16

INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirtieth International Workshop

Predicting Orbital Fractures from Baseball Impact

J. M. Cormier, J.D. Stitzel, S. M. Duma, W. J. Hurst, D. J. Porta, J. Jones

ABSTRACT

Zygoma fracture as a result of baseball impact presents a particular concern due to its prevalence and importance as a structure of the orbit. The purpose of this study was to develop risk functions for zygoma fracture based on ball type and velocity. A normal distribution was assumed for previous data on the fracture strength of the zygoma. The fracture strength data was mapped with the force exerted by a baseball as a function of velocity to develop the zygoma fracture risk functions. The risk functions showed that a major league ball has a 50% chance of causing fracture at a speed of 31 mph. Experimental evaluation of the risk functions was performed using six cadaver tests and two baseballs of different stiffness values. Tests with a softer baseball did result in injury, however they occurred at velocities 50% higher than the major league ball with fewer resulting bone fragments. The experimental results validated the risk functions at the lower and upper level. Post test analysis of the skull was performed using CT imaging including 3D reconstruction as well as autopsy. 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.

INTRODUCTION

Little league baseball is the most popular sport among youth athletics. Approximately 16 million children participate in some form of organized baseball in the United States. The average annual injury rate between 1994 and 1998 among children 5 to 14 years of age was 103,731 (Yen *et a*, 2000) per year. 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 (Fan *et al* 2002, Green *et al* 1990, Hampson 1995, Krsarsai *et al* 1999). 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 (Arbogast *et al* 2002, Gassner *et al* 1999, Gillespie *et al* 1987, Hodgson 1967, Nahum *et al* 1968, Nyquist *et al* 1986, Schneider *et al* 1972, Vinger *et al* 1999). The purpose of this study was to develop risk functions to predict the probability of zygoma fracture from impact with a baseball. The data used to develop the risk functions was based on previous experimental work performed on cadavers using rigid impactors (Hodgson 1967, Nahum *et al* 1968, Schneider *et al* 1972). Determining the forces exerted by a baseball has also been done previously and therefore this information will be utilized as well. The result of combining the two types of research is a risk function that is based on the type of ball and the speed of the ball at impact. This is a more intuitive relationship that can be utilized to aid in the mitigation of facial injuries.

METHODOLOGY

The methods for the current study 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. After the experimental evaluation, computed tomography (CT) images as well as autopsy provided injury information.

Part 1: Zygoma Fracture Risk Functions

In order to develop functions for predicting the risk of zygoma fracture, previous research on the breaking strength of the zygoma was utilized. Three studies that performed impact tests to the zygoma were selected. Hodgson (1967), Nahum *et al*. (1968) and Schneider and Nahum (1972) used rigid impactors to determine the breaking strength of the zygoma to dynamic impacts (Table 1). 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. The peak forces were used in the current study to develop risk functions for zygoma fracture due to baseball impacts, assuming similar loading areas between the rigid impactors and baseballs.

Table 1. Peak Forces (N) Resulting in Zygomatic Fracture

Nahum 1968			Schneider 1972	Hodgson 1967
1828.2	1970.6	1396.7	1580	1761.50
1476.8	1628.0	1067.6	1140	2882.45
2740.1	3469.6	943.0	970	1734.81
2815.7	2304.2	1548.0	2850	1601.36
1405.6	1014.2	1699.2	1910	
1890.5	911.9	1859.4	1630	

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) obtained from the previous work was assumed to have a normal distribution of mean (μ) and standard deviation (σ) described by the normal distribution function (Equation 1). The previous 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 will result in a relationship for risk of zygoma fracture based on the exerted force alone.

Equation (1)
$$P(x) = \frac{1}{s\sqrt{2p}}\, e^{-\frac{1}{2}\left(\frac{x-m}{s}\right)}$$

Equation (2)
$$D(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-m}{s\sqrt{2}}\right)\right]$$

A more useful relationship was obtained by mapping the force exerted by the ball at a range of speeds with the strength data. Therefore the force exerted by the baseball when striking an object was also necessary to develop the risk functions for this study. Previous research by Vinger (1999) determined the forces exerted onto an artificial orbit from baseball impact. Load cells in the artificial orbit measured the force during the event. The artificial orbit was mounted on a sliding table to allow rearward motion prior to impact. Vinger 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 (Vinger 1999). 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. These softer balls are manufactured to have a lower stiffness in the hopes of mitigating injury. 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).

