EVALUATION OF EAR-MOUNTED SENSORS FOR DETERMINING IMPACT HEAD ACCELERATION

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ABSTRACT

The objective of this study was to compare the coupling of ear-mounted accelerometers with the head during moderate rate and high rate impacts. Impact tests were performed on PMHS equipped with ear-mounted accelerometers and head-mounted accelerometers using a drop tower and a shock tube. Peak head impacts ranged from 130 -350g's for drop tests, and 380-3150g's for shock tube tests. Peak acceleration and HIC values were well correlated between sensors (R^2 = 0.87 and 0.76 respectively), an improvement attributed to sensor positioning within the bony canal. A model based on the drop tower data predicted the ear sensor response to within 15% of initial peak measured acceleration.

Keywords: ACCELERATIONS, CADAVERS, DROP TESTS, HIC, INSTRUMENTS

EAR MOUNTED ACCELEROMETERS used for assessing the severity of head impacts has been of interest to the motorsports community and the military (Knox, 2004). Despite their potential utility, previous research investigating the capability of an ear-mounted accelerometer for prediction of head acceleration during impact has revealed significant limitations. A study by Knox (2004) using IRL and CART earpiece accelerometers on dummies and volunteers showed a linear correlation between the earpiece response and head acceleration for impact in the anterior-posterior direction up to 10 g. From these results they concluded that earpiece accelerometers 'provide a good measure of primary head acceleration'. However a study by Begeman (2006) using larger exposure to impact (up to 140 g) on cadavers equipped with earpiece accelerometers showed a marked progressive phase lag and overshoot with increasing frequency between head and earpiece acceleration. They concluded that loose coupling intensifies phase lag and overshoot at higher frequencies, and that stiffer coupling between the earpiece and the head would improve the correlation in these higher rate and magnitude exposures.

The objective of this study was to investigate the mechanical coupling between human head acceleration and a small tri-axial accelerometer package inserted into the ear bony canal of post mortem human specimens (PMHS). Impact tests were performed on the specimens over a broad range of frequency inputs using moderate rate drop tests and high rate shock tube tests. This study assesses the correlation between head acceleration and ear sensor acceleration over a wide range of impacts using measures that historically have been used to quantify head injury risk. Moreover, a transfer function is developed for characterizing the coupling response between the ear sensor and the head.

METHODS

Four male PMHS were obtained for testing through the Virginia State Anatomical Board and other tissue suppliers accredited by the American Associate of Tissue Banks. The test protocol was reviewed by the University of Virginia Cadaver Use Committee. An anthropometric summary of the specimens is found in Table 1.

Two head-mounted reference accelerometer packages composed of three orthogonal Endevco accelerometers (7264B-500 for drop tests, 7270A-6K for shock tube tests) were rigidly mounted to each PMHS skull (one per side) using a small aluminum block attached with screws (total mass 30 gm). The location of each reference accelerometer was approximately at the intersection of the Frankfort plane and mid-coronal plane. Two small ear-mounted accelerometer packages composed of three orthogonal Endevco accelerometers (7269-500 for drop tests, 73-6K-6K-6K-M1 for shock tube tests) were inserted into the bony canal of both ears of each PMHS. Each ear sensor was secured using silicone for drop tests and syntactic foam for shock tube tests. CT scans were taken of each PMHS before testing to determine the placement of the ear sensor and bony canal dimensions.

Two PMHS selected for shock tube testing were each potted using FastCast-891 (Goldenwest MFG Inc) at approximately the C5 vertebral body in a cup with attachments for a Hybrid-III neck mount.

The two PMHS selected for drop testing were each potted in a box with threaded inserts for gripping, and embedded in 16 lbs/ft^3 of syntactic foam (FOAM-1616, US Composites).

Drop tests were performed using an adjustable drop tower with an aluminum honeycomb crush structure to increase the duration of impact. Each PMHS was tested at two drop levels (height of 812.8 mm and 1371.6 mm) and at two orientations (X and Z) for a total of four drop tests per specimen. Shock tube tests were performed using a helium-driven shock tube at three levels of shock pressure (3, 5 and 8 0.01" Mylar membranes). Each shock tube specimen was tested three times at each pressure level in the same orientation (X). The specimen was positioned 5.5 cm from the end of the tube with the centerline of the tube approximately at the nose of the specimen.

Drop tests were sampled at 10 kHz with a 3.3 kHz anti-aliasing filter, while shock tube tests were sampled at 1 MHz with a 200 kHz anti-aliasing filter. Data was filtered using eight-pole Butterworth filter with cut-off frequencies of 1650 Hz and 10 kHz for the drop and shock tube tests, respectively.

