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Validation of a Helmet-Based Accelerometer System for Measuring Head Biomechanics in Ice Hockey

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ABSTRACT

The large number of mild traumatic brain injuries (mTBIs) occurring each year, along with increasing evidence that these injuries are more serious than previously thought, has created a demand to understand how mTBIs occur so that they can be prevented. The use of helmet-based instrumentation to estimate head impact biomechanics in sports is an increasingly popular method by which to study mTBI in real-world scenarios. One of these helmet-based systems, the HIT System for ice hockey, has limited validation data available. Therefore, the goal of this study was to compare accelerations calculated by this system to reference accelerations measured by an anthropometric test device (ATD). A Hybrid III 50th percentile male ATD head and neck was rigidly mounted and fit with an Easton S9 helmet instrumented with the HIT System for ice hockey. A pneumatic linear impactor was used to impact the helmet at multiple speeds and in different directions with three different interfaces between the ATD head and the helmet: a nylon cap, a dry human hair wig, and a human hair wig wet with water to simulate perspiration. Relationships between peak resultant accelerations as measured by the system and the ATD were defined via linear regression, and average errors in helmet-based system measures were calculated. The error was markedly reduced by applying impact direction-specific calibration factors as defined by the regression relationships to the system measurements. The study showed that there is a strong correlation between helmet instrumentation-measured head acceleration for ice hockey and reference acceleration as measured by the ATD. However, the relationship is not one-to-one, it varies by the interface between the ATD head and the helmet, and it varies by impact direction. These findings are important to account for in the analysis of on-ice data collected using this system.

INTRODUCTION

Mild traumatic brain injuries (mTBIs) occur frequently, with 1.7 million TBIs presenting to emergency departments each year, the majority of which are mild (Faul et al., 2010), and an estimated 1.6 to 3.8 million sports and recreation-related mTBIs occurring each year (MMWR, 2007). The number of mTBIs presenting to emergency departments due to motor vehicle trauma is estimated to be about 300,000 per year (Bazarian et al., 2005). Furthermore, recent research shows that these injuries are more serious than previously thought, and may have long-term neurological consequences (Konrad et al., 2010; Sterr et al., 2006). A study in a swine model showed that, even in cases of mild injury, with the animal quickly returning to seemingly normal behavior, there can still be permanent damage to the brain (Brown et al., 2011). These factors have increased the demand to understand how mTBIs occur so that countermeasures can be developed to prevent them from occurring in sports and motor vehicle crashes.

Helmet-based sports provide a unique environment in which to study mTBI because they represent a real-world scenario in which the head is regularly loaded, the athletes are a defined cohort upone which to measure clinical and neurocognitive baseline, and the helmets provide a means to estimate head biomechanics via instrumentation. The HIT System for ice hockey (Simbex LLC, Lebanon, NH) is an example of helmet-based instrumentation that can be used to collect biomechanical data during on-ice play. However, existing validation data on this system is limited (Gwin et al, 2006). Therefore, the goal of this study was to compare metrics measured by the HIT System for ice hockey, such as the magnitude, direction and shape of linear and rotational acceleration pulses, to reference head kinematics.

METHODS

A Hybrid III 50th percentile male anthropometric test device (ATD) head and neck with a 3-2-2-2 accelerometer array (Padgaonkar et al., 1975) was rigidly mounted and fit, following USA Hockey guidelines (USA Hockey, 2012), with a size large Easton S9 helmet instrumented with the HIT System for ice hockey. A pneumatic linear impactor with an ultra-high molecular weight polyethylene impacting surface was used to impact the helmet at various speeds and in different directions. In a first phase of testing, three different interfaces were used between the ATD head and the helmet: a nylon cap (in line with previous validation studies done on the HIT System for football (Beckwith et al., 2012, Rowson et al., 2011), a dry human hair wig adhered to the ATD head, and the same human hair wig wet with water to simulate perspiration. Three impact directions (front, back, and side) and three impacting speeds (2, 3.5, and 5 m/s) were used with 3-5 impacts per speed-direction combination.

Based on results from this first phase, a second phase of testing was performed, using the wet human-hair wig and an extended test matrix. During this second phase, the helmet was impacted at four speeds (1.5, 2.5, 3.75, and 5 m/s) and in five directions (front, back, side, oblique 30° from front, and oblique 30° from back). Five impacts were performed per speed-direction combination. This test matrix was performed on two sets of instrumentation to test inter-HIT System reliability.

