

# Homeomorphic Model of the Effect of Impact Trauma on the Human Eye

Venkaatesh Sathyanarayanan<sup>1</sup>, Kausalendra Mahadas<sup>2</sup> and George K Hung<sup>2\*</sup>

<sup>1</sup>Qualcomm Atheros Inc., 1700 Technology Drive, San Jose, CA, USA

<sup>2</sup>Department of Biomedical Engineering, Rutgers University, 599 Taylor Road, Piscataway, NJ, USA

## Abstract

A homeomorphic model of the human eye has been developed to simulate the effect of impact forces on the internal components of the eye. This is the first time a Mass-Spring-Damper (MSD) model has been used to investigate forces and displacements throughout the outer tunic, the vitreous body, and the retina. Whereas most of the existing Finite Element Models (FEM) are extremely complicated in their structure and composition, and takes up to 6-10 hours for a single simulation run, our MSD model, with its inherent computational advantages, completes a single round of simulation within tens of seconds. The model also provides detailed information about the node positions, velocities and force profiles, with a special emphasis on the retina. Moreover, a prediction paradigm was developed to indicate the estimated extent of retinal damage based on the angle and magnitude of the applied forces. Further, a user-friendly GUI was developed to allow additional new investigations into ocular trauma. The results of the model simulations under various force impact conditions were shown to be accurate and consistent with known experimental findings. Thus, our homeomorphic MSD model can be a useful tool for the physician to assess retinal damage non-invasively prior to clinical intervention.

**Keywords:** Mass spring damper system; Impact trauma; Ocular injuries

## Introduction

Based on a studies conducted by the American Society of Ocular Trauma, the United States Eye Injury Registry [1,2] has provided the following staggering statistics:

1. 2.5 million eye injuries occur annually
2. 40,000 individuals end up with some form of permanent eye defect
3. More than a thousand lose their vision completely

Ocular health is essential for smooth functioning of one's daily life. Any adverse effects on vision can lead to personal trauma and loss of productivity. Research on the ocular injuries has helped in the understanding of the causes of injuries and in turn has stimulated the development of preventive and treatment methods.

Modeling of the eye is an important step in the understanding of the quantitative aspects of eye trauma. Therefore, a homeomorphic computer model of the human eye was developed by the Vision Research Laboratory Group at Rutgers University based on a network of two-dimensional, interconnected Mass-Spring-Damper (MSD) system. This is the first model of the human eye using MSD systems to study the effect of impact forces. The primary goal was to build a model with a custom graphical user interface (GUI) which can run simulations for an impact trauma scenario requiring only a few minutes of computation time. This requirement precluded the use of the more popular Finite Element Models, which are cumbersome and computationally intensive. Therefore, a simpler and more efficient MSD system was used to build a robust model, whose impact force dynamics are close to the values as seen in the published literature. The material properties of the model elements was validated through parametric tests to ensure good model performance. Moreover, the GUI built for the model has the capability to replay the impact scenario by showing how the eye compresses through various changes in the positions of the point masses and simultaneously showing the force profiles impinging on the point masses.

In building the model of ocular structures, there was a particular focus on representing the human retina to study the effect of various levels of impact forces on the retina. A prediction paradigm was developed that could realistically predict retinal damage and quantify its extent for specific impact scenarios. As part of the prediction paradigm, scleral length and equatorial length changes of eye, along with impact energy of the projectile, were taken as the factors that could contribute to retinal damage. Finally, parametric studies were conducted to determine the performance of the predictor for various sets of input parameters.

## Modeling of objects

A model is a virtual representation of a real object by abstracting the essential properties from it. Physically-based modeling is based on physical laws by taking into consideration parameters such as force, velocities, acceleration, positioning of points, and energies [3]. The advent of high performance computing provided the means to perform simulations of complex dynamical systems and match the results with known physical data.

## Deformable models

Objects can be broadly classified into two types – rigid and non-rigid. The present study is concerned with non-rigid objects – one which can change shape or size when acted upon by external forces. A detailed survey on the deformable models has been provided by Meier

**\*Corresponding author:** Dr. Hung GK, Department of Biomedical Engineering, Rutgers University, 599 Taylor Road, Piscataway, NJ 08854, USA, Tel: 848-445-6583; Fax: 848-445-3753; E-mail: [shoane@rci.rutgers.edu](mailto:shoane@rci.rutgers.edu)

**Received** September 16, 2013; **Accepted** October 14, 2013; **Published** October 20, 2013

**Citation:** Sathyanarayanan V, Mahadas K, Hung GK (2013) Homeomorphic Model of the Effect of Impact Trauma on the Human Eye. J Comput Sci Syst Biol 6: 317-326. doi:10.4172/jcsb.1000128

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et al. [4]. Deformable models can be divided broadly into two main types and sub-categories as shown in Figure 1.

One of the earliest methods used was the free-form model. An online link (<http://www.youtube.com/watch?v=Bhilh0rQtY>) provided a clearly-presented video to help understand how the free-form model works. Mathematically, the given object is deformed by making a region undergo a set of linear transformations which lead to stretching, bending, twisting, etc.

“Splines” can be used to represent changes in shape. They are basically nth-order piecewise polynomials. A combination of these splines can be used to represent smoothly any curve. Consider a set of points which are interpolated by an nth-order degree curve. For many such sets of points, there are multiple splines which intersect at a common point. These points are called as the control points. By moving around these control points, the portions under their influence also changes in shape and size.

These geometric models can be made to mimic the object by intelligently manipulating these parameters. To make the model more realistic, point masses could be introduced along the curve joints that assume negligible mass along the curve [3]. The Mass-Spring model can be thought of as point masses connected by springs arranged in the form of meshes. These models are discrete in nature and the masses are lumped.

In the Finite Element model, the object is divided into elements joined at discrete points called nodes. For each element, a function is calculated which solves the continuous equilibrium equation. When the system’s total potential energy reaches a minimum, equilibrium is attained. In the case of the Mass-Spring model, each of the springs has to return to its original length to achieve equilibrium, and thus the equilibrium criterion is considered discrete. The functions of the elements are approximated by a weighted sum of interpolation functions with the weights being the values of the node points.

