DATA-DRIVEN AND ANISOTROPIC TEARING FOR CLOTH SIMULATION

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ABSTRACT

DATA-DRIVEN AND ANISOTROPIC TEARING FOR CLOTH SIMULATION

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Cloth simulations improve realism of video games by extending interactivity of virtual environment and characters. Cloth is a heterogeneous material and it has anisotropic features which can increase immersion especially in a tearing scenario. Today, most video games ignore this fact mainly due to its complexity. However, style of the final output is highly valuable for video games and addition of anisotropic tearing can improve output quality.

Shape of cloths can change, meaning that relative distance of two points on the cloth is not fixed. However, cloths try to conserve original shape and respond to physical changes. Generated response due to change in relative distance of two points is known as stress. Tearing occurs when stress values are higher than an anisotropic property of cloths, tensile strength limit. This thesis proposes a new method to make cloth simulations more realistic by calculating a data driven and anisotropic tensile strength limit.

Tearing have similar significance to elasticity according to a user study that was conducted with 14 users. Our results show that, users can estimate cloth elasticity level. However, if cloths have similar elasticity level, then users confuse these cloths and can not guess cloth type correctly. Therefore, these results provide evidence to using same elasticity data for different cloths with similar elasticity level is possible, users will not be able to perceive the difference.

Keywords: Finite Element Method, Tearing, Data Driven, Anisotropic, Cloth Simu-

lation

ÖZ

KUMAŞ SİMÜLASYONU İÇİN VERİ GÜDÜMLÜ VE YÖN BAĞIMLI YIRTILMA

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Kumaş simülasyonları, sanal mekanların ve karakterlerin etkileşim seviyesini geliştirerek, video oyunlarının gerçekçilik düzeyini artırmaktadır. Kumaş heterojen bir materyal olup, yön bağımlı niteliklere sahiptir. Bu nitelikler özellikle yırtılma senaryosunun etkisini artırabilecek niteliktedir. Günümüzde, bilgisayar oyunlarının çoğu bu nitelikleri karmaşık yapısından dolayı değerlendirmemektedir. Fakat, video oyunları için üretilen görüntünün son hali oldukça değerlidir ve yön bağımlı yırtılma bu kaliteyi doğrudan artırabilir.

Kumaş üzerindeki iki nokta arasındaki mesafe sabit değildir, kumaşların şekli değişebilmektedir. Fakat, kumaşlar şekillerini korumak istemekte ve fiziksel değişikliklere tepki üretmektedir. İki nokta arasındaki mesafe değişiminden kaynaklanan tepkinin büyüklüğü stres olarak adlandırılmaktadır. Kumaşın yırtılabilmesi için, stres değerlerinin, kumaşın yön bağımlı bir niteliği olan kumaş esneme gücünün limit değerinden daha fazla olması gerekmektedir. Bu tezde, kumaş esneme gücünün limit değerinin hesaplanabilmesi için veri güdümlü ve yön bağımlı bir yöntem önerilmekte, böylece kumaş simülasyonlarının daha gerçekçi yapılması amaçlanmaktadır.

Gerçekleştirdiğimiz istatistiki araştırmaya 14 kişi katılmıştır. Araştırma sonuçlarına göre, kumaşın yırtılabilmesi ve elastikiyeti arasında önem farkı yoktur. Ayrıca, kullanıcılar kumaşların elastikiyet seviyesini tahmin edebilmektedir. Fakat, kumaşlar benzer elastikiyet seviyelerine sahipse, kullanıcılar kumaşları birbiri ile karıştırmakta ve kumaşı doğru tahmin edememektedir. Bu sonuçlar, benzer elastikiyet seviyesine sahip kumaşlar için aynı veri kümesinin kullanılabileceğini ortaya koymaktadır, kullanıcılar

aradaki farkı farkedemeyecektir.

Anahtar Kelimeler: Sonlu Elemanlar Yöntemi, Yırtılma, Veri Güdümlü, Yön Bağımlı, Kumaş Simülasyonu

To my family

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CHAPTER 1

INTRODUCTION

Realism is an important factor in the field of video games. Physical effects and simulations can make video games more realistic and accurate. Cloth and hair simulation started to appear in video games in recent years. Simulated character clothes and simulated hair make characters more believable. Cloth simulations can simulate flags, clothes of characters, curtains, sails, etc. Therefore, instead of using static-animated cloths, using cloth simulation is very important.

In the real world, cloths and materials are composed of molecules which separated from each other by empty space. It is possible to say materials are not continuous [1]. However, contrary to reality, assuming the continuity of the materials without any emptiness is called *continuum*. In a continuum, matter fills all region equally and subdividing regions into smaller parts is possible.

Continuum mechanics use discrete continuum regions to calculate material behaviours. Using differential equations, it is possible to calculate physical changes in a continuum. The *finite element method* (FEM) is a numerical technique for finding approximate solutions to boundary value problems for differential equations. Basically, solving differential equations of each region separately leads to an approximate result of the whole continuum.

It is possible to simulate a wide range of deformable materials as continuum with FEM [2, 3]. However, a realistic and accurate cloth simulation requires additional methodologies. There are several reasons for that, some cloths are highly elastic and that makes time integration very hard [4]. Cloths are characterized by high bending resistance with folds and wrinkles, so special algorithms are needed to calculate correct bending values [5, 6].

During elastic deformations, deformed objects return to their original shape after all external forces applying on the object are removed. However, materials have an elasticity limit, when this limit is surpassed, the material will not be able to return to its original shape and fractures will appear. Fractures can appear due to tensile or compressive deformation [2].

Stretching and bending behaviours are anisotropic for cloths. Same amount of force can result in different deformations of the cloth when applied towards different directions. Therefore, using anisotropic stretching and bending data in simulations can make simulations more accurate [7].

Anisotropic stretching leads to having different elasticity limits in different directions. Therefore, an accurate fracture simulation needs to consider anisotropic tearing. In this thesis, a new method proposed to make anisotropic tearing in cloth simulation with usage of real world cloth tearing data. Results show that, we can manipulate tensile strength in an anisotropic way with our methodology and we can simulate different cloth types just by entering data of cloth into the simulation. According to conducted statistical analysis, tearing is important to end users and they can estimate elasticity difference between cloth types. So they can guess cloth type from elasticity level of cloths. However, users confuse cloth types when cloths with similar elasticity level shown to them. Therefore, using same elasticity data for different cloths with similar elasticity level is possible, users will not be able to perceive the difference.

1.1 Outline

The outline of this thesis is as follows:

- Chapter 2 explains details of cloth simulation, tearing, anisotropy, collision detection, cutting and provides an overview to the related work.
- Chapter 3 describes the proposed method, explains tensile strength calculation in detail, gives a summary of the simulation system from an algorithmic perspective and presents the details of user study that was conducted to evaluate the proposed method and simulation.
- Chapter 4 demonstrates results of the proposed method with different experiments, covers analysis of user study and explains significant results of the user study.
- Chapter 5 concludes with results and gives a summary of contributions.

CHAPTER 2

BACKGROUND AND RELATED WORK

In this thesis, we are focusing on making tearing more realistic for video games. In this chapter, we provide background information about cloth simulations in detail. We describe visualization of cloth with meshes. Then, we explain continuum mechanics, its underlying mathematics, its usage with soft bodies. We explain time integration methodologies which necessary to calculate following iterations of the simulation. We describe anisotropic behaviour of cloth and explain anisotropic stretching, anisotropic tearing, bending and cutting methodologies. Finally, we explain anisotropic fracture methodologies with the related work and recent approaches in the literature.

2.1 Virtual Representation of Cloth

Virtual representation of materials have direct influence over what a simulation can achieve. It is possible to represent cloth with a volume based hierarchy or with a triangle based hierarchy.

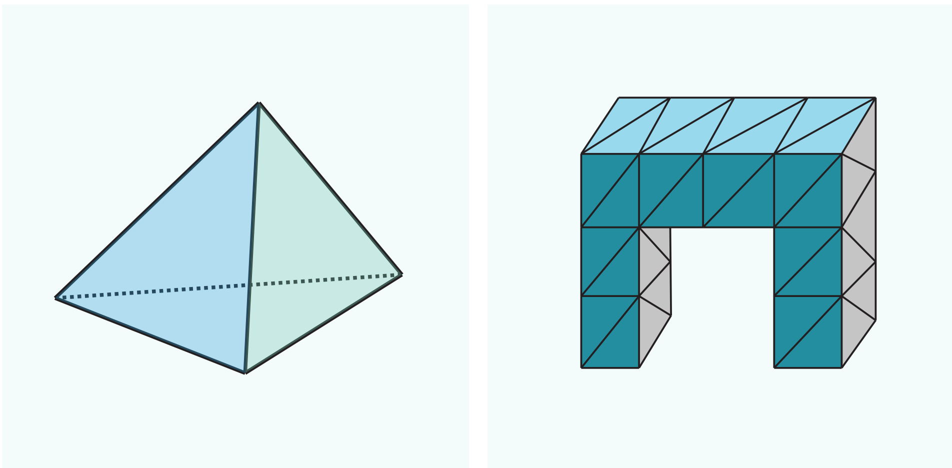

Figure 2.1: A tetrahedron and a tetrahedron based object

Tetrahedron is a geometrical shape that have four triangular faces. Faces of tetrahedron define a polyhedron (see Figure 2.1). Tetrahedron usage is not common in video games, because interior of the meshes is not important. Most of the time, meshes exist only for graphical reasons in video games. It is possible to represent cloth mesh with tetrahedrons. However, our simulation does not need thickness of the cloth. Tetrahedron mathematics requires larger matrices at calculations than triangular polygons. So we prefer triangle based cloth representation due to calculation speed advantage.

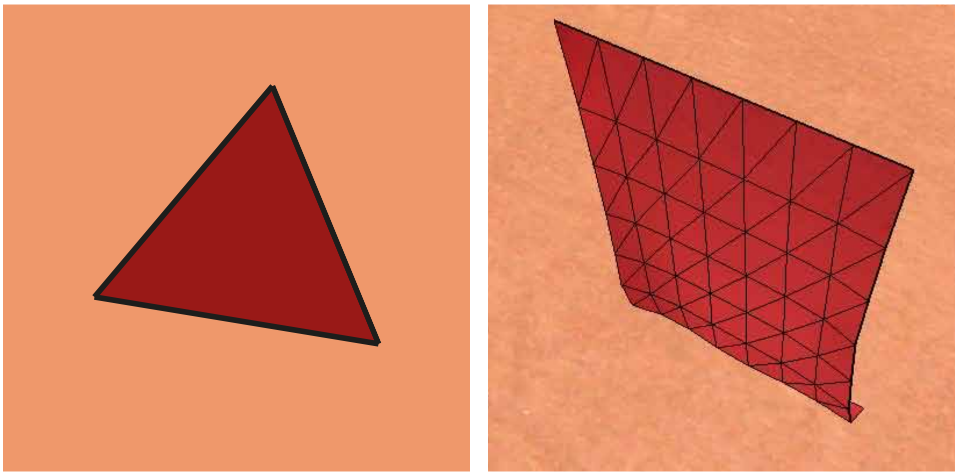

Figure 2.2: A triangle and a triangle based square cloth

In the simulation, each cloth object have a list of triangles, edges and vertices. Triangles hold information lists of 3 edges and 3 vertices they have. Edges hold information lists for triangles and vertices they have. Vertices hold up to *n* triangle information and *m* edge information.

2.2 Continuum Mechanics

In the real world, materials are composed of molecules separated from each other by empty space. So we can say materials are not continuous [1]. Contrary to reality, assuming the continuity of the materials without any emptiness is called *continuum*. In a continuum, matter fills all region equally and subdividing regions into smaller regions is always possible.

Initial shape of an object is called rest shape. Rest shape represents undeformed state for the object. An object is a continuous region $\boldsymbol{\Omega}$ in R^3 and each point $\boldsymbol{x} \in \boldsymbol{\Omega}$ is a material coordinate in rest shape. When an object is deformed, each rest point $\boldsymbol{x}$, becomes $\boldsymbol{p}(\boldsymbol{x})$ under new deformed state. It is possible to calculate displacement $\boldsymbol{u}(\boldsymbol{x})$ of each point with the following equations:

$$\boldsymbol{x} = [\boldsymbol{x}_x, \boldsymbol{x}_y, \boldsymbol{x}_z]^T \tag{2.1}$$

$$\boldsymbol{p}(\boldsymbol{x}) = [\boldsymbol{p}_x, \boldsymbol{p}_y, \boldsymbol{p}_z]^T \tag{2.2}$$

$$\boldsymbol{u}(\boldsymbol{x}) = \boldsymbol{p}(\boldsymbol{x}) - \boldsymbol{x} \tag{2.3}$$

Strain ε is relative elongation or compression of a material with respect to its rest form. There is not any strain when material is in the rest shape. It is possible to have elongation and compression at the same time in different directions over one volumetric region. Strain is represented by a symmetric 3 x 3 matrix or tensor and in Equation (2.4), each strain variable represent strain along indexed directions in the tensor [8]:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{xz} & \varepsilon_{yz} & \varepsilon_{zz} \end{bmatrix} \tag{2.4}$$

Strain is derived from the spatial variation or spatial derivatives of the displacement field [8]. It is possible to calculate Green's strain tensor ($\boldsymbol{\varepsilon}_G$) with usage of gradient of displacement field ($\boldsymbol{\nabla_u}$).

$$\boldsymbol{u}(\boldsymbol{x}) = [u(x,y,z), v(x,y,z), w(x,y,z)]^T \tag{2.5}$$

$$\boldsymbol{\nabla_u} = \begin{bmatrix} \frac{\partial \boldsymbol{u}}{\partial x} & \frac{\partial \boldsymbol{u}}{\partial y} & \frac{\partial \boldsymbol{u}}{\partial z} \\ \frac{\partial \boldsymbol{v}}{\partial x} & \frac{\partial \boldsymbol{v}}{\partial y} & \frac{\partial \boldsymbol{v}}{\partial z} \\ \frac{\partial \boldsymbol{w}}{\partial x} & \frac{\partial \boldsymbol{w}}{\partial y} & \frac{\partial \boldsymbol{w}}{\partial z} \end{bmatrix} \tag{2.6}$$

$$\boldsymbol{\varepsilon}_G = \frac{1}{2}(\boldsymbol{\nabla_u} + [\boldsymbol{\nabla_u}]^T + [\boldsymbol{\nabla_u}]^T \boldsymbol{\nabla_u}) \tag{2.7}$$

Stress ($\boldsymbol{\sigma}$) represents force per unit area. It is possible to represent stress with a $3x3$ matrix or tensor:

$$\boldsymbol{\sigma} = \begin{bmatrix} \boldsymbol{\sigma}_{xx} & \boldsymbol{\sigma}_{xy} & \boldsymbol{\sigma}_{xz} \\ \boldsymbol{\sigma}_{xy} & \boldsymbol{\sigma}_{yy} & \boldsymbol{\sigma}_{yz} \\ \boldsymbol{\sigma}_{xz} & \boldsymbol{\sigma}_{yz} & \boldsymbol{\sigma}_{zz} \end{bmatrix} \tag{2.8}$$

Equations (2.4) and (2.8) are tensors for tetrahedron objects. However, we are going to use triangle based objects in the simulation, so usage of $3x3$ matrices for strain and stress is not necessary. When calculating strain it is possible to analyse vertex positions relative to each other in two dimensional local space of each triangle (u, v). That simplifies representations of strain and stress to [9]:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{uu} & \varepsilon_{uv} \\ \varepsilon_{uv} & \varepsilon_{vv} \end{bmatrix} \tag{2.9}$$

$$\boldsymbol{\sigma} = \begin{bmatrix} \boldsymbol{\sigma}_{uu} & \boldsymbol{\sigma}_{uv} \\ \boldsymbol{\sigma}_{uv} & \boldsymbol{\sigma}_{vv} \end{bmatrix} \tag{2.10}$$

Calculating stress from strain depends on elasticity (E) of material. Young's modulus, e, relates the stiffness of the material while the Poisson coefficient, ν, characterizes its transverse contraction upon its extension [9]:

$$\boldsymbol{E} = \frac{e}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \tag{2.11}$$

Using only one value for e and ν makes cloth have a linear isotropic elasticity. If anisotropic behaviour desired, values of e and ν must change proportional to the situation of cloth triangles. Stress calculation possible with [9]:

$$\begin{bmatrix} \boldsymbol{\sigma}_{uu} \\ \boldsymbol{\sigma}_{vv} \\ \boldsymbol{\sigma}_{uv} \end{bmatrix} = \boldsymbol{E} \begin{bmatrix} \varepsilon_{uu} \\ \varepsilon_{vv} \\ \varepsilon_{uv} \end{bmatrix} \tag{2.12}$$

It is possible to calculate strain with an easier method [9]. Cloths are generally have perpendicular fiber directions which are called weft and warp. It is possible to calculate weight of triangle edges to assembly weft and warp directions whenever desired. It is possible to calculate the deformed weft and warp directions by using triangle position weights.

