PREDICTING ZYGOMA FRACTURES FROM BASEBALL IMPACT

Joseph M. Cormier[1], MS, Joel D. Stitzel[1], MS, William J. Hurst[1], BS, David J. Porta[2], PhD; Jeryl Jones[3] DVM, Stefan M. Duma[1], PhD

[1]Virginia Tech – Wake Forest Center for Injury Biomechanics
[2]Dept of Biology, Bellarmine University
[3]Dept of Small Animal Clinical Sciences, VMRCVM, Virginia Tech

ABSTRACT

The purpose of this study is to develop injury risk functions that predict zygoma fracture based on baseball type and impact velocity. Zygoma fracture strength data from published experiments were mapped with the force exerted by a baseball on the orbit as a function of ball velocity. Using a normal distribution, zygoma fracture risk functions were developed. Experimental evaluation of these risk functions was performed using six human cadaver tests and two baseballs of different stiffness values. High speed video measured the baseball impact velocity. Post test analysis of the cadaver skulls was performed using CT imaging including three-dimensional reconstruction as well as autopsy. The developed injury risk functions accurately identify the risk of zygoma fracture as a result of baseball impact. The experimental results validated the zygoma risk functions at the lower and upper levels. The injuries observed in the post test analysis included fractures of the zygomatic arch, frontal process and the maxilla, zygoma suture, with combinations of these creating comminuted, tripod fractures of the zygoma. Tests with a softer baseball did result in injury but these had fewer resulting zygoma bone fragments and occurred at velocities 50% higher than the major league ball.

Keywords: zygoma, orbit, baseball

INTRODUCTION

Little league baseball is the most popular sport among youth athletics, as approximately 16 million children participate in some form of organized baseball in the United States.[1] The average annual injury rate between 1994 and 1998 among children 5 to 14 years of age was 103,731 per year.[1] Facial fractures resulting from baseball impact can have detrimental effects on the skeletal structure of the face. In particular, a zygoma fracture can present injury to the facial structure as well as the orbit.[2-5] Preventing these injuries in organized sports like baseball is accomplished through protective equipment and the use of balls with a lower stiffness. The benefit of these devices can be improved if the forces necessary to cause injury are known as a function of ball characteristics.

The zygoma has been the focus of previous research due to the prevalence of facial injuries in sporting and automotive events.[6-13] Previous experimental work has been performed on cadavers using rigid impactors in order to determine fracture tolerances.[9,10,12] The purpose of this study was to develop risk functions to predict the probability of zygoma fracture from impact with a baseball.

METHODS

The methods are divided into two parts. The objective of part one was to develop risk functions for zygoma fracture from baseball impact. The objective of part two was to evaluate the validity of the risk functions by performing experimental tests on human cadavers.

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Part 1: Zygoma Fracture Risk Functions

In order to develop functions for predicting the risk of zygoma fracture, published research on the breaking strength of the zygoma was utilized. Three studies that performed impact tests to the zygoma were selected. Hodgson, Nahum *et al.*, and Schneider and Nahum used rigid impactors to determine the breaking strength of the zygoma to dynamic impacts (Table 1).[9,10,12]

Table 1: Peak Forces (in Newtons) Resulting in Zygoma Fracture

Nahum (1968)			Schneider (1972)	Hodgson (1967)
1828	1971	1397	1580	1762
1477	1628	1068	1140	2882
2740	3470	943	970	1735
2816	2304	1548	2850	1601
1406	1014	1699	1910	
1891	912	1859	1630	

A cylindrical rod with an area of 1 in^2 was used in the three tests to impact the zygoma of the cadaver subjects. The force during impact was recorded using load cells attached to the cylindrical impactors. This compilation yields a sample size of 28 data points to use for the development of the zygoma fracture risk functions.

It was assumed that the distribution of zygoma strength for the human population has a normal distribution. Therefore, the sample of strength data (x) was assumed to have a normal distribution of mean (μ) and standard deviation (σ) described by the normal distribution function (Equation 1). The data was also assumed to be non-censored values of the force resulting in zygoma fracture. The cumulative distribution function represents the probability that a given value of force will cause a zygoma fracture. This relationship was obtained by integrating the normal distribution function, using the error function (erf) for each value of applied force (Equation 2). This has no closed form solution, however, the risk of fracture can be determined for any value of impact force by integrating the density function at the desired force. This process resulted in a relationship for risk of zygoma fracture based on the exerted force alone.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)} \qquad \text{Equation (1)}$$

$$D(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \qquad \text{Equation (2)}$$

A more useful relationship was obtained by mapping the force exerted by the baseball at a range of speeds to the strength data. Therefore, the force exerted by the baseball when striking an object was necessary to develop the risk functions. Experiments by Vinger *et. al.* (1999) determined the force exerted onto an orbit from baseball impact.[13] Load cells in an artificial orbit measured the force during baseball impacts at a range of impact velocities. The artificial orbit was mounted on a sliding table to allow reward motion following impact. Vinger *et. al.* (1999) used a variety of balls having Compression Displacement (CD) ratings of 25 to 291. The CD rating for a baseball is determined by compressing the ball 6.35 mm (0.25 in) between two flat plates. The displacement must be obtained within 12 to 15 seconds and the average force of two compressions performed 90 degrees apart determines the CD rating.[13] As a comparison, the major league ball has a CD rating of 250, whereas a CD rating of 25 corresponds to a Reduced Injury Factor (RIF 1) ball. The authors found a strong linear relationship between impact speed and peak force for the variety of balls used, with the range of R^2 values being from 0.981 to 0.997. The values obtained for the soft, CD 25 and major league CD 250 balls were used for the current study (Figure 1).