### Anatomy of the human eye

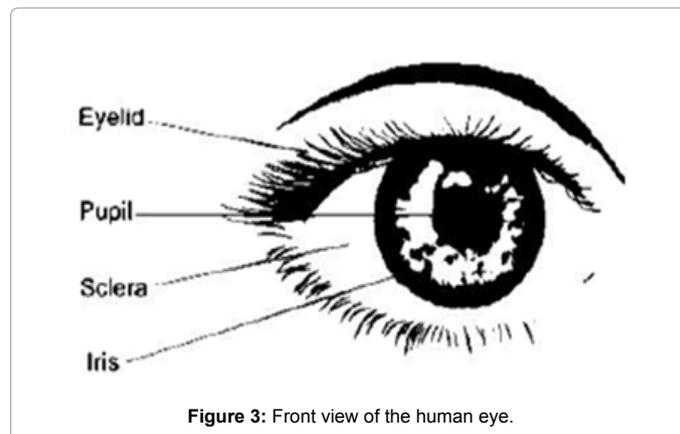
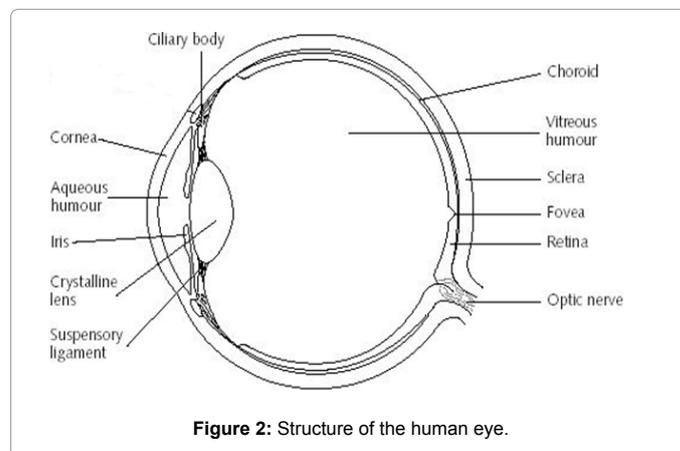
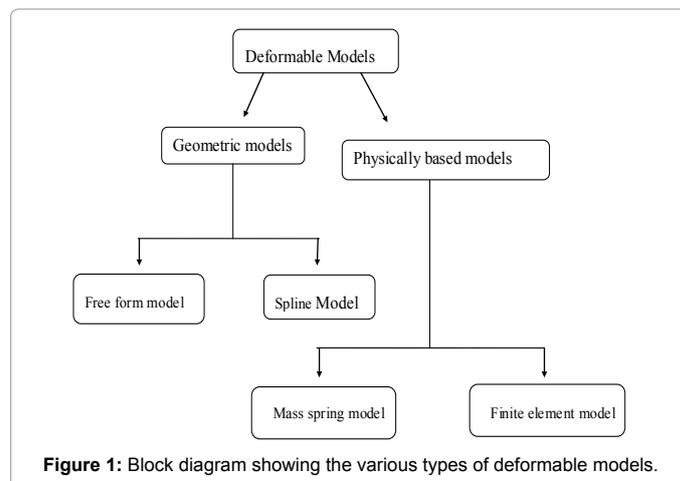
The human eye is a sensory organ which senses light rays, impinging on rods and cones in the retina and converting them into electrical that are sent to the brain through the optic nerve. It thus acts as a transducer by converting the light energy into electrical energy, which is then interpreted by the brain as a percept.

The bony orbit is a cavity in the skull protecting the human eye. Surrounding the eyeball are the fatty tissues – the adipose fat which act as a cushion for the eyes and protect them from coming in contact with the bony orbit. There are six muscles – extra-ocular muscles, attached to the eye which controls its movement. The interior of the eye consists of many parts (Figure 2) each of which has a role in the smooth functioning of the sensory organ.

The eye consists of two chambers – the anterior and the posterior chambers. The anterior chamber consists of the cornea and the water like fluid called the aqueous humor. The cornea is the primary optical component for focusing light entering the eye, along with the lens. The curvature of the cornea helps in refracting the light rays onto the inside of eye. The sclera is the white, opaque part which is continuous with the transparent cornea. The sclera, along with the cornea, forms the outer corneo-scleral shell which provide protection for the eye. The gel-like vitreous humor inside the eye helps maintain the shape of the eye.

Let us trace the path followed by the light rays once it enters the eye and how each part of the eye enables it to be finally converted into

electrical signals sent to the brain. The entering light is refracted by the cornea on to the inside of the eye. It then passes through the pupil which acts as a window for the light to enter. The pupil is the dark opening in the center of the eyes as seen in Figure 3. The iris controls the opening of pupil and allows just the optimum amount of light. After that, the light passes through the lens. The lens bends the light rays to focus the image on the retina. The retina, which containing rods and cones, is the light sensitive tissue which captures the image. The light signals are then converted into electrical signals which are passed onto the brain for further processing.



## Ocular injuries

As mentioned in the Introduction section, the number of incidents of ocular injuries is quite staggering – about 2.5 million injuries occurring annually with 40,000 individuals having some form of permanent eye damage. The pie chart in Figure 4a displays the various sources of eye injury and Figure 4b displays the places where eye injuries frequently occur.

Blunt eye trauma is a major cause of injury (Figure 4a). The major causes of injuries as were projectiles (13%), blunt objects (13%), fingers/fists/other body parts (12%) etc [5]. It thus makes sense to study the effects of blunt trauma in humans. This can be done by: building an ocular trauma model, developing an understanding of mechanisms for ocular trauma, and validating these mechanisms by various impact tests.

The two basic types of blunt eye trauma are

1. Penetrating
2. Non-penetrating

Penetrating traumas are cases where a sharp object tears through the globe of the eye. Non-penetrating trauma, where the corneo-scleral integrity is maintained, is the focus of this study. Blunt eye trauma can cause many types of injury starting from mild ones, such as corneal abrasions and eye lid lacerations, to the severe injuries such as retinal detachment, hemorrhage, orbital fracture, etc. The various types of the blunt trauma injuries are listed and explained below [6].