Maximum values of HIT System-measured resultant acceleration and respective maximum ATD-measured acceleration were plotted for each impact. From these maximum values, regression analysis was used to define the relationship between HIT System-measured acceleration and reference acceleration as measured on the ATD. Two types of error were calculated for the HIT System maximum acceleration values compared to the ATD maximum values. The first was total percent error (Equation 1) i.e. the absolute difference between the two measures, expressed as a percentage of the Hybrid III measure, and the second was the percent error of the data adjusted using calibration factors (Equation 2); in other words, the error was re-calculated after the HIT System measures were converted based on the regression analyses. The average and standard deviations of these errors were calculated.

$$Percent\ Error = \frac{|HIT_{max} - HIII_{max}|}{HIII_{max}} \times 100$$

Equation 1: Percent error of HIT System maximum resultant acceleration

$$Percent\ Error\ of\ Calibrated\ Data = \frac{|(a \times HIT_{max} + b) - HIII_{max}|}{HIII_{max}} \times 100$$

Equation 2: Percent error of HIT System maximum resultant acceleration after data is transformed based on regression analysis – a and b are coefficients of the regression equation.

RESULTS

The first phase of testing showed an effect of the interface between the ATD head and the helmet on the relationship between helmet instrumentation-measured peak linear acceleration and reference peak linear acceleration as measured by the ATD (Figure 1).

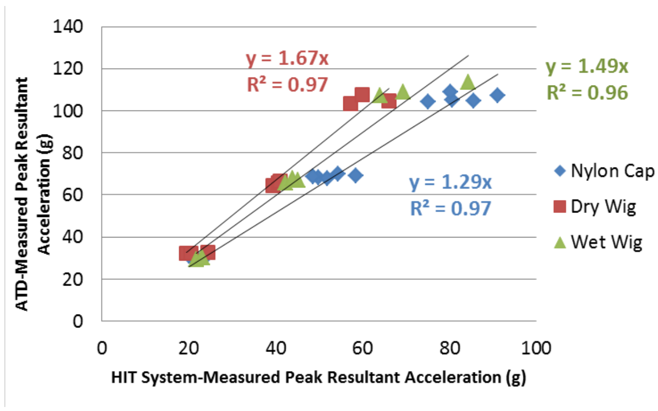

Figure 1: Relationship between system-measured maximum head acceleration and reference maximum head acceleration for three interfaces between the ATD head and the helmet

The second phase of testing showed that, for both linear and rotational acceleration, the two instrumentation systems performed similarly (Figure 2).

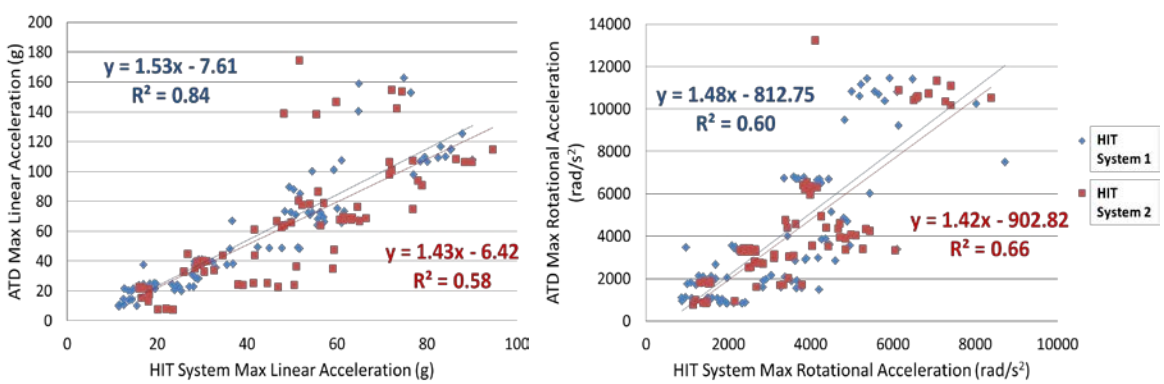

Figure 2: Relationship between system-measured peak head acceleration and reference peak head acceleration for linear (left) and rotational (right) acceleration for both instrumentation systems.