We initialize cloth triangles in two dimensional local space. Each triangle vertex is in the form of $(\boldsymbol{u}_a, \boldsymbol{v}_a)(\boldsymbol{u}_b, \boldsymbol{v}_b)(\boldsymbol{u}_c, \boldsymbol{v}_c)$ and we project cloth into three dimensional world space after initialization.

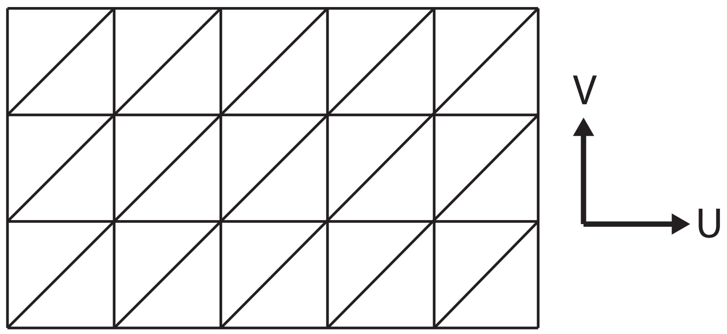

Figure 2.3: $\boldsymbol{U}$ and $\boldsymbol{V}$ directions

Weft ($\boldsymbol{U}$) and warp ($\boldsymbol{V}$) directions must be chosen before the initialization step for the cloth. It is possible to choose any direction as long as they are perpendicular. However, it must be remembered that chosen weft and warp directions will affect the behaviour of cloth. Because, cloth will be produced with different cloth fiber directions. $(1, 0)$ and $(0, 1)$ are standard $\boldsymbol{U}$ and $\boldsymbol{V}$ values for our simulation. After choosing $\boldsymbol{U}$ and $\boldsymbol{V}$ it is possible to pre compute following linear systems:

$$\sum_i r_{ui}\boldsymbol{u}_i = 1 \tag{2.13}$$

$$\sum_i r_{ui}\boldsymbol{v}_i = 0 \tag{2.14}$$

$$\sum_i r_{ui} = 0 \tag{2.15}$$

$$\sum_i r_{vi}\boldsymbol{u}_i = 0 \tag{2.16}$$

$$\sum_i r_{vi}\boldsymbol{v}_i = 1 \tag{2.17}$$

$$\sum_i r_{vi} = 0 \tag{2.18}$$

These linear systems lead to following weights:

$$r_{ua} = d^{-1}(\boldsymbol{v}_b - \boldsymbol{v}_c) \tag{2.19}$$
$$r_{ub} = d^{-1}(\boldsymbol{v}_c - \boldsymbol{v}_a) \tag{2.20}$$
$$r_{uc} = d^{-1}(\boldsymbol{v}_a - \boldsymbol{v}_b) \tag{2.21}$$
$$r_{va} = d^{-1}(\boldsymbol{u}_c - \boldsymbol{u}_b) \tag{2.22}$$
$$r_{vb} = d^{-1}(\boldsymbol{u}_a - \boldsymbol{u}_c) \tag{2.23}$$
$$r_{vc} = d^{-1}(\boldsymbol{u}_b - \boldsymbol{u}_a) \tag{2.24}$$
$$d = \boldsymbol{u}_a(\boldsymbol{v}_b - \boldsymbol{v}_c) + \boldsymbol{u}_b(\boldsymbol{v}_c - \boldsymbol{v}_a) + \boldsymbol{u}_c(\boldsymbol{v}_a - \boldsymbol{v}_b) \tag{2.25}$$

With these precomputed values it is possible to calculate current three dimensional distorted $\boldsymbol{U}$ and $\boldsymbol{V}$ directly as a weighted sum of current vertex positions $\boldsymbol{P}_i$ for a triangle whenever desired.

$$\boldsymbol{U} = \sum_{i\epsilon(a,b,c)} r_{ui}\boldsymbol{P}_i \tag{2.26}$$
$$\boldsymbol{V} = \sum_{i\epsilon(a,b,c)} r_{vi}\boldsymbol{P}_i \tag{2.27}$$

It is possible to calculate strain ($\boldsymbol{\varepsilon}$) with following equation ($\boldsymbol{I}$ is an identity matrix) with $\boldsymbol{U}$ and $\boldsymbol{V}$ values from Equations (2.26) and (2.27):

$$\boldsymbol{G} = \frac{1}{2}([\boldsymbol{U}\boldsymbol{V}]^T[\boldsymbol{U}\boldsymbol{V}] - \boldsymbol{I}) \tag{2.28}$$

Then, we can extract weft strain, warp strain and shear strain values from the Green-Lagrange strain tensor:

$$\boldsymbol{\varepsilon}_{uu} = \frac{1}{2}(\boldsymbol{U}^T\boldsymbol{U} - 1) \tag{2.29}$$
$$\boldsymbol{\varepsilon}_{vv} = \frac{1}{2}(\boldsymbol{V}^T\boldsymbol{V} - 1) \tag{2.30}$$
$$\boldsymbol{\varepsilon}_{uv} = \frac{1}{2}(\boldsymbol{U}^T\boldsymbol{V} + \boldsymbol{V}^T\boldsymbol{U}) \tag{2.31}$$

Usage of stress Equation (2.12) is possible with recently calculated strain values (2.29), (2.30), (2.31) and elasticity matrix (2.11).

Calculating each triangle vertex's force value related to weft, warp and shear stress as follows [9]:

$$\boldsymbol{F}_j = -\frac{|d|}{2}(\boldsymbol{\sigma}_{uu}(r_{uj}\boldsymbol{U}) + \boldsymbol{\sigma}_{vv}(r_{vj}\boldsymbol{V}) + \boldsymbol{\sigma}_{uv}(r_{uj}\boldsymbol{V} + r_{vj}\boldsymbol{U})) \tag{2.32}$$

For accuracy and stability of cloth simulation, elastic Jacobian contribution must be calculated [9]. Jacobian contribution is usable with simulations which use an implicit time integration method [4]. Simulation presented in this paper uses an implicit method and we will explain it in the following section. Jacobian contribution:

$$\begin{aligned}\frac{\partial \boldsymbol{F}_j}{\partial \boldsymbol{P}_i} = -\frac{|d|}{2}(&\frac{\partial \boldsymbol{\sigma}_{uu}}{\partial \boldsymbol{\varepsilon}_{uu}}(r_{uj}\boldsymbol{U})(r_{ui}\boldsymbol{U})^T + \frac{\partial \boldsymbol{\sigma}_{vv}}{\partial \boldsymbol{\varepsilon}}(r_{vj}\boldsymbol{V})(r_{vi}\boldsymbol{V})^T \\ &+ \frac{\partial \boldsymbol{\sigma}_{uv}}{\partial \boldsymbol{\varepsilon}_{uv}}(r_{uj}\boldsymbol{V} + r_{vj}\boldsymbol{U})(r_{ui}\boldsymbol{V} + r_{vi}\boldsymbol{U})^T \\ &+ (\boldsymbol{\sigma}_{uu}(r_{uj}r_{ui}) + \boldsymbol{\sigma}_{vv}(r_{vj}r_{vi}) \\ &+ \boldsymbol{\sigma}_{uv}(r_{uj}r_{vi} + r_{vj}r_{ui}))\boldsymbol{I})\end{aligned} \tag{2.33}$$

2.3 Implicit Time Integration Method

In each simulation frame, each point will have initial position $\boldsymbol{p}^t$ and initial velocity $\boldsymbol{v}^t$. After calculation of internal and external forces, all forces will be summed as total force $\boldsymbol{f}(\boldsymbol{x}^t, \boldsymbol{v}^t)$ for each point. It is possible to calculate new position $\boldsymbol{x}^{t+1}$ and new velocity $\boldsymbol{v}^{t+1}$ of each point with explicit euler time integration [8]:

$$\boldsymbol{v}^{t+1} = \boldsymbol{v}^t + \Delta t \boldsymbol{f}(\boldsymbol{x}^t, \boldsymbol{v}^t)/m \tag{2.34}$$

$$\boldsymbol{x}^{t+1} = \boldsymbol{x}^t + \Delta t \boldsymbol{v}^t \tag{2.35}$$

Explicit time integration is easy to implement. However, it is not stable enough when delta time is high [10, 4]. High delta time values are essential to make simulations in real time. Therefore, we make some modifications to equations (2.34) and (2.35) to make simulation stable:

$$\boldsymbol{v}^{t+1} = \boldsymbol{v}^t + \Delta t \boldsymbol{f}(\boldsymbol{x}^{t+1})/m \tag{2.36}$$

$$\boldsymbol{x}^{t+1} = \boldsymbol{x}^t + \Delta t \boldsymbol{v}^{t+1} \tag{2.37}$$

With modifications each equation needs output of other equation as input. These equations called Implicit Euler. It is not possible to calculate each equation explicitly, they are depending on each other and that is why this method is called implicit (Implicit Euler Scheme).

Implicit integration equations form a non linear algebraic system. Positions and velocities of next time step is unknown and must be calculated [8]. Putting known information into vectors and matrices is the first step to solve implicit equations. Vector $\boldsymbol{x}$ is positions of nodes at frame start $\boldsymbol{x}^t$ and vector $\boldsymbol{v}$ is velocities of nodes at frame start $\boldsymbol{v}^t$ and vector $\boldsymbol{f}$ is filled with total force acting on nodes.

$$\boldsymbol{x} = [\boldsymbol{x}_1^T, ..., \boldsymbol{x}_n^T]^T \tag{2.38}$$

$$\boldsymbol{v} = [\boldsymbol{v}_1^T, ..., \boldsymbol{v}_n^T]^T \tag{2.39}$$

$$\boldsymbol{f} = [\boldsymbol{f}_1^T, ..., \boldsymbol{f}_n^T]^T \tag{2.40}$$

Lumped mass matrix $\boldsymbol{M} \epsilon \boldsymbol{R}^{3n \times 3n}$ is filled with mass of vertices on diagonal m_1, m_1, m_1, m_2, m_2, m_2, ..., m_n, m_n, m_n. As an example $\boldsymbol{M}$ matrix with 2 vertices only:

$$\boldsymbol{M} = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_2 \end{bmatrix} \tag{2.41}$$

Example $\boldsymbol{M}$ matrix is in size $3n \times 3n = 6 \times 6$, however in simulation there can be hundreds of vertices. Therefore, it should be noted all vectors and matrices are very large in the simulation.

It is possible to write Equation (2.36) and Equation (2.37) as following in matrix and vector forms:

$$\boldsymbol{M}\boldsymbol{v}^{t+1} = \boldsymbol{M}\boldsymbol{v}^{t} + \Delta t \boldsymbol{f}(\boldsymbol{x}^{t+1}) \tag{2.42}$$
$$\boldsymbol{x}^{t+1} = \boldsymbol{x}^{t} + \Delta t \boldsymbol{v}^{t+1} \tag{2.43}$$

With substitution of Equation (2.43) into Equation (2.42):

$$\boldsymbol{M}\boldsymbol{v}^{t+1} = \boldsymbol{M}\boldsymbol{v}^{t} + \Delta t \boldsymbol{f}(\boldsymbol{x}^{t} + \Delta t \boldsymbol{v}^{t+1}) \tag{2.44}$$

It is possible to solve Equation (2.44) by using Newton-Raphson method [8]. However, Newton-Raphson method tries to guess values and guess improves with every new guessing iteration. When some error ratio is achieved, it completes guessing. Usage of this method is very expensive for real time applications. It is possible to linearise forces of equation at $\boldsymbol{x}^t$, [8]:

$$\boldsymbol{M}\boldsymbol{v}^{t+1} = \boldsymbol{M}\boldsymbol{v}^{t} + \Delta t[\boldsymbol{f}(\boldsymbol{x}^{t}) + \frac{\partial}{\partial x}\boldsymbol{f}(\boldsymbol{x}^{t})](\Delta \boldsymbol{v}^{t+1}) \tag{2.45}$$
$$= \boldsymbol{M}\boldsymbol{v}^{t} + \Delta t \boldsymbol{f}(\boldsymbol{x}^{t}) + \Delta t^2 \boldsymbol{K}\boldsymbol{v}^{t+1} \tag{2.46}$$

With some simplification it becomes:

$$[\boldsymbol{M} - \Delta t^2 \boldsymbol{K}]\boldsymbol{v}^{t+1} = \boldsymbol{M}\boldsymbol{v}^{t} + \Delta t \boldsymbol{f}(\boldsymbol{x}^{t}) \tag{2.47}$$
$$\boldsymbol{A}\boldsymbol{v}^{t+1} = \boldsymbol{b} \tag{2.48}$$

Equation (2.48) don't need guessing iterations and is not implicit. Calculating matrix $\boldsymbol{A}$ ($3n \times 3n$ matrix) and vector $\boldsymbol{b}$ with usage of vectors $\boldsymbol{x}$, $\boldsymbol{v}$, $\boldsymbol{f}$ and matrix $\boldsymbol{K}$ is a simple task.

Matrix $\boldsymbol{K}$ is a matrix ($3n \times 3n$ matrix). We need to fill it with the Jacobian of forces $\boldsymbol{f}$. We already calculated Jacobian contributions of forces in Equation (2.33). Jacobian of force node i related to node j is $\frac{\partial \boldsymbol{F}_i}{\partial \boldsymbol{P}_j}$ (3×3 matrix) and we can write it as $\boldsymbol{K}_{i,j}$

shortly. Each Jacobian needs to be placed in relative position in big Jacobian matrix $\boldsymbol{K}$. $\boldsymbol{K}_{i,i}$, $\boldsymbol{K}_{i,j}$, $\boldsymbol{K}_{j,i}$, $\boldsymbol{K}_{j,j}$ must be placed into positions $(3i, 3i)$, $(3i, 3j)$, $(3j, 3i)$ and $(3j, 3j)$ respectively.

Finally, simulation has vectors $\boldsymbol{x}$, $\boldsymbol{v}$, $\boldsymbol{f}$ and matrices $\boldsymbol{M}$ and $\boldsymbol{K}$, calculating matrix $\boldsymbol{v}^{t+1}$ is simply putting these values in Equation (2.48). It should be noted these vectors and matrices have large size and simple mathematics libraries will not be able to calculate these big matrices. We use Armadillo math library [11] in the simulation to calculate large matrices, speed up calculations and have good code readability.

2.4 Bending

Simulations try to find a balanced state for materials which means a configuration where the overall strain is minimized. However, cloth can be buckled and visually unrealistic when strain is minimized. Cloth simulation should not stop when strain is minimized, it should try to make cloth flat at the same time. Triangle based continuum does not have any thickness, so cloth will not try to make itself flat automatically, cloth needs to gain bending behaviour with an additional algorithm. With usage of bending algorithm, foldings and wrinkles will seem realistic.

There are different bending models. In one model angle between normals of triangles used to determine bending force [5]. In another model a spring is connected to non mutual vertices of neighbour triangles to add bending behaviour and it is noted that spring is not constrained, so cloth is easily folding [12]. In another model 1-ring neighbours of target vertex considered in bending calculation and it uses corotational subdivision finite elements [13].

In our simulation, model [5] is preferred because our cloth structure already have information of which triangles connected to an edge and triangle normal is already being calculated for rendering purposes. So it has minimal impact on the computation cost of the simulation.

