Physically-Based Facial Modelling and Animation with Wrinkles: 6 Month Report

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Abstract

Physically-based animation techniques enable more realistic and accurate animations to be created. As well as advancing the state of the art, physics-based techniques have received high levels of interest for applications requiring such high accuracy, like surgery simulation. In the context of facial animation, models often consist of muscle and skin models, sometimes with skull and wrinkle models. These models can have various representations, from vector muscles with a single-surface geometric skin mesh, to a complex physics-based muscle and layered skin model using techniques like the mass-spring (MS) or finite element (FE) method. Presented here is a brief review of relevant facial anatomy, and of techniques that have been used to create and animate physically-based facial and soft-body models, and to simulate skin wrinkles. Examples of simple physics-based skin implementations that have been created using the MS method, FE method and Nvidia PhysX (a popular physics engine) are also discussed.

1 Introduction

Facial modelling and animation is one of the most challenging yet vital areas of computer graphics. Facial surfaces are not only extremely complex, but any small inaccuracies of facial movement greatly reduce its realism due to our familiarity of how faces should appear and deform. Computational models of human or non-human faces, as well as being crucial in the films and games industries, are necessary for a range of other applications including low bandwidth teleconferencing, visual speech applications and facial surgery simulation. Since the pioneering work of Parke [Par72], there has been a vast amount of research with aims of generating more realistic and efficient facial models and animation.

Today, facial models, which can be represented using polygonal or parametric surfaces, or a volumetric representation, can be created using various techniques, such as using data from laser scanners or photographs, using anthropometric data, or interpolating between existing faces in a face space. Some popular animation techniques include key framing, with the help of processes like facial rigging, and parameterised, performance-based and pseudo-muscle animation. However, by using a *physically-based* model, incorporating an anatomically-based muscle model with a biomechanical facial tissue model, the effects of muscle contractions can be propagated through the facial tissue to automatically deform the model in a more realistic and anatomically correct manner.

Physics-based facial models often consist of *muscle* and *skin models*, sometimes along with a *skull model*, which enables factors like skull penetration to be accounted for. As studies suggest that wrinkles can greatly improve the realism of a face [CBCM09], *wrinkle models* to simulate wrinkles that aren't produced by the deforming skin model are sometimes also used. However, it is often the case that only the skin model is simulated using physics-based techniques, whereas simpler and more computationally efficient geometric models are used, for example, for the muscle and wrinkle models (e.g. [TW90, KHS01, ZST05]). Although there are numerous individual physically-based muscle models (e.g. [Wat87, SPCM97, NT98]) and skin models that can accurately reproduce wrinkles (e.g. [MTPKB$^+$02, FM08, KSY08a]), there are currently no known models that represent the whole face using physics-based techniques.

Various physics-based techniques exist for simulating deformable soft bodies. *Mass-spring* (MS) systems have been widely researched for use in interactive or real-time applications like games due to their efficiency (e.g. [TW90, KHS01, ZPS04, WYX+09]). However, their lack of accuracy has led to research into using the *finite element* (FE) method, a popular engineering technique, for facial simulations (e.g. [CLK01, SNF05, BJTM08]). Unlike the MS method, the FE method is based on continuum mechanics, making it more suitable for modelling continuous material like soft-tissue, and comparisons between MS and FE systems have shown this accuracy difference [HHR+03, KGKG98]. On the other hand, FE systems usually have high computational costs, making them less suitable for real-time or interactive applications. More recently, the *mass-tensor* (MT) method, which intended to be a compromise between computational cost and accuracy, has been used for physics-based soft-tissue simulations (e.g. [CDA00, MSNS05, KJW+10]), although little research on this method has currently been reported. Some *physics engines*, such as Nvidia PhysX[1], are also capable of simulating soft-bodies. PhysX uses an algorithm for animating soft-bodies that focuses on performance and stability for use in games, rather than accuracy [MHHR06].

The increased accuracy of physically-based facial simulations, particularly when using the FE method, over geometric models has led to them receiving particular attention in areas where such highly accurate simulations are a necessity, like surgical planning (e.g. [KRG+02, CLP03, GZDH04]). Recently, fast simulations using the FE method are becoming more of a reality, potentially expanding their use to more common applications like films and games. Increases in computational power and *GPGPU (General Purpose computation on the GPU) architectures* like CUDA[2], OpenCL[3] and Microsoft DirectCompute (part of the DirectX APIs[4]) that allow exploitation of powerful GPUs have allowed for huge improvements in computational speed of such simulations, which are now possible in real-time [LGK11, TCC+09].

The aim of this research is to develop a fast and accurate physically-based facial simulation method, focusing on the simulation of facial wrinkles. This could be used to, for example, greatly improve the accuracy and realism of facial animation in games and films. The following sections detail the research and experiments done so far, including sections studying the anatomy of the head, and existing models of muscle, skin, wrinkles, and complete facial systems. Existing software is also commented on. The final sections of the report explain the demos that have been programmed for experimenting with physics-based techniques, as well as the short and long term research plan. Further information about various sections in this report can be found online[5].

2 Anatomy of the Human Head

When producing a realistic physically-based facial model, it is important to accurately model biological structures of the head by which its appearance is determined, such as soft-tissue and the skull; therefore, understanding the anatomy of the head is essential. The human head is a complex structure of bones, cartilage, muscles, nerves, blood vessels, glands, fatty tissue, connective tissue and skin; however, there are currently no known models that simulate anatomy to this level of detail, and details that have little effect on the deformations produced are often excluded. Several relevant resources have been continuously referred to while completing the following sections [Far10, PW08, MTPKB+02, Fly07, Bar05].

2.1 Skin

In humans, skin is the largest and heaviest of the organs, covering the entire external surface of the body. As shown by Figure 1, two primary layers can be identified - the *epidermis* and the *dermis*, each of which are divided into several sublayers. The dermis rests on the *hypodermis (subcutaneous layer)*, which is not a part of the skin but consists of connective tissue that attaches the skin to underlying bone and muscle. While the structure of skin is similar all over the body, skin thickness varies, and various factors such as age, gender and hydration have an effect on the structure, texture and appearance of skin. The density of human skin is roughly $1100kg/m^3$ [Fly07].

[1] http://www.nvidia.com/object/physx_new.html
[2] http://www.nvidia.com/object/cuda_home_new.html
[3] http://www.khronos.org/opencl/
[4] http://msdn.microsoft.com/en-gb/directx/
[5] http://staffwww.dcs.shef.ac.uk/people/M.Warburton/research.php

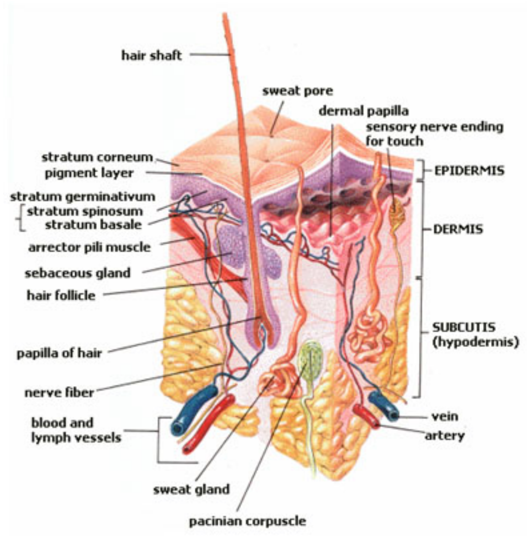

Figure 1: Diagram showing the general structure and layers of skin [web11].

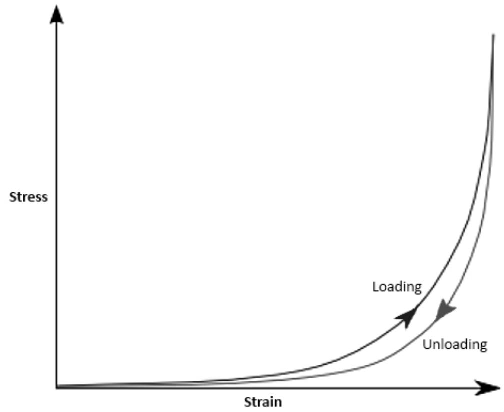

Figure 2: Graph of the stress to strain relationship in skin, also illustrating hysteresis.

2.1.1 General Mechanics of Skin

Each layer of the skin and the hypodermis differ in terms of structure and can be described by different material properties, although each layer has *non-linear*, *anisotropic*, *inhomogeneous* and *viscoelastic* properties. The elastic nature of skin refers to its tendency to return to its rest shape when an applied load is removed. The viscous nature of skin refers to the fact that the internal forces that are generated due to deformation are dependent on both the amount and rate of deformation. Other properties of skin due to its viscoelastic nature include:

- *Hysteresis* - The stress-strain curve during loading is different to that during unloading.
- *Stress relaxation* - The force opposing a deformation that is held constant reduces over time.
- *Creep* - Strain increases over time when under a constant load.
- *Preconditioning* - Repeated applications of the same load can result in different deformations.

