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The effects of the extraocular muscles on eye impact force–deflection and globe rupture response

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ABSTRACT

There are over 1.9 million eye injuries per year in the United States, with blunt impacts the cause of approximately one-half of all civilian eye injuries. No previous experimental studies have investigated the effects of the extraocular muscles on the impact response of the eye. A spring-powered blunt impactor was used to determine the effects that the extraocular muscles have on the force–deflection and injury response of the eye to blunt trauma. A total of 10 dynamic impact tests were performed at 8.2 ± 0.1 m/s on five human cadaver heads. With the extraocular muscles left intact, the average peak force was found to be 271 ± 51 N at 7.5 ± 0.9 mm posterior translation; with the muscles transected, the average peak force was 268 ± 26 N at 7.6 ± 1.3 mm of posterior translation. From the data available from this study, the peak impact force and overall amount of translation during the impact are not affected by the extraocular muscles. Additionally, from the data presented in this study, the eyes with the extraocular muscles left intact do not rupture with a different injury pattern or display an increased risk for rupture than the eyes with the extraocular muscles transected. Therefore, it is believed that the effect of the extraocular muscles is not sufficient to drastically alter the response of the eye under dynamic impact. This information is useful to characterize the boundary conditions that dictate the eye response from blunt impact and can be used to define the biofidelity requirements for the impact response of synthetic eyes.

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1. Introduction

There are over 1.9 million eye injuries per year in the United States (McGwin et al., 2005). Some of the most severe eye injuries can occur in automobile accidents, from sports related impacts, in the workplace and even at home (Chisholm, 1969; Berger, 1978; Mader et al., 1993; Duma et al., 1996, 2002; Vinger et al., 1997; Kuhn et al., 2000; Rodriguez and Lavina, 2003). Blunt impacts are the largest single cause of eye injuries at approximately one-half of all civilian eye injuries (McGwin et al., 2005).

Additionally, the rate of eye injuries has dramatically increased in warfare from affecting approximately 2% of all casualties during World War I and World War II, to affecting nearly 13% of all casualties during Operation Desert Storm (Heier et al., 1993; Wong et al., 2000). In order to assess the capability of protective equipment in reducing eye and facial injuries, a new advanced headform is being developed that can predict fracture of facial bones, as well as eye injury from impact loading. Because of its emphasis on eye and orbital injuries, the name of this new advanced headform will be the FOCUS Headform, which stands for Facial and Ocular CountermeasUre Safety Headform. However, in order to develop a biofidelic eye for the FOCUS headform, it is necessary to determine the boundary conditions that characterize the *in-situ* response of the eye, in particular the effects that the extraocular muscles have on impact response of the eye.

There are a total of six extraocular muscles of the human eye, four rectus muscles, and two oblique muscles, the superior oblique and the inferior oblique. These extraocular muscles control the movements of the eye. Under typical conditions, these muscles actively control the movements of the eye with less than 0.5 N of force (Clement, 1987; Simonsz et al., 1986; Miller et al., 2002).

Previous studies have been performed to determine the injury tolerance of the eye to globe rupture from blunt impact (Weidenthal, 1964; Green et al., 1990; Vinger et al., 1999; Bass et al., 2002; Stitzel et al., 2002; Kennedy et al., 2006); however, nearly all of the reported tests were conducted using enucleated eyes mounted in a gelatin solution without the extraocular muscles intact. No known prior study has investigated the effects of the extraocular muscles on the impact response of the eye. It is hypothesized that the presence of the extraocular muscles may alter the response of the eye compared to these enucleated *ex-vivo* tests, both in the injury response of the eye (to globe rupture) and

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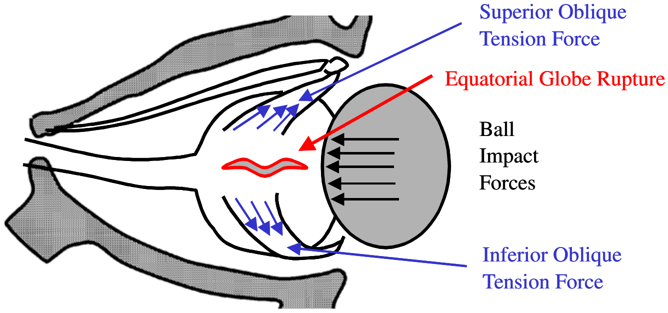

Fig. 1. Under dynamic impact, the oblique extraocular muscles of the eye may resist posterior translation of the eye, leading to localized stress concentrations and globe rupture for lower-energy impacts compared to tests conducted on enucleated eyes. (The four rectus muscles are not shown.)

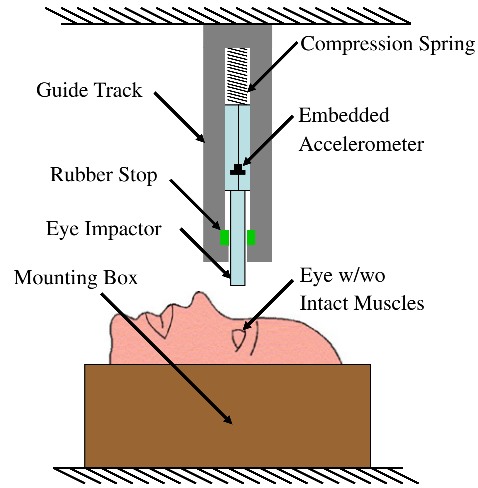

Fig. 2. Test apparatus for dynamic extraocular muscle force–deflection impact tests.

the overall force–deflection response of the eye. It is hypothesized that intact extraocular muscles, in particular the two oblique muscles, would develop tension to oppose anterior–posterior translation of the eye under impact. This tension may lead to a stress concentration on the corneo-scleral shell, in turn leading to globe rupture under lower severity impacts when *in-situ*, compared to *ex-vivo* experiments where the extraocular muscles have been transected (Fig. 1).