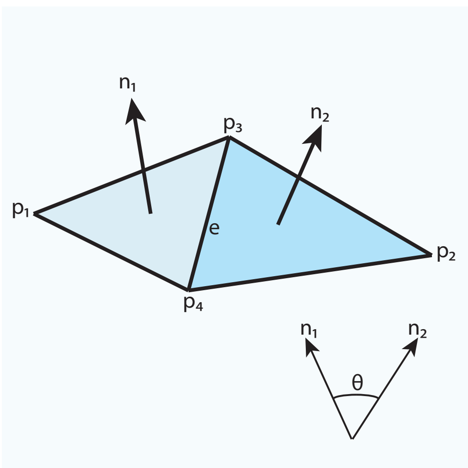

Figure 2.4: Bending angle between normal of two triangles

All edges that have connection with two triangles generate bending force in this model. Corner edges does not generate bending force because they are member of only one triangle. First triangle has vertex positions $(\boldsymbol{p}_1, \boldsymbol{p}_3, \boldsymbol{p}_4)$ and second triangle has vertex positions $(\boldsymbol{p}_2, \boldsymbol{p}_3, \boldsymbol{p}_4)$. Normals of triangles:

$$\boldsymbol{N}_1 = (\boldsymbol{p}_1 - \boldsymbol{p}_3) \times (\boldsymbol{p}_1 - \boldsymbol{p}_4) \tag{2.49}$$
$$\boldsymbol{N}_2 = (\boldsymbol{p}_2 - \boldsymbol{p}_4) \times (\boldsymbol{p}_2 - \boldsymbol{p}_3) \tag{2.50}$$

Mutual edge $(\boldsymbol{E})$ is the edge between vertex positions $\boldsymbol{p}_4$ and $\boldsymbol{p}_3$. The angle Θ is the angle between normalized normals $(\hat{\boldsymbol{n}}_1)$ and $(\hat{\boldsymbol{n}}_2)$.

$$\boldsymbol{E} = \boldsymbol{p}_4 - \boldsymbol{p}_3 \tag{2.51}$$

Bending forces should only change angle Θ, they should not cause rigid body motion and should not cause in plane deformation. $\boldsymbol{u} = (\boldsymbol{u}_1, \boldsymbol{u}_2, \boldsymbol{u}_3, \boldsymbol{u}_4)$ is a vector set which can fulfil requirements. $\boldsymbol{u}_1$ must be parallel to $\hat{\boldsymbol{n}}_1$ and $\boldsymbol{u}_2$ must be parallel to $\hat{\boldsymbol{n}}_2$, otherwise they will break requirements. $(\boldsymbol{u}_1 + \boldsymbol{u}_2 + \boldsymbol{u}_3 + \boldsymbol{u}_4)$ must be zero, so that makes $\boldsymbol{u}_3$ and $\boldsymbol{u}_4$ in span of $\hat{\boldsymbol{n}}_1$ and $\hat{\boldsymbol{n}}_2$.

$$\boldsymbol{u}_1 = |\boldsymbol{E}| \frac{\boldsymbol{N}_1}{|\boldsymbol{N}_1|^2} \tag{2.52}$$
$$\boldsymbol{u}_2 = |\boldsymbol{E}| \frac{\boldsymbol{N}_2}{|\boldsymbol{N}_2|^2} \tag{2.53}$$
$$\boldsymbol{u}_3 = \frac{(\boldsymbol{x}_1 - \boldsymbol{x}_4) \cdot \boldsymbol{E}}{|\boldsymbol{E}|} \frac{\boldsymbol{N}_1}{|\boldsymbol{N}_1|^2} + \frac{(\boldsymbol{x}_2 - \boldsymbol{x}_4) \cdot \boldsymbol{E}}{|\boldsymbol{E}|} \frac{\boldsymbol{N}_2}{|\boldsymbol{N}_2|^2} \tag{2.54}$$
$$\boldsymbol{u}_4 = \frac{(\boldsymbol{x}_1 - \boldsymbol{x}_3) \cdot \boldsymbol{E}}{|\boldsymbol{E}|} \frac{\boldsymbol{N}_1}{|\boldsymbol{N}_1|^2} + \frac{(\boldsymbol{x}_2 - \boldsymbol{x}_3) \cdot \boldsymbol{E}}{|\boldsymbol{E}|} \frac{\boldsymbol{N}_2}{|\boldsymbol{N}_2|^2} \tag{2.55}$$

The elastic bending stiffness is k^e and it is a material dependent value. Bending force can be calculated with the following equation for vertices i = 1,..,4

$$\boldsymbol{F}_i^e = k^e \frac{|\boldsymbol{E}|^2}{|\boldsymbol{N}_1| + |\boldsymbol{N}_2|} sin(\Theta/2) \boldsymbol{u}_i \tag{2.56}$$

In the previous equation $sin(\Theta/2)$ is unknown. Calculation with following equation is possible:

$$sin(\Theta/2) = \mp \sqrt[2]{(1 - \hat{\boldsymbol{n}}_1 \cdot \hat{\boldsymbol{n}}_2)/2} \tag{2.57}$$

Sign of Equation (2.57) is unknown, following equation have sign of $sin(\Theta)$, so we use sign result of following equation as sign in Equation (2.57):

$$\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_2 \cdot \hat{\boldsymbol{E}} \tag{2.58}$$

2.5 Anisotropic Stretching

Crafting a cloth requires wowing cloth fibres in complex patterns. That makes cloth a heterogeneous material. Complex patterns and heterogeneity makes cloth display different behaviours in different directions. That is called anisotropy, not being isotropic, displaying different behaviours in different directions.

There are studies which analyse this behaviour for cloth simulations. In the study [9], various amounts of force were applied at real world experiments and the obtained force-displacement relationship was used in simulation.

In another study [14], cloth deformation was analysed with advanced cameras and experiment setup was able to create deformations in different directions at the same time, resulting data was used to calculate elasticity matrix ($\boldsymbol{E}$) on the fly as a function of strain (ε).

In another study [7], measurement of displacement for different force values were carried. Measurements were repeated with different cloth directions and different force values. Resulting values were used to calculate elasticity matrix ($\boldsymbol{E}$) on the fly as a function of angle between principal eigenvectors of strain. Stretching and bending data of this study is publicly available. We use this method in our study with given cloth data values, so next paragraphs will explain how it works.

Using constant elasticity matrix ($\boldsymbol{E}$) in equation $\boldsymbol{\sigma} = \boldsymbol{E}\boldsymbol{\varepsilon}$ results in isotropic stretching. To make system anisotropic, elasticity matrix ($\boldsymbol{E}$) must differ according to current status of simulated cloth. Usage of a data driven elasticity matrix can make stress calculation anisotropic. Data driven elasticity matrix is called $\boldsymbol{C}$ and equation becomes $\boldsymbol{\sigma} = \boldsymbol{C}\boldsymbol{\varepsilon}$.

$$\boldsymbol{C} = \begin{bmatrix} c_{11} & c_{12} & 0 \\ c_{12} & c_{22} & 0 \\ 0 & 0 & c_{33} \end{bmatrix} \tag{2.59}$$

It is possible to calculate eigenvalues and eigenvectors of strain matrix (ε) with eigenvalue decomposition. Resulting eigenvectors are $\boldsymbol{\lambda}_1$ and $\boldsymbol{\lambda}_2$. Angle between these two eigenvectors is ϑ.

Stretching database have data values for angles $0°$, $22.5°$, $45°$, $67.5°$ and $90°$. So if ϑ is not in range $0°$ and $90°$ it must be clamped. If ϑ is between two different angles (for example $72°$ is between $67.5°$ and $90°$) a new interpolated matrix calculated from these two matrices. Resulting data values c_{11}, c_{12}, c_{22} and c_{33} are put into matrix $\boldsymbol{C}$ and it is possible to calculate $\boldsymbol{\sigma}$ after that.

$$\boldsymbol{\sigma} = \boldsymbol{C}\boldsymbol{\varepsilon} \tag{2.60}$$

Resulting matrix $\boldsymbol{C}$ offers piecewise linear elasticity and is anisotropic.

2.6 Collision Detection and Resolution

Each vertex of deformable mesh have unique velocity and position. Because of that, each unique position in an edge and a triangle have different velocity depending on existing vertices. Detection and solution of collisions must consider these positions and at the same time must consider time as a fourth dimension of space.

Geometrical collision detection systems checks point-point, point-edge, edge-edge, point-triangle collisions. However, only considering edge-edge and point-triangle collisions enough to build a geometrically accurate collision detection system [15].

It is possible to detect collisions using fifth degree polynomial equations [15]. However, there is not a direct mathematical solution to fifth degree polynomial equations. One way to solve this problem is approximating solution with binary search. However, approximating a fifth degree polynomial equation for each possible collision pair is not fast.

Simplifying a fifth degree polynomial equation into a third degree one is possible using multiple equations [16].

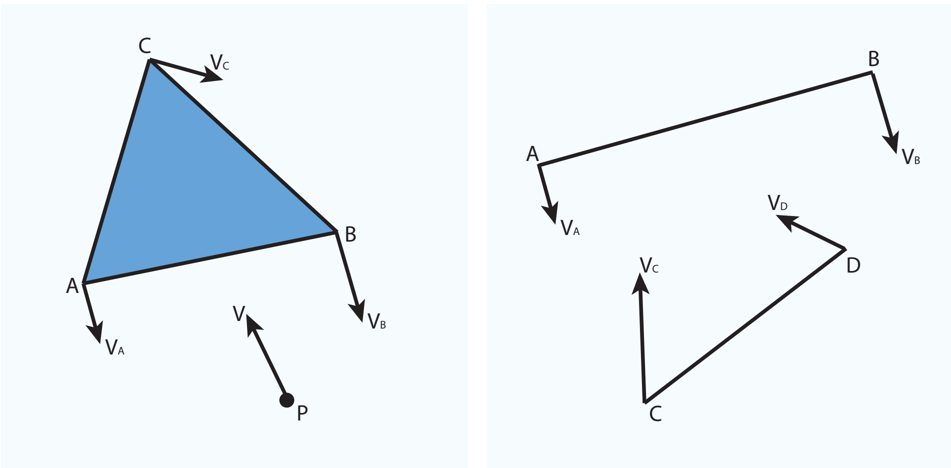

Figure 2.5: Point-triangle and edge-edge collision candidates

For the point - triangle case, if moving point is $\boldsymbol{P}(\overrightarrow{t})$ and triangle points are $\boldsymbol{A}(\overrightarrow{t})$, $\boldsymbol{B}(\overrightarrow{t})$ and $\boldsymbol{C}(\overrightarrow{t})$ with velocities $\boldsymbol{V}$, $\boldsymbol{V}_A$, $\boldsymbol{V}_B$ and $\boldsymbol{V}_C$, it is possible to calculate if a collision will happen in time range $0 \leq t \leq 1$. Each point has constant velocity along this time frame and initial time of frame is t_0. Position of points after t time have passed:

$$\boldsymbol{P}(t_0 + t) = \boldsymbol{P}(t_0) + t\overrightarrow{\boldsymbol{V}} \tag{2.61}$$

$$\boldsymbol{A}(t_0 + t) = \boldsymbol{A}(t_0) + t\overrightarrow{\boldsymbol{V}}_A \tag{2.62}$$

$$\boldsymbol{B}(t_0 + t) = \boldsymbol{B}(t_0) + t\overrightarrow{\boldsymbol{V}}_B \tag{2.63}$$

$$\boldsymbol{C}(t_0 + t) = \boldsymbol{C}(t_0) + t\overrightarrow{\boldsymbol{V}}_C \tag{2.64}$$

If point and triangle will collide, dot product of triangle normal and vector $\overrightarrow{\boldsymbol{AP}}$ will be zero at collision time.

$$\overrightarrow{\boldsymbol{AP}}(t) \cdot \overrightarrow{\boldsymbol{N}}(t) = 0 \tag{2.65}$$

Equation (2.65) is a third degree polynomial and it is possible to solve it mathematically. There can be three different t values as solution. t values that are in range $[t_0, t_0 + \Delta t]$ indicate a collision moment if they satisfy next equation:

$$\overrightarrow{\boldsymbol{AP}}(t) = u\overrightarrow{\boldsymbol{AB}}(t) + v\overrightarrow{\boldsymbol{AC}}(t) \tag{2.66}$$

If there are collision candidate t values to solution of Equation (2.65), we can use that t values in Equation (2.66) and solve Equation (2.66) as a linear system of equations. Resulting u and v values must satisfy following conditions: $u\epsilon[0,1]$ and $v\epsilon[0,1]$ and $0 \leq u + v \leq 1$. If u and v satisfy conditions that means collision point is in triangle.

For edge-edge pair points of first edge are $\boldsymbol{A}(\overrightarrow{t})$ and $\boldsymbol{B}(\overrightarrow{t})$, and points of second edge are $\boldsymbol{C}(\overrightarrow{t})$ and $\boldsymbol{D}(\overrightarrow{t})$ with velocities $\boldsymbol{V}_A$, $\boldsymbol{V}_B$, $\boldsymbol{V}_C$ and $\boldsymbol{V}_D$. Following equations need to be solved in a similar fashion to solution of point-triangle pair:

$$(\overrightarrow{\boldsymbol{AB}}(t) \times \overrightarrow{\boldsymbol{CD}}(t)) \cdot \overrightarrow{\boldsymbol{AC}}(t) = 0 \tag{2.67}$$

$$u\overrightarrow{\boldsymbol{AB}}(t) = v\overrightarrow{\boldsymbol{CD}}(t) \tag{2.68}$$

Equation (2.67) is a third degree polynomial equation and solution can have three unique t values. It is possible to use resulting t values in Equation (2.68) and solution must satisfy following conditions to be accepted as a collision candidate: $u\epsilon[0,1]$ and $v\epsilon[0,1]$ and $[t_0, t_0 + \Delta t]$.

Each detected candidate collision can create a collision in future at specified time. However, one collision can alter future. For example a collision at time 0.001 can prevent a next candidate collision of time 0.02 from happening or can create new candidate collisions which was not detected before. It is possible to choose collision candidate with smallest t value and prevent it from happening and make another collision detection phase to find out if any collision can be detected for future [17]. However, running multiple phases like this can have drastic impact on simulation if many collisions going to happen in same time frame. For cloth it is common to have many collisions at the same time. So using this methodology is only useful if simulation does not need to run in real time.

Another methodology is preventing all collisions from happening at same time [16, 18]. Preventing is done with altering velocities of points that will interact in collision. However, solving all collisions at the same time is a violation of chronological simulation. So there is a probability simulation has created new collisions, therefore, simulation must repeat collision detection phase and solve remaining collisions. However, this repeated solving phases may not converge because simulation is not solving them chronologically. When amount of repeating cross a certain threshold value, that means collision phase will not converge. In this situation, we can rigidify cloth vertices which participated in collisions. This way collision system will think rigidified vertices as a rigid object and not as a deformable. With rigidify methodology, system can solve collisions temporarily [16, 18]. It must be noted, rigidify methodology is not accurate as much as chronological collision solving and needed only when system is not converging.

Triangle based systems don't have any thickness, when a collision candidate detected and if there is no time to prevent it from happening (t = 0), a solution to the problem becomes hard to find. Numerical errors at calculations can help this to happen faster, so using a numerically robust technique can help [19]. However, even with numerically robust techniques, collisions can happen at t = 0 and in this situation, there is no way to prevent it from happening, because, it is already happening. Using impulses and repulsions can help to preventing collisions [18], but it is not guaranteed and collisions like this can happen. Having no thickness at triangles means simulation doesn't know how to separate them and can fail to make repulsions at correct directions. It is possible to use history based repulsions to give correct directions under this situation [20].

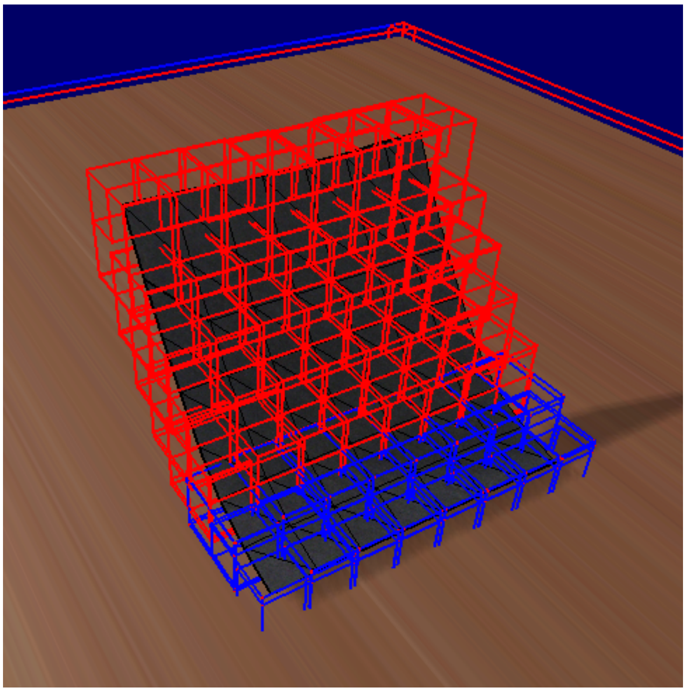

Figure 2.6: AABB around cloth and ground

Axis aligned bounding boxes (AABB) can speed up collision detection. In every collision detection phase, AABB information of vertices, edges, triangles and objects get updated. Past and current positions used at calculation of each AABB. For one pair, if their AABB is not colliding, this pair is not considered as a geometric collision candidate and simulation simply discards the pair.

Making simultaneous collision resolution [21] is another resolution method which can work in real time simulations and can be a fair alternative to method which we preferred to use.

2.7 Fracture

"Fractures are localized position discontinuities that arise due to the breaking of atomic bonds in materials" [22]. It is possible to detect these discontinuities and generate fractures as a response. Fractures can be result of tensile or compressive discontinuities. There are different approaches for detecting discontinuities [23, 24, 25, 3, 22].

Simplest approach is accepting long elongation as a discontinuity. It is very easy to implement this approach and resulting algorithm is very fast, because it involves only checking length of edges (springs in spring based simulations) [23, 26]. However, this method can create fractures while cloth is moving around (example is rigid motion), because only criteria to create fracture is checking length of edges.

Another approach is evaluating stress values and checking if values are higher than specific threshold values. Each vertex can be connected to more than one triangle. Therefore, while deciding to create a fracture over a node, using stress matrix of only one triangle and not considering attribution of neighbour triangles can lead to wrong results. Fracture algorithm must consider neighbour triangles too.

