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Whitewater STAR Methodology

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Laboratory Tests

A pendulum impactor is 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 36.3 kg with a 16.3 kg impacting mass at the end, and has a moment of inertia of 72 kg·m^2. The impactor face is constructed of nylon and has a diameter of 20.3 cm and a radius of curvature of 12.7 cm. This contact surface is designed to mimic a rock or other rigid surface a whitewater participant might impact. The pendulum impacts a helmeted, medium NOCSAE head, which is modified to fit a 50th percentile male 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 during an impact and is representative of the head, neck and torso of a 50th percentile male. Test conditions include three impact locations (Table 1) and two impact speeds (3.1 and 4.9 m/s). Helmet position on the headform is set according to fitting guidelines provided by the manufacturer. Two samples per helmet model were tested at six different impact configurations.

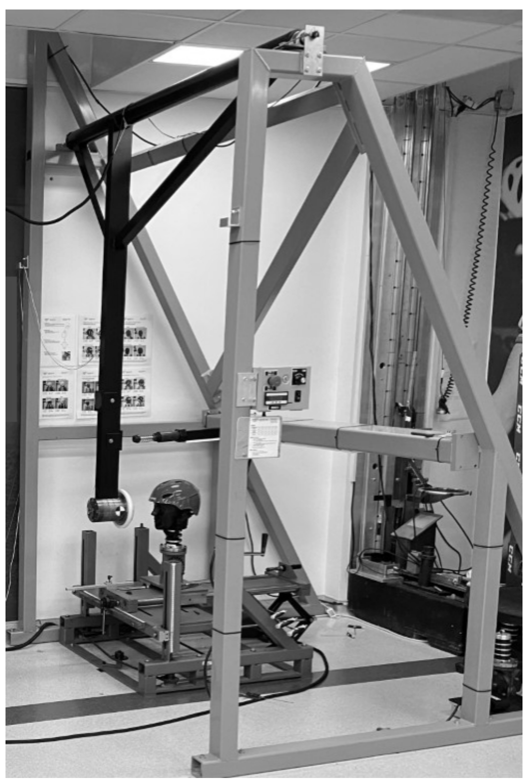

Figure 1: Pendulum impactor used for Whitewater STAR testing.

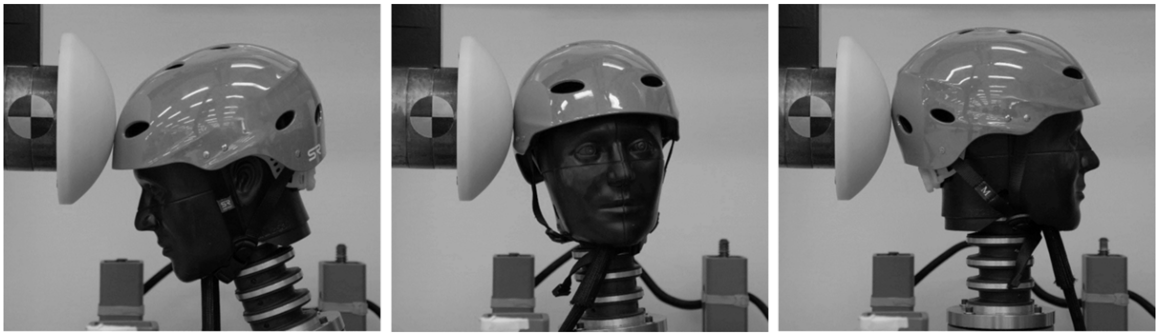

Figure 2: Impact locations from left to right: front, side, back.

Table 1: Relative NOCSAE headform translations and rotations on the linear slide table for each impact configuration.

Location	Y (cm)	Z (cm)	Ry (deg)	Rz (deg)
Front	0	+5.3	-20°	0°
Side	0	+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 is in a position of 0° Y and Z-axis rotation and the median (midsagittal) and basic (transverse) plane intersection of the headform is aligned with the center of the impactor. The x-position is set such that the helmet contacts the impactor face when the pendulum arm is in a neutral vertical position for each location.

The NOCSAE headform is instrumented with three linear accelerometers and a triaxial angular rate sensor (ARS) at its center of gravity to measure linear and rotational impact kinematics. Data are sampled at 20,000 Hz and filtered using a 4-pole Butterworth low pass filter with a cutoff frequency of 1650 Hz (CFC 1000) for accelerometer data and 256 Hz (CFC 155) for ARS data.

STAR Ratings

The STAR equation was originally developed to estimate the incidence of concussion that a college football player may experience while wearing a given helmet over the course of one season [1]. Common real-world impacts are simulated using laboratory testing, with the resulting concussion risk for each impact estimated and then weighted based on the relative frequency that a player might experience that impact scenario during a season of play (termed "exposure"). 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. Concussion risk is modeled using the peak resultant linear acceleration (a) and rotational acceleration (α) from laboratory impacts (Equation 1). Exposure is equivalent to one for whitewater activities because participants typically only undergo one major head impact annually [4].

$$STAR = \sum_{L=1}^{3} \sum_{V=1}^{2} E(L,V) * R(a,\alpha) \quad \text{(Eq. 1)}$$

Concussion risk was modeled using a multivariate logistic regression analysis of biomechanical data obtained from instrumented football players who sustained diagnosed concussions [3]. The associated risk function combines peak linear head acceleration (PLA) and peak rotational head acceleration (PRA), which are both known to be associated with brain injury, into a single metric (Equation 2) [5].

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

The range of final STAR values across helmets are then distributed into a discrete number of stars (1 to 5) for consumer interpretation (Table 2). Lower STAR values are associated with a greater number of stars and are representative of better performing helmets. The Whitewater STAR rating thresholds were determined through the average STAR score across all tested helmets. A 5-star rating threshold was set to a 50% reduction in STAR score relative to the mean STAR score for whitewater helmets, and then each subsequent rating threshold was set in increments of 50% more risk from the 5-star threshold (Table 2). For example, the 4-star threshold is 1.5 times the 5-star threshold, and the 3-star threshold is two times the 5-star threshold.

Table 2: Thresholds to match STAR values to number of stars in a 5-star rating scale.

STAR Value	Number of Stars
< 1.21	5
< 1.82	4
< 2.43	3
< 3.03	2
< 3.64	1
≥ 4.24	Not Recommended

References

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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,” Annals of biomedical engineering, vol. 41, issue 5, pp. 873-882, 2013.

[4] J. Spittler, R. Gillum, and K. DeSanto, “Common Injuries in Whitewater Rafting, Kayaking, Canoeing, and Stand-Up Paddle Boarding,” Current sports medicine reports 19: 422-429, 2020.

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