

ESTIMATING SHOULDER INJURY RISK USING LOW RATE LATERAL IMPACTS TO DUMMIES

Craig P. Thor¹, Kathleen Bieryla², Hampton C. Gabler¹

¹Virginia Tech-Wake Forest, Center for Injury Biomechanics.

²Virginia Tech, The Kevin P. Granata Musculoskeletal Biomechanics Laboratory.

ABSTRACT

This paper is an investigation of low rate loading of the shoulder. The paper first presents a review of the literature on the impact tolerance of the shoulder in high and low rate loading conditions. Currently, there are no injury criteria, nor biofidelic anthropomorphic test dummies for these low rate scenarios. This study investigates dummy loading situations that are known to be non-injurious using both the 5th percentile female and 50th percentile male Hybrid III ATDs. Correlating the non-injurious loading conditions outlined in the literature with ATD tests provides a methodology for relating dummy impact forces as they pertain to human lateral shoulder impact loads. The differences in the human shoulder response and the dummy shoulder response will be resolved through the relationships established with similar loading methods. The ATD tests are compared to a previous testing methodology, resulting in a relationship between non-injurious shoulder loads of the human and the corresponding impact loads of the ATD.

Keywords: Shoulder, Lateral Impact, Injury Criteria, ATD Testing, Low Rate.

INTRODUCTION

Research into lateral loading of the human shoulder falls primarily into three categories; falls, sports injuries, and motor vehicle crashes. Shoulder injuries of moderate severity represent 52% of all shoulder injuries in car crashes [1]. Shoulder injuries, unlike head and thoracic injuries, are rarely life threatening. The issue surrounding shoulder injury however is not always the severity of the initial event but the lasting effects of the injury. The unique anatomical properties of the shoulder often result in reoccurrences of injuries due to induced instabilities in the joint. For young athletes experiencing anterior shoulder separations, recurrence rates can be as high as 80-90% [2]. As a result, it is not the threat to life produced by a shoulder injury that is of importance, but rather the threat to livelihood.

The occurrence of many shoulder injuries are the result of direct lateral impacts to the shoulder. Acromioclavicular injuries are the most common injury found in elite collegiate level athletes, representing 40% of all shoulder injuries. 80% of these injuries are the result of a direct lateral insult to the shoulder [3]. However, in falls, lateral impacts to the shoulder are less common [4]. A number of approaches have been taken to quantify the parameters that can either directly lead to or indicate a shoulder injury.

Injury Mechanisms

Often, for a specific shoulder injury type, there is a dominant injury mechanism. Most of the skeletal injuries are the result of direct loading of the shoulder from sports impacts, intruding structures in car crashes or lateral falls onto the shoulder. Many of the dislocations and subluxations of the shoulder joint produce ligamentous injuries, where the corresponding injury mechanisms are often related to the direction of loading in relation to arm location and rotation.

The Abbreviated Injury Scale (AIS) ranks injury severity by threat to life using a six-level scale where 0 = no injury and 6=fatal injury [5]. Using the AIS scale, the highest severity shoulder injury is AIS 3 (serious severity). The vast majority of shoulder injury types however are of AIS 2 (moderate severity) or AIS 1 (minor severity).

Injury Tolerance

High Rate Lateral Loading of the Shoulder

Recently, the automotive industry has begun to address the need for increased research into the impact response of the shoulder. The goal is the development of more biofidelic side-impact anthropomorphic test dummies (ATDs) [3, 6, 7, 8, 9, 10, 11]. A number of groups have completed tests to analyze the response of the shoulder complex to high rate lateral loading conditions. The primary goal of the high rate lateral shoulder loading research has been to create an understanding of injury criteria in severe impacts that would be seen in automobile crashes.

High rate injury tolerance research has mainly been conducted through the use of cadaveric subjects, impacted in the shoulder via an impactor or through sled tests. Marth (2002), Bolte et al (2000; 2003), and Comipgne et al (2004) used a 23 kg impactor to impact the shoulder at the glenohumeral joint level. Each group employed a range of impact speeds, padding conditions and utilized a number of injury metrics to determine those with the best correlation [3, 6, 7, 8]. Irwin et al (1993) and Koh et al (2001) chose to analyze the same injury metrics, but instead utilized a specialized sled which accelerated cadavers into instrumented barriers [9, 10].