1. Corneal abrasion - A slight rupture of the surface of the cornea exposed.
2. Hemorrhage resulting in collection of blood in the anterior chamber – causing a reddish appearance. This condition is known as Hyphema.
3. Hemorrhage in the vitreous or retina causing retinal detachment.
4. Damage of the iris and the ciliary muscles.
5. Dislocation of the lens due to heavy impact.
6. Rupture of the globe due to very high pressure resulting in high speed impact and also a fracture of the orbital wall.

## Mechanisms of eye trauma

Various mechanisms have been proposed to explain the many types of ocular injuries. The blunt impact of an object such as a tennis ball, soccer ball, etc., when it hits the human eye, much of the force or the energy is absorbed by the orbital bones that protect the eye. The rest

of the energy is passed onto the eye. For objects such as gun pellets or a racquet ball, whose diameter is smaller, all the impact can be impinged on the eye directly. In either case, the tissues at the point of impact can be damaged. Pressure waves can also impact the parts of the eye farther away such as the retina, optical nerve, etc. For sharp objects, the globe is perforated or ruptured.

The transmission of forces through the eye from the site of impact can cause injuries to various parts of the eye. Giovinazzo [7] proposes three types of mechanisms for the blunt trauma effect.

1. Coup injury
2. Contre – coup injury
3. Equatorial expansion

In coup injury, a direct blow causes impact at the site of impact causing localized injuries. In contre-coup injury, impact forces create pressure waves that travel through the eye, and affects the parts of eye at a distance from the site of impact. The impact is largely felt at places where there is transition in the material properties such as the interface between the aqueous chamber and the lens.

In equatorial expansion, the globe compresses along the line of impact. Thus, the corneo-scleral shell, which holds the eye together, faces a great deal of tension and tends to expand. This pressurizes the tissue attached to them, especially the retina and also the choroid. This is the mechanism investigated in this study, which will be shown to be useful for injury prediction in the computer model of the eye.

Some of the factors affecting the type and amount of injury are as follows

1. Momentum of the object
2. Energy imparted by the object on the eye
3. Impact force
4. Area of impact
5. Duration of impact

A combination of the above-mentioned factors can be used as predictors in deciding the occurrence, type, and degree of injury.

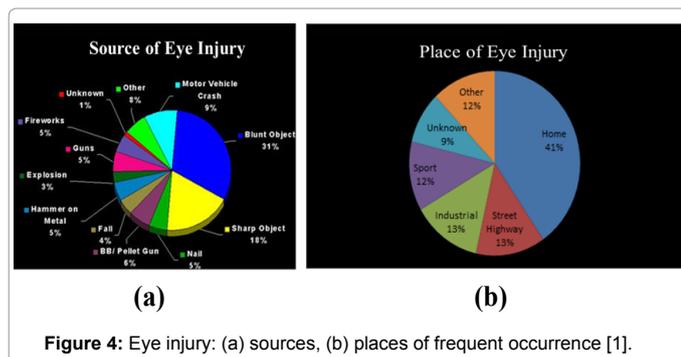
Duma et al. [8] used the techniques of logistic regression to determine significant projectile characteristics for ocular injuries. The predictors used were: mass, velocity, diameter, energy, and normalized energy. The types of eye injuries were divided into five groups - corneal abrasion, hyphema (hemorrhage near iris, ciliary etc), lens dislocation, retinal damage (retinal tear and detachment), and global rupture. The best predictors were found to be the normalized energy (energy per unit impact area) and impact energy.

## Mass-spring system

The MSD system is the simplest deformable model. An object is typically modeled as a set of meshes with the point masses at the vertex and the edges represented by massless springs. The dynamics of the point masses and the springs are governed by differential equations obtained by following the laws of physics (Newton's laws and Hooke's law). Numerical integration techniques are used to solve the differential equations over the required time period.

The equations governing the MSD system are:

$$f_i = \sum attachedspringsk * (l - l_0), \text{ where } f \text{ is the force on the node/}$$



point mass  $i$ ,  $k$  is the spring constant,  $l$  is the current length of the spring, and  $l_0$  is the initial length of the spring.

$a = \frac{1}{m} \sum f_i$ , where  $a$  is the acceleration equal to the  $1/m$  times the sum of the forces on the point mass due to the springs connected to it.

$v = (a_{current} - a_{previous}) * \Delta t$ , where  $v$  is velocity and  $\Delta t$  is the time step used in numerical integration.

$x = v\Delta t + x_{previous}$ , where  $x$  is the current position.

Thus, the network of mass points connected by springs was used to approximate the behavior of the deformable objects in terms of the propagation of the force waves, energy, and the corresponding positions of the nodes – representing various parts of the eye. These MSD systems were initially used to model objects in visual graphics because of the simplicity of modeling [9]. Van Gelder [10] presented a method to find the spring constants from the elastic properties, which became very popular with researchers, enabling them to introduce the MSD model into applications that required a high degree of realism and accuracy [11]. In addition, Lloyd et al. [12] presented an alternate approach in relating the elastic properties to the spring constants that can also be useful.

The greatest advantages of the Mass-Spring system thus are:

1. Conceptual simplicity
2. Computational speed

Conceptual simplicity means the building of the model, such as positioning of the nodes and programming the solution algorithm, is simpler. With regards to computational speed comparing the MSD model and non-linear Finite Element Model (FEM) (linear FEM may be comparable in speed to MSD but does not realistically represent the model), the MSD requires substantially fewer number of iterations for computation.

## Methods

### Driving factors of the model

The aim of our modeling approach is to build an interactive application for studying the impact trauma on the human eye under a variety of conditions. The basic necessities of an interactive application are:

1. Ease of use
2. Faster simulation

### Ease of use

Most of the currently available models take a very cumbersome approach that it is extremely difficult for a person not very familiar with the model to use it efficiently. The proposed model is user-friendly and flexible. Another advantage is the reusability of the model, whereby newer, more sophisticated models can be built upon the original model.

