INJURY BIOMECHANICS RESEARCH
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Effects of the Extraocular Muscles on the Response of the Human Eye Under Static and Dynamic Loading Conditions

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ABSTRACT

The purpose of this study is to determine the effect of the extraocular muscles on the response of the eye under static and dynamic loading conditions. Two different types of tests have been performed. First, static displacement tests were conducted utilizing computed tomography to visualize the displacement of the eye within the orbit. Six eyes were tested in situ in matched pairs, one eye with the extraocular muscles transected, and one eye with the extraocular muscles left intact. A rigid impactor was used to displace the eye in 5 mm increments from 0 mm to 30 mm and the load required to displace the eye was measured. Second, dynamic impact tests are planned to elucidate differences in response at high rates. Again, matched pairs of eyes will be tested with the extraocular muscles left intact on one eye and transected on the other. The impactor is accelerated to approximately 10 m/s prior to striking the cornea and the load and displacement response of the eye is measured under this dynamic impact. Force-displacement responses of eyes with intact and with transected muscles will be analyzed. At present, only one dynamic impact test has been performed. Also, a comparison of the injury outcomes of eyes with and without intact musculature is planned. For static tests, the extraocular muscles increase the force required to produce a given deflection by thirteen percent, though this varies with the specific indenter geometry. For the first dynamic impact test, the peak forces are greatest with extraocular muscles intact (295 N for intact vs. 250 N for transected), while the translation of the eye is greater with the extraocular muscles transected (16 mm for transected vs. 12 mm for intact). Data from both static and dynamic test results suggest that extraocular muscles affect the in situ response of the eye to impact, especially when relatively large translations of the eye are observed. Since enucleated eyes are frequently used for impact testing, it is important that additional testing be performed to elucidate any differences in force-deflection and injury response.

INTRODUCTION

More than 30,000 people lose sight in at least one eye every year in the United States alone (Parver, 1986). Among the severe injuries that can result in the loss of an eye is globe rupture. Globe rupture can occur as the result of the impact of the eye with a blunt object such as an airbag, sports equipment such as a ball or hockey stick, and military devices such as night vision goggles (Chisholm, 1969; Duma et al., 1996; Ghafouri et al., 1997; Lueder, 2000; Power et al., 2002; Bass et al., 2002).

Previous studies have been performed to determine the injury tolerance of the human eye to globe rupture from blunt impact (Bass et al., 2002; Stitzel et al., 2002); however, none have investigated the effect that ocular muscles have on the response of the eye. The research hypothesis for the current study is that when an eye is subjected to blunt trauma, the forces that are created by the extraocular muscles, in particular the oblique muscles, significantly contribute to the risk of the globe rupturing.

Using a parametric study with *in situ* human cadaveric eyes, the research plan will quantify the tensile forces exerted on the eye from the superior and inferior oblique muscles, quantify the eye displacements between matched impact tests with the extraocular muscles intact versus transected, evaluate the rate dependence of the forces and displacements as a function of the extraocular muscles, and characterize the effectiveness of existing eye injury criteria that were developed from research performed on specimens without the extraocular muscles intact. The successful completion of this project will result in an improved understanding of eye injury biomechanics and the implications of *in vitro* eye testing versus *in situ* eye testing.

METHODS

In order to observe rate effects of the extraocular muscles on eye response, two types of tests were performed: static displacement tests and dynamic impact tests. The static tests also allowed the use of Computed Tomography (CT) imaging, to observe the deformation of the eye as it was displaced into the orbit.

Static Testing

The purpose of the quasi-static tests was to investigate the effect of the presence of the extraocular muscles on the biomechanical response of the human eye *in situ*. A total of three post-mortem human heads were used for the static matched pair tests. For each test, the specimen was fixed in a fiberglass box using expandable foam. For each specimen, the extraocular muscles were transected at their scleral insertions for one eye and were left intact in the contralateral eye. A custom designed catheter was inserted into the eye through the lateral aspect of the sclera, positioned such that it would not interfere with the indentor as it contacted the eye or during the displacement of the eye. The catheter was connected to a saline bag and an inline pressure transducer (Omega, PX302-015GV, Stamford, CT) that was utilized to ensure that the eye was pressurized to physiologic conditions (0.04 MPa). The specimen was placed inside the scanning aperture of a CT machine and the eye was displaced in 5 mm increments up to a final indention of 30 mm. A load cell (Interface, 1210AF-500, Scottsdale, AZ) was mounted at the far side of the indention system at a distance such that it would not produce imaging artifacts on the CT scan. A schematic of the test setup is shown (Figure 1). The CT scans were taken immediately after reaching each specified indention. Force and pressure data were continually collected at a sampling rate of 10 Hz for the duration of the test on each eye.