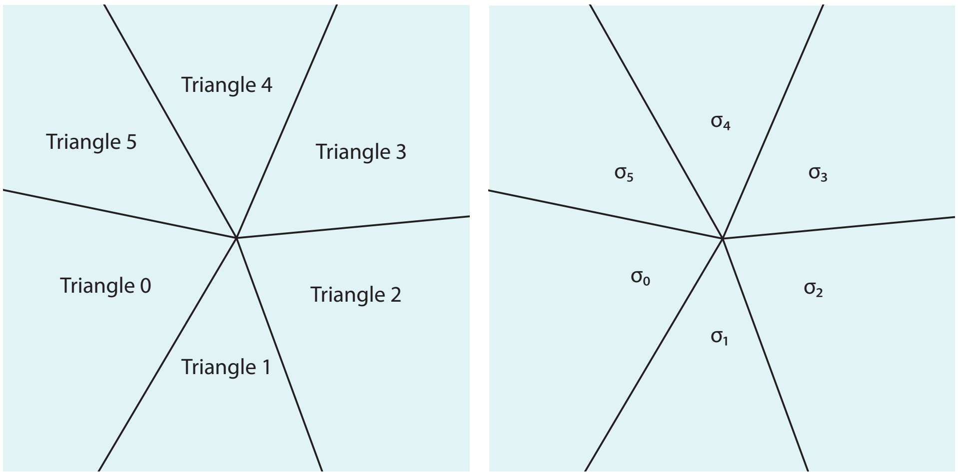

Figure 2.7: Triangles around a node with different stress values

Calculating mean value of triangle stresses around a node is an algorithm that consider attribution of neighbour triangles. However, using this method is not logical as much as it seems. A very small triangle can be neighbour with a very big triangle. Generally we name very small triangles as ill-shaped triangles, because having very low size leads to being ineffective against other triangles at the mean value calculation. For example, our small sized triangle can be stretched very much and as a result, can have very high stress. When we calculate mean stress around nodes, weighted contribution of small sized triangle is very low. Therefore, calculated mean stress becomes less than material elasticity limit, and it is not possible to generate fracture even tough, there is a very stressed triangle. This example scenario explains why it is not a good idea to use mean stress values.

Another method for continuum based simulations is calculation of separation tensor

[24]. In this method each vertex has a unique separation tensor that being calculated every iteration of simulation. This method has same vulnerability with mean stress calculation method. Main reason for this is separation tensor calculation is based on area size of the triangles. Small triangles have less effect on the main result. This problem also mentioned in paper [3].

Approach proposed at [3] uses stress values of triangles to calculate how much relief can be created with each possible fracture line. If a candidate fracture line can relieve enough stress around a node, simulation can create that fracture. Stress (σ) calculation does not depend on the size of triangles, so this method has an advantage at stress calculation over previous methods.

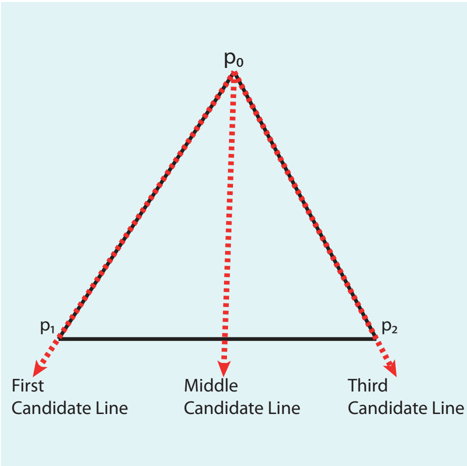

Figure 2.8: Candidate fracture lines for each triangle

A cloth vertex can be connected to one or more triangles as in Figure 2.7. There are infinite amount of candidate fracture lines along that vertex. However, simulation needs to find an optimal fracture line quickly. In paper [3], there is not any explanation on how to find an optimal line to create fracture. So we adopted a method that uses three candidate lines from each node to each neighbour triangle as in Figure 2.8.

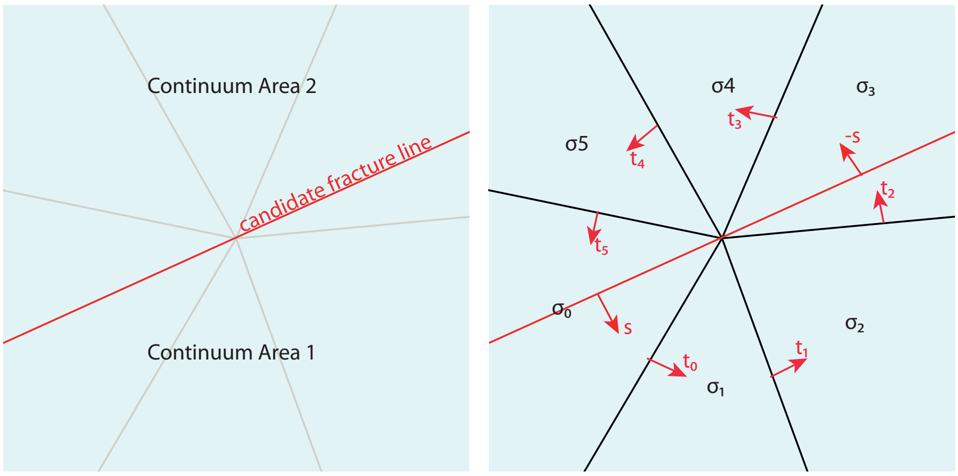

Figure 2.9: A candidate fracture line and tangent vectors of triangles

Candidate fracture line separates neighbourhood into two continuum areas as in Figure 2.9. Stress difference between two continuum areas along fracture normal line is what will be relieved if candidate turns into a real fracture. Stress of triangles already known due to Equation (2.60), therefore it is possible to calculate total stress of each continuum area. Algorithm needs to find candidate which will relieve highest amount of stress, so for each candidate line relief amount being calculated as follows:

$$\boldsymbol{q}_1 = \boldsymbol{\sigma}_0^+(\boldsymbol{t}_0 - \boldsymbol{s}) + \sum_{i=0}^{N-1} \boldsymbol{\sigma}_i^+(\boldsymbol{t}_{i+1} - \boldsymbol{t}_i) + \boldsymbol{\sigma}_N^+(-\boldsymbol{s} - \boldsymbol{t}_N) \tag{2.69}$$

Traction vector $\boldsymbol{q}_1$ is result of continuum area 1. In a similar fashion, it is possible to calculate traction vector $\boldsymbol{q}_2$ from continuum area 2. After calculating $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$, finally we can calculate relief amount under the name separation strength. If we subtract $\boldsymbol{q}_1$ from $\boldsymbol{q}_2$ result can generate fractures to unbalanced loads (rigid motion is an unbalanced load type). However, materials do not create fractures while moving around. Solution is usage of Equation (2.71), with this equation smallest common component will be calculated and only balanced loads will generate fractures.

$$\boldsymbol{q} = \hat{\boldsymbol{q}}_1 - \hat{\boldsymbol{q}}_2 \tag{2.70}$$

$$\zeta = min(\boldsymbol{q}_1 \cdot \hat{\boldsymbol{q}}, \boldsymbol{q}_2 \cdot \hat{\boldsymbol{q}}) \tag{2.71}$$

Candidate line with highest calculated separation strength (ζ) will generate a real fracture if its ζ value is higher than material (cloth) elasticity limit (toughness).

2.8 Anisotropic Fracture

Bonds between molecules keep materials together even when material is deformed. Surpassing elasticity limit destroys bonds between molecules and fractures start to appear. Contrary to continuum mechanics theory some materials are not continuous. For example, cloths are produced from threads called weft and warp. As we can see in Figure 2.10 cloths are very heterogeneous materials. Material elasticity is not constant through all areas. Anisotropic stretching and bending let us simulate cloth in a realistic way.

Cloth threads are individually weak. In daily life, common cloth failure type is tearing of one individual thread. The resistance of individual threads is called tearing strength, the resistance of cloth as a whole is called tensile strength. Taylor [29] studied strength difference between individual threads and cloth as a whole.

Shape of cloth pile can affect tensile strength and can maximize stress to one point [30]. When stress maximized on one point cloth does not resist stress as a whole, instead one or more individual thread resists all stress alone. As a result, stress maximization can tear individual threads. It is possible to use results of this study in a cloth simulation, however in a simulation like that each thread must be simulated individually. Our cloth representation model is not yarn based so we can not simulate individual threads.

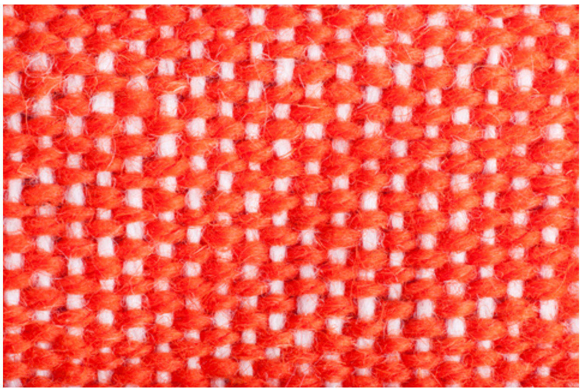

Figure 2.10: Woven wool

It is obvious that, one thread does not have strength as much as a tensile. Main reason for this situation is heterogeneous structure of cloth. Same heterogeneous structure makes cloths have different strength in different directions. Study [31] shows that there is strength difference between warp and weft (filling) directions of cloth.

Using a single strength value (isotropic) for whole cloth is not an accurate way to simulate tearing of cloth. As shown in study [31] cloth have anisotropic tensile strength. So anisotropic tearing data can increase simulation accuracy.

Study [32] uses anisotropic strength regions for solid materials in the simulation of solid materials. Region strengths selected with randomized seeding and selected strengths blended together to make region passings smoother. One person can manually assign very high strength values to regions and therefore, can make them 'no fracture regions'. These regions can be a shape that is hidden into deformable solid.

Another study [33] explicitly models 'advancing crack fronts' and creates influence over fractures by that way. Gathered results seem to be very complex and imaginable. However, methodology needs human interference with each new model and results are not accurate, but only seems to be realistic.

Liu [34] explicitly sets 'single vector field' for solids which enforces fractures appear along its direction. In a similar fashion [35] explicitly sets 'main fiber direction' for solids and it is the preferred direction for fibers. Influence of main direction becomes less with higher strain rate.

2.9 Cutting

Cutting is a physical phenomenon similar to fracture. There are different solutions to simulate the cutting behaviour. Simulation can use very high resolution meshes which will simulate objects nearly at atomic level. Continuum mechanics can handle the rest, tensile and compressive stresses will generate fractures and result will look like cutting due to high resolution of meshes. However, a simulation like this will not run in real time and will require very accurate calculations to properly simulate the required behaviour.

Real time applications such as video games require cutting to happen in real time. As mentioned in paper [27], cutting for deformable objects requires different algorithms than just simulating deformable objects. There are two questions which need an answer. Which objects can cut other objects and are there any required circumstances to create a cut.

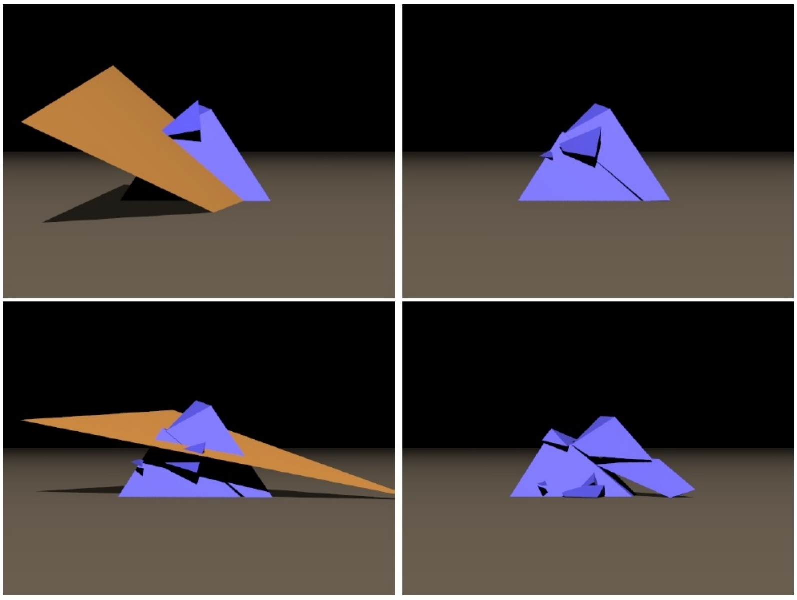

Figure 2.11: A single tetrahedron is progressively cut (retrieved from [27])

In the approach [27], there are two simulation primitives in the simulation. Simulation primitives are a tetrahedral deformable simulation object and a triangulated cutting surface as in Figure 2.11. Triangles of cutting surface used to generate an intersection free simulation state when cutting surface and deformable object is intersecting. Simulation even can start at intersecting state, because simulation takes action based on current status, not based on object movement and history.

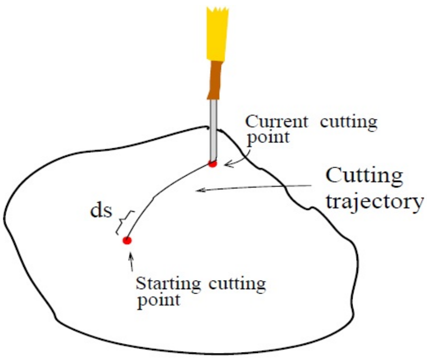

Figure 2.12: Cutting with tool (retrieved from [28])

Another approach is considering stress of deformable object while a cutting object moving inside of that deformable object [28]. A cutting attempt only considered valid if cutting tool made a considerable movement and there are enough stress in the cutting trajectory. Approach visualized in Figure 2.12.

CHAPTER 3

PROPOSED METHOD

This chapter describes the proposed method which we are using to create variation over tensile strength values. Then, we explain selecting best tear candidate upon many candidates. We describe how to use sharp nodes and edges with a cutting methodology. Chapter continues with describing the user study that was conducted to analyse results of the simulation. Finally, in the last section, we give an overview of the simulation, which is a pseudo-code of the simulation.

3.1 Anisotropic Tearing

Previous works are not enough to simulate cloth tearing accurately, because different fracture directions can have different tensile strengths because of the anisotropic nature of the material. Therefore, explicitly giving constant values to regions or selecting only one main direction to influence system is not accurate enough. An accurate methodology needs to calculate unique strength values for every imaginable direction over cloth. Weft and warp threads of cloths generally have a symmetric pattern. We can construct an anisotropic tearing methodology based on the symmetric pattern.

We can collect data from four different directions as depicted in Figure 3.1, and use these data in the simulation to improve accuracy. $0°$, $45°$, $90°$, $135°$ line directions from a point over cloth, would cover all $360°$ continuum. Because, we assume that, cloth has a symmetric pattern. It is possible to collect more data from different directions to make simulation more accurate. However, adding more directions to system will increase data collection time.

In this methodology, every candidate fracture line has a projected direction over $360°$ continuum and degree between $0°$ and candidate fracture line needs to be calculated. At initialization of cloth, simulation already selected $\boldsymbol{V}$ initialization vector as $0°$ vector, so simulation can use $\boldsymbol{V}$ as base direction at calculations.

There is α degree between base direction ($\boldsymbol{V}$) and candidate fracture line ($\boldsymbol{C}$) as in Figure 3.2. It is possible to calculate α as follows:

$$determinant = \boldsymbol{C}_x \boldsymbol{V}_y - \boldsymbol{V}_x \boldsymbol{C}_y \tag{3.1}$$

$$\alpha = atan2(determinant, \boldsymbol{C} \cdot \boldsymbol{V}) \frac{360}{2\pi} \tag{3.2}$$

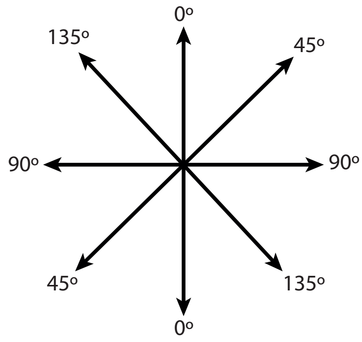

Figure 3.1: Data set directions

We need a positive α which is in the range $[0, 180)$, so we perform the following calculation:

$$\alpha = (\alpha + 360) \mod 180 \tag{3.3}$$

Fracture generation becomes possible when the candidate fracture line has higher separation strength value than the required separation strength of the material along that line. It is possible to calculate existing separation strength (ζ) along candidate line with Equation (2.71). However, required separation strength ($\Re$) to generate an actual fracture is unknown.