In 2005, Koh et al combined the data from these studies, including only the high speed tests (>3.0 m/s). This created a large population of cadaver shoulder injury studies (N=31). Many of the conclusions of the 2005 combined analysis supported those found by the individual studies [3, 6, 7, 8, 9, 10]:

- There was no statistically significant relationship between impact force and threat of AIS 2+ shoulder injury.
- The strongest correlation of all metrics existed between the displacement of the acromion with respect to the sternum and the threat of AIS 2+ shoulder injury.

The combined study found that acromion-to-sternum deflection (40 mm) and Cmax (20%) resulted in a 50% probability of AIS2+ shoulder injury and had the strongest correlation ($p=0.0003$). Cmax is a compression percentage defined as the shoulder deflection of the first thoracic vertebrae (T1) to shoulder edge divided by the shoulder width [10, 11].

Low Rate Loading

Our review of the literature revealed fewer studies on low rate loading of the shoulder. For our study, lower rate impacts are considered to be less than 3 m/s. Along with the high rate tests, Compigne et al (2004) used a 23 kg pneumatic impactor to conduct a number of low rate (1.5 m/s) impactor tests to analyze the motions of the shoulder structures in oblique loading conditions. These tests revealed no AIS2 level injuries and only two AIS1 level injuries, both glenohumeral joint contusions [8].

The study performed by Sabick et al (1999) at the University of Iowa, sought to quantify the effect that arm-bracing had on the loads in the pelvis and shoulder. For this study, younger males (age 25-55) were enlisted to fall on a padded force plate, starting from a kneeling position. The participants were told to fall laterally onto the plate with their arms crossed on their chest. All forces were recorded and given as a ratio of body weight for each participant.

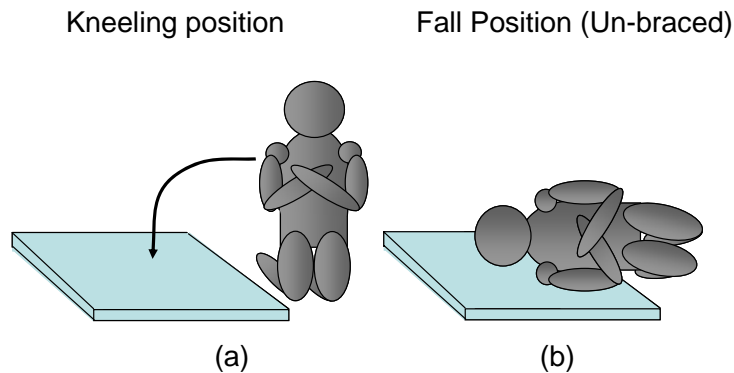


Figure 1: Experimental setup for the Sabick tests. (a) Subjects start from kneeling and (b) fall onto a padded force plate.

The peak resultant forces experienced in the shoulder ranged from 1.06 – 5.16 times the subjects body weight (BW) with an average of 2.84 BW for the relaxed falls. None of the participants in this study were injured. This study revealed that the shoulder complex can withstand large direct impacts from falls. Even larger forces in the 4-5 BW range were not found to be injurious and there was no indication that the participants were near an injury threshold [12].

Current dummies still lack a biofidelic shoulder. All tests to determine shoulder injury risk either require the use of human volunteer or cadaveric subjects. While dummies are being developed, there is a near term need in the development of safety equipment to correlate human subject responses with dummy impact responses of the shoulder.

OBJECTIVE

The purpose of this study is to determine lateral impact loads of the shoulder from anthropomorphic test dummies in configurations known to be non-injurious.

METHODS

Previous research has focused primarily on the injury tolerance of the shoulder to high rate loading. Much less is known regarding injury criteria in low rate loading. Preliminary anthropomorphic testing dummy (ATD) impacts are presented here to investigate impact loads from lateral falls directly onto the shoulder with a rigid surface. These ATD tests provide insight into the loading conditions for low rate tests of direct impacts to the shoulder. The tests were designed to provide a correlation between the ATD and the human volunteer testing under loading conditions similar to those used by Sabick et al (1999).

Two Hybrid III ATDs representing a 50th percentile male (77 kg) and a 5th percentile female (50 kg), respectively, were chosen for this study. The two dummy ATD sizes were included to determine any

differences that may result from subject body size. The test configurations were chosen to be comparable with those performed by Sabick et al (1999). The tests were conducted in a manner that would record an impact force from a lateral fall, starting from a kneeling position. The support block and the impact block were positioned in a manner that allowed the shoulder of the ATD to absorb the energy of the fall. The falls allowed only the shoulder to strike the impact block, thus recording only shoulder impact forces. The fall was initiated by pitching the ATD to the minimum angle that required a force to hold the ATD upright. Releasing from this position allowed the ATD to rotate under its own weight. The impact block was positioned on a force plate in the testing platform. The impact forces were recorded at 1000 Hz and filtered using a 600 Hz channel filter class.