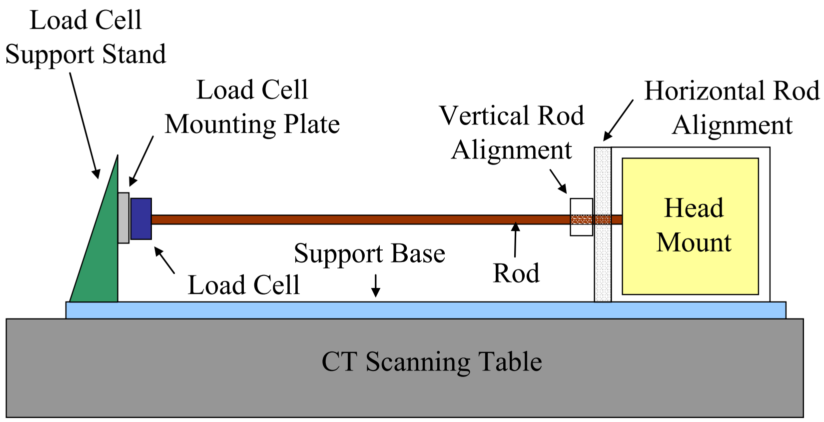

Figure 1: Side view of the static displacement test apparatus.

Dynamic Testing

The purpose of the dynamic impact testing is to investigate the effects of extraocular muscles on the biomechanical response of the human eye *in situ* for dynamic impacts. The effects of the extraocular muscles were elucidated by matched pair testing on human cadaver heads. The testing protocol is similar to that used for the quasi-static tests. The specimens are mounted in a rigid plastic container using expandable foam. For each specimen, the extraocular muscles were transected at their scleral insertions for one eye and were left intact in the contralateral eye.

The impact tests are performed using a spring-powered dynamic impactor (Figure 2). The impactor is accelerated to a velocity of approximately 10 m/s prior to impacting the eye. A load cell (Omega, LC201-100, Stamford, CT) is used to measure the loads exerted on the eye specimen by the impactor. An accelerometer (Endevco 7264B, 2000 G, San Juan Capistrano, CA) attached to the impactor assembly facilitates inertial compensation of the impactor load and determination of impactor displacement.

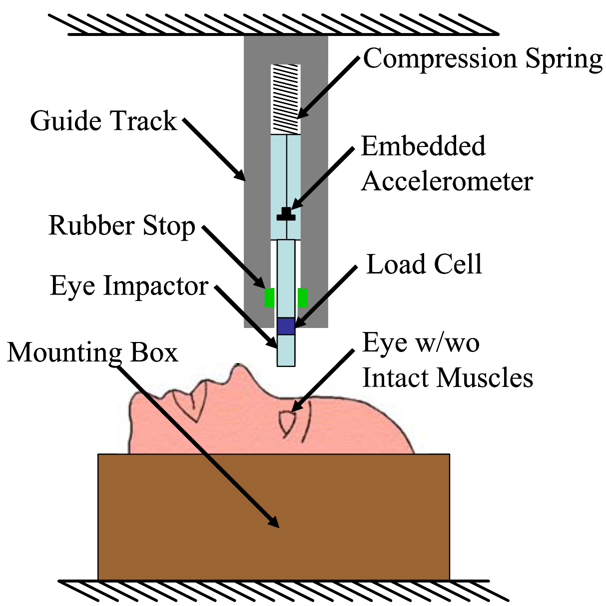

Figure 2: Test apparatus for dynamic eye impact tests.

The eye is impacted by a Delrin cylindrical indenter with a diameter of 19 mm and a flat face. The maximum stroke of the impactor is 25 mm after the impactor strikes the cornea of the eye. Force and acceleration data are continually collected at a sampling rate of 100 kHz for the duration of the test on each eye. High speed color video (Vision Research, Phantom IV, Wayne, NJ) is also taken at a rate of 5,000 frames per second in order to determine the exact time that the impactor struck the eye. Following testing, the force and pressure data are filtered to CFC 600 as per SAE J211.