The force values obtained by Vinger (1999) were then combined with the zygoma strength data from the previous studies. This was done by plotting the risk curves using the ball speed that corresponded to the respective force (Figure 2). This results in the relationship for risk of zygoma fracture based on the type of ball and the speed of impact.

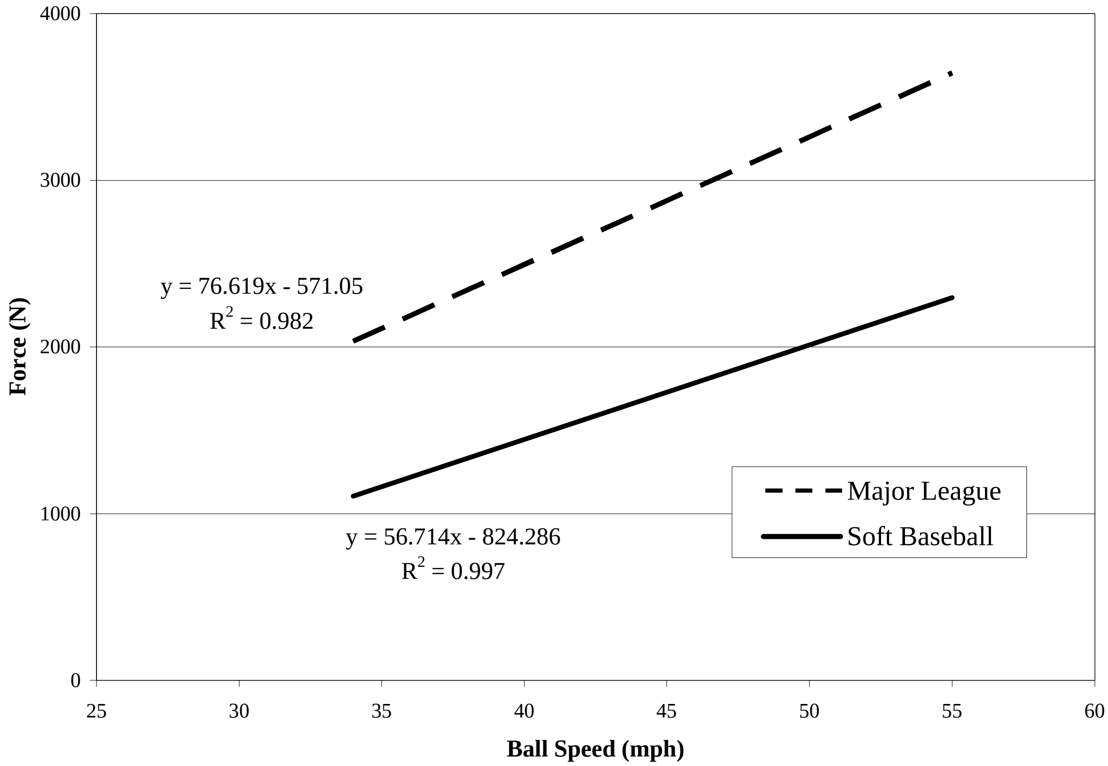

Figure 1: Impact force for ball type and speed at impact and CD rating (Vinger 1999).