Skin has an almost biphasic linear stress-strain relationship (see Figure 2), which is how many physically-based computer graphics models represent skin. On most areas of the face, it is roughly 1.5 to $2mm$ thick, with exceptions on particularly fatty areas such as the lips. It is composed of roughly 70% water, 25% protein and 5% lipids. Various studies have been conducted to explore and find numerical values for the mechanical properties of skin (e.g. [Hen05]). Barbarino et al. focussed on facial skin, using MRI scans and the inverse FE method to determine the mechanical properties [BJM11]. This study also validates the assumption of modelling each layer with uniform mechanical response and thickness (which is how all of the models in Section 3.5 are represented) through different facial regions. Such studies are extremely useful, and values found, such as Young's moduli, can be used directly with a FE skin simulation. Table 1 provides some numerical values for the mechanical properties of skin collected from various literature. It should be noted that, when describing material properties, the *Young's Modulus* is a measure of material stiffness often specified in pascals (Pa or N/m^2) or megapascals (MPa), and the *Poisson Ratio* is the ratio of transverse contraction strain to longitudinal extension strain of a material, where a ratio of 0.5 means the material is incompressible. The following subsections describe the structure and properties of different skin layers.

2.1.2 Epidermis

The epidermis is the outer layer of the skin. It varies in thickness over different areas of the body, from between around $50\mu m$ on the eyelids to around $100\mu m$ on the palms and soles. The epidermis can be divided into five layers, the thickest and most significant being the *stratum corneum* (the outer layer). The stratum corneum is a layer, around 10 to $20\mu m$ thick, of dead cells that consists

Resource	Soft-tissue Location	Properties
Wu et al, 1999	Face	**Average general skin elasticity and connective tissue parameters:** **Young's (MPa):** 10 (low strain), 100 (large strain), 0.008 (CT) **Poisson:** 0.333 **Thickness (mm):** 3
Magnenat-Thalmann et al, 2002 [MTPKB+02]	General	**Young's (MPa):** Young Skin: 6 (SC), 0.05 (D), 0.6 (H) Aged Skin: 12 (Dry SC), 0.05 (D), 1 (H) **Poisson:** 0.49 **Thickness (mm):** Young Skin: 0.015 (SC), 0.05 (D), 1.235 (H) Aged Skin: 0.015 (SC), 0.2 (D), 1.085 (H)
Flynn and McCormack, 2008 [FM08]	Forearm	**Young's (MPa):** 5 - 4000, about 240 at 75% relative humidity (SC) **Poisson:** 0.49 **Thickness (mm):** 0.02 (SC)
Kuwazuru et al, 2008 [KSY08a]	Face	**Young's (MPa):** Young Skin: 6 (SC), 0.136 (VE), 0.04 (PD), 0.08 (RD), 0.034 (H) Aged Skin: 12 (SC), 0.272 (VE), 0.04 (PD), 0.16 (RD), 0.034 (H) **Poisson:** 0.49 **Thickness (mm):** Young Skin: 0.02 (SC), 0.18 (VE), 0.2 (PD), 1.1 (RD), 2 (H) Aged Skin: 0.02 (SC), 0.08 (VE), 0.5 (PD), 1.1 (RD), 2 (H)
Beldie et al, 2010 [BWL+10]	Face	**Young's (MPa):** 0.015 (S), 0.00042 (CT), 0.0062 (M) **Poisson:** 0.49 (S), 0.495 (CT), 0.49 (M)
Kim et al, 2010 [KJW+10]	Face	**Young's (MPa):** 0.003 (CT), 0.79 (M, across fibre), 0.5 (M, along fibre) **Poisson:** 0.46 (CT), 0.43 (M)
Yin et al, 2010 [YGC10]	Fingertip	**Young's (MPa):** 3 (SC), 0.136 (VE), 0.08 (D), 0.034 (H), 17,000 (B) **Poisson:** 0.48 **Thickness (mm):** 0.15 (SC), 0.12 (VE), 1.16 (D), 3.86 (H), 4.2 (B)
Lapeer et al, 2011 [LGK11]	General	**Range of values for skin under varying amounts of strain collected from other literature:** **Young's (MPa):** 0.004 - 18.8 **Poisson:** Ideally 0.5

Table 1: A summary of mechanical properties of skin collected from various experiments and models of skin.
Key: SC: Stratum Corneum, VE: Viable Epidermis, PD: Papillary Dermis, RD: Reticular Dermis, H: Hypodermis, D: Dermis, CT: Connective Tissue, M: Muscle, B: Bone

mainly of the strong protein *keratin*, making it tough and flexible. It acts as a barrier to bacteria and to retain water in the skin, while helping to hold the skin firmly together. It is composed of roughly 60% proteins and 20% water, which contrasts to roughly 70% water composition in the rest of the epidermis. Its surface is covered by a network of small grooves and changes frequently as new epidermal cells are continuously pushed up from the stratum basale during differentiation, with each cell having a life cycle of around 45 to 75 days before it is shaved off. It has been found that modelling the stratum corneum has a large effect on the deformations produced by skin models, whereas the effects of the other epidermal layers are much smaller.

2.1.3 Dermis

The dermis is mainly composed of *collagen* and *elastin* fibres, and it ranges in thickness across the body from around $1mm$ to $3mm$. The upper, *papillary layer* is composed mainly of thin collagen fibres, whereas the thicker, denser *reticular dermis* is composed of thicker fibres. The interwoven collagen fibres are arranged curled up in bundles parallel to the skin surface. They are tough and contribute the majority of the mass of the skin, whereas elastin fibres provide elasticity and resilience. The sudden increase in stress when skin is being deformed is due to the stretching of collagen once it has been uncurled and aligned with the deformation.

2.1.4 Hypodermis and Deep Fascia

The hypodermis consists of loose connective tissue composed of fat cells and loosely arranged fibres. This viscoelastic composition allows skin to freely move around, and the elasticity enables the skin to be then brought back to place again; however, there is little reported data about its mechanical properties. The hypodermis is quite variable in thickness depending on many factors such as gender, age, nutrition and body position. Some parts of the face, such as eyelids and external ear, are fat-free and therefore contain no hypodermis. No clear boundary exists between the dermis and hypodermis. Connected to the hypodermis (also called the *superficial fascia*) is the *deep fascia*, which is a thin but strong and dense layer of fibrous tissue containing closely packed bundles of collagen fibres. The deep fascia surrounds structures like muscles, binding them together and, for example, connecting facial muscle surface to the skin.

2.1.5 Wrinkles

Two groups of wrinkles can be identified, which are expression and permanent wrinkles. *Expression wrinkles* are temporary and caused by the contraction of muscles. The direction of such wrinkles are perpendicular to the muscle's line of action. As humans age, their skin thins, dries, wrinkles and becomes unevenly pigmented. Permanent *aging wrinkles* start to form, particularly at points affected by a lot of stress. This happens as, with age, the elastic fibres of the skin become stretched, reducing the elasticity of the skin, and the change of the collagen fibres make the skin less homogeneous. Also, a loss in subcutaneous fatty tissue results in sagging skin and fallen nasal tips. Aging wrinkles can be grouped according to Glogau's classification of mild wrinkles (typically occuring between ages 28 and 35), moderate, advanced and severe wrinkles (typically occuring between ages 60 and 75) [Bra06]. The Fitzpatrick classification of wrinkle lines can be used to classify the degree of wrinkling around the mouth and eyes, from class I (fine wrinkles) to class III (fine to deep wrinkles with numerous lines) [Der10].

As well as age, other factors can also determine the properties of skin, which in turn determines the appearance of wrinkles; for example, females usually have softer and thinner skin than males, making wrinkles generally more pronounced in males [Bar05]. However, due to lower initial skin collagen content, women's skin appears to age earlier than men's, and it is suggested that women's skin appears around 15 years older than a man's skin of the same age throughout their adult life [Bar05]. Research also shows that wrinkling often appears in different areas according to gender; for example, women tend to develop more wrinkles in the perioral region around the mouth than men [PTKK09]. Factors such as sun exposure and smoking can damage the skin, causing permanent wrinkles to form, and factors including weight (particularly after losing subcutaneous fat, which happens naturally with age), skin moisture content and stress can also affect the structure of the skin, affecting the formation of wrinkles [Ken06]. Figures 10 and 11 in Appendix B illustrate some facial expression and aging wrinkles.

2.2 The Skull

The skull is a series of flattened or irregular bones that define the overall shape of the face. Apart from the mandible, the bones are immovably jointed together. The skull is divided into two parts - the *cranium*, consisting of 8 bones that enclose the brain, and the *facial skeleton*, which has 14 bones. The facial skeleton can be further divided into three sections - the upper third, consisting of the nasal bones and orbits, the central third, containing the maxillae, nasal cavities and nose, and the lower third, containing the mandible. Although it is the contraction of muscles that move the mandible, many physically-based animation approaches use a simpler approach of moving the mandible, which moves and deforms the muscles that influence it (e.g. [KHS01, ZPS04]). Most bones of the skull are either paired, or relatively symmetrical and cross the median plane (the plane which divides the face in an almost symmetrical manner), providing symmetry to the head. The average shapes and sizes of regions of the skull, including the proportion of the three facial skeleton regions, vary with gender and age [TMSP]. Figure 8 in Appendix A shows the different bones of the skull.