RESULTS

Static Testing

In all tests, slightly increased force was required to achieve a specified deflection of the eye when the extraocular muscles were intact. A plot of force versus displacement for a matched pair of human eyes tested *in situ* is given (Figure **3**). For each case, with extraocular muscles intact and with the muscles transected, the forces observed to achieve each displacement step were averaged. A linear relationship was observed between the force with the extraocular muscles intact versus the force with the extraocular muscles transected (Figure **4**). Overall, the force with the muscles intact was approximately 13% higher than with the muscles transected, to achieve the same displacement.

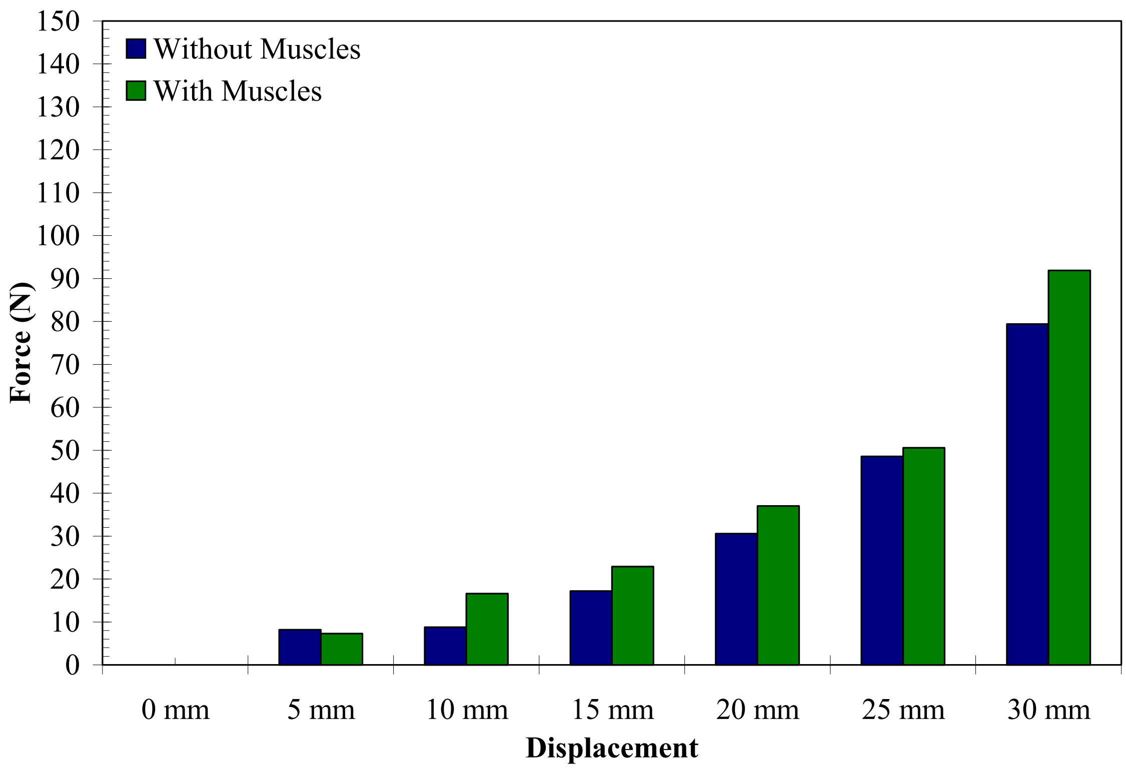

Figure 3: Average static force versus displacement measurements for a matched pair of human eyes tested *in situ*.