Figure 2: Positioning of the ATD and the impact block prior to fall initiation.

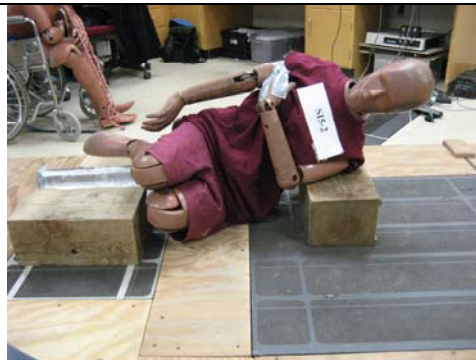


Figure 3: Post impact positioning of ATD.

RESULTS

Five tests were conducted for each ATD. The results are presented in Table 1. Figure 4 and Figure 5 present the force-time response corridors for the 5th and 50th percentile ATDs.

Table 1: ATD shoulder impact forces expressed in peak force filtered at 600Hz and in relation to the weight of the ATD.

	Test #	Peak Force (N)	Average (N)	Standard Deviation (N)	Peak Force (BW)	Average (BW)	Standard Deviation (BW)
5th Percentile Female	SI5-1	3635	3893.6	949.4	7.57	8.11	1.978
	SI5-2	3880			8.08		
	SI5-3	4865			10.13		
	SI5-4	4628			9.64		
	SI5-5	2460			5.12		
50th Percentile Male	SI50-1	2452	5328.4	1667.8	3.21	6.97	2.181
	SI50-2	5380			7.04		
	SI50-3	5914			7.74		
	SI50-4	6444			8.43		
	SI50-5	6452			8.44		

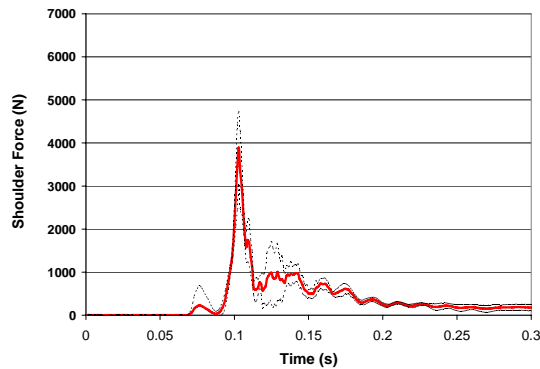


Figure 4: Average force vs. time plot with a corridor representing +/- 1 standard deviation for the 5th percentile female ATD tests

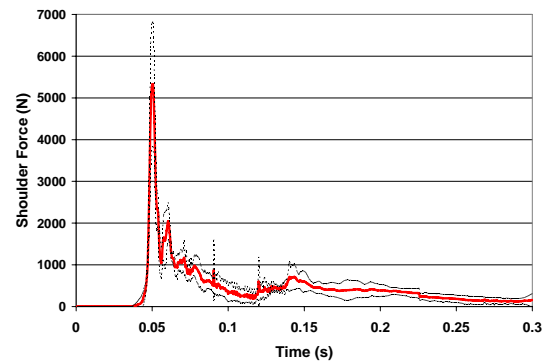


Figure 5: Average force vs. time plot with a corridor representing +/- 1 standard deviation for the 50th percentile male ATD tests

The two test samples did not show a significant difference in average peak force ($p = .0665$) based on a pooled t-test. However, both data sets had outliers whose peak forces were significantly lower than the others for the respective sets (SI5-5, SI50-1). The average peak loads experienced by the ATD were significantly higher than those presented by Sabick et al [12]. However, because there is no significant difference between the average peak forces of the 5th and 50th percentile dummies, both can be considered for comparison with the Sabick et al study.

DISCUSSION

The rate of loading has been shown to be an important factor in determining the probability of injury for lateral shoulder impacts. The loading rates experienced in the Sabick et al study presented lateral shoulder impact forces that did not produce injury. These same impact forces were found to be injurious in higher rate tests. The test methodology for our ATD tests and the Sabick et al tests were the same. However, the forces measured in the ATD tests were higher than those for the Sabick et al tests. The differences in shoulder impact forces can be explained by two distinct differences. First of all the Sabick et al study used a padded force plate. To test for the importance of padding in this study, the ATD tests must be repeated utilizing the same padding used by Sabick et al. Secondly, and more importantly, the shoulder of the ATD is non-compliant, translating to higher impact forces than that of a human shoulder. The strut-like properties of the s-shaped human clavicle and the ability of the shoulder to articulate during a fall allows for energy dissipation from a lateral shoulder impact. The ATD has a stiff metal shoulder that does not allow for the same energy dissipation.