2.3 Facial Muscles

Muscles are contractile fibrous tissues responsible for the movement of body parts. Most facial muscles originate in the skull (muscle *origin*) and attach to the subcutaneous layer (muscle *insertion*), although some attach to just skin or just bone. Most of these muscles also have one origin and one insertion. When a muscle contracts, the insertion is pulled towards the origin. Although there are more than 50 muscles on the head (some of which can be considered groups of smaller muscles themselves), some deeper muscles are not anatomically considered as facial muscles, and some have little influence on facial deformation. These are therefore often excluded from models. Figure 9 in Appendix A shows the positions and shapes of the most significant muscles on the head.

Muscles of the face belong to the group of *skeletal muscles*. They contain bundles of cylindrical fibres (cells) that can span the entire length of a muscle. The perimysium surrounds these bundles, and each muscle is surrounded by the epimysium. Both of these are sheets of thin connective tissue that are part of the deep fascia. Thick, tough tissues called tendons, which are composed of around 86% collagen, are continuations of the epimysia, and these attach muscles to bones. Loose connective tissue attaches facial muscles to skin. There are two major modes of muscle contraction. Under isotonic contraction, the muscle shortens, whereas under isometric contraction, there is tension on the muscle but the muscle length stays the same (e.g. if a load is too heavy for the muscle to lift).

Contradictory to how most current physically-based facial models function, facial muscles interweave with one another and operate as a coordinated team, rather than contracting independently. Individual facial muscles can be grouped into two main groups - *muscles of expression* and *muscles of mastication*, with some muscles falling into both groups. There are also three different types of facial muscle that can be grouped according to the orientation of the muscle fibres, which are:

- *Linear/Parallel muscles* - Bundles of fibres sharing a common origin and pulling in a common direction.
- *Elliptical/Circular sphincter-type muscles* - Fibres that loop around orifices and squeeze towards some virtual centre.
- *Sheet muscles* - A broad, flat sheet of almost parallel fibres without a common origin, behaving like a series of linear muscles spread over an area.

As with the skull, most muscles that don't cross the median plane are paired. Most facial muscles are linear muscles. The three elliptical muscles of the face are the two *orbicularis oculi* around the eyes and the *orbicularis oris* around the mouth, each of which attach only to skin. A significant pair of sheet muscles that have a large effect on facial wrinkles are the two *frontalis muscles* on the forehead that lift the eyebrows. These muscles also have no bony attachment.

3 Physically-based Modelling and Animation Approaches

A physically-based facial model typically contains a muscle and a skin model. Low level inputs for animating the face are usually muscle contraction values for individual muscles that are used to deform the muscles and the skin they are attached to. Some previously developed systems have also provided higher level controls, for example, to specify facial expressions, which automatically adjust the lower level muscle controls (e.g. [TW90]). Although the skin model often produces some larger wrinkles as it deforms, a wrinkle model may also be used to produce additional wrinkling effects that aren't produced directly by the skin model. It is usually the case that the skin model is based on physics to some extent, for example, using a MS (mass-spring) or FE (finite element) model, whereas muscles and wrinkles are often simpler physical or geometric models. A geometric skull model is also an important part of physics-based facial models. The skull greatly influences the shape of the face while providing a useful boundary for the deformation of soft-tissue during animation (as the soft-tissue cannot penetrate the skull). It also provides a surface to which muscle origins can be attached, and enables more realistic and accurate jaw movement through a more anatomically correct simulation of the movement of the temporomandibular joint (e.g. [GHM+07, CRG+10]). Figure 3 shows the different levels of detail to which physics-based skull, muscle, skin and wrinkle models can be implemented, along with examples of currently implemented models. As of yet, there are no known models that represent the whole of a structure, such as the face, including wrinkles, using physics-based techniques.

The most widely researched physics-based techniques for facial animation are MS systems and FE models. MS systems are usually quite efficient and suitable for real-time animation; however, they are unable to model the exact properties of soft-tissue [KGKG98], and it is difficult to predict and generate the desired behaviour using such models. On the other hand, the FE method generally produces more accurate animations at the expense of increased computation and complexity. Unlike the MS method, the FE method is based on continuum mechanics, making it more suitable for modelling continuous materials like soft-tissue. There are also physics engines available that use different algorithms for simulating soft-body deformations. As these are mainly aimed at the games industry, they usually focus on performance and stability rather than accuracy, and they haven't been widely used in research for producing physics-based soft-body models. MT (mass-tensor) models have also been used for facial animation systems, although more work will be required within the forthcoming months of this project to explore and experiment with such models.

Table 2 summarises the similarities and differences between the MS method, the FE method, and Nvidia PhysX. This particular popular physics engine was chosen to further explore first as various comparisons and reviews have rated it better than several free, open-source alternatives with respect to the overall optimum accuracy, performance and stability [BB07, SR06], although popular commercial physics engines like Havok[6] are not included in these reviews. Some reviews are also available that explain in further detail methods like MS and FE for simulating deformable materials in computer graphics [GM97, NMK+06].

3.1 Time-Integration

No matter what physics simulation approach is used, a *time-integration* scheme is required to advance the simulation. The equation of motion of a dynamic simulation can be represented by the following second order ordinary differential equation:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f} \tag{1}$$

where $\mathbf{M}$ *is the mass matrix,* $\mathbf{C}$ *is the damping matrix,* $\mathbf{K}$ *is the stiffness matrix,* $\mathbf{x}$ *is the vector of displacements for each system degree of freedom, and* $\mathbf{f}$ *is the vector of external forces for each degree of freedom.*

MS systems often include additional terms, for example, for volume preservation of the system. To simulate a system, initial positions $\mathbf{x}$ and velocities $\dot{\mathbf{x}}$ for each node are required, as well as any constraints (e.g. to prevent movement of nodes that are attached to the skull). The simulation can then be advanced forward in time.

There are two main types of time-integration schemes - *explicit* and *implicit* [NMK+06]. Explicit schemes directly compute values at the next time-step using the known values for the current time-step, whereas implicit schemes use both the values for the current and next time-step and require an iterative solver. As explicit schemes project blindly into the future, they are conditionally stable and require a satisfactorily small time-step, whereas implicit schemes are unconditionally