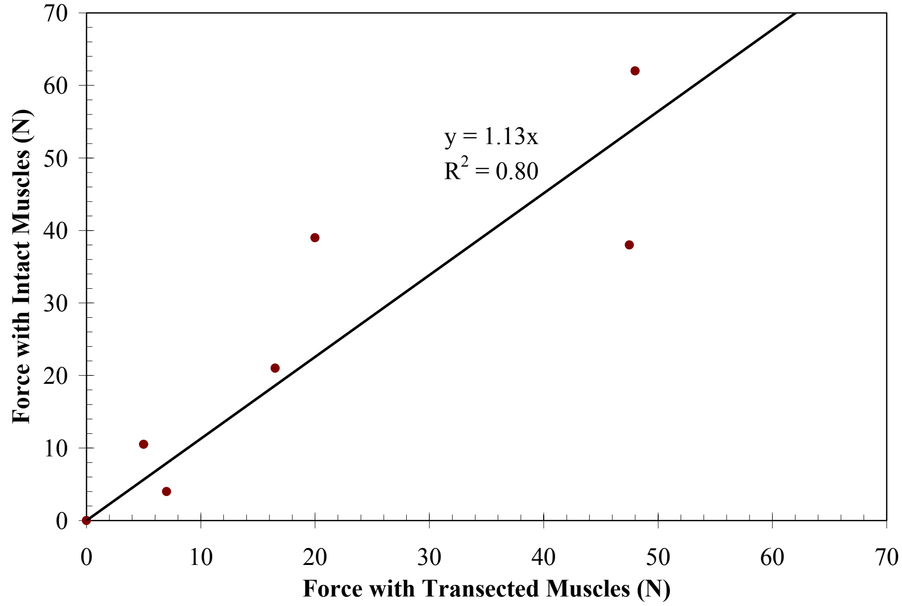

Figure 4: Correlation between the average force required to achieve each displacement with the muscles intact versus the muscles transected.

Intraocular pressure measurements were only recorded during the displacement steps for one static test. Figure 5 presents the measured intraocular pressure of an eye with the extraocular muscles intact, collected at 5 mm indenter displacements. There is a steady increase in intraocular pressure with each step. Also, for the same tests, the CT scans for each displacement step are shown (Figure 6 – 11). As a reference, eye rupture pressures for static and dynamic events are 0.36 MPa and 0.91 MPa, respectively (Kennedy et al., 2004).

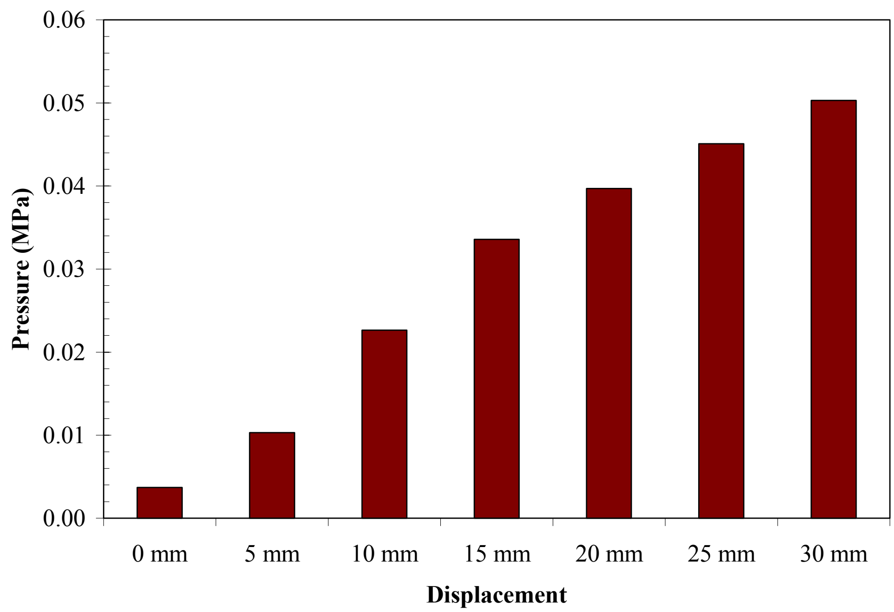

Figure 5: Intraocular pressure from a static displacement test of a human eye with the extraocular muscles intact.