Stratifying the data by location of impact revealed that the relationship between system-measured peak head acceleration and reference peak head acceleration was affected by impact direction. Separation of the data by impact direction improved correlations between system and reference peak acceleration. Some impact directions, such as side, resulted in very strong correlations between the HIT System and reference measures (Figure 3). Other impact directions, such as oblique back, had somewhat weaker correlations (Figure 4).

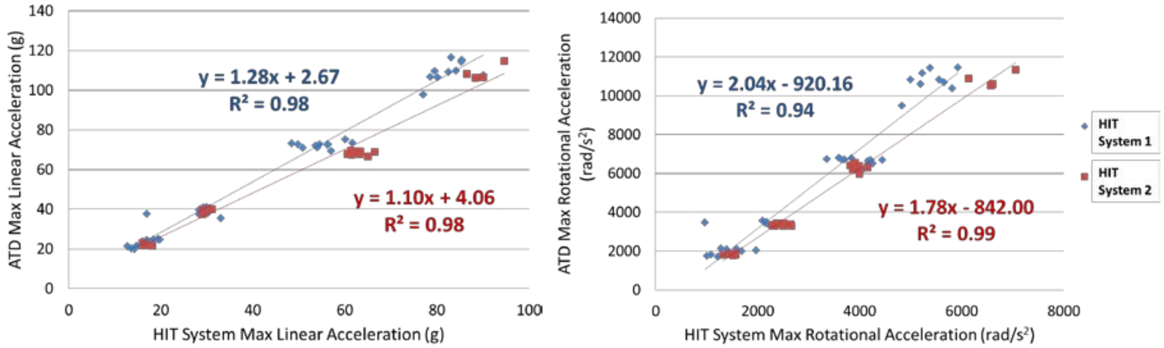

Figure 3: Relationship between system-measured peak head acceleration and reference peak head acceleration for linear (left) and rotational (right) acceleration for side impacts.

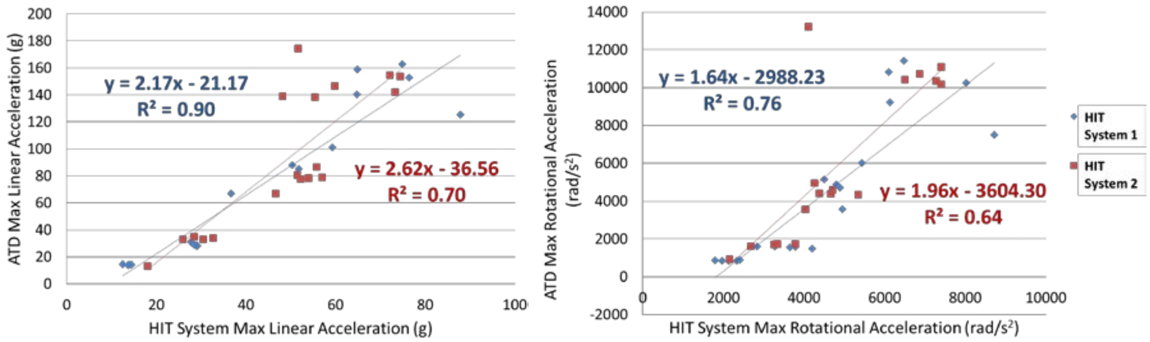

Figure 4: Relationship between system-measured peak head acceleration and reference peak head acceleration for linear (left) and rotational (right) acceleration for oblique back impacts.

The errors in peak resultant linear acceleration calculated for each instrumentation system and for both combined were lowest for back and side impacts, particularly after calibrating the HIT System data based on the regression relationships (Table 1). The calibration factors markedly reduced the measurement errors. Table 1 also summarizes the regression slopes, which are not equal to one and differ by impact direction. Peak resultant rotational acceleration showed the same patterns in percent error and regression slopes (Table 2).

