MEASUREMENT ACCURACY OF HEAD IMPACT MONITORING SENSOR IN SPORT

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Head injury and brain trauma exposure in sport have been recognized as potential contributors to long-term neurological disorders. As a result sensors have been proposed as an impact severity monitoring tool for on-field measurement of head accelerations. The purpose of this study was to characterize the accuracy of a head impact monitoring sensor system. Peak acceleration responses from a Smart Impact Monitor (SIM) sensor were compared against reference sensors from a Hodgson-WSU headform. The headform with SIM was impacted for 7 impact conditions and 3 inbound energies. Moderate to strong positive correlations were found between the SIM and reference sensors for all impact conditions. At higher inbound energy the SIM overestimated, suggesting that under higher risk conditions the SIM represents a conservative tool in identifying dangerous impacts.

KEY WORDS: head injury, brain trauma, impact magnitude, acceleration, validation.

INTRODUCTION: Concussions associated with changes to the semipermeable membrane lead to a metabolic cellular energy crisis exhibiting itself through symptomology (Giza & Hovda, 2001). Typically symptoms are short-lived; however these injuries have the potential to effect patients for months-to-years post-injury (Rimel et al., 1982). Furthermore, head impacts not manifesting through symptoms characteristic of concussive injury express risks through an accumulation of continuous repetitive trauma to neural tissues leading to the disruption of protein integrity and subsequent neurodegeneration (Omalu et al, 2005; McKee et al., 2013; Kondo et al., 2015). Head impact sensors have become a popular tool for measuring head impacts by academics and sport organizations. These tools provide a means of monitoring head impact exposure and are useful to coaches, medical staff, players and parents in identifying when as athlete receives a dangerous head impact (Crisco et al., 2012; Jadishke et al, 2013). Consequently, impact sensor companies are faced with the challenge of ensuring their products are providing accurate response data. Triax Technologies Inc. (Connecticut, USA) has developed a head impact sensor, Smart Impact Monitor (SIM), to measure impacts sustained during play/sport in real-time. This SIM is designed to measure the linear and angular kinematic response of the head associated with injury risk and brain tissue strain (Ommaya & Hirsch, 1971; King et al., 2003; Post & Hoshizaki, 2015). The purpose of this study was to compare the peak linear and peak angular acceleration responses of the SIM to ATD headform center of gravity reference sensors, for head impacts of varying conditions and energy levels.

METHODS: The Triax Smart Impact Monitor, SIM-G model with its headband attachment, a large Hodgson-WSU headform and simple pendulum system were used in this study (Figure 1). The waterproof SIM is made with a printed circuit board containing a tri-axial gyro, a high-g and low-g tri-axial accelerometer, rechargeable lithium Ion battery and 900 MHz radio. The SIM measures angular head motion via the tri-axial gyro and linear acceleration levels within a 3-150 g range. SIM sensor linear accelerometer has a low-pass filter with cut-off frequency of 780 Hz and the gyro uses a 250 Hz low-pass filter. Calculation of a geometric transform is required when using a rigidly coupled external device to measure linear accelerations experienced by headform center of gravity. All data was transformed to the calculated CG using the following transformation equation;

$$a_C = a_S + \omega \times (\omega \times \overrightarrow{SC}) + \alpha \times \overrightarrow{SC}$$

Where a_C and a_S is linear acceleration at head center of mass and sensor respectively, ω is angular velocity, α is angular acceleration, SC is the vector from sensor to center of mass.

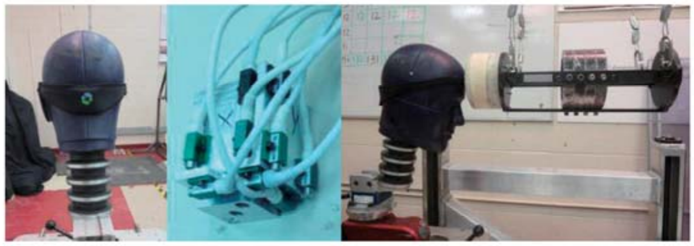

Figure 1: Triax Smart Impact Monitor positioning (left), headform accelerometer array (middle), and pendulum impacting system and NOCSAE headform (right)

A Hodgson-WSU (NOCSAE) headform (mass 4.85 kg; circumference 57.8 cm) and Hybrid III neckform (mass 1.54 kg) instrumented with nine single-axis accelerometers (Endevco 7264C-2KTZ-2-300) was used for SIM linear and angular accelerometer comparisons. The head/neck complex was attached to a low- friction sliding table (12.782 ± 0.001 kg) which is mounted on rails to allow for movement upon impact. The sliding table also allows for the head to be adjusted with 6 degrees of freedom so that each impact condition can be achieved. A pointer was used to ensure that the pendulum system was positioned so that the center of the metal frame was aligned with the impact site on the headform. The headform accelerometers were placed near the head center of gravity on a solid block in a 3-2-2-2 array (Padagaonkar et al, 1975) sampled at 20 kHz and filtered at 300 Hz (Figure 1). The accelerometer signals were passed through a TDAS Pro Lab system (DTS, Calabasas CA) and processed by TDAS software. Angular acceleration was calculated using the first principles of rigid body dynamics and linear acceleration was measured directly. The SIM with headband attachment was placed firmly in position along the back of the headform around the nuchal line, consistent with the manufacturers' instructions. The SIM records for 62 ms at 1 kHz when an impact exceeds a 16 g threshold.