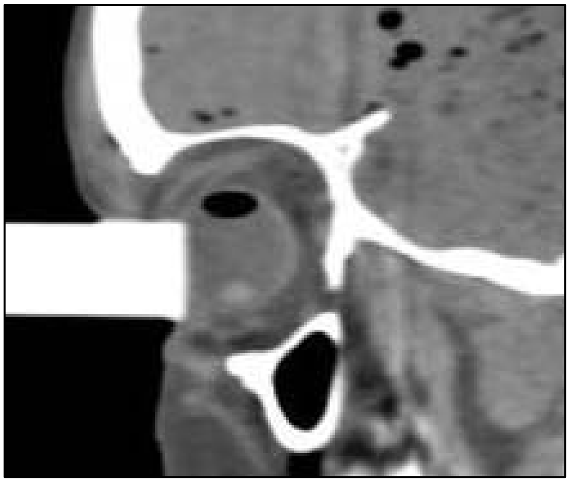

Figure 6: Sagittal CT image at 5 mm displacement.

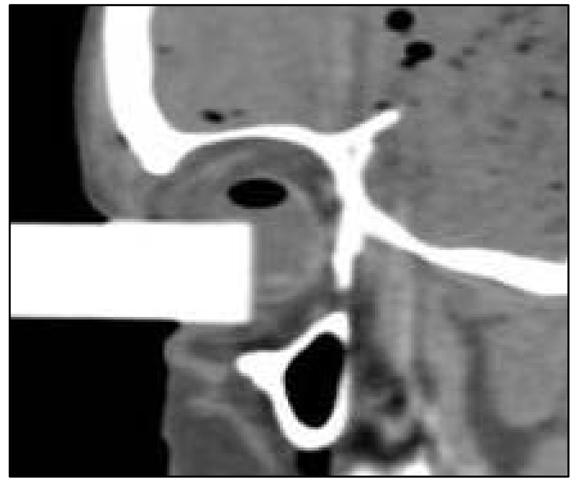

Figure 7: Sagittal CT image at 10 mm displacement.

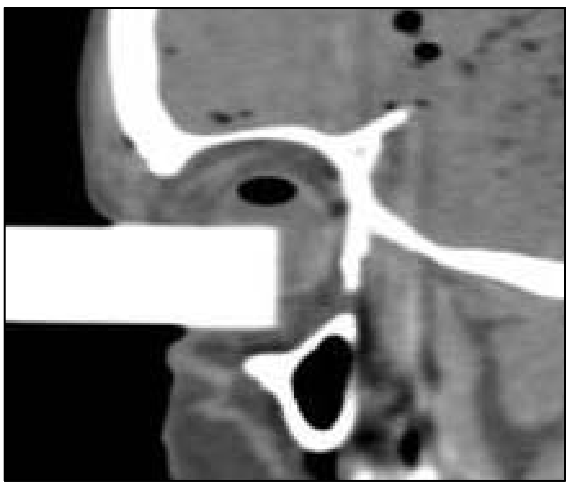

Figure 8: Sagittal CT image at 15 mm displacement.

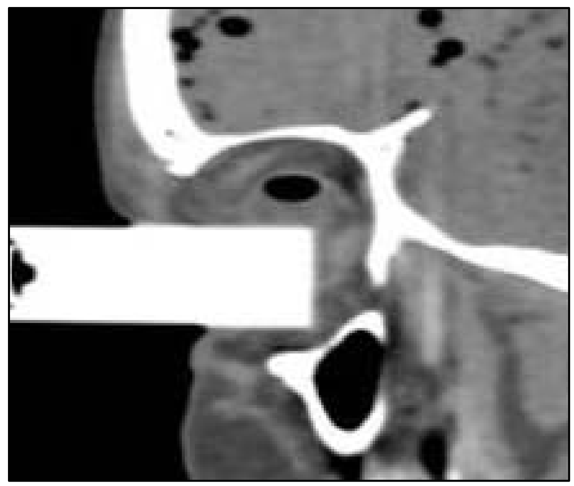

Figure 9: Sagittal CT image at 20 mm displacement.

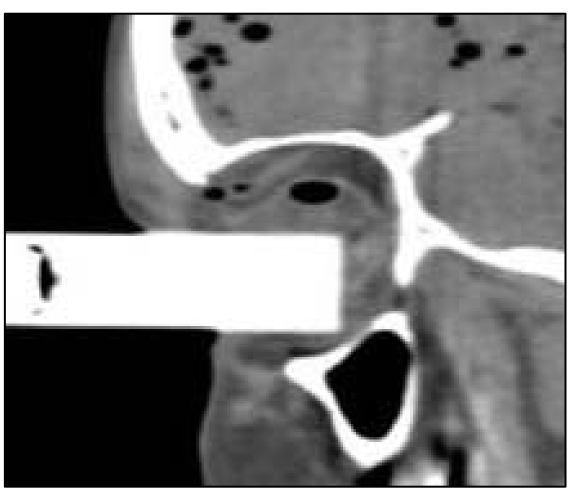

Figure 10: Sagittal CT image at 25 mm displacement.