[6] `http://www.havok.com/`

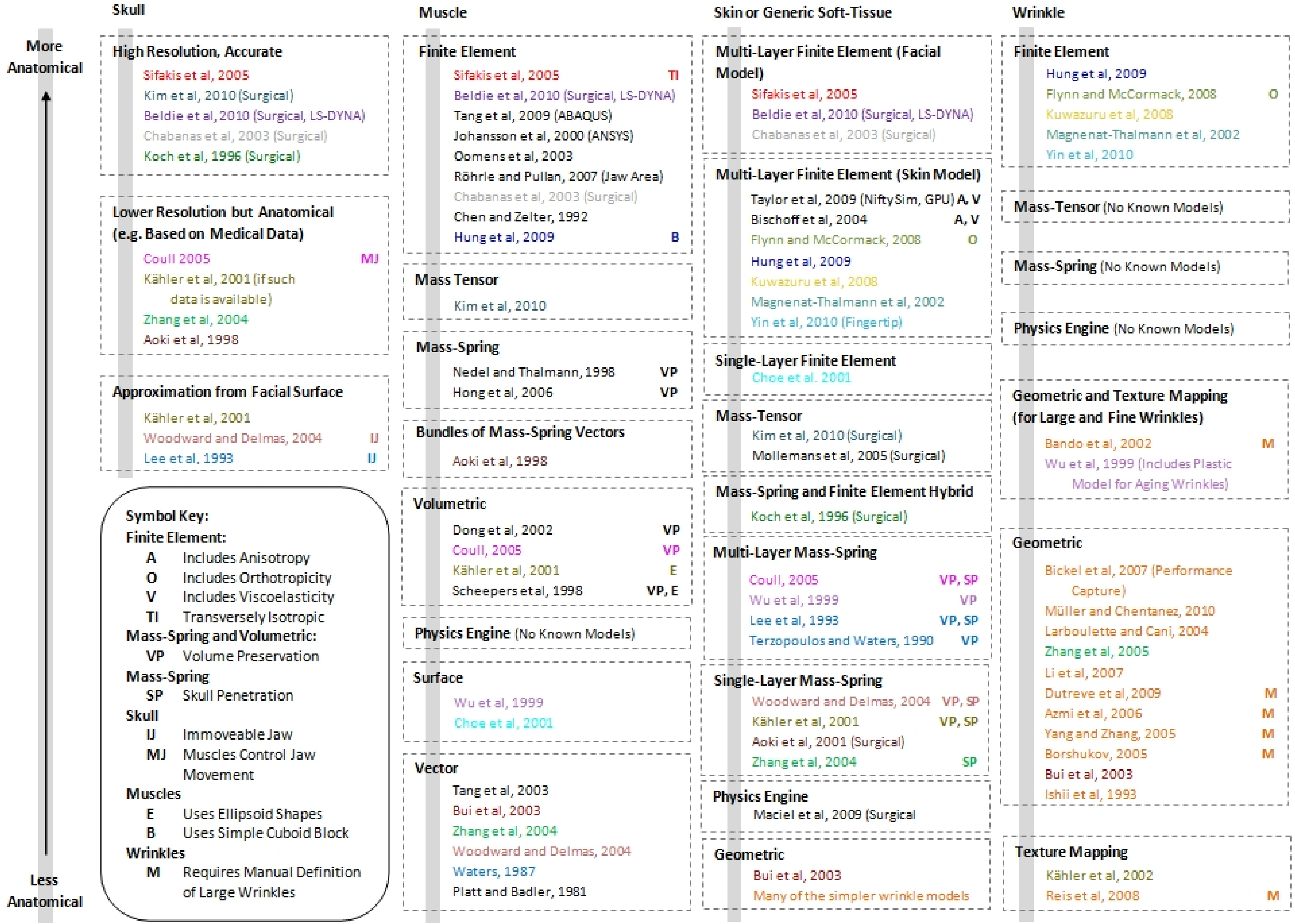

Figure 3: The different levels of detail to which aspects of physically-based soft-tissue models can be implemented. References to some examples of physics-based soft-tissue animation systems are included and colour coded to show the techniques used to create the aspects (skull, muscles, skin and wrinkles) included in their models. For example, the system by Lee et al, 1993 [LTW93], used an approximation of the facial surface for a skull, Waters' vector muscle model [Wat87], and a multi-layer mass spring soft-tissue model. The examples within the sub-categories are ordered approximately by their level of anatomical accuracy, although the level of difference within each sub-category varies.

Criterion	Mass-Spring	Finite Element	PhysX
Accuracy	**(2)** Although formulae from classical physics are used, such as Hooke's law for spring deformations (elasticity), the biomechanics of skin cannot be accurately represented by a structure of point masses connected by springs, as skin is a continuous structure.	**(1)** Based on continuum mechanics, this method can accurately simulate deformations of continuous surfaces and volumes. Provided the correct material properties are simulated, the accuracy is limited only by the mesh resolution and element interpolation functions.	**(3)** Efficient algorithms based on physics are used, rather than implementations of computational physics procedures, resulting in less accurate estimates of deformations.
Computational cost	**(2)** Although techniques like volume preservation and prevention of edge collapse make the method more complex, MS systems are usually capable of producing real-time animation.	**(3)** Even simpler models of isotropic materials are often slower than real-time (unless GPGPU is used).	**(1)** PhysX uses a time-integration algorithm designed for performance and stability which uses constraints to directly modify positions without having to calculate forces or velocities first.
Stability	**(3)** High spring stiffnesses have a large effect on stability, despite the time-integration algorithm used.	**(2)** FE systems tend to be more stable than MS systems, although this also depends on parameters such as material stiffness.	**(1)** As the time-integration algorithm directly modifies positions, it is stable for even large time-steps.
Ease of material definition/parameter specification	**(2)** Stiffness parameters, especially for complex materials like skin, can be difficult to get right to correctly simulate the desired material, although algorithms are available for automatically determining anisotropic MS model parameters according to reference models [BHS03].	**(1)** Parameters for creating models are usually known as they have physical relevance (such as Young's modulus) and can be calculated from laboratory experiments.	**(3)** Like with MS, parameters can be difficult to get right. Parameters like stiffness and volume preservation are based on values between 0 and 1 rather than real units.
Range of possible model materials	**(2)** Although non-linear anisotropic materials can be modelled, materials must be approximated by distributing the mass over point nodes rather than over a continuum. MS material properties are a subset of those that can be modelled using the FE method.	**(1)** A large range of material properties can be modelled accurately provided the correct material matrix is used.	**(3)** Only homogeneous isotropic soft-bodies can be created, although a workaround is to attach multiple soft-bodies together.
Estimated amount of work required	**(2)** MS systems are relatively simple to implement, although various techniques, such as volume preservation and spring incompressibility, are required for more accurate simulations.	**(3)** FE systems can become complex, particularly when including properties such as viscoelasticity, anisotropy and non-linearity. A lot of optimisation is also required to improve computational efficiency.	**(1)** A soft-body mesh can be simply created using the PhysX framework. The simulation and features like collision detection are handled by the framework. A tetrahedral soft-body mesh can also be automatically created from a triangular surface mesh using PhysX Viewer (included with the PhysX SDK).

Table 2: A summary comparison of the MS method, FE method and Nvidia PhysX soft-body deformations for modelling soft-tissue, including a ranking (where 1 is best and 3 is worst) that ranks each method according to the specified criteria.

stable but are more computationally expensive. Explicit methods that use many relatively inexpensive time-steps are usually sufficient and are popular for dynamic simulations.

The simplest and least computationally complex scheme is the forward Euler method; however, this method usually requires a very small time-step to converge to a solution. A simple improvement with no additional cost is the forward-backward Euler method, which uses forward Euler to calculate velocities, but then uses the updated velocities to calculate the displacements. A popular compromise between stability and complexity is the explicit Runge-Kutta method [PTVF07]. Shinya et al. described the cost and stability of MS systems using various time-integration methods, and proposed the linearised explicit Euler method - a more stable version of the explicit Euler method for linear systems [Shi05].

3.2 Skull Models

A simple low resolution skull model can be created as an offset from a facial surface (e.g. [LTW93, WD04]); however, the benefits of a more realistic high resolution skull model include increased accuracy when considering *skull penetration*, and more realistic muscle origin attachments. Such accurate muscle models are also necessary for many surgical systems which involve some form of bone displacement (e.g. [KGC+96, CLP03, BWL+10]). Skull models created with simpler animation systems sometimes have a non-rotatable jaw (e.g. [LTW93, WD04]); however, a *rotatable mandible* can greatly improve realism of actions involving jaw movement [ZPS04]. While many systems simplify the rotating of the mandible by using a simple geometric function, which in turn moves attached soft-tissue, in reality, muscles contract to move the jaw, which is simulated in Coull's animation system [Cou05].

3.3 Muscle Models

The first known work on physics-based facial animation integrated a simple muscle model into a single layer tension-net, which is a simple MS system [PB81] where muscles are represented as forces applied to regions of nodes. Waters later improved upon this by developing new 2D geometric muscle models for linear and sphincter muscles [Wat87]. A linear muscle is represented by a single vector that has a zone of influence defined by an angle and length, and a sphincter muscle is represented by a single centre point with an elliptical zone of influence. This vector approach was later extended to include sheet muscles [ZPS04]. Other variations on this model include representing linear muscles as quadrilaterals where the origin and insertion are line segments [CLK01], and using a *3D sphincter muscle* to allow effects such as 'pursing up' of the lips without considering collision detection [EM01, CLK01]. A vector muscle approach similar to Waters' muscle model has been used in the film industry by Pixar to animate the face of the baby, Billy, in the movie Tin Toy [PW08].

Although simple, vector muscle models are limited as the muscles have no volume within the soft-tissue model. As a real muscle deforms and its shape changes to preserve volume (e.g. when a muscle bulges due to contraction), this affects the shape of surrounding soft-tissue. Scheepers et al. developed volumetric muscle models to model arm muscles [SPCM97]. Ellipsoids are used to model muscle bellies as these can simply be scaled along three axes to simulate bulging while preserving volume and height-to-width ratio. More complex muscles can also be modelled using multiple muscle bellies. Kähler et al. developed muscle models that also use ellipsoid shapes but in a piecewise fashion to represent muscle fibres [KHS01, HKA+01, Käh03]. Similar to the non-volumetric 3D sphincter muscle models, effects such as 'tucking in' the lips can be simulated by also allowing sphincter muscles to move along a central axis, rather than being defined by a centre point. Unlike with the previous models, the intertwining of muscles is handled using springs to connect muscles together.

Coull used a similar muscle model to that of Kähler et al. with the main difference being that arbitrarily shaped volume preserving facial muscles can be defined [Cou05]. Linear muscles can also contain numerous origins and insertions, which is useful for modelling sheet muscles. Another muscle modelling approach also creates arbitrarily shaped geometric models, but these are based on anatomy and automatically created from anatomical data [DCKY02]. Muscles are grouped into categories with different volume preserving deformation models. Unlike the previous models, collision detection handles the interaction of muscles with other muscles and structures. Although more complex, this approach is likely to be real-time on modern computers.

Physics-based muscle models have also been developed. A simple MS muscle approach has been developed that is suitable for real-time applications [NT98]. Arbitrarily shaped MS muscles can be created, and the concept of *angular springs* was introduced to preserve muscle volume, although this introduces more parameters that can be difficult to correctly set. Additional behaviours like collision detection are handled using constraints. The FE method has also been used for accurately simulating muscle contractions but with increased computational cost. Chen and Zelter modelled muscles using isoparametric blocks with 20 nodes [CZ92, Che92]. When these elements deform, they also deform an underlying higher resolution mesh representing the actual muscle shape using free-form deformation. However, their approach used linear, homogeneous, isotropic materials for simplicity. Oomens et al. also developed a FE model of skeletal muscle using non-linear, isotropic materials, and, although the results were decent qualitatavely, quantitatively, the strains produced were too high [OMvO+03]. Other FE muscle models have been implemented using commercial FE packages (e.g. [JMB00, TZT09]).