### Faster simulation

Most available computer models of eye use the Finite Element technique. However, for testing a single case of ocular trauma it takes approximately 6 hours [13] even with the computational power of the modern computers. Also, most of these models have been built using FEA software such as MADYMO. But unfortunately, a person who wants to use the application needs to buy the software, which is very costly.

Our approach used the MSD system, which is able to complete a single case of simulation in less than 10 seconds in most cases, which is a quantum leap in terms of the computational power. Thus, the above mentioned factors have been the guiding principles behind building our model. On the other hand, the proposed model has been built entirely using MATLAB, which is cheaper and is a popular educational software.

An executable file for running the MATLAB based GUI is available upon request from the authors.

### Construction of the model

The model is a 2-D approximation of the eye which consists of point masses interconnected by springs and dampers. The first step in this process of modeling is deciding on:

1. Density of the nodes
2. Positioning of the nodes

The density of the nodes is decided on the one hand by the accuracy requirement of the model, and the computational load on the other. The placement of the point masses, the connecting springs, and the damper system is based on the need for uniformity and symmetry. Uniformity refers to uniform spread of point masses and by symmetry, which means that the behavior of the model should be consistent with the orientation and the point of contact of the applied forces. We initially experimented with a structure containing concentric circular layers with radial springs and noticed that the applied forces were all transmitted radially towards the center and again spread outwards from there, which was not realistic.

For the proposed model, a network of 256 nodes, or point masses, was chosen. The steps involved in building this model is outlined below:

A square mesh – 16 across 16 nodes, is built (Figure 5a). The square mesh is transformed into a circular mesh (Figure 5b). The part of the circular mesh in front over an angle of  $\pm 40^\circ$  from equator is removed to mimic the front opening of the eye (green colored nodes). This is surrounded by the fatty tissues (in red colored nodes) and an outermost layer representing the outer bony orbit (blue colored nodes) (Figures 5c and 5d).

### Structure of springs

As illustrated in Figure 6, the  $N_s$  represent the nodes, and the  $K_s$  represent the springs. In this figure, a typical mesh is shown, where the corners are occupied by the nodes and interconnected by six springs – the vertical, horizontal, diagonal ( $K_5$ ) and anti-diagonal ( $K_6$ ) springs. The orientation of the springs ensures that the model behaves uniformly to force propagation in all directions.

**Filaments:** The sclera of the eye helps to maintain the shape of the globe and holds the different components of the eye as a single unit. In our model, to mimic the sclera and perform its function, filaments

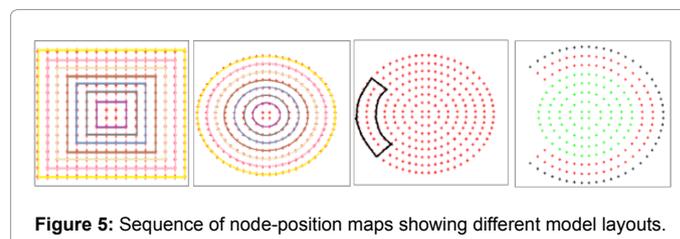


Figure 5: Sequence of node-position maps showing different model layouts.

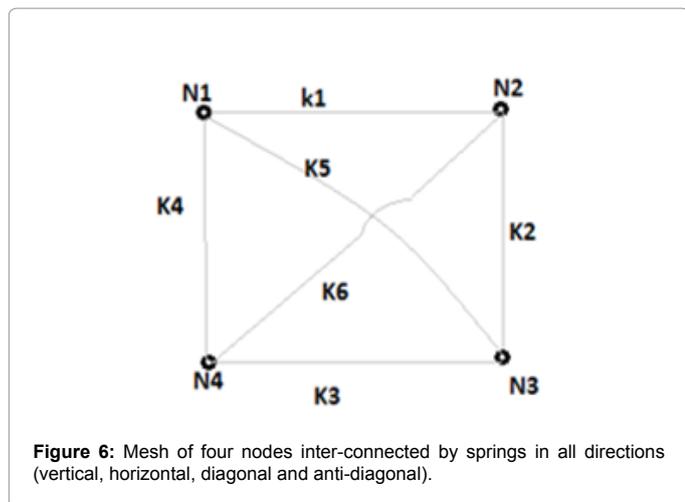


Figure 6: Mesh of four nodes inter-connected by springs in all directions (vertical, horizontal, diagonal and anti-diagonal).

are introduced. They are essentially densely-populated springs interconnecting distant nodes on the outer layer of the eye. The forces on these filaments represent the tension in the sclera when subjected to blunt force trauma

The structure of the filaments is illustrated in Figure 7a. By default, every node in this scleral layer is interconnected to nodes at distances two, three and four hops on both directions (clockwise and counter-clockwise) by the special filamental springs. The choice of density of connectivity of the filamental springs alters the response of the model to forces, as a higher density would mean a lesser amount of deformation for the same force. The user is provided with an option for altering this parameter in the GUI.

### Retina

The retina is represented by a portion of the scleral layer of the eye (Figure 7b). The sclera, choroid and retina are tightly packed together. To separately represent the retina and the sclera would need a highly dense network of nodes. This would mean a very large number of nodes, and in turn a great deal of computational load. Therefore for purposes of simplicity, the retina is represented by the appropriate portion of the ocular layer in the MSD model. The retina occupies 72% of the inside surface of the globe [14], therefore the angle covered by the retina would be:

$$\text{Angle covered by retina} = 72 * \frac{360}{100} = 259.2^\circ \text{ This would mean } \pm 129.6^\circ \text{ from the equator.}$$

### Lens

Due to the lack of a dense network, the lens of the eye is represented by the region as illustrated in Figure 7c. Based on the data available on the position and size of the lens [15], the lens for our model was approximated the connected springs as shown in the figure.