Table 1
Impact Conditions defined by Site and Angle

Impact Condition	Site	Angle
Front Boss Center of Gravity (FBCG)	midpoint between the anterior mid-sagittal and right coronal planes in absolute transverse plane	perpendicular to the headform surface
Front Boss Positive Azimuth 45° (FBPA)	midpoint between the anterior mid-sagittal and right coronal planes in absolute transverse plane	a 45° rotation of the head- and neckform structure in the transverse plane
Front Positive Azimuth 45° (FPA)	anterior intersection of the mid-sagittal and absolute transverse planes	a 45° rotation of the head- and neckform structure in the transverse plane
Front Positive Elevation 15° (FPE)	anterior intersection of the mid-sagittal and absolute transverse planes	a 15° elevation of the head- and neckform structure relative to the impactor
Rear Boss Center of Gravity (RBCG)	midpoint between the posterior mid-sagittal and right coronal planes in absolute transverse plane	perpendicular to the headform surface
Rear Boss Negative Azimuth 45° (RBNA)	midpoint between the posterior mid-sagittal and right coronal planes in absolute transverse plane	a -45° rotation of the head- and neckform structure in the transverse plane
Rear Negative Azimuth 45° (RNA)	posterior intersection of the mid-sagittal and absolute transverse planes	a -45° rotation of the head- and neckform structure in the transverse plane

The headform with SIM was impacted using a simple pendulum system (Figure 1) at inbound velocities between 1.0-3.0 m/s to elicit approx. 30, 50 and 80g. Seven impact conditions were used to characterize the SIM sensor responses under centric and non-centric loading of varying head locations and angles (Table 1) that have been shown to create risk of concussion (Walsh et al., 2011). The pendulum system consisted of a hollow metal frame (3.36 kg) that was suspended using 3/32" aviation cable (length 9.25'). The free-swinging pendulum was suspended using four cables attached to a ceiling mounted beam directly above the headform. Round metal weights or 1 kg or 2 kg each were inserted into the metal frame to achieve an inbound mass of 10 kg (Figure 1). A hemispherical vinyl nitrile (VN) impact striker (diameter 13.2 cm; mass 0.677 kg) containing a 602 foam layer (thickness 3.57 cm) was attached to the impacting end of the pendulum frame (Figure 1). Three impact trials were performed for each condition and energy level for a total of 63 impacts. The biomechanical response of the SIM was compared to the headform peak linear and peak angular accelerations resulting from each impact.

RESULTS and DISCUSSION: Acceleration results from the pendulum impacts to the Hodgson-WSU headform outfitted with the SIM are shown in Table 2. Impact loads were determined using a 10 kg pendulum at inbound velocities between 1.0-3.0 m/s to elicit a low, medium, and high (approx. 30, 50, 80) linear acceleration response for each condition. All impacts were above the 16 g SIM threshold (Table 2). Independent-samples t-tests were conducted to compare peak linear accelerations (PLA) of the headform and SIM for each impact energy level. There was no significant difference in the PLA values for headform (M=31.5, SD=4.1) and SIM (M=28.3, SD=7.0) for the low energy impacts; t(40)=1.84, p=0.74. In addition, no significant difference was found in PLA values for headform (M=47.6, SD=5.2) and SIM (M=50.8, SD=16.1) resulting from the impacts of medium energy levels; t(40)=-0.883, p=0.382. A significant difference was found in PLA for headform (M=61.8, SD=8.4) and SIM sensor (M=75.0, SD=21.9) resulting from high energy impacts; t(40)=-2.575, p=0.014. As the energy level increased, the SIM readings showed, on average, higher PLA than those of the headform. The high energy impact loading showed values that are within a concussive injury risk prediction range (Zhang et al., 2004; Willinger & Baumgartner, 2003) therefore at these higher risk levels the SIM PLA values reflect a conservative approach in identifying dangerous impacts due to this overestimation in response in laboratory testing.

Table 2
Peak Linear and Angular Acceleration (SD) Results for the Headform (HF) and Smart Impact Monitor (SIM) from Low, Medium and High Energy Levels Impacts.