Physically-based facial systems that use the FE method for the simulation of skin usually also use FE models for muscles. Like with the skin models that such systems use, linear, isotropic constitutive models tend to be suitable for surgical systems due to the small deformations that such models experience (e.g. [CLP03, BWL+10]). On the other hand, the muscle material used with the system developed by Sifakis et al. for detecting muscle activations from performance capture data (meaning muscle shape deformations can be large) is transversely isotropic [SNF05]. Röhrle and Pullan created a detailed non-linear, transversely isotropic FE model of the muscles of the jaw, using motion capture data as boundary conditions, to simulate actions such as opening and closing the jaw, and biting [RP07]. The results showed the importance of modelling the muscles of mastication as complex 3D shapes, rather than simple actions lines, to achieve desirable animations.

3.4 Facial Muscle and Skin Systems

Waters was the first to model the face using a 2D MS mesh with his geometric muscle model [Wat87]. Terzopoulos and Waters then developed a multi-layered MS skin model using the same geometric muscle model and arranging the springs into tetrahedral and cross-strutted hexahedral elements [TW90]. The model consists of three 3D layers, and different non-linear spring stiffness values within each layer represent the different properties of various sub-layers. *Incompressibility* and *volume preservation* are also modelled, although viscoelasticity isn't. Many other MS skin models are based on this model, and various enhancements have been made to it; for example, Lee et al. simplified the model using two layers of triangular prism elements that modelled the same layers of skin as the original model [LTW93], and a simple skull model (using an offset from the skin surface) and an approach that generated forces to prevent skull penetration were introduced [LTW95].

Zhang et al. developed a similar MS facial model that also uses Water's muscle model [ZPS04]. Although the skin was modelled as a single layer, various enhancements to MS facial models were proposed. *Edge repulsion springs* are used to prevent *edge collapse* (when a node in a triangular element crosses to the vector opposite), helping to simulate skin incompressibility, and a real skull with a hinged jaw is modelled to allow more accurate muscle-skull attachments and improved skull penetration constraints. *Adaptive refinement* is used to adapt the local resolution depending on the level of detail in a particular area. Further improvements to this include an automatic muscle mapping approach for efficient creation of muscles from an image, and an adaptive simulation algorithm which simulates only nodes whose deformation is less than a specified distance (determined by an offline computation step) [ZPS03]. *Adaptive simulation*, however, can only be done for expressions for which the offline computation stage has been performed.

Kähler et al. and Coull also created facial models that used their previously discussed muscle models [KHS01, HKA+01, Käh03, Cou05]. Coull's facial model used a skin model with a similar two-layered prism structure as that proposed by Lee et al. [LTW93], and additional stiff structural springs were used for volume preservation instead of keeping track of the volumes of the elements as they deform. Also, rather than the common approach of using biphasic springs, a non-linear function is used to vary the spring stiffness values as they compress. For simplicity, the facial model developed by Kähler et al. used a 2D skin mesh where nodes are attached to either muscle or the skull by springs. Sifakis et al. created a high resolution volumetric FE model of the face including a skull and 32 muscles [SNF05] that was to be used primarily for simulating speech [SSRMF06]. Tetrahedral finite elements were used. Although the animations produced appear extremely realistic, the system has very high computation times.

Physics-based modelling approaches have received particular attention for surgical planning and for use in virtual surgery systems due to their potential accuracy. Koch et al. proposed one of the first such systems for predicting facial outlook after surgery using a 2D FE skin model that is connected to the skull by springs [KGC+96]. This is a rare example of a combination of the MS and FE approaches being used. The surgical planning system by Chabanas et al. used the FE method, and this system was one of the first to allow the prediction of post-operative facial expressions [CLP03]. Various other similar facial surgical planning systems which, like with that developed by Chabanas et al, use linear, isotropic materials with simple tetrahedral elements (e.g. [ZGHD00, Gla02, GZDH04]). Beldie et al. used LS-DYNA[7], a commercial FE package, to create a detailed, patient-specific facial model for simulation of maxillofacial surgery and facial expressions, which had high accuracy and error within a 2mm threshold [BWL+10]. This also shows that deformations of complex facial models can be accurately simulated using commercial FE packages. Like with many surgical simulation systems, a linear, isotropic constitutive model was used, which is suitable for such simulations due to the small deformations that are undergone. Several comparisons and reviews of physically-based approaches for surgical planning on the face are available (e.g. [SLG+07, MSN+07]).

3.5 Independent Skin Models

Various detailed models of blocks of skin have been created that focus on accurate simulation of skin deformation using the FE method rather than computational cost. These are usually used to study the deformation and experiment with the mechanical properties of skin. Larrabee and Sutton created the first such model, which is a 2D FE model attached to an immovable surface by springs representing the subcutaneous tissue [LJS86]. Boisseux et al. developed a two-layer linear, isotropic, elastic FE model for effects of cosmetics and aging by simulating temporary and permanent wrinkles [BKTK00]. Each triangle in the skin mesh has a shape memory, and the rest shape of the triangles are modified according to previous deformations, simulating the plasticity of skin. Due to the simplicity of the skin model, the wrinkles formed in unrealistic sinusoidal patterns and thus had to be postprocessed. This model has since been further developed into three-layer model to study the mechanical properties of skin with aging [MTPKB+02], and experiments show that the two-layer model leads to a contradiction between the prediction of the folding capacity of skin and clinical observations, whereas the three-layer model predicts quite well the clinical aspects of skin wrinkling with age.

Yin et al. experimented with a four-layer linear FE model of a wrinkling fingertip in water that also used isotropic layers [YGC10]. The model is based on the fact that the vasoconstriction of substrate tissue due to water immersion leads to mismatched deformation between the films (such as the epidermis) and the substrate. Although not directly applicable to this project, wrinkles can be modelled by films that undergo compression due to other types of mismatched deformation, and, as an extended application, the developed mecahnical model was also used to provide qualitative insights into general skin wrinkling and aging.

Kuwazuru et al. developed a more detailed five layer model of a block of facial skin to simulate aging using the *multi-stage linear buckling theory* rather than the FE method [KSY08a], which was used to simulate and evaluate wrinkle properties, such as size and strain, and their relation to aging [KSY08b]. Three stages of buckling are considered, each of which are simulated independently using a different multi-layer buckling model to evaluate bucking within different layers of skin. Like with the previously described models, linear, isotropic materials were used, although the *natural tension* of skin was included, which is useful for simulating aging. It is important to note that experiments with various soft-tissue models considered here have found that the epidermis, in particular the stratum corneum, and the dermis have a large effect on skin wrinkling compared to the hypodermis [MTPKB+02, YGC10], and the influence of the viable epidermis is negligible [YGC10].

Flynn and McCormack created an inhomogeneous FE model to simulate forearm wrinkling that also modelled viscoelasticity and natural tension [Fly07, FM08, FM10]. Four different models were experimented with, each of which modelled different combinations of the stratum corneum, dermis and hypodermis, and results again found that only the three-layer model correctly followed trends of real skin. The results of this model correlated well with an in vivo laboratory experiment and followed experimental trends, with the maximum range and average roughness of wrinkles being mostly within the range of values from the experiment. A commercial FE package, ABAQUS[8], was used for the FE simulation. Hung et al. used a similar model to this for simulating wrinkles due to

[7] http://www.lstc.com/lsdyna.htm
[8] http://www.simulia.com/products/abaqus_fea.html

contraction of underlying muscle [HMSH09], although the muscle was simply modelled as an extra layer in the block. This model was also experimented with by varying the layer thicknesses and properties to simulate, for example, mature skin. Like with previous similar experiments, these showed the importance of modelling the inhomogeneity of skin. The freely available CMISS[9] FE package, developed by the same institution where the research took place, was used for the simulation.

A non-linear rheological constitutive model of soft-tissue that includes both anisotropic and viscoelastic properties according to various material parameters has also been developed [BAG04, Bis06]. The quasi-linear viscoelasticity theory was used at the level of representing collagen fibres - a more detailed level than previous approaches that use the theory. ABAQUS was also used for this FE simulation. The results showed that complex anisotropic viscoelastic properties of skin, such as hysteresis and preconditioning, could be simulated following trends of real skin. Skin wrinkling was not explicitly considered.

Lapeer et al. developed a GPU implementation of a non-linear FE soft-tissue model for use with an interactive surgical simulator [LGK11]. The *total Lagrangian explicit dynamic* (TLED) algorithm is used to integrate the equations of motion. Three different isotropic hyperelastic FE models are considered, and the parameters of the models were determined from in vitro experiments on skin. Although the GPU uses lower floating point precision than the CPU, comparisons showed that this led to no significant differences in the accuracy between the CPU and GPU implementations, and the simulations closely matched the simulation of a skin model created using ABAQUS for validation. Huge performance increases were also recorded when using the GPU, with over 1,000 iterations per second (required for the haptic device) capable when simulating a model with 50,000 tetrahedral elements, whereas the CPU implementation could only handle 500 elements at that threshold.