### Material properties

Taking the mass densities (see Table 1) into consideration, the following values are determined for the point masses: The mass of the eyeball is taken to be 7.5 grams. Thus considering there are 100 nodes representing the eyeball, the mass of each node is  $= 7.5 * 10^{-5}$  Kg. Since the adipose fat has a similar density, the mass of those nodes are taken to be the same as that of the eye. The bony orbit is modeled as nodes with extremely high masses so that they are effectively static.

### Spring constant

In a Mass-Spring model, the values of the spring constant is critical as the springs transmit the forces across the model (Figure 8). The issue of identification of the spring parameters has been discussed in detail in Lloyd et al. [12]. Another popular work regarding identification of the spring parameters based on elastic material parameters was provided by Van Gelder [10]. The spring constants in our model were obtained

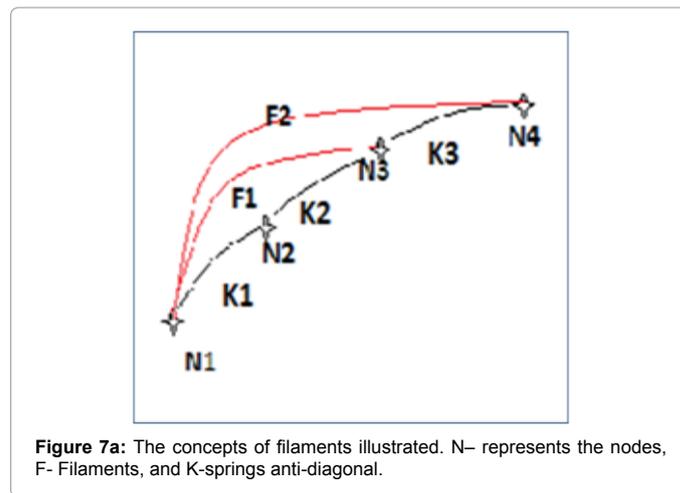


Figure 7a: The concepts of filaments illustrated. N- represents the nodes, F- Filaments, and K-springs anti-diagonal.

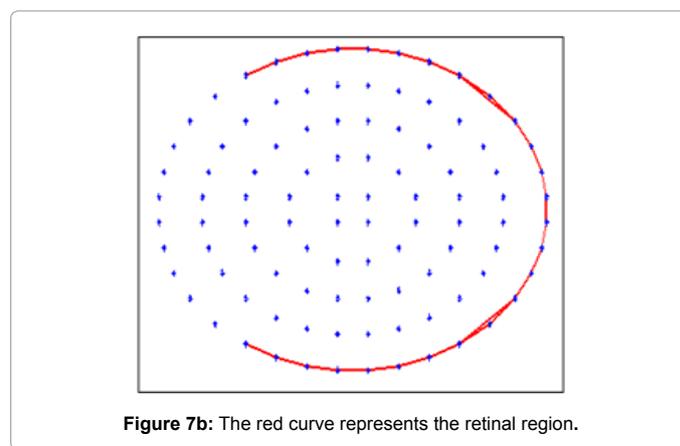


Figure 7b: The red curve represents the retinal region.

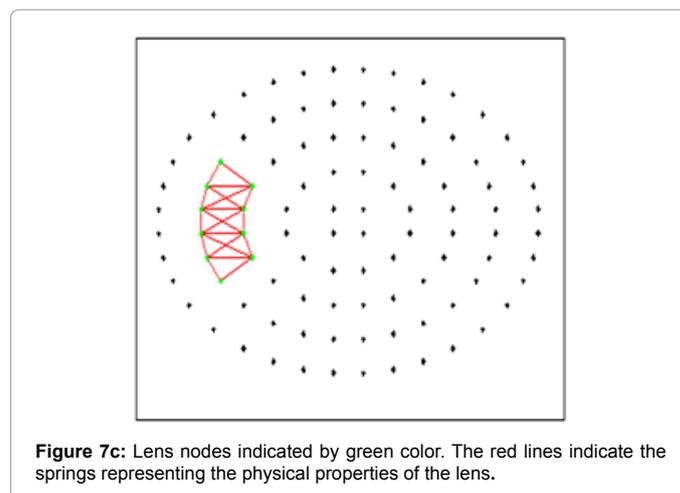


Figure 7c: Lens nodes indicated by green color. The red lines indicate the springs representing the physical properties of the lens.

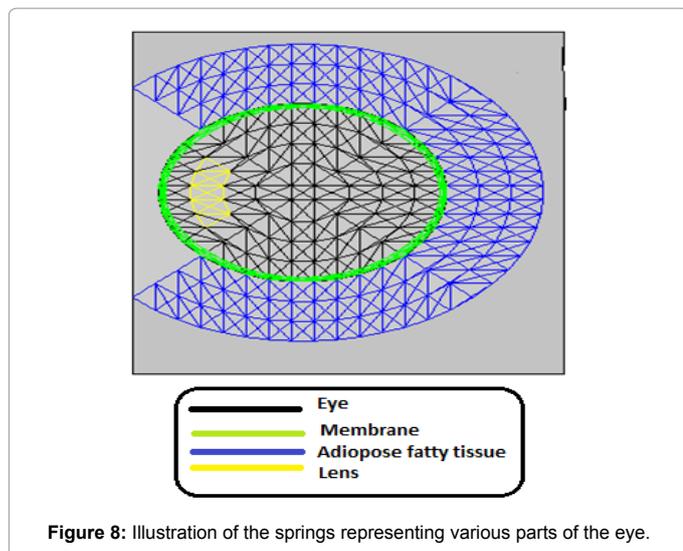


Figure 8: Illustration of the springs representing various parts of the eye.

from the values of modulus of elasticity using the equation provided by Van Gelder [10].

The advantage of using the Van Gelder model is that it realistically distributes the spring parameter values to the springs. On the other hand, if uniform material property were assumed, one would not be able to realistically model the material, and the results would not be accurate.

The equation relating the spring constant and the elastic modulus is,

$$k = \frac{E \sum_i \text{area}(AT_i)}{l^2}$$

where  $E$  is the young's modulus,  $l$  is the length of the spring, and  $k$  is the spring constant.