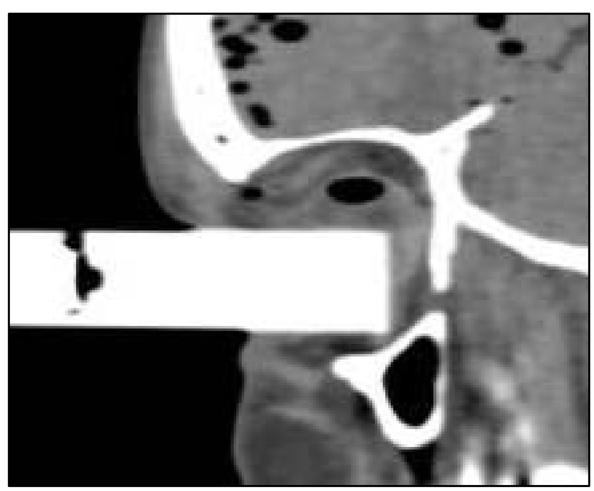

Figure 11: Sagittal CT image at 30 mm displacement.

Dynamic Testing

Due to issues surrounding the availability of acceptable tissue, only one head was available for the first round of matched pair impact tests. Therefore, at present, two tests have been conducted, one on the left eye, which had the eye muscles transected, and one on the right eye, in which the eye muscles and conjunctiva were intact. Both eyes suffered globe rupture during the impact event. The ruptures occurred on the sclera at the equator of the eye, and were consistent with other researchers' observations of globe rupture due to blunt impact (Stitzel et al., 2002). A comparison of force-deflection data for eyes with intact versus transected extraocular muscles is shown (Figure 12). Unfortunately, pressure measurement of the intraocular pressure was ineffective at these dynamic rates, due to the choked flow condition present at the insertion of the catheter into the eye.