Table 1 - Specimen Anthropometry

Specimen	Age	Mass (kg)	Stature (cm)	Ear	Bony Canal		
					Diameter (mm)	Depth (mm)	Sensor from Entrance (mm)
Shock 1	52	54.4	155	Left	14.8	9.0	17.2
				Right	9.3	8.1	14.4
Shock 2	73	77.1	193	Left	10.8	17.7	3.5
				Right	10.7	13.6	14.5
Drop 1	57	84.8	175	Left	15.6	20.7	3.8
				Right	18.6	27.0	10.9
Drop 2	68	78.9	183	Left	18.1	22.1	8.1
				Right	14.3	34.7	21.0

A transfer function was developed to model the relationship between the ear sensor and head-mounted reference sensor acceleration. A simple, two-pole linear continuous-time transfer function was chosen that has a form similar to that describing a spring-mass-damper system. The form of the transfer function is presented in Figure 1A, where ζ is the damping coefficient, T_ω is the resonance time constant, and K is the compliance:

A) $\frac{K}{1+2\zeta T_\varpi s+(T_\varpi s)^2}$ B) $a(t) = A(t-D)^B e^{-C(t-D)}\ for\ t > D$

Figure 1 - A) Linear Transfer Function Model and B) Impact Acceleration Form

Transfer functions were created for the drop tests and the shock tube tests separately to identify whether this model works for the wide range of input frequencies tested. The data from specimens Drop 1 and Shock 1 were used to optimize the parameters of the transfer functions based on the minimization of weighted sum of squared errors using Matlab (The Mathworks, Inc).

Once the transfer function parameters were determined, model validation was performed by predicting the head acceleration of specimens Drop 2 and Shock 2 using only the transfer function and ear sensor acceleration. This was achieved by assuming a shape for the head acceleration (Figure 1B) where A is a scale factor, B is the loading coefficient, C is the load decay coefficient, and D is a time shift. These coefficients were determined by minimizing the sum of the squared errors between the measured ear acceleration and the predicted ear acceleration from the transfer function. The optimized head acceleration shape was then compared to the measured head acceleration data.

RESULTS

All analyses used the resultant acceleration measured by the head-mounted and ear-mounted sensors. The resultant acceleration is invariant to the local orientation of each tri-axial sensor package, and does not require the predetermination of transformation matrices.

Peak resultant accelerations from the drop tests ranged between 130 and 350 g while shock tube tests resulted in peak accelerations between 380 and 3150 g. A one-way ANOVA test was performed using the peak acceleration data that indicated that peak ear sensor acceleration was strongly

correlated with peak reference acceleration (R^2 = 0.87, $p < 0.001$), where peak ear acceleration was approximately 25% higher than peak reference acceleration (Figure 2a). The ANOVA test also indicated that peak ear acceleration was also dependent on specimen ($p = 0.009$), while all other test factors showed no statistical significance ($p > 0.05$).

HIC was calculated for both the reference and the ear sensor acceleration. HIC values ranged between 350 and 2030 for the drop tests, and between 450 and 58000 for the shock tube tests (Figure 2b). ANOVA results showed that specimen and orientation were not statistically significant ($p > 0.05$) in the correlation between reference HIC and ear sensor HIC values (R^2 = 0.76,). Post-test analysis of the drop test data revealed that the left ear-mounted sensor on the Drop 2 became damaged, causing erroneous measurement post-impact. This affected three of 16 drop tests data sets (the high X, and both Z orientation tests for the left ear sensor). HIC was not calculated for these three data sets.

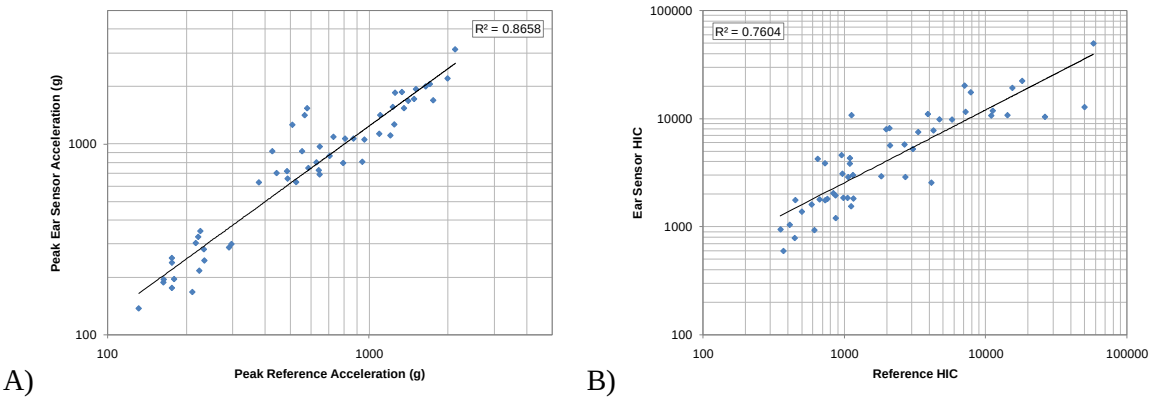

Figure 2 - Correlation for A) Peak Acceleration and B) HIC Value

Estimates of the coefficients of the transfer function for both the drop and shock tube tests are shown in Table 2. The K coefficient appears invariant to the type of impact test, with an average value of 1.4. However, there are significant differences in the coefficients ζ and T_ω between the models. T_ω, the inverse of the resonance frequency, was found to be 162 Hz and 95 kHz for the drop and shock tube models respectively.