Taylor et al. developed a slightly more advanced framework for modelling anisotropic, viscoelastic soft-tissue on the GPU that also uses the TLED algorithm [TCC$^+$09]. A speed-up of up to 56.3x compared with a CPU implementation was observed, and transversely-isotropic materials modelled with roughly 55,000 hexahedral elements can be simulated with a cost of around $2ms$ per time-step on a mid-range desktop PC. It was also found that modelling properties such as anisotropy and viscoelasticity increase computational cost by as little as 5.1% using the developed model. This framework has not yet, however, been used to create a model as complex as the human face. The developed software ('Nifty Sim') is freely available[10] and is currently being experimented with, although no significant progress has been made with this yet.

3.6 Other Deformable Soft-Body Models

PhysX soft-body simulation is based on a *constrained particle dynamics* simulation algorithm that focuses on speed, robustness and stability [MHHR06]. Unlike traditional physics-based approaches, the algorithm manipulates vertex positions directly using constraints, rather than calculating internal object forces first, requiring fewer integration steps for each time-step. As positions are directly manipulated, this allows collision constraints to be easily formulated. The semi-implicit Verlet time-integration method is used, and the stability of the solver depends on the shapes of the constraint functions, rather than the time-step. By simply using these constraints, the algorithm makes many simple approximations of physics to make it fast to compute. The only known application of PhysX in research has been to develop a real-time virtual surgery system [MHL$^+$09]. Some limitations of PhysX were found through this; for example, soft-bodies must be isotropic and homogeneous, although a workaround is to attach two soft-bodies using a rigid-body and a distance joint. It was also found that soft-body to soft-body collision detection can be relatively poor. One advantage of PhysX, however, is that it can be readily hardware accelerated on the GPU using CUDA, and some tests showed speed increases of over 10x when performed on the GPU.

3.7 Other Wrinkle Models

As well as the highly accurate and detailed skin and wrinkle models, other simpler wrinkling approaches have also been proposed that don't model physics to such accuracy. These include geometric techniques that deform the geometry of a mesh, and texture mapping techniques that

[9] `http://www.cmiss.org/`
[10] `http://sourceforge.net/projects/niftysim/`

use an approach like bump or normal mapping to render wrinkles. Although texture mapping techniques are generally less computationally complex, simple to use to define wrinkles, and don't require a high resolution mesh, geometric techniques applied to a suitably high resolution mesh are often able to produce more realistic looking wrinkles, particularly with close up views and shadows.

Reis et al. proposed a texture mapping technique that uses normal maps to define facial wrinkles, and a texture map to define various activation areas [RDMB08]. Although simple and computationally efficient, the appearance of wrinkles is limited by the limitations of texture mapping techniques, and it is dependent on the quality of the texture maps. The geometric method by Ishii et al. uses Voronoi division and a shading algorithm to account for light absorption and scattering within layers to generate detailed skin textures including furrows and fine details [IYYT93]. Kähler et al. used a simple wrinkling approach that uses several bump maps [KHYS02]. One bump map is created directly from a synthetic human skin model and used to create a skin structure in a similar way to Ishii et al. but without geometric deformation, and another is created from hand-drawn wrinkle images depending on the facial pose.

Various geometric techniques allow the user to simply define dynamic wrinkles using an image (e.g. [YZ05]), and the system by Bando et al. also automatically generates and renders fine wrinkles using bump mapping, greatly improving the wrinkling detail [BKN02]. Alternatively, the approach of Azmi et al. enables wrinkles to be drawn directly onto an uploaded 3D facial mesh [AWM06]. Dutreve et al. presented a facial wrinkling approach that blends reference wrinkles maps (each of which are associated with a skeleton pose) according to the current facial pose, meaning wrinkles for many poses can be created from a small set of wrinkle definitions [DMB09]. Each of these approaches also allow various different parameters, such as wrinkle width or influence area, to be specified; however, the appearance of the wrinkles will depend on the definition of the wrinkles by the artist.

The approach by Li et al. automatically generates dynamic wrinkles on a facial mesh according to a user specified number of wrinkles, user defined regions, and the movement of keynodes [LYKL07]. Although less work is required, the user also has less control over the positions and sizes of the wrinkles that lack anatomical accuracy. The method by Larboulette and Cani automatically generates wrinkles according to some user-defined locations and parameters, refining the resolution of the underlying mesh if necessary [LC04]. Alternatively, the approach by Müller and Chentanez automatically adds wrinkles to an existing mesh by loosely attaching a high resolution wrinkle mesh to the base mesh [MC10]. Unlike previous approaches, the loose wrinkle mesh attachment can deform in the tangental direction, rather than just deforming the mesh in the normal direction. The geometric wrinkle solver is also independent of the main solver for the base mesh, enabling the method to be used with existing animations in a plug-and-play fashion. On a modern computer, it is expected that most of these wrinkling techniques that make use of some geometric deformation function should be capable of real-time simulation on reasonably high resolution meshes.

Bickel et al. proposed a system to create facial animations with wrinkles using performance capture techniques [BBA+07]. Both fine and large wrinkles can be captured by tracking colouring applied to a subject's face, although the minimum size of wrinkles is limited by the colouring that can be applied to the face to guide wrinkling, and the captured data cannot be used in other scenes or on or a different model than the one it was captured for. Sanchez developed a real-time, model-independent wrinkling system that uses motion capture data to evaluate the strain of facial movements, and produces a normal map of wrinkles that is layered onto the face [San06]. The wrinkling model, however, must first be configured to the performer, relating the wrinkling effects observed on the performer to strain sustained by the facial tissue. In the film industry, lifelike animation is often required; for example, a scene in the final instalment of The Matrix trilogy involving 'The Superpunch' required a high amount of facial skin deformation and wrinkling [Bor05]. However, this was primarily done by an artist who added deformations to captured performance data, and, even though the animation looked lifelike, it was not physically-based and required a lot of manual work.

Some wrinkling techniques use a geometric muscle model to produce wrinkles. Bui et al. extended Waters' muscle model [Wat87] to produce bulges and wrinkles on the face [BHN03], although this still required the face to be manually divided into regions, and only a simple single layer skin model was used. On the other hand, Zhang et al. used a layered skin mesh, similar to that proposed by Lee et al. [LTW93], with Waters' muscle model, and developed a geometric wrinkle model that produced wrinkles according to muscle contractions [ZST05]. This approach therefore has increased anatomical accuracy to produce more accurate and realistic wrinkles, and it is still capable of real-time animation. A limitation of many wrinkling approaches is that a high resolution mesh is required at areas that wrinkle, even if there is currently no wrinkling in such an area, whereas the approach of Zhang et al. uses adaptive refinement to dynamically refine mesh resolution when required.

Wu et al. developed a similar wrinkling method using a different layered MS model and muscle model to simulate both large and fine static and dynamic wrinkles [WKMMT99]. Unlike previous approaches, aging wrinkles are simulated and a linear plastic model is used to change the skin shape based on previous deformations, like with the skin model by Magnenat-Thalmann et al. [MTPKB+02]. Both geometric and texture mapping approaches are used to render wrinkles. On the other hand, various simplifications to the wrinkle and skin models (e.g. incompressibility isn't modelled) mean that the wrinkles produced don't look particularly realistic, particularly in the real-time rendering mode. The facial model also lacks a model of a skull.

3.8 Creating Physically-based Facial Models

Detailed layered physically-based facial models with muscles are normally difficult and time-consuming to create. Approaches to create the models are also dependent on the required model structure (e.g. element shapes). Simple automatic approaches have been used that just create a layered mesh from a surface mesh (e.g. [WT93]) (surface meshes can be easily created from different resources, such as photographs, a 3D digitiser or a laser scanner). Medical data such as *computed tomography* (CT) and *magnetic resonance imaging* (MRI) scans, or *anthropometric data* can be used to create an anatomical *reference head model* with skin, muscles and a skull, using either a manual or automatic process, and similar data or facial surface data can then be used to adapt such a model to a different shaped face (e.g. [AHTN01, KHYS02]), although accurate surgical models benefit from constructing individual models using patient-specific medical data and material parameters [KRG+02, CLP03]. The *Visible Human Dataset*[11] contains such reference medical data and images that have been used by previous projects when creating a reference physics-based head model [SNF05, KGC+96].

Kähler et al. proposed a method to deform a physically-based head model, including a skull, muscles and skin, using sparse sets of manually defined *anthropometric landmarks* that are automatically refined in an iterative procedure [KHYS02]. Using such a technique, a refernce head model can be fitted to even poor scan range data. The same research also proposes a technique for simulating geometry changes of the head due to growth and aging according to anthropometric landmarks for different aged heads, although such changes are mainly useful for creating young head models where such geometry changes are observed.