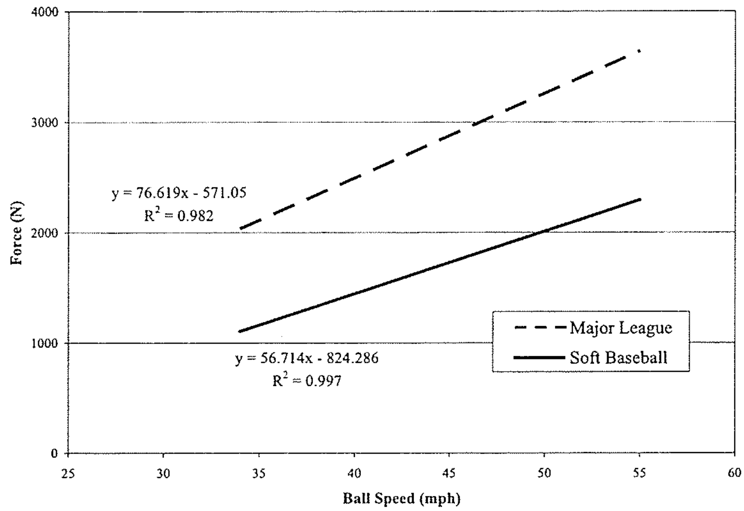

Figure 1: Impact Force for Baseball Type and Speed (Vinger, 1999)

The force values obtained by Vinger et. al. were then combined with the zygoma strength data.[13] This resulted in the injury risk functions for zygoma fractures based on the type of ball and the speed of impact (Figure 2).

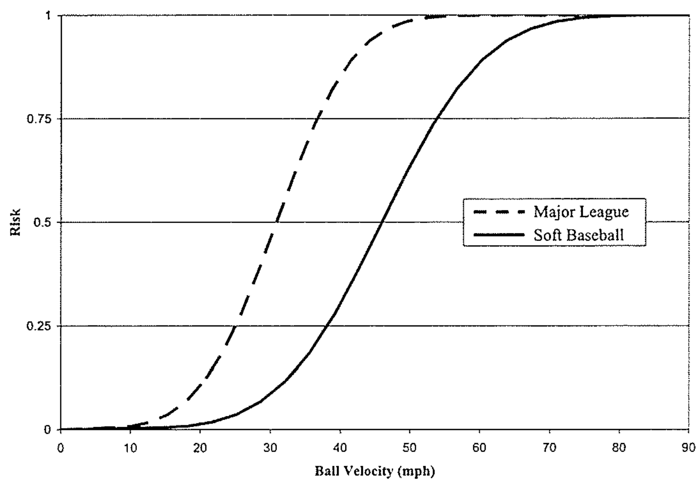

Figure 2: Risk of Zygoma Fracture as a Function of Baseball Speed for the Major League and Soft Baseball

Part 2: Evaluation of Risk Functions

To evaluate the utility of the predictive functions developed in part one, six experimental tests were performed on human cadavers (Table 2).

Table 2: Subject Information for Baseball Validation Tests

Subject	Gender	Age	Weight (kg)
1	Female	59	65.8
2	Male	44	59.0
3	Female	86	52.6
4	Female	70	45.0

A pneumatic cannon was used to project baseballs toward the zygoma of four unembalmed cadaver subjects. Prior to obtaining the tissue, two of the heads had been removed at the cervical spine. To account for the loss of body mass, the two heads were attached to a reaction mass. This facilitated orientating the head for testing and more importantly, simulated the body mass that would have normally been present. This was necessary in order to recreate the methods used by Vinger, in that the ball struck the instrumented orbit, and bounced in the opposite direction before motion of the orbit occurred.[13] This simulates what would actually occur if the head was left intact. In the two cases in which the head remained intact, the head was secured to maintain the desired orientation, while allowing motion to take place after impact. Therefore, the forces exerted onto the cadaver subjects used in this study are assumed to be the forces observed by Vinger. High speed video (Phantom IV, Vision Research, Wayne, NJ) was used to determine ball speed and to insure the impact location was correct.

The presence and extent of injury was determined by performing autopsies and taking CT images of the subjects. Transverse CT images were taken at 2 mm intervals of the subjects used in three of the zygoma tests. These images were then reconstructed to form 3D images that were used to aid in the identification of fractures incurred by the subjects.

RESULTS

The results from the experimental evaluation showed agreement at the upper and lower bounds with the developed risk functions (Table 3).