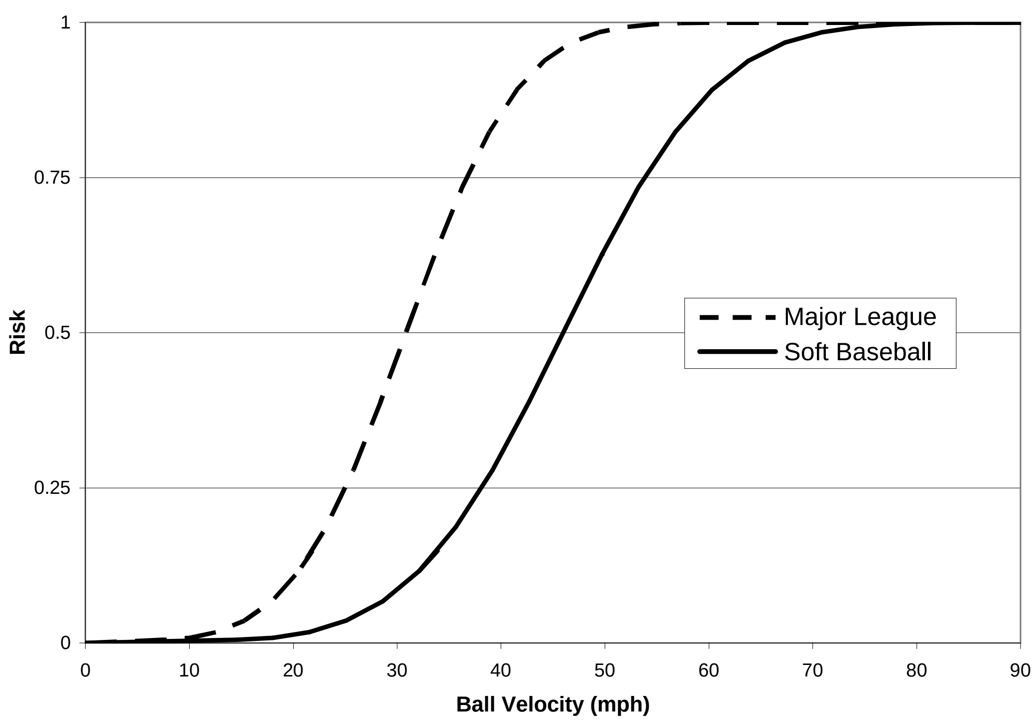

Figure 2**:** Risk of zygoma fracture as a function of ball speed for the major league and soft baseball.

Part 2: Evaluation of Risk Functions

To evaluate the utility of the predictive functions developed in part one, experimental tests were performed on human cadavers (Table 2). A pneumatic cannon was used to project baseballs toward the zygoma of four unembalmed cadaver subjects (Figure 3). 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, (1999), in that the ball struck the instrumented orbit, and bounced in the opposite direction before motion of the orbit occurred. 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 insure that no motion of the head took place until after the impact was complete.

Table 2. Subject Information for Zygoma Impact Study

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

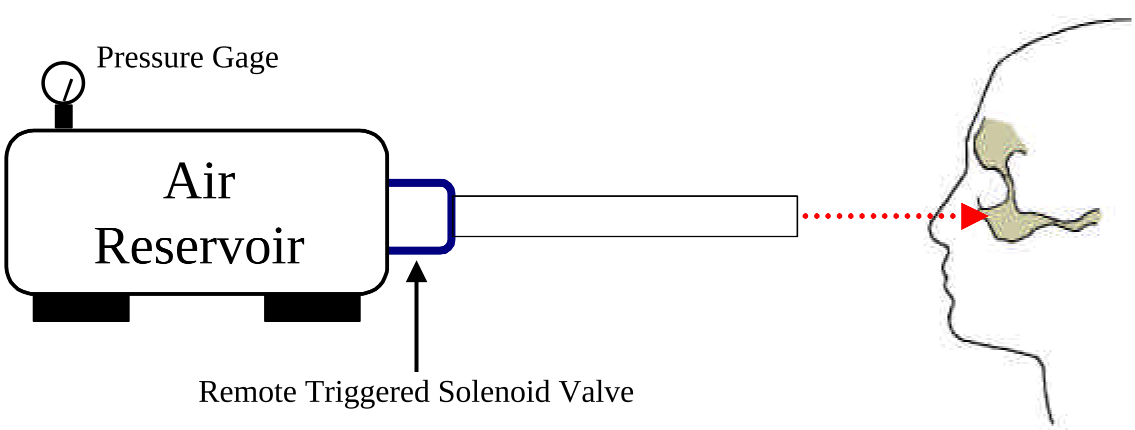

Figure 3: Test apparatus for deploying baseballs for the evaluation of zygoma fracture risk functions.