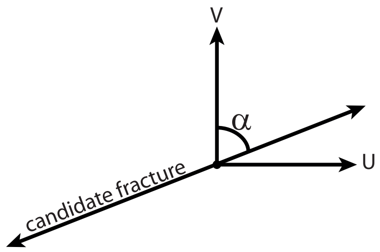

Figure 3.2: Degree between base direction and candidate fracture line

With α and anisotropic tear data of cloth, calculating $\Re$ is simple. First, it is required to have a data set as in example Table 4.1. If α is not one of the main direction values ($0°$, $45°$, $90°$, $135°$), interpolated value must be calculated. Resulting value is the required separation strength ($\Re$) to generate an actual fracture over that line.

Table 3.1: Example tear data set

Required Separation Strength For Main Directions		
Direction	Cloth 1	Cloth 2
$0°$	5.32	9.45
$45°$	6.48	10.16
$90°$	5.76	11.54
$135°$	8.13	10.28

3.2 Selecting Best Tear Candidate

Without tears, cloths will stay consistent in the simulation. However, when tearing is enabled, cloths will start to generate tears if conditions are satisfied. Simulation will generate tears only if there is higher separation value than required separation strength along one direction.

There can be multiple tear candidates at the same time in one iteration of the simulation. Simulation selects the best candidate among many and tears only selected candidate. The reason for selecting a single candidate is that, stress can be effecting many neighbours at the same time and generating multiple tears in the same iteration can lead to inaccurate results. Therefore, after every tear there must be a relaxation phase. Our relaxation methodology is waiting one iteration and checking separation strength in the following iteration.

Selecting one candidate among many requires a special methodology. Because, all candidates are not equal. Each unique tear direction can have different required separation strength due to anisotropic separation strength data. Therefore, some candidates can be better candidates even tough they have less separation strength than others.

An example situation is candidate line A have separation strength of 10 and required strength to create a fracture is 8, at the same time there can be another candidate line with name B which have separation strength of 20 with required strength of 19. So we must decide which one is a better candidate for a real fracture.

Our methodology at choosing is ranking them with percentages. Ratio of strength (ω) is the ratio of separation strength over required strength and this formulates a choosing methodology as follows:

$$\omega = \frac{existing \;\; separation \;\; strength}{required \;\; separation \;\; strength} \tag{3.4}$$

Candidate line with the highest ratio (ω) wins the competition and generates a tear in that iteration.

Now we can compare lines A and B of the previous example. Ratios for our example are $\omega_A = 1.25$ and $\omega_B = 1.053$. ω_A has higher ratio than ω_B, so candidate line A have better chance to become a real fracture.

3.3 Cutting

Tensile deformation based tears and cutting based tears are different phenomenons as discussed in background chapter. Simulation needs an approach to generate tears based on cutting. First, we need to define a cutting tool methodology. Any object that have nodes and edges should be able to cut deformable objects. To achieve that, we mark nodes and edges of rigid objects as sharp. Simulation loads rigid objects with sharpness info embedded on them. An example sword can be seen in Figure 3.3. Side edges and front node of sword marked as sharp. With this marking methodology, it is possible to make any edge or node sharp.

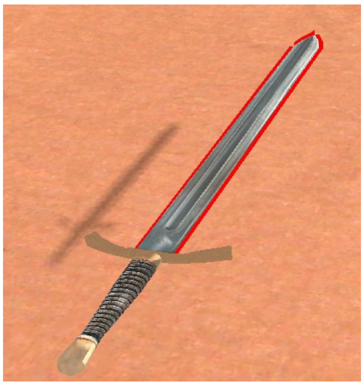

Figure 3.3: Sword as a cutting tool with sharp areas are visible in red

Our simulation uses a three pass collision resolution system as explained in [18] and in the background chapter of this thesis. First pass tries to prevent collisions based on proximity. Second pass solves collisions which first pass failed to prevent. Third pass solves remaining collisions with rigidify methodology. Only second pass is important for cutting. Because, second pass is the only section of collision system that actual collisions are being considered. Each collision of sharp edge - cloth edge and sharp node - cloth triangle couple being noted while collision system progress. Simulation analyses that noted couples after tearing stage. If a collision has enough impact power at collision point than cut can be generated. Minimum threshold value is selected according to nature of deformable material. This enables each cloth to have a unique resistance value.

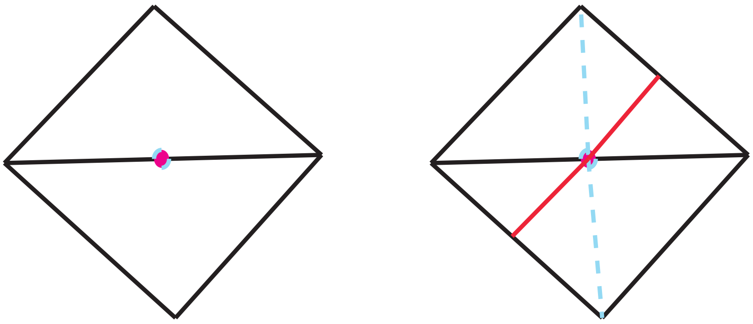

Figure 3.4: Edge - Edge cut

Collision point and direction of sharp edge are important at generation of edge - edge cuts. It is important to protect triangle consistency while cutting. Therefore, before generating an edge-edge cut, simulation subdivides triangle of the colliding edge based on collision point. New edges resulted from subdivision shown with blue lines in Figure 3.4. After subdivision, we create actual cut edges based on trajectory of sharp edge. Cut edges are shown with red lines in Figure 3.4.

Collision point is important at generation of node-triangle cuts. We create three new edges inside of cloth triangle. Cut edges, which are based on the collision point

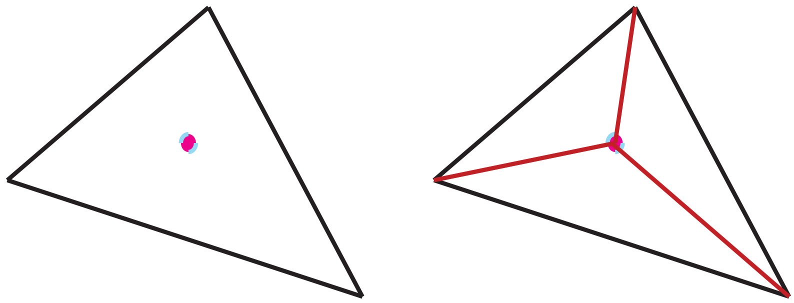

Figure 3.5: Node - Triangle cut

shown with red lines in Figure 3.5. Node - triangle cuts create three new triangles and remove the old triangle in the process.

3.4 User Study

To find out whether usage of anisotropic tearing provides an improved user experience or not, a user study designed. There are three phases in the questionnaire. Users watch four different cloth videos in the first phase. Each video is 15 seconds. In first 5 seconds, cloth moves under effect of wind. In the following 5 seconds, cloth makes movement to left and right. And in the final 5 seconds, cloth tears due to colliding object. Users vote how much realistic cloths were in the first phase. Following phase of the questionnaire contains six different videos of cloths. These videos are similar to videos of first phase. However, cloth textures are disabled in the videos of second phase. Users can guess cloth type from movements and tearing results of the cloth. In the final phase we ask how much effect movements and tearing have over cloth realism.

Our user study seeks an answer to following questions:

- Do users find cloth simulations realistic?
- Can users guess cloth type from movements and tearing results of cloth without seeing its own texture?
- Can users guess elasticity level of a cloth from movements and tearing results of cloth without seeing its own texture?
- Do users find animating cloth through elasticity based simulation important?
- Do users find tearing cloth through elasticity based simulation important?

Procedure of the user study can be summarized as follows: We informed users about the study. Then, they are sit in front of the computer that the experiment was being conducted on. The experiment included two applications; a web-based questionnaire and a video player to show prerecorded videos of the simulation. The questionnaire was designed to be self explanatory, so that it can be filled out by the participants easily. Cloth videos were shuffled for each experiment run, in order not to affect the results. The subjects were allowed to watch simulation videos only once so that the training effect was minimized among the subjects. The reason for this limitation is to find out what common players think when they see a cloth without training themselves about the nature of this cloth.

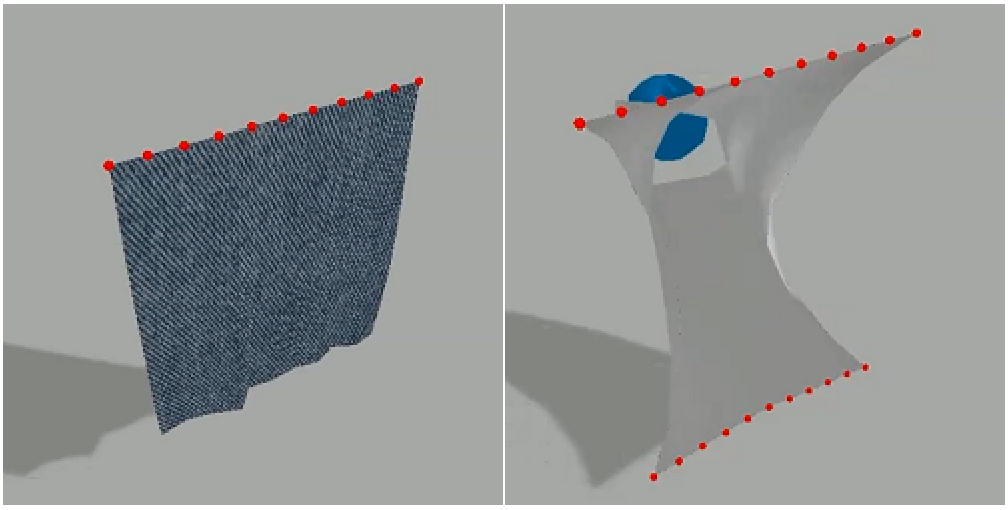

Figure 3.6: Screen captures from first step of the questionnaire

Material composition affects cloth behaviour. For example, if a denim has high spandex ratio in its composition, then it will be more elastic than normal denim. Therefore, giving cloth names is not enough. Questionnaire started with explaining material composition of cloths, so all participants knew what type of cloths they were dealing with. A copy of the questionnaire can be found in Appendix A.

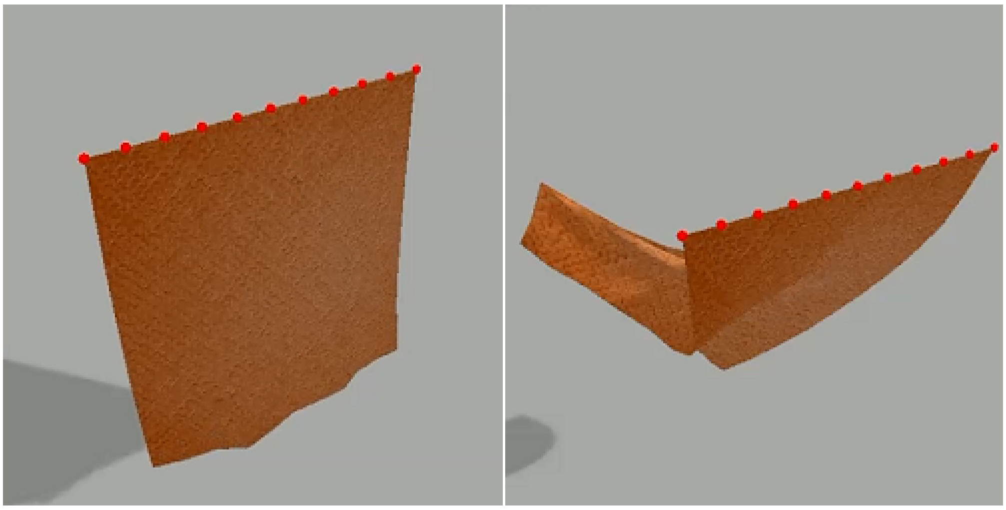

Figure 3.7: Screen captures from second step of the questionnaire

3.5 Simulation Overview

Cloth simulation forms a complex system when there are rigid objects included in the simulation. Simplified simulation algorithm as follows:

```
// initialization;
forall the objects do
    initialize nodes, edges, triangles;
    if object is deformable then
        calculate FEM related constants such as r_u and r_v;
    end
end

// simulation loop;
while simulation is running do
    forall the objects do
        reset value of force for all nodes;
        add gravity, wind values to force of nodes;
        if object is cloth then
            calculate stress with fem and add stress related force to nodes;
            calculate bending and add bending related force to nodes;
        end
        make implicit integration and calculate velocity and positions of nodes;
    end
    CollisionCount ← −1;
    while CollisionCount is not 0 do
        CollisionCount ← 0;
        forall the collision objects do
            update AABB of object;
        end
        For all edge-edge candidates if their AABB is colliding detect if they
        are colliding really. If so increase CollisionCount and resolve collision;
        For all point-triangle candidates if their AABB is colliding detect if they
        are colliding really. If so increase CollisionCount and resolve collision;
    end
    forall the cloth objects do
        Calculate positive stress of triangles;
        For each possible tear candidate calculate separation strength and
        calculate ratio of strength from separation strength and candidate
        orientation;
        if highest ratio of strength > 1.0 then
            Generate a fracture/tear along candidate line with highest ratio;
        end
        Make cut based tears;
    end
end
```

CHAPTER 4

RESULTS AND DISCUSSION

This chapter demonstrates results of the proposed method with four different experiments; interaction experiment, anisotropic tearing experiment, cutting experiment and gravity experiment. We show results of experiments with visuals and then discuss results of the experiments in detail. In the last section, analysis of user study covered. There are many hypothesises in this section and we try to prove them with statistical tests. Then, significant results of these tests discussed in detail.

4.1 Interaction Experiment

Collision with different rigid objects can lead to different results in the simulation. Because, each unique object has different design and different interaction area. In collision resolution, position of participating nodes have an important effect on the future of simulation. If we compare a sword and a hammer, swords have nearly infinitesimal area at sword point, but hammers have a very wide interaction zone. Therefore, hammer effects more cloth nodes while colliding with the cloth.

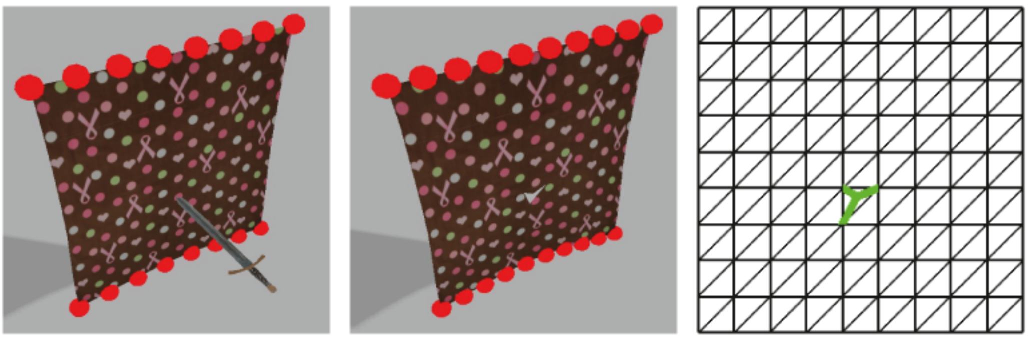

Figure 4.1: Sword pushed into cloth (Cut edges in green)

When we push sword and hammer into the cloth, results are different. Sword cuts cloth and then passes through it as in Figure 4.1. Hammer creates a stress zone over cloth while we are pushing it through the cloth. Hammer does not have any sharp area, as a result, tensile stress related tears start to appear and then hammer can pass through the cloth as in Figure 4.2.

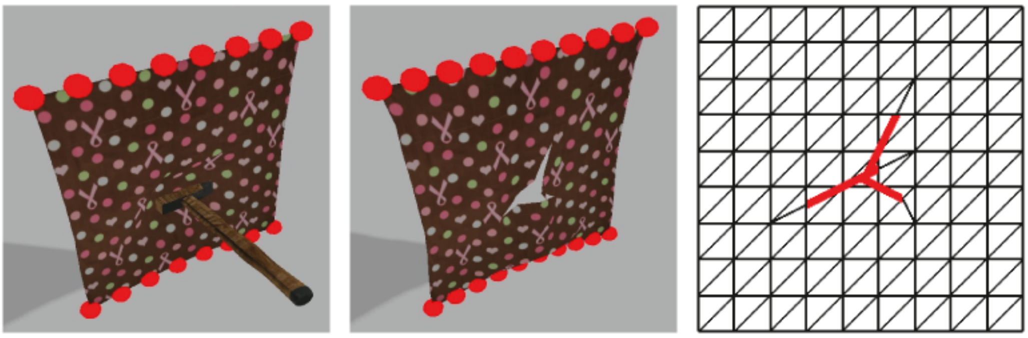

Figure 4.2: Hammer pushed into cloth (Tear edges in red)

4.2 Anisotropic Tearing Experiment

Each unique tear data set can lead to different results in same conditions. In this experiment, our target is showing effects of anisotropy. The following table has four different data sets for the experiment. First data set is isotropic, second data set is anisotropic and has very high value at $0°$, third data set is anisotropic and has very high value at $90°$, last data set is anisotropic and has relatively similar values.