Table 3: **Test Matrix and Results for Major League and Soft Baseball Impact Tests**

Test	Subject	Ball Speed (mph)	Ball Type	Anatomical Location	Injury Risk	Injury
1	66 kg Female	70.8	Major League	Zygoma	0.99	yes
2	59 kg male	60.7	Major League	Zygoma	0.99	yes
3	45 kg Female	27.2	Major League	Zygoma	0.25	no
4	53 kg Female	21.7	Major League	Zygoma	0.15	no
5	66 kg Female	77.9	Soft Baseball	Zygoma	0.99	yes
6	53 kg Female	34.5	Soft Baseball	Zygoma	0.17	no

The autopsy performed showed that test 1 resulted in a tripod fracture, which is a fracture at each bone that the zygoma attaches to the remainder of the skull: the maxilla, temporal and frontal bones. In addition to a tripod fracture test one resulted in a comminuted tripod fracture meaning the zygoma was completely separated from the rest of the skull due to the impact. The autopsy also revealed a total of 37 bone fragments created as a result of impact with the major league ball. The CT images clearly showed the fractures at the frontal process as well as at the maxilla, zygoma interface. The fracture of the zygomatic arch was not fully represented in the 3D CT images. The autopsy indicated that test 2 also resulted in a fracture of the zygomatic arch and the frontal process (Figure 3).

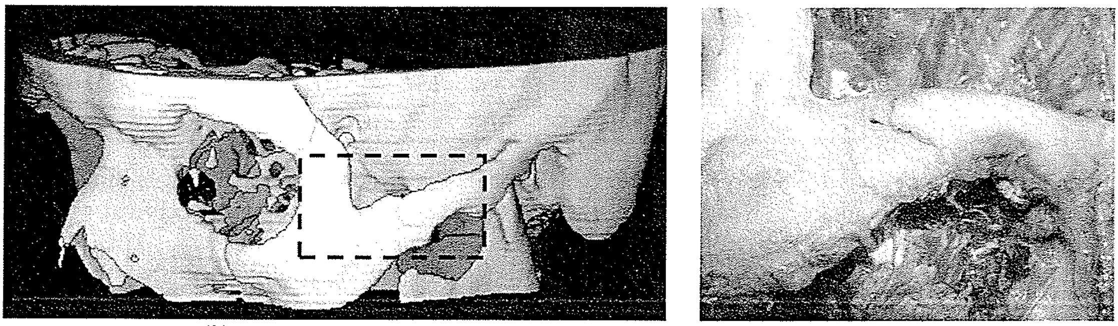

Figure 3: Post Test CT Image and Autopsy Photo Showing Injury for Test 2

A fracture was also present along the zygoma, maxilla suture but it did not propagate across the entire bone. There were 6 bone fragments created as a result of the major league ball impact. These fractures found during the autopsy were represented in the 3D CT images.

Test 5 was performed using the soft baseball. The autopsy revealed fractures of the frontal process and zygomatic arch. A partial fracture at the zygoma, maxilla suture was also present. A total of 9 bone fragments were found in the orbital region. The fracture of the frontal process and zygoma, maxilla suture were only partially represented by the 3D images. The fracture of the zygomatic arch was also slightly represented in the 3D images.

DISCUSSION

The softer baseball was shown to have mitigating properties, reinforcing the influence of ball stiffness on injury risk. In addition to the difference in injury probability, the softer baseball produced fewer bone fragments at higher velocities than the major league ball. As a comparison, tests 1 and 5 were performed on the same subject using the major league and soft baseball. Impact with the major league ball, in test one resulted in 37 bone fragments, while the soft baseball in test 5, at a higher speed created only 9 bone fragments. The number of bone fragments produced could only be identified by autopsy examination.

In some instances the 2D CT images did reveal fracture of the skeletal structures. However, the 2D images were taken prior to testing both sides of the skull. This diminished the usefulness of using these images due to the lack of an uninjured side to compare with an injured side of the skull. The most useful method was the 3D reconstructions of the 2D slices. There were instances in which the 3D images failed to show all fractures that were found in the autopsy. This has been shown in a previous study of facial fractures as well.[8] When a fracture did occur, and the bone was not displaced, it was difficult to identify the fracture using CT imaging alone. Non-displaced fractures were more common in the lower energy, soft baseball tests.

CONCLUSIONS

This study determined the probability of zygoma fracture from baseball impact as a function of ball type and speed. The risk functions showed lower risk associated with impact from a softer baseball due to the lower forces exerted onto the skeletal structure during impact. A 50 % risk of fracture was represented by a velocity of 31 mph for the major league ball, and 46 mph for the soft baseball. Based on validation experiments with human cadavers, the risk functions developed are accurate at the high and low levels of fracture risk. Additional testing will elucidate the accuracy of the model at intermediate impact velocities. These risk functions can be used to aid in the development of protective equipment used to reduce the probability of zygoma fracture from baseball impact.

The results of this study also show that precautions need to be taken in using CT imaging to identify facial fractures. If the impact event caused fracture, but was not severe enough to displace the bone, it is possible that the fracture will be underrepresented in the CT images. This is an important finding that emergency physicians should be aware of when diagnosing facial fractures from a low energy impact.

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