Table 2 - Transfer Function Model Parameters, Fit and Validation

Test	Model Parameters			Model Fit		Model Validation	
	K	ζ	$1/T_\omega$	R^2	Mean Peak Acceleration Error	Mean Peak Acceleration Error	Mean HIC Error
Drop	1.40	0.504	162 Hz	0.813±0.05	20%	21%	20%
Shock	1.38	20.0	95 kHz	0.681±0.09	34%	18%	73%

The drop test model fit reasonably well with the drop test data (R^2 = 0.81), suggesting the form of the transfer function was a good representation of the coupling between an ear sensor and the head (Figure 3A). The peak acceleration of the model was typically less than the measured peak acceleration, and the average error in peak acceleration between the model fit and the ear response was 20% (Table 2). This form of transfer function was not as good at capturing the response of the ear sensor for the shock tube tests. Overall, the model under-predicted the peak accelerations in the ear accelerometer by an average of 34% and often failed to capture transient response of the ear accelerometer post-impact.

Using the transfer function along with ear acceleration from the validation data sets, the drop test model also did a good job predicting the response of the head acceleration, given the ear sensor response (Figure 3B). On average, the estimated peak head acceleration and HIC values was within 20% of the measured head acceleration. The shock tube model predicted peak head accelerations within 18% of the measured peaks (less than measured peak), but the predicted impulse was larger, resulting in HIC values that were an average of 73% higher.

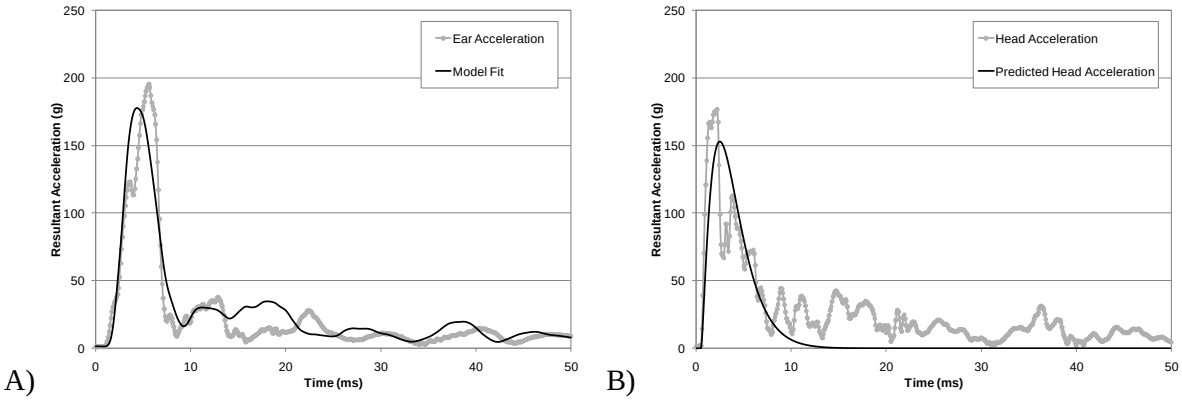

Figure 3 - Example of the A) Model Fit to Ear Acceleration and B) Predicted Head Acceleration

DISCUSSION

If ear-mounted sensors can accurately and reliably predict head acceleration from impact, they have the potential to be a valuable tool for early diagnosis of head injury in racecar drivers and military personnel. The results of this study show good correlation of peak acceleration and HIC value between the head acceleration and ear-mounted acceleration for a wide range of impact loads. This finding was contrary to previous studies that indicated that coupling was poor at impact levels greater than 150 g (Begeman, 2006). In the current study, the more consistent coupling between the ear sensor and the head might be attributable to the smaller sensors positioned more deeply within the bony ear canal rather than the outer ear mounts of the prior studies. The deeper location provides an anatomically stiffer coupling between the sensor and the head because the intra-aural skin is thin with very little subcutaneous tissue lining the bony canal. Another possible consideration is that by locating the ear sensors deeper in the ear, the sensor array is closer to the head CG. In addition, using a stiffer mounting medium would also be expected to improve the ear sensor coupling.

The form of transfer function chosen for this study was well suited for high-momentum impacts as seen in the drop testing, but less well suited for low-momentum but high-energy impacts as seen in shock tube testing. Higher-order or non-linear transfer functions may be necessary to capture the coupled response at very high frequencies. This transfer function was then used to predict head acceleration from ear sensor data. Predicted head accelerations were generally in good agreement for the drop test model and data, but not for the shock tube tests. Predicted peak head accelerations were typically lower than the measured peak head accelerations.

It was assumed that the system could be described using resultant acceleration, and rotational effects on the sensor measurement between the ear and head were negligible. Justification of this assumption was based on the bulk of the analysis being done on the early stages of the impact, where translational acceleration in the direction of applied impact was likely to dominate the system.

If a small sensor inserted into the bony ear canal can be tolerated, it could easily fit into earpieces used in many scenarios such as racing, law enforcement and the military. Such measurement techniques have the potential for advancing the study of impact head acceleration in vehicle crashes improving crashworthiness, and improving on injury diagnosis.

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