Table 4.1: Experiment tear data set

Required Separation Strength For Main Directions				
Direction	Cloth 1	Cloth 2	Cloth 3	Cloth 4
$0°$	12.00	35.00	12.00	5.00
$45°$	12.00	25.00	25.00	7.65
$90°$	12.00	12.00	35.00	6.46
$135°$	12.00	25.00	25.00	7.98

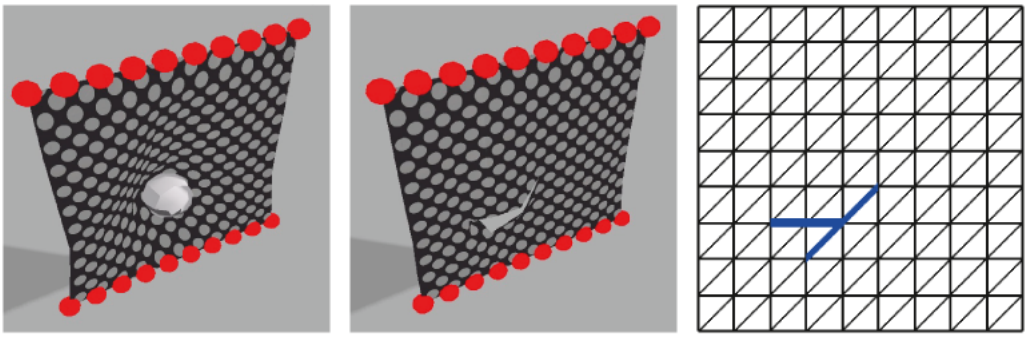

Figure 4.3: Ball versus cloth 1 (Isotropic)

Isotropic cloth can generate tears anywhere possible as seen in Figure 4.3. Because, all directions have same required separation strength value.

Vertically resistant cloth lead to a horizontal only tear as seen in Figure 4.4. This result is not surprising, because even with isotropic tear data resulting cloth had diagonal and horizontal tears. So adding more resistance to diagonal and vertical directions lead to a horizontal only tear.

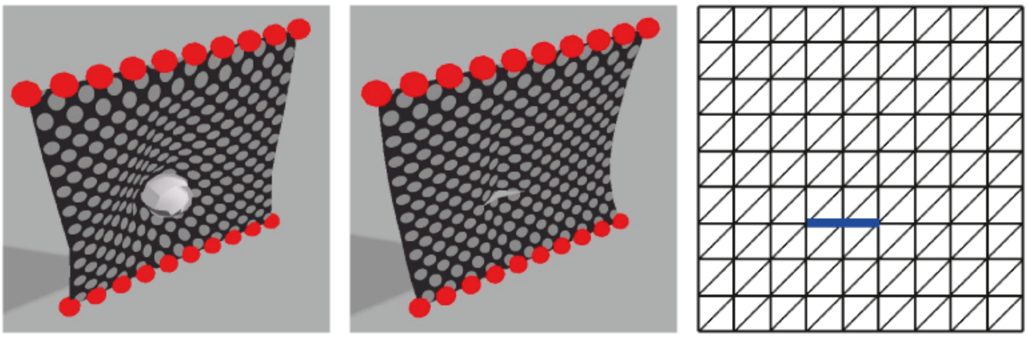

Figure 4.4: Ball versus cloth 2 (Anisotropic and vertically resistant)

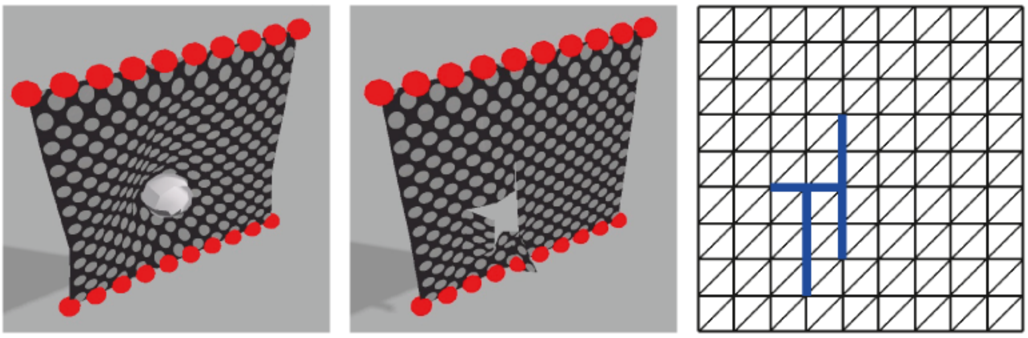

Figure 4.5: Ball versus cloth 3 (Anisotropic and horizontally resistant)

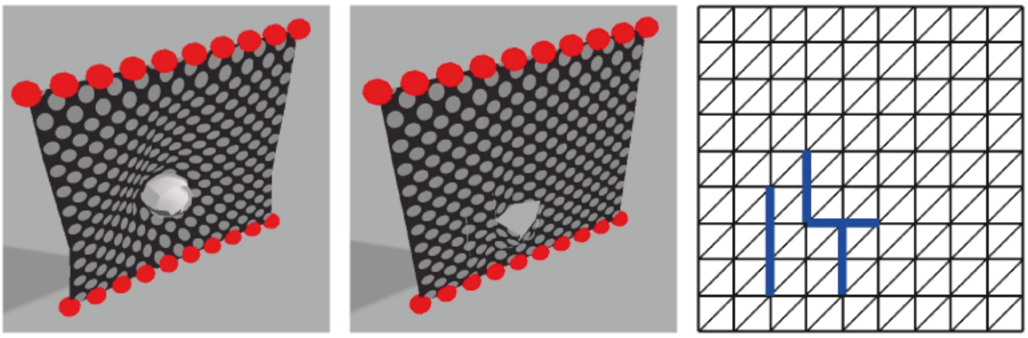

Figure 4.6: Ball versus cloth 4 (Anisotropic and vertically weak)

Horizontally resistant cloth have two vertical line tears and one horizontal tear connecting them as seen in Figure 4.5. Chronologically first vertical tears are created, after that cloth resisted until a horizontal tear can happen and did not let ball to pass through until that horizontal tear generated.

Vertically weak cloth have many vertical tears over cloth as seen in Figure 4.6. This data set has very low vertical resistance, so a result like this is not surprising.

In these experiments, ball collides with cloth under same circumstances and each of them have same tensile anisotropic elasticity. However due to different tear resistance data sets, we have different results at the end. It is entirely possible to alter future of simulation with usage of different tear data sets.

4.3 Cutting Experiment

Cutting add great value to cloth simulation. For example when we stab a cloth, simulation can generate tears based on node-triangle collision as seen in Figure 4.7. However if we disable cutting, same stabbing would need to push cloth forward until a tensile stress related tear generated, and this scenario would not be realistic.

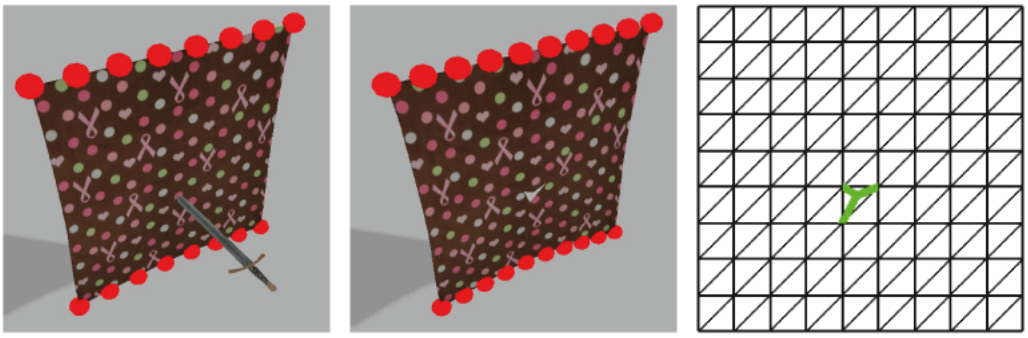

Figure 4.7: Node-Triangle based cut due to sword stabbing

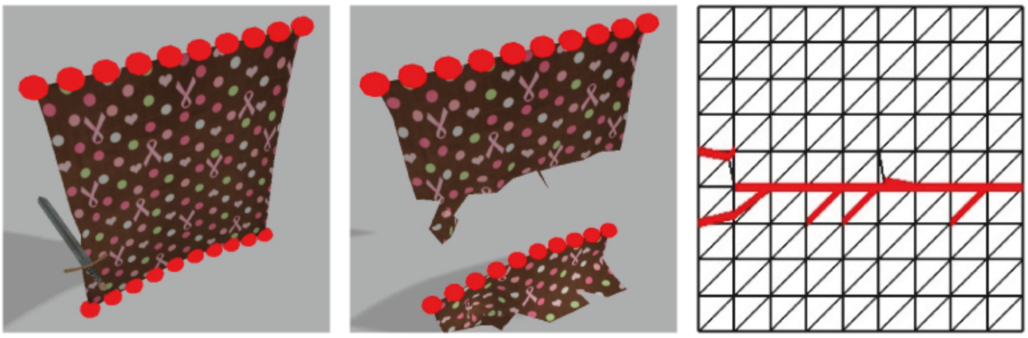

Figure 4.8: Edge-Edge based cut due to sword movement

When we try to cut cloth from side, sword makes many edge-edge based cuts as seen in Figure 4.8. When we use high delta time in the simulation, cloths respond to internal changes faster due to high internal forces. That means cloth moves faster due to cloth elasticity when used with high delta time. That situation causes more cuts than needed. Because, sword have higher chance at colliding with cloth while it is changing shape faster and that situation leads to unnecessary cuts. So it is ideal to make simulation a bit slower than usual to prevent unnecessary cuts when cutting is enabled in the simulation.

4.4 Gravity Experiment

In the gravity experiment, we expect to see if cloth add any realism to scene. We use cloth as a ceiling to some columns. That kind of structures generally appear at bazaars. In the experiment, we drop two balls over the structure, first ball have very low mass and second ball is ten times heavier than the first one.

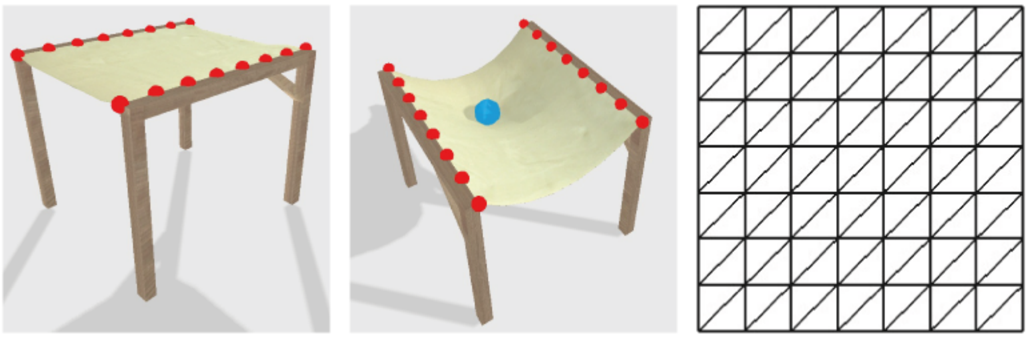

Figure 4.9: A lightweight ball stay above cloth ceiling while gravity is enabled

Figure 4.10: A heavy ball tears ceiling cloth due to gravity

The first ball does not seem to be heavy enough to generate tears at ceiling, it just stays over ceiling as seen in Figure 4.9. Second ball is very heavy and easily generates a horizontal tear at the ceiling and drops to ground as seen in Figure 4.10. Even without dropping something over ceiling, that structure seems to be alive. Cloth is not flat and gives response to wind. So usage of cloth at structures achieves adding realism into simulation.

4.5 User Study Results

Fourteen users participated in the user study. Following three subsections analyse gathered data with usage of statistical tests and then discuss significant results in detail.

4.5.1 Analysis of Cloth Realism

This section includes analysis results for step 'Vote Realism'. In this step, we asked how realistic cloths were. Frequency analysis conducted for all cloth types. Results suggest that, median value of pants and swimsuit higher is (4.50) than denim and t-shirt (4.00). Most of the participants chosen score 4 (Good) or score 5 (Very Good). For pants and swimsuit most repeating value is 5 (Very Good). All frequency results show positively skewed distribution. Participants found cloths realistic and preferred to give high scores according to results.

4.5.1.1 Denim Realism

Table 4.2: Denim statistics

N	Valid	14
	Missing	0
Median		4.0000
Mode		4.00

Table 4.3: Denim frequencies

	Frequency	Percent	Valid Percent	Cumulative Percent
2.00	1	7.1	7.1	7.1
3.00	4	28.6	28.6	35.7
4.00	7	50.0	50.0	85.7
5.00	2	14.3	14.3	100.0
Total	14	100.0	100.0	

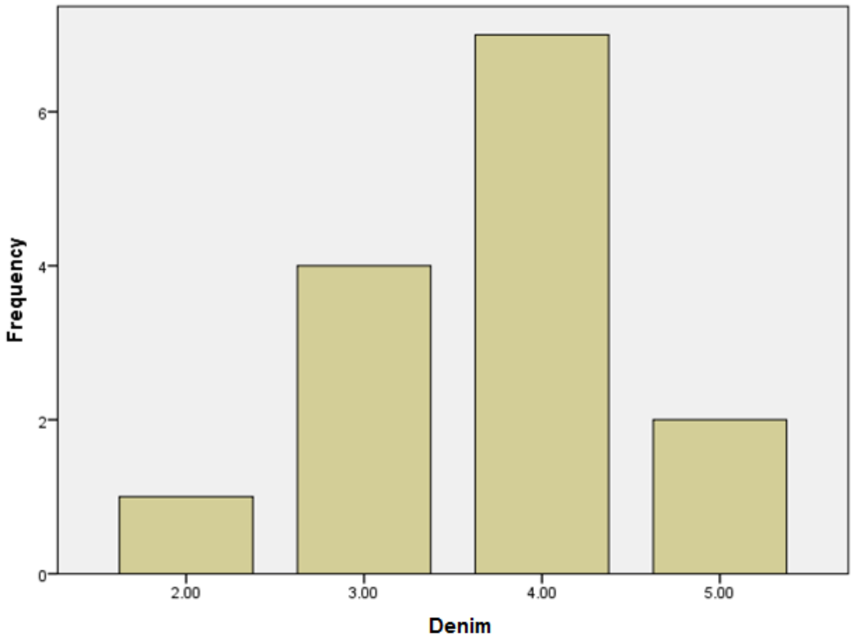

Figure 4.11: Graph of denim frequencies

4.5.1.2 T-shirt Realism

Table 4.4: T-shirt statistics

N	Valid	14
	Missing	0
Median		4.0000
Mode		4.00

Table 4.5: T-shirt frequencies

	Frequency	Percent	Valid Percent	Cumulative Percent
3.00	2	14.3	14.3	14.3
4.00	9	64.3	64.3	78.6
5.00	3	21.4	21.4	100.0
Total	14	100.0	100.0	

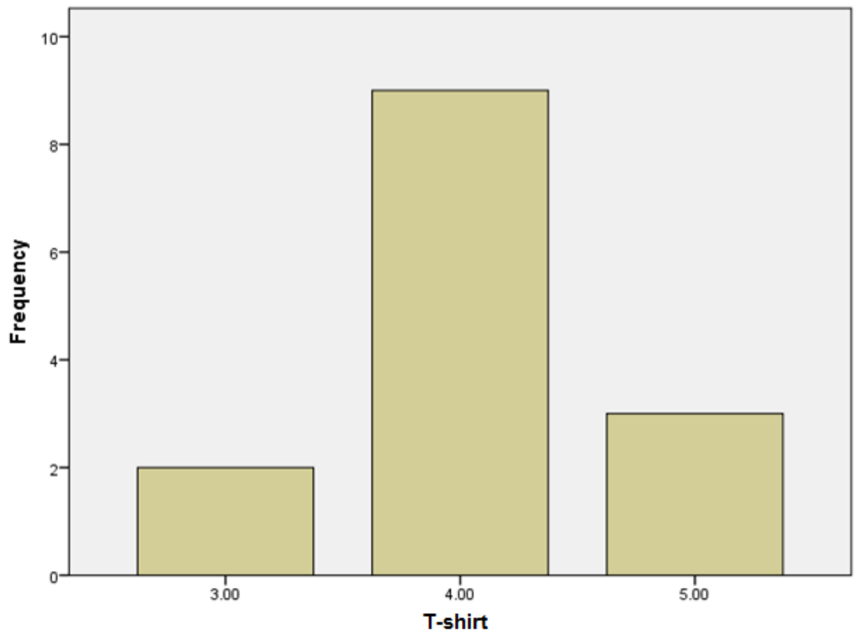

Figure 4.12: Graph of t-shirt frequencies

4.5.1.3 Pants Realism

Table 4.6: Pants statistics

N	Valid	14
	Missing	0
Median		4.5000
Mode		5.00

Table 4.7: Pants frequencies

	Frequency	Percent	Valid Percent	Cumulative Percent
3.00	1	7.1	7.1	7.1
4.00	6	42.9	42.9	50.0
5.00	7	50.0	50.0	100.0
Total	14	100.0	100.0	