For example, in Figure 6, if one wants to compute the spring constant of the spring K5, the areas of the triangles formed on the side K5 formed by the nodes [N1 N4 N3] and [N1 N2 N3] are summed to find the value of the summation in the above equation.

There is a great variation in the values of the mechanical properties of the eye used in the computer models by different researchers [16,17]. Based on a careful study of the related literature, the values of the elastic modulus were taken to be as indicate in Table 2 below.

## Damping

During a blunt impact, the energy transferred onto the eye by the blunt object becomes a factor in deciding the level of injury. The energy is then slowly dissipated, where the rate of dissipation is decided by the viscoelastic properties of the tissues. There is not much information available in the published literature for the values of the damping ratios for a Mass-Spring model of the eye.

For our model, the dampening forces can be described by the following set of equations. The damping force is proportional to the negative of the velocity of the node.

$$f_{damp} = -c.v$$

where  $c$  is the damping coefficient and  $v$  is the velocity.

For a simple Mass-Spring-Damper system the equation relating the damping coefficient, mass, and spring constant is given by:

$$c = 2 * \xi * \sqrt{k * m}$$

where  $\xi$  is the damping ratio,  $m$  is the mass,  $k$  is the spring constant and  $c$  is the damping coefficient.

The aqueous and vitreous humors share the bulk of dampening, along with the fatty tissue cushioning the eye. The material property of the fatty tissues has been investigated, and the damping factor was calculated to be 0.22 [18]. This value was taken for our model.

Regarding the vitreous, one popular earlier method was to take the vitreous humor out from the eye and put in a centrifuge. The material properties of the resulting material were found to be similar to that of water. However, in recent years, this was found to be erroneous as the properties change once the vitreous is taken out the eye. Thus, using ultrasonic imaging to find the material properties of the tissues became a popular approach [19].

For our model, based on a damping ratio  $\xi = 0.22$  for adipose tissue [18], the damping coefficient was found to be  $C_{\text{Adipose fatty tissue}} = 1.44$

As there is insufficient information available for the overall damping ratio of the eye, a nominal value of  $\xi = 0.1$  was taken. The damping coefficient was found to be  $C_{\text{nominal of eye}} = 0.705$ .

## Description of the GUI

The Matlab GUIDE is a handy tool used for building a graphical user interface. The GUIDE has been used in this study for building a GUI which has user friendly options to input the parameters, build the model and plot the response.

The GUI is basically divided into two parts:

1. Set parameters panel
2. Plotting panel

The simulation of the GUI involves setting up the input parameters for the model obtained from user and calculating the system dynamics such as the position, velocity and the forces for all time instances. A flow chart of the program describing various stages of the simulation is provided in the Appendix.

The input parameters are:

1. Impact force (in Newtons)
2. Impact area (choosing the radio buttons)

Part of Eye	Mass Density g/m³
Cornea	1400
Sclera	1400
Ciliary	1600
Fatty tissue	999
Vitreous	999
Aqueous	999
Lens	315

Table 1: Mass densities of various parts of the eye (in g/m³). These values were taken from the work of Power [25]. The major portion of the eye is occupied by the vitreous, aqueous, and the lens.

Part of the eye	Elastic modulus in KPa (Ref. source)
Sclera	$2.6 * 10^3$ [15]
Fatty tissues	47 [25]
Lens	$6.88 * 10^3$ [24]
Nominal value for the rest of the eye	42 [25]

Table 2: The elastic modulus values in kiloPascals used in our model are listed for the various parts of the eye along with the their sources from literature.

3. Angle of impact
4. Duration of impact force
5. Duration of the system dynamics – Simulation time

When the user runs the program, the user is presented with a GUI. A default set of values are provided. To change the values, the user can use the appropriate options. The angle of input is provided by the user by choosing the radio buttons. Moreover, the user is also provided with an option to draw the angle of impact. There are also advanced control options provided. It is recommended that the advanced options to be used only after having a good understanding of the system.

## Results

### Validation of the model

The Mass-Spring model of the eye was used to study the effect of impact forces. The simulations provide a clear overview of how the forces transmit through the nodes of the eye. Since the time taken for a particular simulation is in the range of tens of seconds, unlike the Finite Element models which may take hours, the user can more easily study the model for various types of impact scenarios by the changing the impact force, duration of the impact, etc.

Because of the inherent difficulty in trying to model the realistic behavior of the eye, most of the models take certain parameters, such as viscous forces, in an ad-hoc manner. However, for our model, a great deal of care has been taken to include accurate physical parameters in its construction. The resulting dynamics were shown to be similar to those in the published literature, as described below.

A simulation to find corneal apex displacement for various magnitudes of the impact forces was performed. The impact duration of a projectile on the eye is normally in the range of 0.1 to 0.3 milliseconds. The plot of the results obtained is shown in Figure 9. The simulation plots correspond to the shapes of the experimental plots of Stitzel et al. [15], with the displacement being in the range of 1 to 3 mm.

### Dynamic plots

The transmission of forces across the nodes following blunt impact is shown in Figure 10. The forces are applied to the front of the eye (at left as shown in the first frame) initially for a certain time period. These forces transmit through the nodes and reach the other side of the eye representing the retinal region in the sixth frame.

At every time instant, the forces felt at each node are calculated and mapped onto the color-map. With the 'HOT' color-map the forces are plotted where reddish color means a greater force being experienced.

### Static plots

The magnitude of the forces experienced by the nodes is over time is plotted for the following nodes:

1. Center of the eye
2. Frontal impact side of the eye
3. Right side of the eye – part of retina
4. Top part of the eye – part of the retina

In Figure 11, one can observe the peak forces (plotted in Newtons) over a time period (in milliseconds). One can observe two peaks, the first one corresponds to the node reaching maximum force during the impact period, and the second one when the impact force just becomes

zero. This kind of profile is for the case of a smooth rectangular impact force profile, but can change when one chooses a triangular, sharper impact force profile.