Rather than adapting all of the reference model soft-tissue, some approaches can automatically adapt part of the model, such as the skin and skull, and allow modifications and other structures to be defined, like muscles, using an editor. Aina proposed an approach to automatically adapt a detailed reference skull model to any given face model using manually placed landmarks [Ain09], although strategic landmark placement is required for desirable results. Further research then focussed on the automatic creation of facial muscles by adapting those from a reference face [AZ10]. For defining muscles, Kähler et al. developed an interactive editor that creates muscles by processing user specified grid points [KHS01]. Muscle mesh resolution is adapted according to the resolution of the grid mesh, and the grid-point layout can be adapted to create a similar muscle structure for a different shaped head model.

When creating physics-based models, the mesh topology is an important factor to consider, as it can have a significant impact particularly on the accuracy and efficiency of FE systems. *Tetrahedral* and *hexahedral elements* are popular with 3D FE models [TCC+09]. The advantages of tetrahedra include their simplicity compared to hexahedra when meshing complicated geometries, and they have simpler and smaller shape functions. On the other hand, tetrahedra are susceptible to *volume locking* (when a soft-body mesh 'resists' deformation and appears overly rigid) when used to model almost incompressible materials like soft-tissue, and hexahedra allow the creation of meshes with fewer degrees of freedom and increased accuracy. Although under-integrated hexahedra (more efficient hexahedra elements) suffer problems such as *zero-energy modes* (deformations that produce no strain or stress), methods are available to supress these. While these methods reduce the efficiency of hexahedra, the lower number of elements required usually still outweighs the inefficiency of hexahedra. Mesh generation algorithms for creating tetrahedral and hexahedral

[11] Part of The Visible Human Project (`http://www.nlm.nih.gov/research/visible/visible_human.html`).

meshes suitable for FE analysis are available, such as the *mesh-matching algorithm* [CPL00], which has been improved and evaluated by creating patient-specific FE meshes [LCSP05].

4 Finite Element Analysis Software Packages

A lot of research on using the FE method for facial animation has involved implementing a version of the method tailored to the task. There are, however, numerous FE solvers available that are suitable for simulating highly deformable materials like skin, some of which are free to use. Most such solvers perform FE analysis in several stages, rather than in real-time. A *pre-processing* stage requires a FE mesh to be created or imported, and for parameters such as any boundary conditions, material properties (either a built-in or user-programmed material model) and forces to be set for a single or several stages of the FE analysis. The next stage then performs the whole FE analysis and outputs data that can later be read and analysed in the *post-processing* stage. These FE packages therefore probably aren't suitable for use in an interactive scenario like games where the output is desirable after each time-step of the FE analysis. On the other hand, they might be more suitable for scripted scenarios, for example, for creation of film scenes, and they will be useful for comparison and evaluation of any FE systems that are used or implemented for this project.

One FE solver, which has been used for analysis of some of the skin models described in Section 3.5, is ABAQUS. This has better features than other commercial packages like ANSYS[12] for delevoping custom materials and elements, making it popular within academia where complex material models are often required. ABAQUS also has more capabilities with regard to non-linear problems, although it seems that ANSYS is preffered in industry due to its intuitiveness and eas of use, and because many problems in engineering can also be approximated by the simpler material models already available with the package[13]. As mentioned in Section 3.1, an important factor to also consider is whether implicit or explicit simulation should be performed. As facial animation involves large deformations with self-contact, explicit simulation will probably be of more use for this project, whereas implicit simulations are preferable for low speed simulations where more accurate stress solutions are critical. ANSYS is an implicit solver, although it can be used in conjunction with LS-DYNA, an explicit solver, whereas ABAQUS contains both types of solvers. Both of these solutions allow switching between solver type within a simulation.

Some freely available packages have been developed within academia for simulation of complex materials like skin, including CMISS (see Section 3.5). FEBio[14] was also developed specifically for FE analysis of non-linear, large deformation problems in solid biomechanics. These packages, although lacking features of the commercial packages, are less complex and could be useful for simply evaluating the accuracy of, for example, FE systems implemented for this project.

5 General Purpose Computation on the GPU (GPGPU)

GPGPU can enable huge increases in computing performance by utilising the power of the GPU for tasks normally performed by the CPU. GPUs emphasise exectuting many threads slowly, rather than one thread quickly like the CPU, making the GPGPU architecture particularly well suited for *massively parallel* applications. There are currently three main architectures for GPGPU programming - CUDA by Nvidia, Khronos OpenCL and Microsoft DirectCompute. Each of these have APIs, such as 'C for CUDA,' that programmers use with existing high-level programming languages to code algorithms using such architectures. Although some third party wrappers are available, most programmers typically program with CUDA using the CUDA C API, with OpenCL using the OpenCL for C API, and with DirectCompute using the High Level Shader Language (HLSL) used with the Direct3D API. Whereas OpenCL is analogous to OpenGL, being cross-platform and works with both Nvidia and ATI GPUs, DirectCompute is part of DirectX (from DirectX 10 onwards), making it only available with Windows Vista and Windows 7, and CUDA can only be used with Nvidia GPUs. On the other hand, CUDA is the most mature and widely used, and user comments suggest OpenCL can also currently be more difficult to use[15]. As of yet, only

[12] `http://www.ansys.com/`

[13] Some user comments comparing ABAQUS and ANSYS can be found on various posts on the iMechanica website, such as `http://imechanica.org/node/6711`.

[14] `http://mrl.sci.utah.edu/software`

[15] Comments comparing GPGPU architectures can be found on various forum threads, such as `http://hardforum.com/showthread.php?t=1516459`

two GPGPU physics-based soft-tissue implementations are known [LGK11, TCC+09], which both use the TLED algorithm. The focus on an explicit dynamic algorithm endow these systems with the data parallelism required for GPU programming. The reported promising speed increases when using GPGPU suggest that such architectures can be extremely useful for programming complex physics-based techniques.

6 Physics-based Demos and Experiments

Some small applications have been developed using C++ to examine different techniques of physics-based animation. More information on these, along with videos and pictures of various simple animations are available online[16]. Each of these simulations took place on a desktop PC with a 2.93GHz Intel Core 2 Duo CPU, 4GB RAM and a Nvidia Quadro FX 380 256MB GPU. As well as simulations of simple blocks of materials acting under the influence of gravity, the demos include three simplified skin and geometric muscle models - one with a MS skin model, another with a FE skin model, and the final with a skin model developed using PhysX. Figures 4, 5 and 6 show the equilibrium positions of these MS, FE and PhysX models respectively when under the influence of a single muscle contraction.

A similar muscle model is used with each skin model. Using this model, a muscle is represented as an ellipsoid. As the ellipsoid deforms, the volume is preserved and a width-to-height ratio determines the increase in height of ellipsoid with respect to the increase in width as the length is changed given a contraction value between 0 and 1. An algorithm that attaches such a muscle to a MS model following the method of muscle-skin attachment as that of Kähler et al. [KHS01] was also implemented.

The MS skin model has the same structure as that proposed by Lee et al. [LTW93]. All nodes around the outside of the model are fixed in the direction of either the X or Z axis to prevent movement outside boundaries defined by the sides of the block. A non-linear spring incompressibility function is used throughout the model. Biphasic springs are used for the dermis, and stiffness values are based on those proposed by Lee et al. Springs in the hypodermis either attach to a node on the muscle, or an invisible rigid plane. At this stage, however, the model has various limitations. The total mass is uniformly distributed over each node without taking into account the weight differences of each layer. Volume preservation and collision detection are not modelled, meaning that, for example, when the width of a muscle changes, this has no effect on the deformation of the hypodermis, although muscle height changes affect the skin deformation due to the multiple spring attachments. Muscles also don't collide with the rigid plane at the bottom of the hypodermis, or the different layers of the skin, which can be seen in Figure 4 where the red muscle penetrates the epidermis. The simulation of this model was run using the simple explicit Euler time-integration method with a time-step of $1ms$, and had a frame rate of over 60 FPS.

The FE model consists of three layers of tetrahedral elements, compared to the two-layer MS model that contains an infinitely thin epidermis. The model is fixed in the same way as the MS model. Each element is linear, and each layer is isotropic although with different material properties, which were chosen based on the values in Table 1. A lumped mass matrix is used, and the total mass of the block is uniformly distributed throughout the block. Although Rayleigh damping has been implemented, the damping parameters have been estimated until a stable simulation was achieved, which meant setting the stiffness coefficient to 0, meaning damping is currently based only on the mass matrix. Further work is required to calculate more accurate damping parameters. To try and achieve optimum stability, accuracy and performance, the fourth order Runge-Kutta time-integration scheme is used rather than the Euler integration scheme; however, the a low time-step of $0.02ms$ was required to achieve a stable system. Some simple optimisation has been done to improve performance, such as by using sparse matrices to represent the symmetric stiffness matrix, although the solver still operates in a single thread on the CPU and is usually not capable of real-time simulation (this example simulation only runs at roughly 0.14 FPS). Unlike with the MS system, the muscle has only one origin and insertion, and, without collision detection, currently acts like a simple vector pulling on a single node.