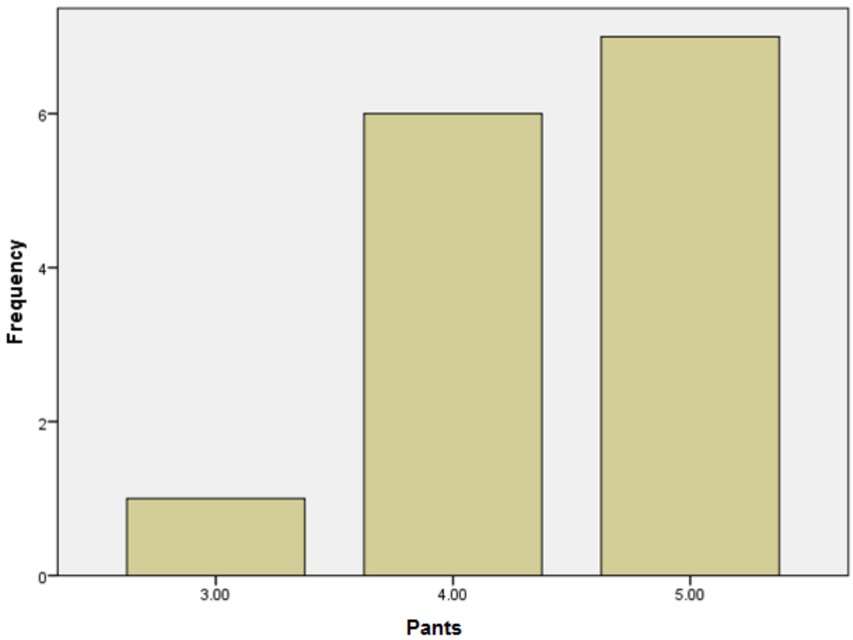

Figure 4.13: Graph of pants frequencies

4.5.1.4 Swimsuit Realism

Table 4.8: Swimsuit statistics

N	Valid	14
	Missing	0
Median		4.5000
Mode		5.00

Table 4.9: Swimsuit frequencies

	Frequency	Percent	Valid Percent	Cumulative Percent
3.00	2	14.3	14.3	14.3
4.00	5	35.7	35.7	50.0
5.00	7	50.0	50.0	100.0
Total	14	100.0	100.0	

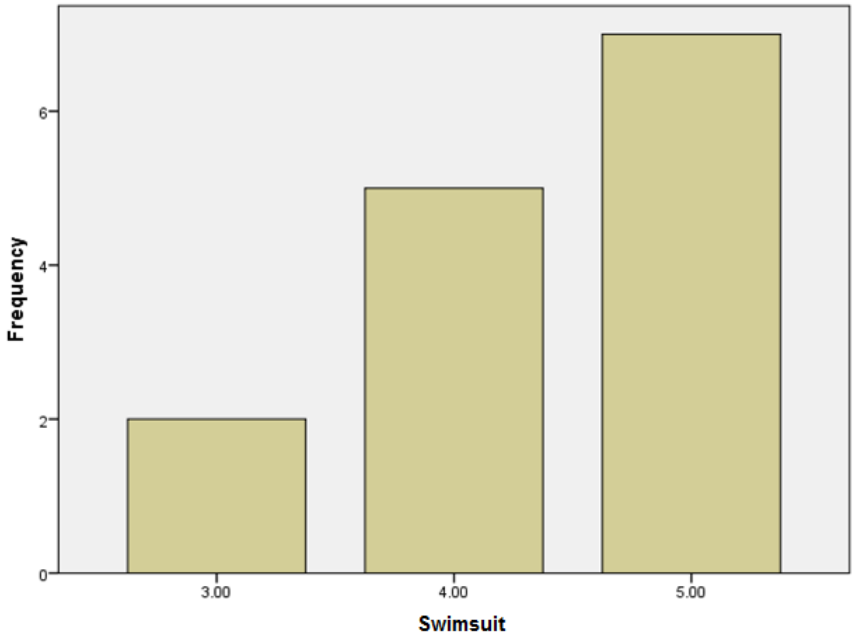

Figure 4.14: Graph of swimsuit frequencies

4.5.2 Analysis of Cloth Type Guessing

This section includes analysis results for the step 'Guess Cloth Type'. In the real world, it is possible to guess cloth type from look or just touching the cloth. However in the virtual world, only look and physical movements give insights about cloth type. Texture of simulated cloth is very important at giving initial insights to participants, other physical aspects (movements, tearing) just add supportive information. Disabling textures and making only supportive information available can show us how much participants can identify cloth type from only supportive information.

Table 4.10: Frequency data of cloth type guesses

Cloth Video	Denim	T-shirt	Pants	Swimsuit	Total
Cloth 1 (Denim)	5	4	4	1	14
Cloth 2 (T-shirt)	0	6	3	5	14
Cloth 3 (Pants)	4	1	7	2	14
Cloth 4 (Swimsuit)	2	3	1	8	14
Cloth 5 (T-shirt)	1	6	2	5	14
Cloth 6 (Denim)	6	4	2	2	14

'Friedman test' can show differences between correct guesses of different cloth types for Table 4.10. Similar to parametric ANOVA, we don't assume our sample is normally distributed. Data rewritten as in Table 4.11, if participant guess is wrong than data is 0, if guess is correct than data is 1, if participant gave one correct and one wrong guesses to duplicated cloths than data is 0.5. Cloths that have data collected twice (cloth 1 and cloth 6 are denim, cloth 2 and cloth 5 are t-shirt in Table 4.10) are called as duplicated cloths.

Table 4.11: Correct guesses data table for Friedman test

	Denim	T-shirt	Pants	Swimsuit
Subject 01	0.0	0.5	0.0	1.0
Subject 02	0.5	0.0	1.0	0.0
Subject 03	0.5	0.5	0.0	1.0
Subject 04	0.5	0.5	0.0	1.0
Subject 05	1.0	0.5	1.0	1.0
Subject 06	0.5	1.0	0.0	1.0
Subject 07	0.0	0.5	0.0	1.0
Subject 08	0.0	0.5	0.0	0.0
Subject 09	0.0	0.0	1.0	0.0
Subject 10	0.5	1.0	1.0	1.0
Subject 11	0.0	0.5	1.0	1.0
Subject 12	0.5	0.0	1.0	0.0
Subject 13	0.5	0.5	0.0	0.0
Subject 14	1.0	0.0	1.0	0.0

Hypothesis of Friedman test for Table 4.11:

H_0 = There is not a statistically significant difference between correct guesses for different cloth types.

H_1 = There is a statistically significant difference between correct guesses different cloth types.

Table 4.12: Rank results of correct guesses of Friedman test

	Mean Rank
Swimsuit	2.79
Pants	2.46
T-shirt	2.46
Denim	2.29

Table 4.13: Statistical results of Friedman test

N	14
Test statistic	1.366
Asymptotic significance	0.714

Results show that, there is not a statistically significant difference between correct guesses for different cloth types (Asymp Sig: 0.714 > 0.05) according to Table 4.13. And highest correct guesses given for swimsuit according to ranks Table 4.12.

4.5.2.1 Elasticity Based Groups

Some cloth types confused with other cloth types and that confusion seems to be following a pattern of failure if we look at guess data of Table 4.10. Subjects confuse cloths with other cloths that have similar elasticity level. Making another analysis based on this fact is possible, however we need to define what cloth types have similar elasticity level before starting the analysis.

Elasticity matrix C of Equation (2.59) have four variables that effect cloth elasticity; c_{11}, c_{12}, c_{22} and c_{33}. Each variable uses anisotropic data and is not constant. Data of these variables must be simplified, so we can compare them easily. Calculating mean value of each variable for each cloth type produces Table 4.14:

Table 4.14: Mean values for elasticity matrix variables

	c_{11}	c_{12}	c_{22}	c_{33}
Denim	223.288325	39.130220	1048.432643	69.412260
T-shirt	83.893843	67.652278	281.209530	22.680790
Pants	2094.145196	45.790863	2129.397111	58.980970
Swimsuit	50.024568	20.011822	113.431254	23.658169

Elasticity matrix C is used at calculation of stress matrix as in Equation (2.60). We can rewrite that matrix as following equations:

$$\sigma_{uu} = C_{11}\varepsilon_{uu} + C_{12}\varepsilon_{vv} \tag{4.1}$$

$$\sigma_{vv} = C_{12}\varepsilon_{uu} + C_{22}\varepsilon_{vv} \tag{4.2}$$

$$\sigma_{uv} = C_{33}\varepsilon_{uv} \tag{4.3}$$

There is huge difference at mean values of c_{11}, c_{22} and c_{33} when different cloth types compared. Swimsuit generating less stress to same strain value when compared to other cloth types. That means swimsuit will respond to changes slower, which means less rigid than others. T-shirt have higher mean values than swimsuit. Denim and pants have higher mean values than t-shirt and swimsuit. When we compare c_{12} values, t-shirt have highest mean value and that does not fit into comparison results of c_{11}, c_{22} and c_{33}. Variable c_{12} used in equations (4.1) and (4.2), in these equations c_{12} is small contributor, because c_{11} and c_{22} have much higher values than c_{12} as seen in Table 4.14. So based on c_{11}, c_{22} and c_{33} we can group cloths into two groups:

Group one: denim and pants

Group two: t-shirt and swimsuit

4.5.2.2 Analysis of Elasticity Based Groups

Correct guesses improved when we 'broaden the context' into a elasticity oriented cloth groups, however we will analyse this specific result later. First, we can test if there is a significant correct guessing difference between group one and group two. Our sample size is small and we don't expect normality, so we can use Wilcoxon signed rank test. Frequency data Table 4.10 rewritten as Table 4.15. Hypothesis of Wilcoxon signed rank test for data Table 4.15:

H_0 = There is not a statistically significant difference between correct guesses for group one and group two.

H_1 = There is a statistically significant difference between correct guesses for group one and group two.

Result of Wilcoxon signed rank test shows that, there is not a statistically significant difference between correct guesses for group one and group two (Asymp Sig: 0.096 > 0.05) according to Table 4.16.

Table 4.15: Frequency data of elasticity based group guesses

	Group one	Group two
Subject 01	2	2
Subject 02	2	2
Subject 03	1	2
Subject 04	3	2
Subject 05	3	3
Subject 06	3	3
Subject 07	2	3
Subject 08	0	1
Subject 09	1	3
Subject 10	3	3
Subject 11	1	1
Subject 12	3	3
Subject 13	1	2
Subject 14	3	3

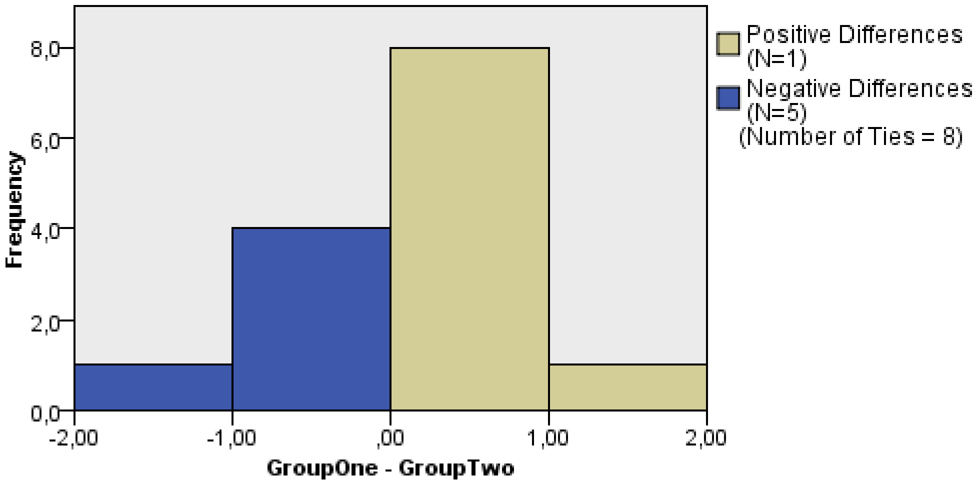

Figure 4.15: Frequency results of Wilcoxon signed rank test for elasticity based group guesses

Table 4.16: Statistical results of Wilcoxon signed rank test for elasticity based group guesses

N	14
Test statistic	3.0
Asymptotic significance	0.096

Previous test shows that, there is not a statistically significant difference between correct guesses group one and group two based elasticity. However, there can be statistically significant difference between cloth types when data grouped based on elasticity. Friedman test can show differences with usage of data Table 4.17:

H_0 = There is not a statistically significant difference between correct guesses for different cloth types based on elasticity groups.

H_1 = There is a statistically significant difference between correct guesses for different cloth types based on elasticity groups.

There is not a statistically significant difference between correct guesses for different cloth types based on elasticity groups (Asy Sig: 0.540 > 0.05) according to Table 4.19. And highest correct guesses given for swimsuit according to ranks Table 4.18.

Table 4.17: Correct guesses data table based on elasticity groups for Friedman test

	Denim	T-shirt	Pants	Swimsuit
Subject 01	0.5	0.5	1.0	1.0
Subject 02	1.0	0.5	1.0	0.0
Subject 03	0.5	0.5	0.0	1.0
Subject 04	1.0	0.5	1.0	1.0
Subject 05	1.0	1.0	1.0	1.0
Subject 06	1.0	1.0	1.0	1.0
Subject 07	0.5	1.0	1.0	1.0
Subject 08	0.0	0.5	0.0	0.0
Subject 09	0.0	1.0	1.0	1.0
Subject 10	1.0	1.0	1.0	1.0
Subject 11	0.0	0.5	1.0	1.0
Subject 12	1.0	1.0	1.0	1.0
Subject 13	0.5	0.5	0.0	0.0
Subject 14	1.0	1.0	1.0	1.0

Table 4.18: Rank results of Friedman test for correct guesses based on elasticity groups

	Mean Rank
Swimsuit	2.68
Pants	2.61
T-shirt	2.50
Denim	2.21

Table 4.19: Statistical results of Friedman test for correct guesses based on elasticity groups

N	14
Test statistic	2.162
Asymptotic significance	0.540

We found that, there is not a statistically significant difference between correct guesses of group one and group two. And there is not a statistically significant difference between correct guesses for different cloth types based on elasticity groups. These results mean, subjects guessed cloths at similar success levels and different cloth types or elasticity levels did not effect results.

Our claim is; correct guesses improved when we 'broaden the context' into a elasticity oriented cloth groups. Table 4.11 have correct data values only if participants guessed cloth type correctly, however Table 4.17 have correct data values if participants guessed elasticity group correctly. So we can compare guess results of each cloth type according to Tables 4.11 and 4.17. We made four different Wilcoxon test to see differences between two:

For denim we have gathered Table 4.20 and hypothesis is:

H_0 = There is not a statistically significant difference between correct guesses for denim cloth and correct guesses for denim cloth based on elasticity group.

H_1 = There is a statistically significant difference between correct guesses for denim cloth and correct guesses for denim cloth based on elasticity group.

For t-shirt we have gathered Table 4.22 and hypothesis is:

H_0 = There is not a statistically significant difference between correct guesses for t-shirt cloth and correct guesses for t-shirt cloth based on elasticity group.

H_1 = There is a statistically significant difference between correct guesses for t-shirt cloth and correct guesses for t-shirt cloth based on elasticity group.

For pants we have gathered Table 4.24 and hypothesis is:

H_0 = There is not a statistically significant difference between correct guesses for pants cloth and correct guesses for pants cloth based on elasticity group.

H_1 = There is a statistically significant difference between correct guesses for pants cloth and correct guesses for pants cloth based on elasticity group.

For swimsuit we have gathered Table 4.26 and hypothesis is:

H_0 = There is not a statistically significant difference between correct guesses for swimsuit cloth and correct guesses for swimsuit cloth based on elasticity group.

H_1 = There is a statistically significant difference between correct guesses for swimsuit cloth and correct guesses for swimsuit cloth based on elasticity group.

Results show that, when we broaden context into elasticity based groups all results effected positively as in Figures 4.16, 4.17, 4.18 and 4.19. According to p values of Tables 4.21, 4.23, 4.25 and 4.27, first three null hypothesises are rejected and null hypothesis of swimsuit is retained. These results tell us there is a statistically significant difference between two data sets and subjects guessing elasticity level better than guessing specific cloth types. For swimsuit data set, difference is not significant. Because, subjects already did guessed swimsuit at very high ratio before broadening context.

