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Adult Football STAR Methodology

Laboratory Tests

A custom pendulum impactor was used to perform all impact tests (Figure 1) [1]. It was chosen for its increased repeatability and reproducibility compared to other impacting methods [2]. The pendulum arm is 190.5 cm long, has a total mass of 37 kg including a 15.5 kg impacting mass at the end, and has a moment of inertia of 72 kg·m^2 of which the impacting mass account for 78%. A nylon impactor face which impacts the helmets is 20.3 cm in diameter with a 12.7 cm radius of curvature to mimic the curved surface of a football helmet. The pendulum impacts a helmeted medium NOCSAE head custom fit to a Hybrid III neck. The head and neck are mounted to a 5-degree-of-freedom Biokinetics slide table with a 16 kg sliding mass. This setup allows for linear and rotational motion to be generated, and is representative of the head, neck and torso of a 50th percentile male. Test conditions include four locations (Table 1) and three velocities (3.0, 4.6, and 6.1 m/s). Helmets were tested with a facemask. Since multiple facemask choices exist for each helmet model, the lightest most common facemask was used and verified with the manufacturers. Helmet position on the headform was set with the NOCSAE nose gauge for a medium headform before each test. Each test configuration was repeated twice with two helmet model samples, totaling 48 tests per helmet model.

Figure 1: Pendulum impactor used for Adult Football STAR tests.

Figure 2: Impact locations clockwise from top left: front, front boss, side, back.

Table 1: NOCSAE headform translations and rotations on the linear slide table for each test condition.

Location	Y (cm)	Z (cm)	Ry (deg)	Rz (deg)
Front	0	+5.3	-20°	0°
Front Boss	0	+2.3	-25°	-67.5°
Side	-4	+5.8	-5°	-100°
Back	0	+4.5	0°	-180°

Notes: All measurements are made using the SAE J211 coordinate system in relation to a “zero” condition in which the headform was in a position of 0° Y and Z-axis rotation and the median (midsagittal) and basic (transverse) plane intersection of the headform was aligned with the center of the impactor. The x-position was set such that the helmet just touches the impactor face when the pendulum arm is in a neutral vertical position for each location.

The NOCSAE head was instrumented with three linear accelerometers and a triaxial angular rate sensor to obtain linear and rotational kinematics. Data were sampled at 20,000 Hz and filtered using a 4-pole Butterworth low pass filter according to SAE J211, with a cutoff frequency of 1650 Hz (CFC 1000) for accelerometer data and 256 Hz (CFC 155) for angular rate sensor data.

STAR Ratings

The STAR equation was originally developed to represent the predictive concussion incidence of one player over a season, has been adapted to allow for equal contribution from each impact location to prevent helmet protection from diminishing at any one location [1]. The equation uses laboratory tests that represent the range of on-field impacts seen in college football, and associates with each impact the amount of times it would occur over one season (exposure) as well as the associated probability of a concussion (risk). The STAR value is found by multiplying the predicted on-field exposure (E) at each impact location (L) and velocity (V) by the risk of concussion (R) for that impact using the peak resultant linear acceleration (a) and rotational acceleration (α) from laboratory impacts (Equation 1).

$$STAR = \sum_{L=1}^{4} \sum_{V=1}^{3} E(L,V) * R(a,\alpha) \quad \text{(Eq. 1)}$$

Exposure, or the number of times an impact will be seen each season, started at 83 for the 3.0 m/s condition, 18 for 4.6 m/s, and 4 for 6.1 m/s which were determined from on-field impacts in collegiate football athletes. These exposure values were then weighted by location so that each impact location would contribute 25% to the STAR value if a helmet performed the same in each direction (Table 2). Exposure values for each location are different because of differences in impact responses due to the non-isotropic nature of the Hybrid III neck and the variance of the impact location relative to the center of gravity of the head. This exposure optimization was based on impacts to a bare head with a 40 mm thick VN-600 foam impactor.

Table 2: Exposure values used for each location and impact velocity to obtain a total STAR value for Adult Football STAR, giving each location 25% contribution based on the laboratory impact responses with a padded bare head.

Location	3.0 m/s	4.6 m/s	6.1 m/s
Front	183.7	39.8	8.9
Front Boss	67.1	14.6	3.2
Side	39.0	8.5	1.9
Back	42.3	9.2	2.0

Risk of concussion was obtained from a multivariate logistic regression analysis of instrumented football player data paired with diagnosed concussions (Equation 2) [3]. The risk of concussion (R) takes into account both linear (a) and rotational (α) components of acceleration which are both known to be associated with brain injury [4].

$$R(a,\alpha) = \frac{1}{1 + e^{-(-10.2 + 0.0433*a + 0.000873*\alpha - 0.00000092*a\alpha)}} \quad \text{(Eq. 2)}$$

The final STAR values for each helmet were further broken into number of stars (1 to 5) based on thresholds given in Table 3.

Table 3: Thresholds to match STAR values to number of stars in a 5-star rating scale.

STAR Value	Number of Stars
0 – 10	5
10 – 20	4
20 – 30	3
30 – 40	2
40 – 50	1

References

[1] B. Rowson, S. Rowson, and S. M. Duma, "Hockey STAR: a methodology for assessing the biomechanical performance of hockey helmets," *Annals of biomedical engineering,* pp. 1-15, 2015.

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[3] S. Rowson and S. M. Duma, "Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration," *Ann Biomed Eng,* no. DOI: 10.1007/s10439-012-0731-0, 2013.

[4] A. K. Ommaya, "Biomechanics of Head Injuries: Experimental Aspects," in *Biomechanics of Trauma*, A. N. a. J. W. Melvin, Ed. Eat Norwalk, CT: Appleton-Century-Crofts, 1985.