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THE DYNAMIC PROPERTIES OF THE HUMAN SKULL: THE EFFECT OF IMPACT LOCATION AND IMPACT ENERGY ON THE VIBRATIONAL RESPONSE OF THE HEAD

Claudia Blandford[1]; Mark Neuert[1]; Thomas R. Jenkyn, PhD, PEng[1]
[1]*Department of Mechanical and Materials Engineering, Faculty of Engineering*
the University of Western Ontario, London, ON

INTRODUCTION

The current state of knowledge in head injury research considers only the acceleration kinematics of the head, and many prominent head injury experts consider the results of this research contradictory and inconclusive[1,2,3,4]. This has prompted investigations into novel injury mechanisms and head injury tolerances, more recently employing finite element analysis tools[5,6]. This suggests that valuable research is dependent on a biomechanically accurate finite element model. The vibrational response of the cranio-facial skeleton (CFS) to impact is a dynamic response often neglected in these validations, in part because of the lack of experimental evidence against which to validate. Past research on the vibrational response of the craniofacial skeleton to impact has focused on the vibrational response of both dry cadaver skulls and in vivo subjects[7,8]. Khalil and Viano (1979) found 11 and 6 resonant frequencies respectively for two individual cadaver specimens, with no comparison of the values of these frequencies or the modal response between the two skulls[7]. Hakansson et al. (1994) induced vibration through bone conducted hearing aids in in vivo subjects and found that resonant frequencies and the frequency response varies largely between patients[8]. The current study examines the in vitro vibrational responses of five skulls to impact using a drop-weight tower impactor. Specifically, this study measures the resonant frequencies of the skulls and how they are affected by impact location and impact energy. Ultimately, we hope to add to a relatively sparse body of literature on the vibrational dynamics of the CFS to be used in the context of validating FE models as well as inspiring alternative avenues of investigation into craniofacial and head injuries.

MATERIALS AND METHODS

Five fresh frozen, denuded and degreased cadaveric skulls were used for this study (mean age, standard deviation: 80, 12 years; 1 female, 4 male). Strain gauges were used to measure the specimen’s response to impact[9]. Strain gauge placement sites were selected in order to maximize craniofacial coverage, and gauges were secured using a protocol for strain gauging on bone[10]. Four of the specimens were configured with 11 triaxial gauges and six uniaxial gauges, and the fifth specimen (#1622) was outfit with nine triaxial gauges and eight uniaxial gauges. A vertical dropped mass tower validated for repeatability and reproducibility[10] produced a short duration (1-5ms), localized subfracture impact on the specimen. The specimen was anchored below the drop chute using a fixturing setup that simulated a neck-like boundary condition[10]. The gauges were wired to a data acquisition system. An accelerometer was connected to the data acquisition system and adhered onto the impactor mass to measure impact force. The data acquisition system sampled all instrumentation at a rate of 50 000 Hz for three impacts at two different drop heights (H1, 125mm and H2, 175mm) and three para-saggital cranial sites (Sites 3-5, Figure 1). Figure 2 shows the experimental setup.

Custom written Matlab™ software was used to process the data into the frequency domain. Each individual impact trial was analyzed to extract the main frequency components and power magnitudes of each peak. The resonant frequencies exposed in each strain gauge spectra were aggregated for each skull, and an agglomerative hierarchical cluster analysis[11], was used to identify the same resonant frequencies exposed by different gauges or trials.

Frequency data was compared between variables of impact site and drop height using a 2-way ANOVA statistical test. 1-way ANOVAs were performed on the ordered resonant frequencies of each specimen to evaluate if these values varied between specimens.

The effect of impact energy, impact location and specimen on the powers of each resonant frequency was also explored by comparing the ratios of these powers for each frequency. As it was typical for a single gauge to record only a few of the possible resonant frequencies a 0 power was assigned to the cases where a particular resonant frequency was not exposed by the gauge for a particular trial. This allowed us to take a weighted average of each resonant frequency and calculate it as a ratio of all resonant frequencies possible. This ratio was calculated in the context of the overall dataset, as well as the distinct datasets of all impact locations for a specific impact energy, and of all impact energies of a particular impact location.

RESULTS

Examination of the frequency spectra resulted in 0 to 3 identified frequencies per strike per gauge for a total data set of between 77 and 166 frequency values per skull. The cluster technique identified between 6 and 9 resonant frequencies for all specimens. The results of this analysis are illustrated in Figure 3, and show the assignment of each frequency value to a particular resonance frequency cluster.