RESULTS

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

The autopsy performed showed that test one resulted in a tripod fracture, which is a fracture at each bone that attaches the zygoma to the remainder of the skull: the maxilla, temporal and frontal bones (Figure 4). 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 5). 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 (Figure 6). 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 effected 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.

Table 3. Test Matrix and Results for Major League and Soft Baseball Impact with Zygoma

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

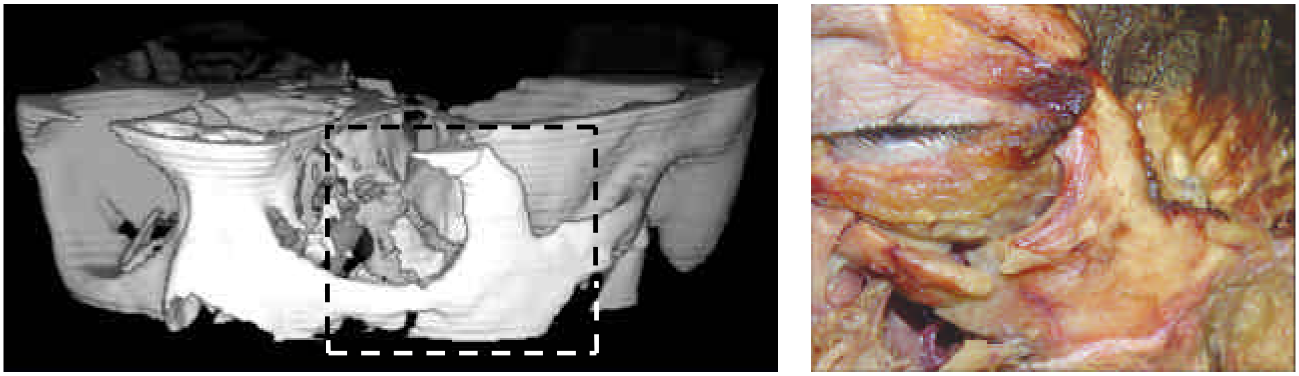

Figure 4: Post test CT image and autopsy photo showing injury for test 1.

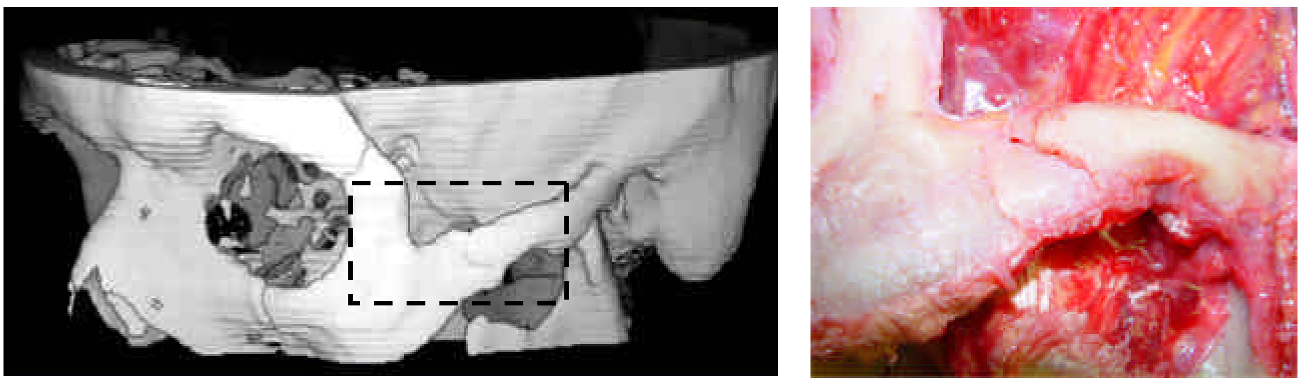

Figure 5: Post test CT image and autopsy photo showing injury for test 2.