### Prediction of retinal damage

The mechanism behind the retinal damage has still not been solidly established [20]. The most commonly accepted cause is vitreous traction. Since in our model the boundaries between the retina, choroid, vitreous interface is not precisely defined because of

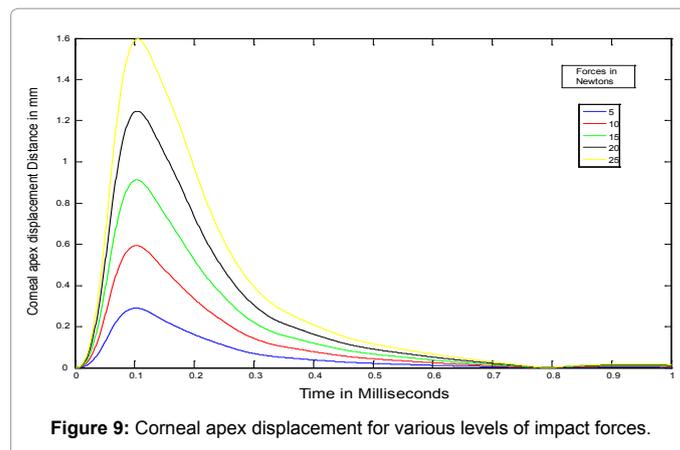


Figure 9: Corneal apex displacement for various levels of impact forces.

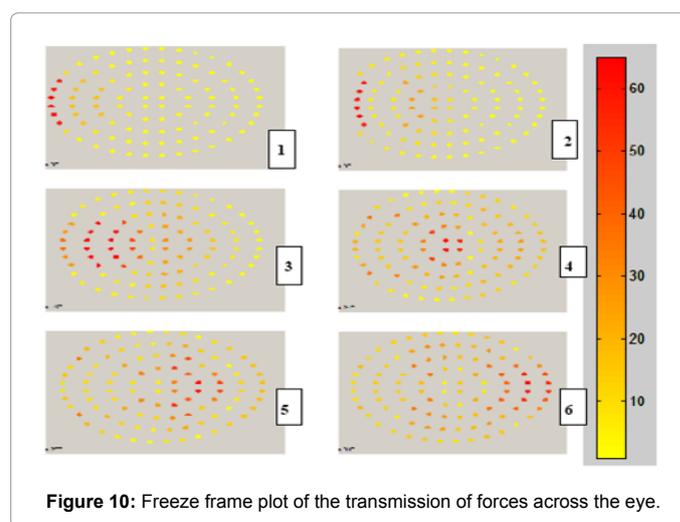


Figure 10: Freeze frame plot of the transmission of forces across the eye.

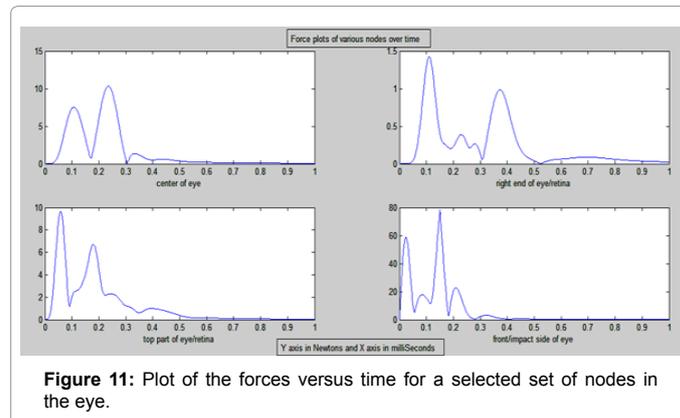


Figure 11: Plot of the forces versus time for a selected set of nodes in the eye.

the computational complexity constraints, we looked for another approach. The expansion of the sclera impacts the retina and as the sclera expands, it pulls the retina along. Beyond a certain threshold a small tear, or a hole, is created. This small hole becomes bigger and can eventually cause retinal detachment. Taking this into consideration, we performed model simulations (Figure 12) and propose two factors for determining the state of retinal detachment as well as the kinetic energy of the impacting body divided by the energy transferred by the projectile.

Thus the predictors involved in predicting the retinal damage are:

1. Scleral length change (S)
2. Weight given: 0.25 Threshold: 1.5% change (St)
3. 12' O clock meridian length change (M)
4. Weight given: 0.25 Threshold: 4% change (Mt)
5. Energy imparted to the system (E)
6. Weight given: 0.5 Threshold: 5.3 Joules (Et)

Formula for prediction: Percentage chances of retinal damage =  $(0.25 \cdot S/St + 0.25 \cdot M/Mt + 0.5 \cdot E/Et) \cdot 100$

If the percentage is greater than 100%, the model just indicates the extent of damage.

## Discussion

A robust and accurate model was developed using a MSD system. This is the first attempt to build a model of the entire human eye using a MSD system. The model can simulate an impact scenario within tens of seconds of computation time. The MSD system was used to model the eye because of the inherent simplicity, elegance, and robustness of the model. It computes the forces and velocities of the point masses in the background using Euler's method to solve the differential equations. The inputs given to the GUI, which was developed for this model, are the impact force and impact duration. With regards to the force profile applied onto the frontal part of the eye, a rectangular shaped pulse with a smooth rise and the fall was used. A scope for future study would be to include the impact forces similar to what it would be for an actual blunt projectile, such as rounded objects of different diameters.