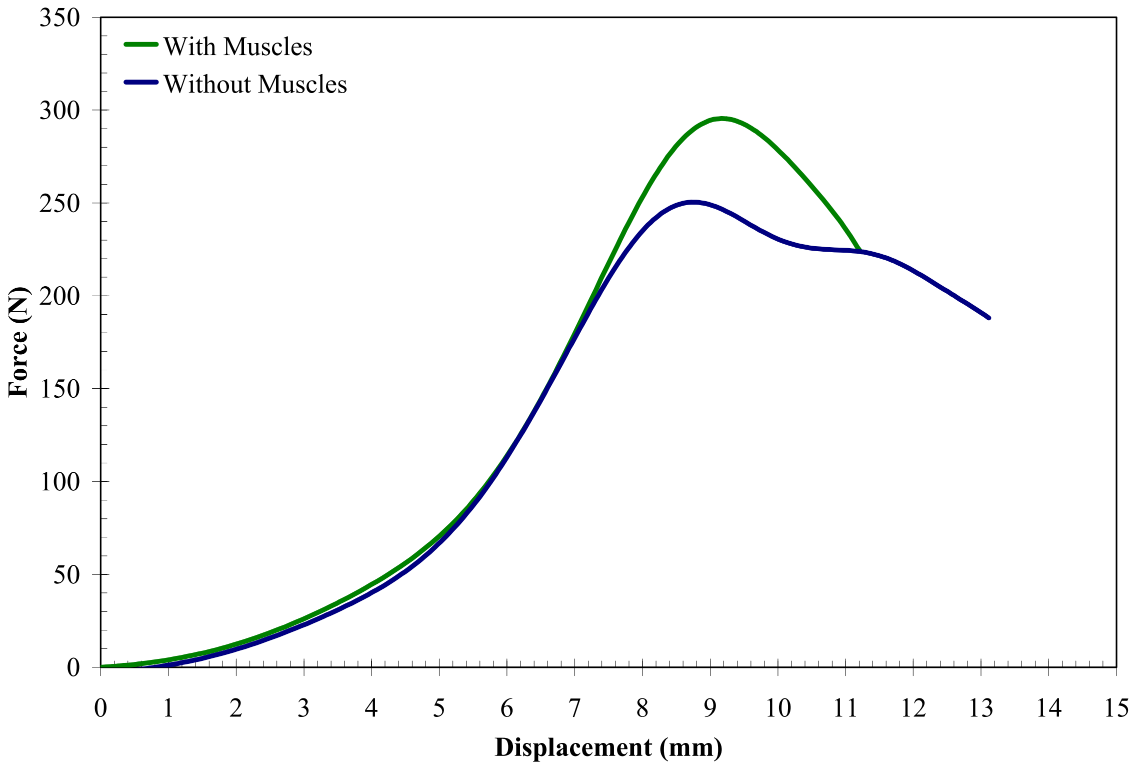

Figure 12: Force versus displacement measurements for a matched pair of human eyes tested *in situ*.

Though a lack of test duplication precludes statistical analysis, the preliminary results based on this test demonstrate general agreement with the hypothesis that eye muscles will increase force required to deflect the eye under impact loading. For this test series, the eye with extraocular muscles intact achieved a peak load of 295 N with a smaller overall displacement of the eye prior to globe rupture. The eye with transected extraocular muscles peaked at 250 N, with more posterior translation than the eye with intact muscles. It is believed that this demonstrates how the extraocular muscles increase the resistive force of the eye and limit rearward translation during impact, which would not be replicated in experiments where enucleated eyes are used for testing. Also of note, with the extraocular muscles intact, the eye ruptures at a lower overall displacement than the eye with the extraocular muscles transected. It is possible that this is due to greater stress concentrations at the muscle attachments to the eye, which cause failure at lower overall loading conditions.

CONCLUSIONS

The two stages of this study, static and dynamic testing of the eye, have both demonstrated greater overall force-deflection response of the eye with extraocular muscles intact versus eyes with the extraocular muscles transected. Slight differences were observed in the force-deflection response for static tests; however, that does not indicate the difference that the extraocular muscles will have at dynamic rates. It was also observed that under static displacements that the eye is able to translate out of the way of the impactor assembly, even under large deflections, and without globe rupture. The static tests have been useful for visualization of the eye response within the orbit; they are limited in that the rate of impact is not consistent with that seen in cases of blunt ocular trauma. The dynamic tests will be most useful in determining the effects of the extraocular muscles on eye impact response. Currently, under dynamic impact, the eye displays higher overall force and less translation with the extraocular muscles intact versus transected muscles. Additional dynamic tests are planned to provide statistical evidence to support the overall hypothesis of this study.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: **Effects of the Extraocular Muscles on the Response of the Human Eye Under Static and Dynamic Loading Conditions**

PRESENTER: ***Eric Kennedy, Virginia Tech – Wake Forest Center for Injury Biomechanics***

QUESTION: *Guy Nusholtz, Daimler Chrysler*
How heavy was your impactor?

ANSWER: Gosh. That's a good question. You know, I don't remember, off the top of my head. I believe it was roughly about 1 pound.

Q: One pound? Have you considered what you might look into, the energy—the available energy effect because you've got a lot going in there with that device and if you had a smaller mass, which might be more typically representative of what we consider for eye injuries, you might get a completely different type of response. I'd expect the results that you get for the muscles when you remove them because you're just pushing—Well, it's basically, you're pushing the thing quite a distance. But if you have a small mass and high velocity, then it's going to be an inertial effect and it may not show it quite as bad.

A: Right. That's a great point. Actually, that's a subject that we've actually done a lot of investigation in. And in fact, we have a paper coming out in the Journal of Trauma that discusses just that, and like I said, I don't actually remember off hand the weight of the impactor, but I did do energy calculations on that as well. We're actually finding that more even than energy, the normalized energy or the energy divided by the cross-sectional area apparent to the eyes as the object impacts it is probably the most useful parameter that you could study when looking at eye injuries.

Q: Are you thinking in terms of either a strain or a stress to failure if you're looking at an energy versus an area so you're looking at sort of a pressure, which would end up being a stress?

A: Yeah.

Q: Is that the direction you're heading?

A: Yeah. That's the direction I think we're heading with that.

Q: Thank you.

A: Thanks.