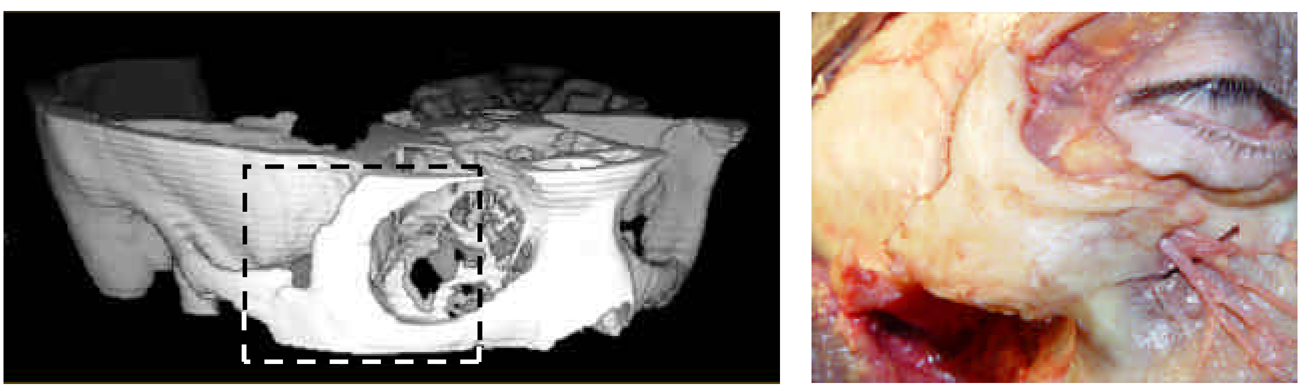

Figure 6: Post test CT image and autopsy photo showing injury for test 5.

DISCUSSION

The developed risk functions are practical because the ball velocity used to define the risk can be intuitively applied. The risk functions can also be used to improve the design of protective equipment to reduce the risk of zygoma fracture. 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 one and five 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 2D images were also less useful because it was difficult to obtain images purely in the transverse plane. This resulted in unsymmetrical images, creating more difficulty in comparing the two sides of the skull to identify fractures. Therefore, the most useful method of imaging used to identify the fractures was the 3D reconstructions of the 2D slices.

The 3D reconstructed CT images allowed for the identification of anatomic regions of the skull. This made it possible to identify fractures by looking for symmetry across the skull as well as displacements in the skeletal structure. 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 (Gillespie *et al* 1987). The limitations of CT imaging are more prevalent when evaluating fractures that have not displaced from their original location in the skeletal body. Therefore, when a fracture does occur, if the bone remains in the same location, it is difficult to identify the fracture using CT imaging alone. This was seen in test 5, which was a zygoma impact using the softer baseball. The lack of displacement of the zygoma may have been due to the lower energy impact of the soft baseball. This reduced the ability of the CT to show all occurring fractures.

CONCLUSIONS

The purpose of this study was to determine the probability of zygoma fracture from baseball impact as a function of ball type and speed. The risk functions showed the lower risk associated with impact with the softer baseball due to the lower forces that would be 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. Experimental evaluation was performed on cadaver subjects to determine the ability of these functions to accurately predict whether or not a zygoma fracture would occur. Based on the cadaver experiments, the risk functions developed are accurate at the high and low levels of fracture risk. The risk functions can also be used to develop protective equipment to reduce the probability of zygoma fracture from baseball impact.

The advantage of the risk functions developed in this study is that the probability of zygoma fracture is related to the easily understood terms of ball type and speed. This may assist the emergency care physician in determining the likelihood that an individual has sustained a zygoma fracture. 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 need to be aware of when diagnosing facial fractures from a low energy impact.

REFERENCES

ARBOGAST K.B., LINCOLN A.E., WINSTON F.K., (2002). Pediatric Facial Fractures: Implications for Regulation. Proc.46th Stapp Car Crash Conference, SAE Paper No. 2002-01-0025, 1-9.