The effect of drop height and impact location on the frequency values obtained for each skull was not found to be significant by a two-way ANOVA test with p-values greater than 0.05 for all specimens. The results of the 1-way ANOVA on frequencies between skulls yielded significant differences in frequency values for the first eight resonant frequencies ($p<0.001$).

The effect of impact location and impact energy on the powers of each resonant frequency was analysed by comparing the power ratios. The power ratios of four of the five specimens remained consistent with varying impact energies, with maximum ratio deviations between 1.7% and 8.9% (Table 2). The frequency ratio difference between impact energies of the fifth specimen (Specimen #1643) was larger than the other specimens at 41%. When impact site was varied, all specimens showed variations in the power ratios (Figure 4) with maximum deviations between 8% and 73% (Table 3) for all five skulls.

DISCUSSION

The results acquired in this study provide insight to the vibrational response of the human skull as a complete structure, specifically, the resonant frequencies that are excited upon impact as well as the effect of impact energy and impact location on these values.

The studies of both Khalil (1979) and Hakansson (1994) have published similar results to the current study despite differences in methodology and context, validating the findings on the effect of impact energy and impact location on the vibrational response. All studies have concluded that each specimen have unique resonant frequencies. This is evident in the current study by the one-way ANOVA results (p-value <0.01) for the specimen’s effect on the first eight resonant frequencies and is also supported by the discussions in both the Khalil and the Hankansson study.

The observation of consistent resonant frequencies with varying impact conditions is expected considering it is generally geometry and dynamic characteristics of a structure that dictates its vibrational response. However, it is interesting to consider why the powers of these frequencies were found to differ with changes in the impact location. One explanation is to discuss that impacts excite operating deflection shapes (ODSs). ODSs can easily be confused with mode shapes, but they differ from mode shapes in that ODSs are the real world vibratory shapes that account for the deformation due to the structure loading (the impact itself) as well as reflect the sum of individual mode shapes of each resonant frequency excited[12]. In the context of power ratios, altering the proximity of an impact to a modal node line will alter the power to which that mode shape (and thus that frequency) is expressed in the ODS measured. In the frequency domain, this translates to a decrease in peak size of that frequency, overall reducing its power ratio relative to all other frequencies excited.

This theory can also be applied to the discussion on the power ratio changes between heights, as in the case of specimen #1643. Specifically, an increase in impact energy will increase the powers of all excited resonant frequencies, exposing frequencies that were previously indistinguishable from the signal noise.

These results are significant as they suggest that although the particulars of an impact have no effect on the resonant frequency values excited, the impact location, and the impact energy in some cases, may have an effect on the expression of these frequencies.

CONCLUSION

The conclusions presented in this study, namely, that vibrational response of differing specimens are unique, and that the resonant frequency values of the human skull are unaffected by impact site or impact energy but the powers of these frequencies have a slight dependency on these variables serve a vital role in describing the structural characteristics of the CFS. Specifically, this is important to note at both the clinical and experimental level. Experimentally, it suggests that FE models should consider the impact conditions in order to get a truly accurate picture of the dynamic characteristics of the CFS in simulation. The development of a dynamically accurate global FE model can allow for rapid and thorough investigations into the variety of head impact research questions still unanswered in this field. Clinically, although the current study does not include data supporting or refuting any current injury mechanisms, if further research reveals injury mechanisms linked to the vibrational response of the head, impact location may be a factor to consider in developing novel safety tolerances or at least broaden investigations in this field to include the vibrational response.

FIGURES AND TABLES

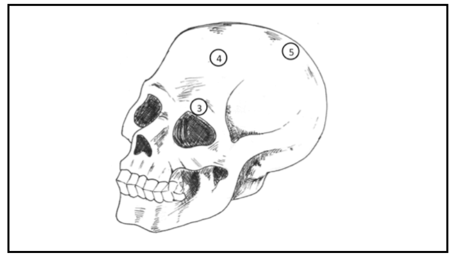

Figure 1: Impact site locations for all specimen on the left side of the skull, except for Specimen 1625, which was impacted at the same locations on the right side of the skull.

Figure 2: Vertical dropped mass tower apparatus with a specimen in position for an impact at impact site 4.