In the succeeding paragraphs we discuss the reasons behind the decisions during various stages involved in building the skeleton of the model. In our model, the various parts of the eye (including the parts surrounding it) which were taken into consideration to be included in the model are the lens, sclera, adipose fatty tissues surrounding the eye, and the bony orbit holding the eye. We have on one hand, the need to

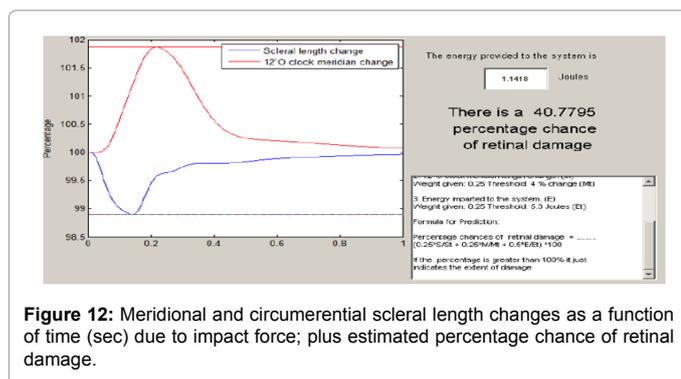
make the model perfectly mimic the eye by individually representing the various parts of eye. On the other hand, this kind of exhaustive modeling technique might take away the advantages the Mass-Spring models which namely are its conceptual simplicity and computational speed. For example, the corneal limbus, which is in the border of the cornea and the sclera, could potentially be more vulnerable to pressure [21] and including it in our model could improve the performance of the model. On the other hand, modeling such specific parts of the eye, which are smaller in size, would require us to increase the density of the mesh greatly and thereby increasing the computational load. It could have also introduced modeling complexities such as in the way we interpret the influence of corneal limbus in the scheme of dynamics of impact trauma. How do we set the mass density and spring constants of the corneal limbus, and also how many filaments do we actually include at the junction of corneal limbus to represent its influence precisely? Once we introduce such changes in the model, a thorough analysis of the performance would have to be done to understand the overall impact on the results. lest it should bring in any artifacts to the model. Such assessments were considered in our study, where we weighed the tradeoff between computational complexity and accuracy of the ocular representation. The decision was to not include these smaller components in the model.

In the eye model, the chosen construction was done through a careful set of experimentations with various types of structures. For example, a structure containing concentric circular layers with radial springs was initially built as a template for the eye model. When forces were applied to the nodes on the periphery, the force waves created seemed to converge towards the center. A force applied on one side seemed to die out as they approached the center and did not effectively cross the center of the model. This highlights the importance of how the orientation of the springs affects the behavior of the model, which led to the approach that was taken as described in the Methods Section.

To simulate all conditions of impact forces effectively it is important to include springs in various orientations to propagate the pressure waves effectively. Further modifications could potentially yield better results which could be a subject for future research.

Regarding the density of the nodes, a careful parametric study was done taking into consideration the two limiting factors, namely the changes in behavior with respect to density and the time taken for one round of simulation. The right balance was found between the two limiting conditions and a 16 by 16 mesh of point masses was chosen. If we use programming languages such as C++ or Java, whose computational performance is considerably superior to Matlab, we could very likely increase the density greatly, and also potentially include finer parts of the eye which have been left out as discussed in the next paragraph.

When it came to choosing the material properties of parts of eye for our model, there was an element of ambiguity with regards to this especially for the elastic properties and damping coefficients. Rosi et al. [17] discussed the inherent difficulty in choosing the elastic properties of the various parts of the eye, since there are a wide range of material properties that are used in the published results. For our model, the parameters were chosen so that the final performance results were within the range of published results. Van Gelder [10] presented a method to find the spring constants from elastic properties which enabled researchers to use MSD for modeling biological systems effectively, and this approach was used in our model. The difficulty arose in deciding the damping coefficient for the eye as there was no



clear value provided in the literature. Based on a parametric study, an appropriate value was chosen as the damping coefficient for the eye.

Along with building a valid model for the eye, a predictor model for the extent of retinal damage has also been developed which takes into account the scleral length change, equatorial length change, and the impact energy. These factors for predicting retinal damage were taken from previously published results [22,23].

With a seemingly uncomplicated model and very fast simulation completion time, a big question mark would be on the performance of the model as to how accurately it mimics the dynamics of the eye during impact trauma. A parametric study was done for various values impact forces. The force plots and corneal displacement plots, as shown in the previous section, were compared against published data [15,23-26]. The results were in the range of values similar to the experimental findings.

Though there are a large number of computer models of the human eye and various other parts of the body built for studying the impact trauma, physicians have not had the confidence to use these models for aiding in diagnosis in real life situations. The main reason for this is the vast computational load involved, taking hours for most of the simulations. Also, there seems to be lack of any major attempts taken by researchers to promote practical clinical usage of their models. The most exciting future work for our model would be in improving this current model to a level of reliability that ophthalmologist can use it for predicting the extent of eye damages in real life situations. For instance, there have been numerous instances wherein an ophthalmologist inspecting an eye with a hemorrhage (reddish eye) has overlooked possible retinal damage as the reddish eye is no longer transparent. Some possible approaches to accomplish this task would be changing the inputs from impact force and duration to actual real life examples such as simulating the type of object that caused the impact, along with its angle of attack and estimated velocity. An example of that would be ocular impact by a baseball ball, for which we have a defined mass and size, and where velocity and angle of attack can be recorded. A rapid simulation using these inputs could provide an early diagnosis of the potential extent of ocular injury. With overcrowding in urgent care rooms and burdened medical resources in the country, such model simulations could be a very useful tool in the clinical environment.

## Summary

The human eye has been modeled in two-dimensions with a Mass-Spring-Damper system. Various cases of impact scenarios with varying parameters such as the area of impact, impact duration, angle of impact, impact forces etc. have been incorporated in to the model.

The reasons for choosing this approach are the simplicity involved in building the model and the reduced time taken in running a simulation which is needed for an interactive application (it takes tens of seconds for each simulation compared to a time of many hours taken for a Finite Element model). The coding was done in MATLAB and a Graphical User Interface (GUI) has been provided to the user for ease of usage of the model. Moreover, the model is adaptable, since extra features can be added to the model for different applications such as studying the dislocation of lens due to impact trauma. Further, since the coding was done in MATLAB, it is easier for researchers to use the model compared to the costly Finite Element analysis software.

The user has the options of defining the structure of the model and entering the parameters depending on a particular impact scenario. Care has been taken to incorporate the physical parameters of the eye

into our model, and it has been successfully demonstrated that the model behavior is similar to those in the published clinical literature. A predictor for retinal damage has been provided which predicts the extent of damage to the retina for a given impact scenario. Another powerful feature is that the user can observe the positions and states of the internal nodes for all time instants.

Finally, an executable file for running the MATLAB based GUI is available upon request from the authors.

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