Table 4.20: Correct guesses for denim and correct guesses for denim based on elasticity group for Wilcoxon test

	Denim guesses	Denim guesses based on elasticity group
Subject 01	0.0	0.5
Subject 02	0.5	1.0
Subject 03	0.5	0.5
Subject 04	0.5	1.0
Subject 05	1.0	1.0
Subject 06	0.5	1.0
Subject 07	0.0	0.5
Subject 08	0.0	0.0
Subject 09	0.0	0.0
Subject 10	0.5	1.0
Subject 11	0.0	0.0
Subject 12	0.5	1.0
Subject 13	0.5	0.5
Subject 14	1.0	1.0

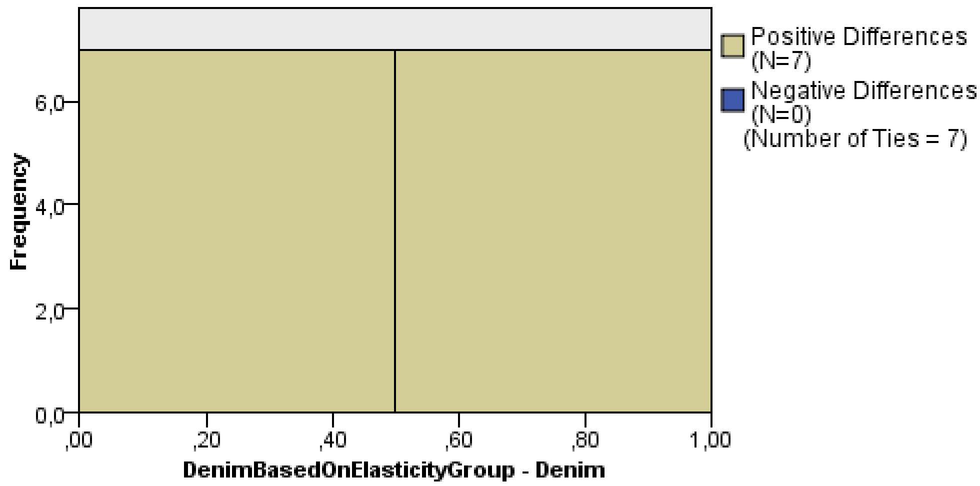

Figure 4.16: Frequency results of Wilcoxon signed rank test for denim guesses and denim guesses based on elasticity group

Table 4.21: Statistical results of Wilcoxon signed rank test for denim guesses and denim guesses based on elasticity group

N	14
Test statistic	28.0
Asymptotic significance	0.008

Table 4.22: Correct guesses for t-shirt and correct guesses for t-shirt based on elasticity group for Wilcoxon test

	T-shirt guesses	T-shirt guesses based on elasticity group
Subject 01	0.5	0.5
Subject 02	0.0	0.5
Subject 03	0.5	0.5
Subject 04	0.5	0.5
Subject 05	0.5	1.0
Subject 06	1.0	1.0
Subject 07	0.5	1.0
Subject 08	0.5	0.5
Subject 09	0.0	1.0
Subject 10	1.0	1.0
Subject 11	0.5	0.5
Subject 12	0.0	1.0
Subject 13	0.5	0.5
Subject 14	0.0	1.0

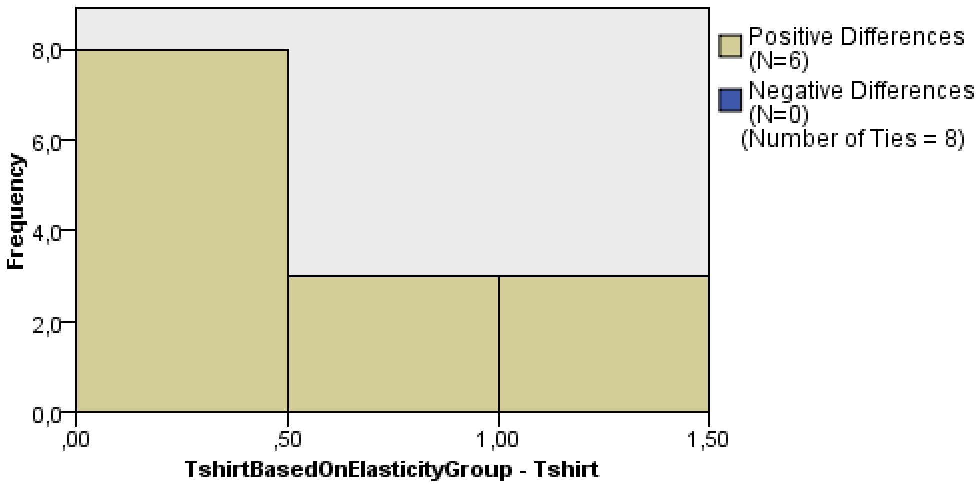

Figure 4.17: Frequency results of Wilcoxon signed rank test for t-shirt guesses and t-shirt guesses based on elasticity group

Table 4.23: Statistical results of Wilcoxon signed rank test for t-shirt guesses and t-shirt guesses based on elasticity group

N	14
Test statistic	21.0
Asymptotic significance	0.024

Table 4.24: Correct guesses for pants and correct guesses for pants based on elasticity group for Wilcoxon test

	Pants guesses	Pants guesses based on elasticity group
Subject 01	0.0	1.0
Subject 02	1.0	1.0
Subject 03	0.0	0.0
Subject 04	0.0	1.0
Subject 05	1.0	1.0
Subject 06	0.0	1.0
Subject 07	0.0	1.0
Subject 08	0.0	0.0
Subject 09	1.0	1.0
Subject 10	1.0	1.0
Subject 11	1.0	1.0
Subject 12	1.0	1.0
Subject 13	0.0	0.0
Subject 14	1.0	1.0

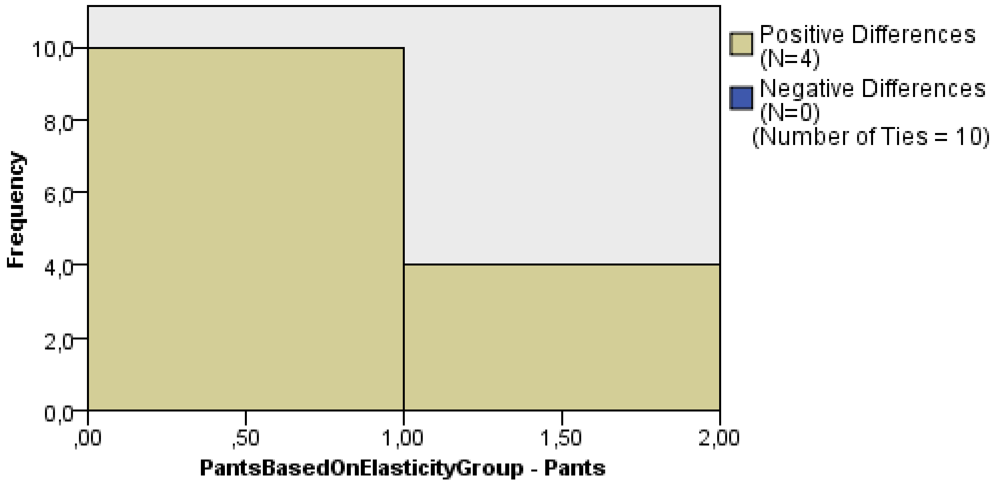

Figure 4.18: Frequency results of Wilcoxon signed rank test for pants guesses and pants guesses based on elasticity group

Table 4.25: Statistical results of Wilcoxon signed rank test for pants guesses and pants guesses based on elasticity group

N	14
Test statistic	10.0
Asymptotic significance	0.046

Table 4.26: Correct guesses for swimsuit and correct guesses for swimsuit based on elasticity group for Wilcoxon test

	Swimsuit guesses	Swimsuit guesses based on elasticity group
Subject 01	1.0	1.0
Subject 02	0.0	0.0
Subject 03	1.0	1.0
Subject 04	1.0	1.0
Subject 05	1.0	1.0
Subject 06	1.0	1.0
Subject 07	1.0	1.0
Subject 08	0.0	0.0
Subject 09	0.0	1.0
Subject 10	1.0	1.0
Subject 11	1.0	1.0
Subject 12	0.0	1.0
Subject 13	0.0	0.0
Subject 14	0.0	1.0

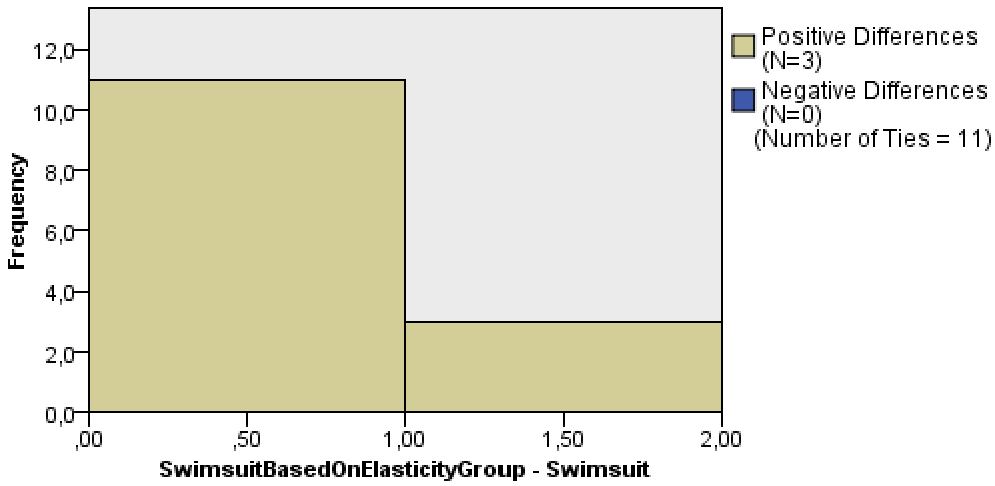

Figure 4.19: Frequency results of Wilcoxon signed rank test for swimsuit guesses and swimsuit guesses based on elasticity group

Table 4.27: Statistical results of Wilcoxon signed rank test for swimsuit guesses and swimsuit guesses based on elasticity group

N	14
Test statistic	6.0
Asymptotic significance	0.083

4.5.3 Analysis of Realism Components

This section includes analysis results for step 'Realism Components'. In this step we asked "How much effect cloth movements have over realism of cloth?" and "How much effect cloth tearings have over realism of cloth?" separately. We can analyse if there is a significant difference between these two concepts over cloth realism.

Table 4.28: Effect of movements over cloth realism

N	Valid	14
	Missing	0
Mean		3.929
Std. Deviation		0.997
SE Mean		0.27

Table 4.29: Effect of tearings over cloth realism

N	Valid	14
	Missing	0
Mean		4.214
Std. Deviation		0.699
SE Mean		0.19

Two-sample T-Test can show if there is a significant difference between these two concepts.

Difference = μ(Movements) - μ(Tearing)

Estimate for difference: -0.286

$\%95$ Confidence interval for difference: $(-0.959, 0.388)$

T-Test of difference = 0 (vs $\neq$): T-Value = -0.88 P-Value = 0.389 DF = 23

H_0 = There is not difference between movement and tearing over effecting cloth realism.

H_1 = There is difference between movement and tearing over effecting cloth realism.

Results show that, $P = 0.389 > 0.05$, so we can not reject null hypothesis, there is not significant difference between these two concepts over cloth realism. They have similar significance, which means tearing is important as much as elastic movements.

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this thesis, we proposed an algorithm to create a variety over tensile strength values with a data driven and anisotropic methodology. Method uses continuum mechanics to get realistic and accurate results. One contribution of the thesis is we demonstrated how anisotropic data can be used to simulate cloth tearing. We can manipulate data to simulate tearing of different cloth types. Therefore, results change according to cloth tear data as explained in the previous chapter.

Another contribution of the thesis is we introduced a cutting methodology and showed benefits and problems of this methodology. Our cutting methodology uses collision system to make cuts. Cutting normally requires very detailed meshes, compression based fractures and thickness for the cloth. However, these requirements not applicable for video games, our methodology removes these requirements and mimics same behaviour in real time with usage of sharp tagged primitives.

The finite element method is a common technique to simulate soft bodies. It is easy to implement FEM and there are many video games using FEM. Video games generally use triangle based polygonal models to render objects, that makes our triangular cloth hierarchy directly usable in video games without any conversion. Video games need to convert existing polygonal cloth models into tetrahedron based cloth models when tetrahedron hierarchy in use.

Conducted user study shows that, tearing is important as much as elastic movements, it adds realism value to simulation. In near future, usage of advanced physical effects in video games will increase. Usage of tearing will be important as much as elasticity of cloths. Our research shows that, participants can recognize elasticity level of cloth easier than cloth itself. So it is possible to use the same data for different cloth types as long as its values similar to what is expected from these cloths.

5.1 Future Work

Cloths use estimated separation strength data in the results chapter of the thesis. It is possible to collect cloth separation strength data from real world experiments. It can be used to compare out simulation results to real world examples.

As mentioned in background chapter, there is not any optimal algorithm to find candidate fracture lines quickly. Simulation had to try many candidate directions for each node and each triangle to find out the best candidate among them. It is possible to find out a new algorithm for detecting best candidate in a short time span as a future work.

In this thesis, our user study targeted common people without separating them into categories. It is possible to target hardcore players, cloth experts, non players, etc. Therefore, these user studies can give a clear idea about what is expected from simulations and quality of the simulations.

In video games, tearing effects are generally designed by artists and they are premade meshes. With simulated tearing effects, it is easier to show cloths have been damaged. However, there are many questions like; which cloths should tear, would clothes of characters tear, with what reason cloths should generate tears. Answers are important because players will expect balanced results and making all cloths are tearable can generate undesired results. Usage of tearable cloths in video games can be another topic for a study to answer these questions.

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APPENDIX A

CLOTH TEARING SIMULATION SURVEY

In this survey we expect to understand whether used simulation techniques improve simulation quality or not.

Expected completion time for the survey is 10 minutes.

You are free to leave at any given moment if you do not want to complete survey for any reason.

A.1 Details of Cloths

In the simulation, cloths use data of real world cloths (stretch, tear, motion data).

For example, when denim texture is used together with denim data, for users, it is easier to believe it is a denim cloth. Because physical motions are similar to real world equivalent.

You can see four different type of cloths below. Please take your time and try to become familiar with their textures and material composition.

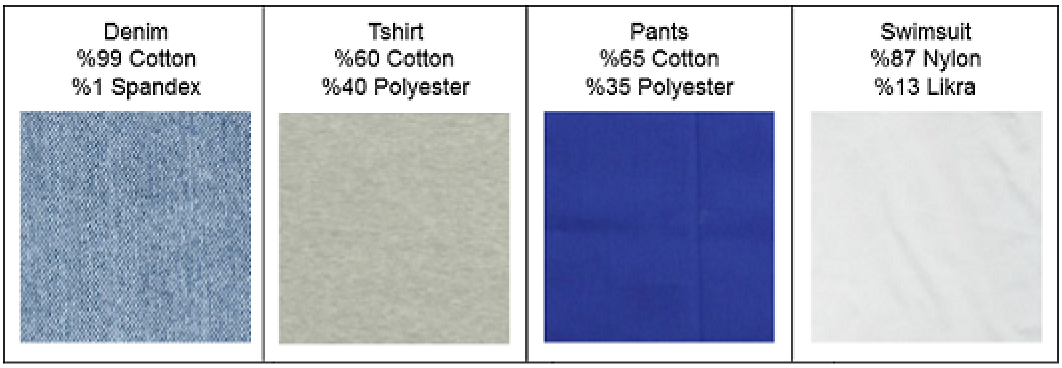

Figure A.1: Details of each cloth used in the survey

A.2 Vote Realism

First step of survey consists four different cloth videos.

Each video is 15 seconds. In first 5 seconds cloth moves under effect of wind. In next 5 seconds cloth makes movement to left and right. And in the final 5 seconds cloth tears due to colliding object.

Object, which is creating tears, is 20 kilograms and have an initial speed of 9 km/s. The object has enough kinetic energy to create tears over cloth.

Please watch videos with given order and vote them for how much realistic they were based on movement and tearing.

Table A.1: Vote realism for cloths

Cloth type	1 (Very Poor)	2 (Poor)	3 (Fair)	4 (Good)	5 (Very Good)
Denim					
Tshirt					
Pants					
Swimsuit					

A.3 Guess Cloth Type

In this step of survey, there are 6 different cloth videos to watch. However cloth texture are hidden on purpose and all are same. What is excepted from user is guessing what cloth type it can be based on movements and tearing results shown in each video.

Please watch videos with given order and guess the cloth type.

Table A.2: Guess cloth type

Video Index	Denim	Tshirt	Swimsuit	Pants
1st Cloth				
2nd Cloth				
3rd Cloth				
4th Cloth				
5th Cloth				
6th Cloth				

A.4 Realism Components

Table A.3: Effect of movements and tearings

	1 (Very Low)	2 (Low)	3 (Fair)	4 (Much)	5 (Very Much)
How much effect cloth movements have over realism of cloth?					
How much effect cloth tearings have over realism of cloth?					

End of survey. Thank you!