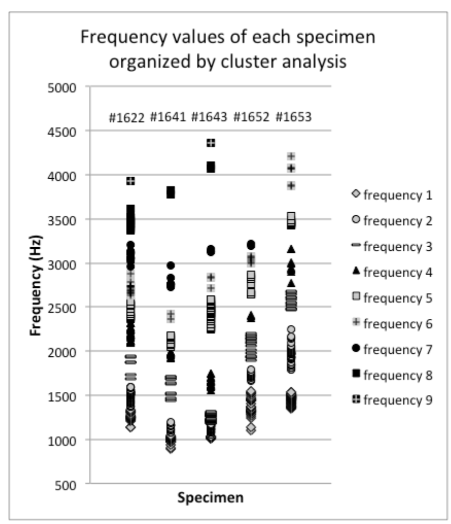

Figure 3: The results of the cluster analysis for all specimens showing the resonant frequencies discovered for each specimen.

Table 1: The power ratio differences between two impact energies of each resonant frequency of each specimen. The bolded values are the maximum power ratio deviations of each specimen.

		Frequency								
		1	2	3	4	5	6	7	8	9
#1622	**H1-H2**	1.3%	4.3%	0.4%	**8.9%**	6.2%	1.1%	0.2%	0.5%	0.2%
#1641	**H1-H2**	**1.7%**	1.1%	0.7%	0.8%	1.1%	0.2%	0.0%	0.0%	
#1643	**H1-H2**	22.1%	17.8%	**41.3%**	11.0%	13.3%	1.8%	1.3%	0.5%	0.1%
#1652	**H1-H2**	2.0%	**2.3%**	0.9%	1.0%	0.2%	0.4%	0.3%		
#1653	**H1-H2**	1.5%	0.7%	0.9%	**2.4%**	0.6%	1.4%			

Table 2: the power ratio differences between all three impact sites of each resonant frequency of each specimen. The bolded values are the maximum power ratio deviations of each specimen.

		Frequency								
		1	2	3	4	5	6	7	8	9
#1622	**S3-S4**	9.2%	**30.7%**	4.2%	16.7%	4.4%	1.4%	1.0%	7.4%	0.2%
	S4-S5	15.0%	**27.9%**	0.7%	20.1%	6.6%	3.4%	4.5%	0.1%	0.2%
	S3-S5	5.7%	2.8%	3.5%	3.4%	2.2%	4.8%	3.4%	**7.5%**	0.0%
#1641	**S4-S5**	**25.1%**	9.0%	6.4%	1.3%	0.9%	1.9%	6.1%	1.3%	
#1643	**S3-S4**	12.2%	64.7%	**76.0%**	15.0%	16.7%	0.0%	0.8%	0.0%	0.0%
	S4-S5	**78.1%**	4.0%	67.2%	0.2%	20.5%	0.0%	4.1%	1.4%	0.3%
	S3-S5	**66.0%**	60.7%	8.8%	15.3%	3.8%	0.0%	3.3%	1.4%	0.3%
#1652	**S3-S4**	29.8%	**37.6%**	2.1%	1.3%	4.9%	2.1%	0.0%		
	S4-S5	11.6%	**25.6%**	1.7%	0.3%	15.2%	3.4%	3.7%		
	S3-S5	**18.3%**	11.9%	3.7%	1.6%	10.3%	5.5%	3.7%		
#1653	**S3-S4**	29.0%	**41.3%**	2.8%	1.6%	7.8%	0.0%			
	S4-S5	14.8%	**28.3%**	9.3%	5.6%	6.2%	4.8%			
	S3-S5	**43.8%**	69.6%	12.1%	7.3%	1.6%	4.8%			

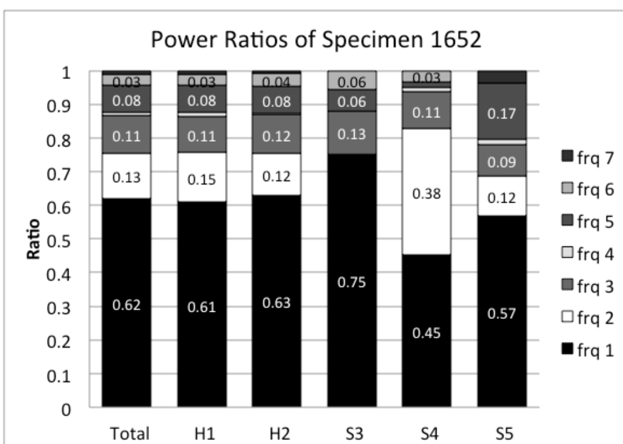

Figure 4: The power ratios of representative specimen 1652. The 2nd and 3rd bars are similar indicating consistency of power ratios between impact energies. The last 3 bars show little consistency suggesting impact location has an effect on the expression of the resonant frequencies.

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