Table 1. Errors and regression slopes for peak resultant linear acceleration measurements

Impact Direction	HIT System 1			HIT System 2			Both HIT Systems Combined		
	Slope	Raw error*	Calibrated error**	Slope	Raw error*	Calibrated error**	Slope	Raw error*	Calibrated error**
Side	1.28	26%	6%	1.1	19%	6%	1.21	23%	7%
Back	1.5	15%	18%	1.24	20%	15%	1.37	18%	16%
Front	1.55	22%	17%	0.83	90%	31%	0.74	67%	40%
Oblique front	1.23	15%	12%	--	--	--	0.53	26%	29%
Oblique back	2.17	25%	26%	2.62	38%	24%	2.33	31%	27%

*raw error is absolute error between ATD and raw HIT system data
**calibrated error is error between ATD and HIT system once the linear fit was applied

Table 2. Errors and regression slopes for peak resultant rotational acceleration measurements

Impact Direction	HIT System 1			HIT System 2			Both HIT Systems Combined		
	Slope	Raw error*	Calibrated error**	Slope	Raw error*	Calibrated error**	Slope	Raw error*	Calibrated error**
Side	2.04	39%	15%	1.78	30%	6%	1.92	35%	13%
Back	0.8	44%	12%	0.75	27%	14%	0.81	37%	13%
Front	1.51	18%	10%	1.63	19%	11%	1.36	19%	23%
Oblique front	0.69	66%	26%	--	--	--	0.6	65%	24%
Oblique back	1.64	81%	43%	1.96	45%	31%	1.76	64%	38%

*raw error is the absolute error between ATD and raw HIT system data

**calibrated error is error between ATD and HIT system once the linear fit was applied

CONCLUSIONS

There is a strong correlation between ice hockey helmet instrumentation-measured head acceleration and reference acceleration as measured by the ATD. However, the relationship is not one-to-one, it varies by the interface between the ATD head and the helmet, and it varies by impact direction. Calibration factors for system measurements have the potential to improve the errors associated with these systems. This study tested only a single impact condition over a range of impact speeds and directions, and other impact conditions, exploring factors such as helmet fit and impacting surface, should be tested to see if the findings persist. These results should be accounted for in the analysis of on-ice data.

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REFERENCES

BAZARIAN, J. J., MCCLUNG, J., SHAH, M. N., CHENG, Y. T., FLESHER, W., and KRAUS, J. (2005). Mild traumatic brain injury in the United States, 1998--2000. Brain Injury. 19(2):85-91.

BECKWITH, J. G., GREENWALD, R. M., and CHU, J. J. (2012). Measuring head kinematics in football: correlation between the head impact telemetry system and Hybrid III headform. Annals of Biomedical Engineering. 40(1):237–48.

BROWNE, K. D., CHEN, X-H, MEANEY, D. F., and SMITH, D. H. (2011). Mild traumatic brain injury and diffuse axonal injury in swine. Journal of Neurotrauma. 28(9):1747–55.

KONRAD, C., GEBUREK, A. J., RIST, F., BLUMENROTH, H., FISCHER, B., HUSSTEDT, I., AROLT, V., SCHIFFBAUER, H., LOHMANN, H. (2010). Long-term cognitive and emotional consequences of mild traumatic brain injury. Psychological Medicine. 41(6):1197–211.

FAUL, M., XU, L., WALD, M. M., and CORONADO, V.G. (2010). Traumatic Brain Injury in the United States: Emergency Department Visits, Hospitalizations and Deaths 2002–2006. Atlanta (GA): Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.

GWIN, J. T., CHU, J. J., and GREENWALD, R.M. (2006). Head impact telemetry system™ for measurement of head acceleration in ice hockey. Journal of Biomechanics. 39:S153.

MMWR (2007). Nonfatal traumatic brain injuries from sports and recreation activities--United States, 2001-2005. Morbidity and mortality weekly report. 56(29):733–7.

PADGAONKAR, A. J., KRIEGER, K. W., and KING, A. I. (1975). Measurement of angular acceleration of a rigid body using linear accelerometers. Journal of Applied Mechanics. 42(3):552.

ROWSON, S., BECKWITH, J., CHU, J., LEONARD, D., GREENWALD, R. M., and DUMA, S.M. (2011) A six degree of freedom head acceleration measurement device for use in football. Journal of Applied Biomechanics. 27(1):8–14.

STERR, A., HERRON, K. A., HAYWARD, C., and MONTALDI, D. (2006). Are mild head injuries as mild as we think? Neurobehavioral concomitants of chronic post-concussion syndrome. BMC Neurology. 6:7.

USA Hockey. Equipment Sizing Guide [Internet]. [cited 2012 Jul 12]. Available from: http://www.usahockey.com/Sizing_Guide.aspx