Impact Condition	Linear Acceleration, g (SD)					
	Low		Medium		High	
	HF	SIM	HF	SIM	HF	SIM
FBCG	30.8 (0.4)	17.9 (1.1)	49.3 (0.6)	27.7 (1.1)	70.6 (1.6)	68.6 (7.4)
FBPA	38.5 (4.7)	21.7 (4.9)	51.8 (1.8)	36.8 (5.0)	67.3 (1.2)	41.3 (7.3)
FPA	33.3 (0.6)	25.8 (0.2)	52.0 (2.2)	58.4 (3.5)	55.5 (3.7)	54.5 (6.3)
FPE	28.7 (0.8)	29.0 (2.8)	51.0 (0.3)	59.9 (6.6)	66.3 (1.3)	79.8 (10.7)
RBCG	31.8 (0.1)	36.2 (1.3)	48.6 (0.2)	42.0 (1.7)	68.8 (0.8)	80.5 (7.1)
RBNA	25.5 (2.0)	36.8 (3.1)	39.4 (2.0)	64.0 (3.0)	54.5 (8.5)	97.1 (1.5)
RNA	32.1 (0.4)	30.5 (1.3)	40.8 (2.4)	66.9 (20.5)	49.8 (0.6)	103.4 (9.6)
ave.	31.5 (4.1)	28.3 (7.0)	47.6 (5.2)	50.8 (16.1)	61.8 (8.4)	75.0 (21.9)

Impact Condition	Angular Acceleration, rad/s^2 (SD)					
	Low		Medium		High	
	HF	SIM	HF	SIM	HF	SIM
FBCG	2603 (36.1)	3337 (140.1)	4179 (28.6)	5793 (270.2)	7111 (61.1)	8300 (260.1)
FBPA	3107 (368.3)	2737 (385.8)	4069 (232.0)	3578 (148.9)	5947 (68.7)	5485 (238.5)
FPA	2347 (58.3)	2983 (79.7)	4160 (40.5)	4205 (433.0)	5714 (53.7)	5455 (31.8)
FPE	1383 (6.7)	1187 (97.1)	3187 (60.1)	3341 (118.2)	4421 (200.9)	6564 (809.5)
RBCG	2960 (104.6)	2435 (107.6)	4804 (310.1)	11286 (438.4)	6376 (235.5)	9712 (5485.7)
RBNA	3336 (254.2)	3460 (215.2)	5383 (283.5)	5812 (470.6)	9254 (586.2)	7123 (819.4)
RNA	2622 (29.4)	2475 (455.0)	5023(117.0)	6457 (2843.9)	7196 (82.0)	5815 (517.7)
ave.	2623 (626)	2659 (751)	4400 (711)	5782 (2736)	6574 (1447)	6922 (2340)

Independent-sample t-tests were conducted to compare peak angular acceleration (PAA) data for the headform and SIM sensor for each impact energy level. T-tests revealed no significant difference for PAA values for headform (M=2623, SD=626) and SIM (M=2659, SD=751) for the low energy impacts; t(40)=-0.717, p=0.865. A significant difference was found in PAA between the headform (M=4400, SD=711) and SIM (M=5782, SD=2736) for the medium energy level impacts; $t(40)=-2.239$, $p=0.031$. Finally, no significant difference was found in PAA values for headform (M=6574, SD=1447) and SIM (M=6922, SD=2340) for the high energy impacts; $t(40)=-0.580$, $p=0.565$. Although significance was found between the headform and SIM at medium energy level impacts, the SIM readings were, on average, higher than the headform. Correlational analyses were used to examine the relationship of PLA and PAA of the SIM calculated at the CG with the reference sensors Hodgson-WSU headform CG for each impact condition. Correlation coefficient results showed that a strong positive relationship exists between the headform and SIM sensor PLA with Pearson's $r>0.9$ for six impact conditions, and $r>0.8$ for the seventh. Further, PAA showed a strong positive relationship between of Pearson's $r>0.9$ between the SIM and reference headform sensors for five impact conditions. The RBCG and RNA impact conditions revealed a moderate positive correlation of Pearson's $r>0.6$ between the two sensor systems. These outcomes are likely the result of the impact conditions being in close proximity to the SIM sensor positioning consequently there was a higher variance in SIM responses from these two impact conditions (Table 2).

CONCLUSION: This research characterized the head acceleration responses of an impact sensor technology in comparison to reference sensors within a Hodgson-WSU headform. At lower energy levels, the SIM sensor and headform showed similar linear and angular acceleration responses suggesting that the SIM sensor is accurate at monitoring low level head trauma. As impact energy increases and acceleration values approach concussive risk levels, the SIM recorded higher average responses than the headform. This tendency to over-estimate impact magnitudes makes the SIM sensor a conservative on-field tool in identifying high-risk head impacts and overall trauma load to the head. In addition, the SIM revealed strong positive correlations to reference ATD headform sensors under centric and non-centric impact loading and varying impact head locations.

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