research at the adolescent level is lacking. Children are not scaled down adults.
Youth Football Helmets

There are very few differences between adult football helmet and youth football helmets.

Data has not previously been available to design youth-specific helmets.
Child Head Acceleration Measurement

- Children instrumented with head acceleration measurement device
- Utilized same devices that were in Virginia Tech players’ every game and practice
- Record video of all participation to identify impacts
Data collected wirelessly for every game and practice
Measuring Youth Head Impacts

- Instrumentation of local youth football teams
  - 136 children between 6 and 14 years old
- 3 years of data collection
- First ever dataset on youth head impact in football
# Head Impact Exposure in Youth Football

Table includes all impacts > 10 g in dataset

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Teams</th>
<th>Players</th>
<th>Impacts per Season</th>
<th>Median Impact (g)</th>
<th>95th Percentile Impact (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 to 8 Years¹,²</td>
<td>2</td>
<td>19</td>
<td>161 ± 111</td>
<td>16 ± 2</td>
<td>39 ± 13</td>
</tr>
<tr>
<td>9 to 12 Years³,⁴,⁵</td>
<td>6</td>
<td>90</td>
<td>236 ± 158</td>
<td>19 ± 2</td>
<td>44 ± 8</td>
</tr>
<tr>
<td>12 to 14 Years⁶,⁷</td>
<td>2</td>
<td>27</td>
<td>300 ± 214</td>
<td>21 ± 2</td>
<td>56 ± 10</td>
</tr>
</tbody>
</table>

Youth Football Game Impact
Youth Football Practice Impact
Identifying High-Risk Head Impacts

Year 1

Majority of high head acceleration impacts occurred during practice

Pop Warner instituted new rules to limit contact in practices

Year 2

Compared teams that adopted new rules with teams that didn’t

Observed nearly a 50% reduction in head impact exposure
Concussion Research Summary

Years of on-field head impact data collection used to:
1. Define biomechanics associated with concussion in humans
2. Develop injury risk functions for concussion
3. Define head impact exposure in football players
4. Develop rule and regulation changes to limit head impacts
STAR Evaluation System was developed from on-field data:
1. Used to evaluate current adult football helmets
2. Validated with on-field concussion rate studies
3. Resulted in a paradigm shift in the helmet market
4. Removed outdated equipment from play across the country