FAN X., MAO Q., (2002). Life-Threatening Oral Haemorrhage of a Pseudoaneurysm After Raising of a Fractured Zygoma. British J. Oral Maxillofacial Surg., 40, 508-9.

GASSNER R. J., HACKL W., TULI T., FINK C., WALDHART E., (1999). Differential Profile of Facial Injuries Among Mountainbikers Compared with Bicyclists. J. Trauma, 47(1), 50-4.

GILLESPIE J. E., ISHERWOOD I., BARKER G.R., QUAYLE A.A., (1987). Three-dimensional reformations of computed tomography in the assessment of facial trauma. Clin. Radiol., 38(5), 523-6.

GREEN R. P., PETERS D. R., SHORE J. W., (1990). Force Necessary to Fracture the Orbital Floor. Ophthal. Plast. Reconstr. Surg., 6, 211-16.

HAMPSON D., (1995). Facial Injury: A Review of Biomechanical Studies and Test Procedures for Facial Injury Assessment. J. Biomech., 28(1), 1-7.

HODGSON V.R., (1967). Tolerance of the Facial Bones to Impact. Amer. J. Anat., 120, 113-122.

KRSARSAI L., HEARN T., GUR E., FORREST C. R., (1999). A Biomechanical Analysis of the Orbital Zygomatic Complex in Human Cadavers: Examination of Load Sharing and Failure Patterns After Fixation with Titanium and Bioresorbable Systems. J. Craniofacial Surg., 10(5), 400-403.

NAHUM A.M., GATTS J.D., GADD C.W., DANFORTH J., (1968). Impact Tolerance of the Skull and Face. Proc. 12th Stapp Car Crash Conference, SAE Paper No. 680785, 302-316.

NYQUIST G.W., CAVANAUGH J.M., GOLDBERG S.J., KING A.I., (1986). Facial Impact Tolerance and Response. Proc. 30th Stapp Car Crash Conference, SAE Paper No. 861896.

SCHNEIDER D.C., NAHUM A.M., (1972). Impact Studies of Facial Bones and Skull. Proc. 16th Stapp Car Crash Conference, SAE Paper No. 720965, 186-204.

VINGER P.F., DUMA S.M., CRANDALL J., (1999). Baseball Hardness as a Risk Factor for Eye Injuries. Arch. Ophthalmol., 117, 354-358.

YEN K.L., METZL J.D. (2000). Sports-specific concerns in the young athlete: Baseball. Ped. Emer. Care, 16, 3, 215-220.

DISCUSSION

PAPER: **Predicting and Evaluating Orbital Fractures From Baseball Impact**

PRESENTER: ***Joseph Cormier, Virginia Tech***

QUESTION: *Guy Nusholtz, Daimler/Chrysler*
I'm a little confused. You said you have risk functions for the zygomatic arch, but you didn't have risk functions [be]cause you didn't have enough subjects?

ANSWER: We didn't develop the responses because we had only 10 tests from the previous study. So we didn't develop the risk function, but this is something that we would like to look into in the future.

Q: Okay. So, I thought you said you had [th]em, but you don't have [th]em.

A: The risk functions that we have are for the zygoma itself, not for the zygomatic arch. I'm sorry if I didn't make that clear.

Q: Okay. The 3-D CT scan–Now, you indicated that autopsy would be the best method of determining that.

A: Right.

Q: For a live subject, you don't want to have to-

A: Right.

Q: Do an autopsy afterwards. Is the CT scan far enough--the 3-D CT scan far enough along so that it gives you a really good–You indicated that there were problems with it–that it gives you a reliable estimation of the injury?

A: Right. One of the other problems is that if you don't know where you're looking for the fracture to occur, it's going to be more difficult to identify a fracture, if you don't know where the person's being struck. If you don't know where to expect the fracture to occur, that might make it harder. But as far as using the CT's, we saw limitations. I can't say, overall what the use of CT's and how accurate it is in the medical industry. But, I think there are some limitations when the bone is not displaced from its original position, and that's what we saw in our tests.

Q: Thank you.