The influence of the extraocular muscles is expected to manifest itself in the force–deflection response of the human eye to blunt impact, with more force being required to force the eye a given distance into the orbit with the muscles intact versus the muscles transected. Therefore, the purpose of this study is to perform dynamic impact testing of human eyes in order to determine the effects that the extraocular muscles have on the force–deflection and specifically the globe rupture injury response of the eye to blunt trauma. This is important for the determination of relevant eye impact tests that can be used for the development of eye injury criteria as well as determining biofidelity requirements for a synthetic human eye.

2. Methodology

A total of 10 tests were performed on five human cadaver heads. All tests were performed on fresh refrigerated cadavers which were never frozen, tests were performed after the specimens equalized to room temperature. All test procedures were reviewed and approved by the Virginia Tech Institutional Review Board. In order to make a comparison on the effects of the extraocular muscles, in each head the extraocular muscles were left intact on one eye and transected on the contra-lateral eye.

The post-mortem human head was mounted in a rigid plastic container using urethane expandable foam. Prior to impact, the eyes were repressurized via a needle insertion through the limbus using a column of water to achieve the physiologic pressure of 15 mmHg (Klein et al., 1992); as a note, none of the injuries sustained during testing passed through the insertion site. Tests were randomized such that extraocular muscle transections varied between left and right sides of the test specimens. Testing order was also randomized between the transected and intact muscles sides.

The impact tests were performed using a spring-powered Delrin cylindrical impactor, which was accelerated to a velocity of approximately 8 m/s (4 J) before it impacted the eye (Fig. 2). The impactor energy level of 4 J was selected to be approximately twice the energy level of previously reported blunt impact studies investigating globe rupture which used similarly sized impactors (Weidenthal, 1964; Green et al., 1990). The 19 mm diameter of the blunt impactor corresponds to a nominal 25 mm average diameter of the eye and was selected to maximize the anterior translation of the whole eye in order to fully engage the extraocular muscles. The impactor had approximately 30 mm of free travel prior to impacting the eye and after contacting the eye, had approximately 25 mm of travel prior to striking the rubber stops.

An embedded accelerometer (Endevco 7264B-2000, Endevco Corporation, San Juan Capistrano, CA) was used to collect data at a sampling rate of 100 kHz for the duration of the test on each eye. Acceleration data was filtered to CFC 1000, then double integrated to determine impactor tip displacement and also multiplied by the impactor mass (112.55 g) to determine impactor force, these data were used to determine the force–deflection characteristics of the *in-situ* eyes.

For both test conditions—muscles intact and muscles transected—the characteristic average response was determined using a method similar to that described by Lessley et al. (2004). This method is a universal technique for averaging a series of curves by accounting for variability in both the *x*- and *y*- coordinates. In this case, this method essentially determines the average force–deflection response curve for each test series: muscles intact and muscles transected. Additionally, force–deflection corridors were calculated using the characteristic average force–deflection response plus or minus the standard deviation of the force at each displacement step.

The force–deflection response is the amount of force required to displace the eye a given distance into the orbit. The force–deflection corridor defines the region where the typical response may be expected, it is defined as the average response plus or minus a standard deviation. For consistency, all plots are cut off at the time of peak force, regardless of whether globe rupture was observed, this is further elaborated in the discussion. Student's *t*-tests were conducted to compare the peak force and displacement at peak force between intact and transected extraocular muscle scenarios. The *F*-statistic was used to compare the variation in peak force and displacement at peak force between test groups.

Because other common types of eye injuries such as hyphema, lens damage, and retinal damage are not possible to inspect on post-mortem eyes, the eyes were evaluated only for globe rupture at the conclusion of each impact test. After the eye was physically assessed *in-situ*, the eye was enucleated and the injury outcome of each of the matched pairs of eyes documented to assess whether or not different injury patterns were seen between the two test conditions.

3. Results

The 10 impact tests were conducted with an overall average impact velocity of 8.2 ± 0.1 m/s on five human cadaver heads (Table 1). With the extraocular muscles left intact, the average peak force was found to be 271 ± 51 N with 7.5 ± 0.9 mm posterior translation at the time of peak force. With the muscles transected the average peak force was 268 ± 26 N with 7.6 ± 1.3 mm of posterior translation at the time of peak force. The force–deflection results, along with the calculated characteristic average response for tests conducted with the extraocular muscles intact and transected are shown in Figs. 3 and 4, respectively. Differences between both the peak force, and displacement at peak force were not found to be significant between the intact and transected muscle scenarios ($p = 0.86$ and 0.90, respectively).

Combining the standard deviation of force to the characteristic average force–deflection, corridors are created for both muscles intact and muscles transected (Figs. 5 and 6). Overall, the force–deflection corridors for the eyes with extraocular muscles intact and with muscles transected were very similar, with the corridor being slightly wider for the extraocular muscles intact

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