Despite the differences in a human and ATD shoulder, a correlation between the human shoulder impacts and the ATD shoulder impacts can be produced for ATD tests run using the Sabick et al methodology. This presents an opportunity to utilize an ATD in low rate loading scenarios in place of a human subject. If the ATD shoulder force falls within the non-injurious range of the correlated Sabick et al human tests, it can be assumed that the ATD force would not produce injury in a human. However, the Sabick et al tests do not provide a threshold at which injury will occur, producing only left-censored data. Thus, any direct correlation between the Sabick et al human shoulder loads and the ATD shoulder loads will also be left-censored. If the loads from ATD lateral impact shoulder testing present forces beyond the scope of the correlated human volunteer tests, it is no longer appropriate to use the ATD

tests to predict injury. Nonetheless, a new method of testing within a non-injurious range of lateral shoulder loads is now possible through the correlation of ATD impacts with human volunteer tests.

CONCLUSIONS

The design of shoulder injury countermeasures could be greatly enhanced if ATDs could be used to verify that shoulder loads are non-injurious. This study has conducted tests comparing the lateral impact loads of ATD shoulder tests with correlated human volunteer tests that are known to be non-injurious. These tests will eventually permit designs to analyze lateral loads of the shoulder without the use of human volunteers.

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REFERENCES

- [1] Marth, D.R., *Biomechanics of the Shoulder in Lateral Impact*. 2002, Wayne State University: Detroit.
- [2] Ong, B.C., J.K. Sekiya, and M.W. Rodosky, *Shoulder Injuries in the Athlete*. *Current Opinion in Rheumatology*, 2002. 14: p. 150-159.
- [3] Kaplan, L.D., Flanigan, D.C., Norwig, J., Jost, P., Bradley, J. Prevalence and Variance of Shoulder Injuries in Elite Collegiate Football Players. *The American Journal of Sports Medicine*, 2005. 33(8): p. 1142-1146.
- [4] DeGoede, K.M., J.A. Ashton-Miller, and A.B. Schultz, Fall-Related Upper Body Injuries in the Older Adult: A Review of the Biomechanical Issues. *Journal of Biomechanics*, 2003. 36: p. 1043-1053.
- [5] Association for the Advancement of Automotive Medicine (AAAM). *The Abbreviated Injury Scale, 1990 Revision, Update 98 (1998)*
- [6] Bolte, J.H., Hines, M.H., McFadden, J.D., Saul, R.A. Shoulder Response Characteristics and Injury Due to Lateral Glenohumeral Joint Impacts. *Stapp Car Crash Journal*, 2000. 44.
- [7] Bolte, J.H., Hines, M.H., Herriott, R.G., McFadden, J.D., Donnelly, B.R. Shoulder Impact Response and Injury Due to Lateral and Oblique Loading. *Stapp Car Crash Journal*, 2003. 47: p. 35-53.
- [8] Compigne, S., Caire, Y., Quesnel, T., Verries, J. Non-Injurious and Injurious Impact Response of the Human Shoulder Three-Dimensional Analysis of Kinematics and Determination of Injury Threshold. *Stapp Car Crash Journal*, 2004. 48: p. 89-123.
- [9] Irwin, A.L., Walilko, T.J., Cavanaugh, J.M., Zhu, Y., King, A.I. Displacement Responses of the Shoulder and Thorax in Lateral Sled Impacts. *Stapp Car Crash Journal*, 1993. 37: p. 165-173.
- [10] Koh, S.-W., J.M. Cavanaugh, and J. Zhu, Injury Response of the Shoulder in Lateral Sled Tests. *Stapp Car Crash Journal*, 2001. 45: p 375-416.
- [11] Koh, S.-W., Cavanaugh, J.M., Mason, M.J., Peterson, S.A., Marth, D.R., Rouhana, S.W., Bolte, J.H. Shoulder Injury and Response Due to Lateral Glenohumeral Joint Impact: An Analysis of Combined Data. *Stapp Car Crash Journal*, 2005. 49: p. 291-322.
- [12] Sabick, M.B., Hay, J.G., Goel, V.K., Banks, S.A. Active Responses Decrease Impact Forces at the Hip and Shoulder in Falls to the Side. *Journal of Biomechanics*, 1999. 32: p. 993-998.2.