The tetrahedral PhysX model consists of a single isotropic material due to the limitations of PhysX. The two-layer skin model with uniform density is fixed in a similar way to the previous models except the nodes around the edge of the block were required to be fixed in all three

[16] http://staffwww.dcs.shef.ac.uk/people/M.Warburton/research/pdf/InitPhysDem.pdf

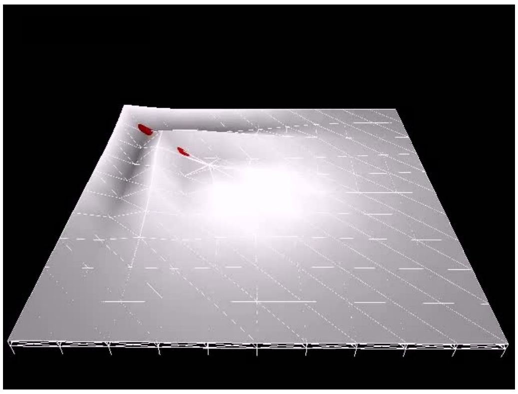

Figure 4: Screenshot of a MS skin block in equilibrium under contraction of a single muscle at 40% contraction rate.

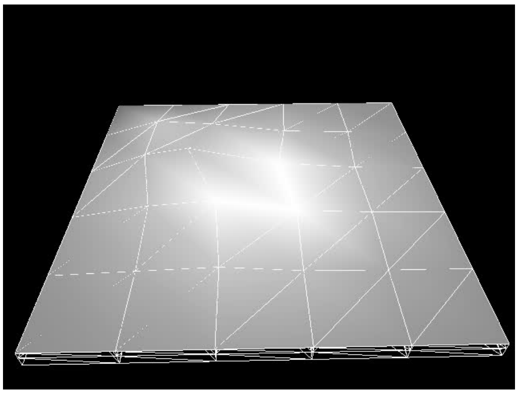

Figure 5: Screenshot of a FE skin block in equilibrium under contraction of a single muscle at 40% contraction rate.

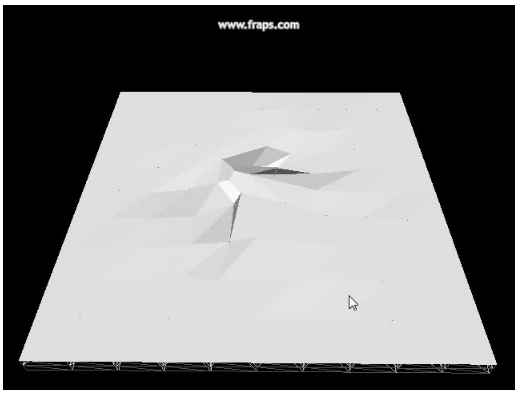

Figure 6: Screenshot of a PhysX skin block in equilibrium under contraction of a single vector muscle at 40% contraction rate.

directions. The muscle model currently used consists of just a vector pulling on a single node on the middle surface, which is how the muscle model with the FE system acts. The soft-body parameters are 0.1 stretching stiffness and 1.0 volume stiffness (simulating stretchy but volume preserving material). This model animates in real-time with a frame rate of over 60 FPS.

It is difficult to compare how accurately each model simulates skin without, for example, reference data collected from experiments on real skin to compare with. It is also difficult to compare the three models to each other as they each take different parameters, although the FE model, while very low resolution, is more likely the most accurate simulation of skin out of the three as parameter values found from experiments on real skin were used. On the other hand, due to the lower resolution, the skin just bulges slightly, rather than wrinkling like with the MS simulation. Also, compared with the MS and PhysX models, the FE simulation is extremely unstable and requires a lower time-step. It is thought that this is due to the more realistic representation of skin used with this simulation. The system becomes more stable, for example, if lower Poisson ratios are used to make the model more compressible, or if the stiffness of the epidermis is reduced to a similar value to that of the dermis to which it is attached. The MS parameters chosen by Lee et al. for real-time animation stability as well as a decent skin approximation, rather than to create an extremely accurate skin model. It can also be seen that the PhysX model just seems to crumple unrealistically, although this isotropic skin representation is the least accurate and configurable out of the three. With further work, several soft-body layers could be attached to produce a representation of skin that is more comparable to the other two models.

7 Evaluating Facial and Wrinkle Animation

Once developed, it will be necessary to evaluate the developed facial animation system, preferably both qualitatively and quantitively. It has already been mentioned that it could be possible to evaluate the system by comparing simple model simulations using our system with those simulated using a tested FE package. This was done by Lapeer et al. using ABAQUS when evaluating the FE simulator for their surgical system [LGK11]. It should be possible to perform a quantitative evaluation in this way by comparing, for example, displacements of nodes. In another wrinkle evaluation method, Bando et al. digitised real skin surface of the forehead while wrinkled, and used their wrinkling model to generate wrinkles on the same digitised forehead while it wasn't wrinkled, allowing the two meshes to be qualitatively and quantitavely compared [BKN02]. More accurate evaluation methods have been proposed for evaluating soft-tissue simulation in surgery (e.g. [CMC+04]), and to quantitatively evaluate the accuracy of wrinkles and deformations produced against the results of laboratory experiments or known values (e.g. [FM08]). Some wrinkling data from experiments is also available from other sources (e.g. [ANK+02]). Such data will also be useful for developing a wrinkling model.

Simple experiments could also be carried out for qualitative evaluation (Coull also performed some simple experiments for assessing the facial animation quality produced by the system devloped for his PhD thesis [Cou05]). For example, in our case, various animations could be shown to people with different amounts of computer graphics knowledge, each of which contain different combinations of either no wrinkles, or wrinkles from an old or young person on the face of either an old or young person. As well as assessing the quality of the wrinkles, these tests will also reveal, for example, whether aging wrinkles actually make a model appear older using the system. The tests could be controlled in a lab, or a more extensive set of data could be collected using the Internet, athough noisy data will be a bigger concern with the latter.

8 Conclusion and Project Plan

Physics-based models are capable of producing more realistic and accurate behaviour than simpler geometric models at the expense of the requirement for increased computational power and increased complexity, requiring detailed understanding of the physics and anatomy of the structures being modelled. By studying the anatomy of skin, it can be seen that various factors affect the structure of skin and the appearance of wrinkles, some of the most significant being age and moisture content, which are often the main factors considered with many wrinkling approaches, along with expression wrinkles.

To create a detailed physically-based facial model that wrinkles, it will be necessary to consider skull, facial muscle, skin and wrinkle models, and the interaction of these models. In the area of facial, skin and wrinkle animation, various combinations of physically-based and geometric models of different structures have been used, from using vector muscle models and simple approximations of skin using the MS method for real-time animation, to exploring the complex mechanical anisotropic viscoelastic properties of skin using complex FE models. Some physics engines like PhysX, and the MT (mass-tensor) method, although less popular within academia, can also be used for soft-body deformation. However, by using GPGPU to greatly improve the speed of computation of complex processes like the FE method, complex accurate facial and wrinkling simulations in real-time are becoming increasingly possible. Despite the physics-based method used, a relevant time-integration method must also be chosen for the desired accuracy, stability and simulation speed.

This research will aim to possibly use GPGPU architectures to develop a fast and accurate physically-based facial simulation method for use in, for example, films and possibly games. This will involve applying a more detailed and accurate skin and wrinkle model (e.g. like the FE model used by Flynn and McCormack [FM08]) to a facial model, possibly also with an accurate physics-based muscle model or an advanced geometric muscle model. There are currently no known techniques that model the face to such accuracy, particularly by representing each structure using physics-based approaches. To achieve optimum computational speed and accuracy, using several physics-based techniques in a hybrid approach might also be necessary, and not much research on such models has currently been found either. This might be because such models are difficult to create or have few advantages. Simple implementations and experiments with such models in the forthcoming months should help determine whether a hybrid approach can and should be used. This project therefore proposes several advances in the areas of physically-based animation, and facial and wrinkle animation.

A plan for the next 6 months of the project is shown in Figure 7. As well as these tasks, it would be useful to make contact with experts within and outside the university; for example, it would be useful to meet with a facial or plastic surgeon to develop a further understanding of facial and skin anatomy. The tasks listed below should then be focussed on at the start of the second year of the project. These probably won't be able to be completed before the 12 month mark, although they should be started if time permits:

- Develop simple models to simulate skin that is stretched when the jaw rotates.
- Create simple models to simulate wrinkling on different areas of the face, such as the eyes.
- Create a simple physics-based head model using techniques chosen depending on the initial experiments with the simple models.

For the last task, the head model could be created using an existing skull and skin surface model, or simple models can be approximated from any existing data, or created from scratch. Muscles can then be inserted either manually or possibly automatically using any existing data. This model and the implementations of the physics-based techniques will provide a starting point for a more complex facial model.

After completing the tasks above, the second year of the project will focus mainly on the creation and animation of the complex full facial model. As part of the project, techniques to create a head model for use with our system, for example, perhaps by deforming a head model, should be implemented, along with controls that allow an animator to easily animate a model, for example, by specifying muscle contractions (low level) or facial expressions (high level). The third year of the project should be used to complete the implementation of the facial animation system, evaluate the system and and write up the final thesis.

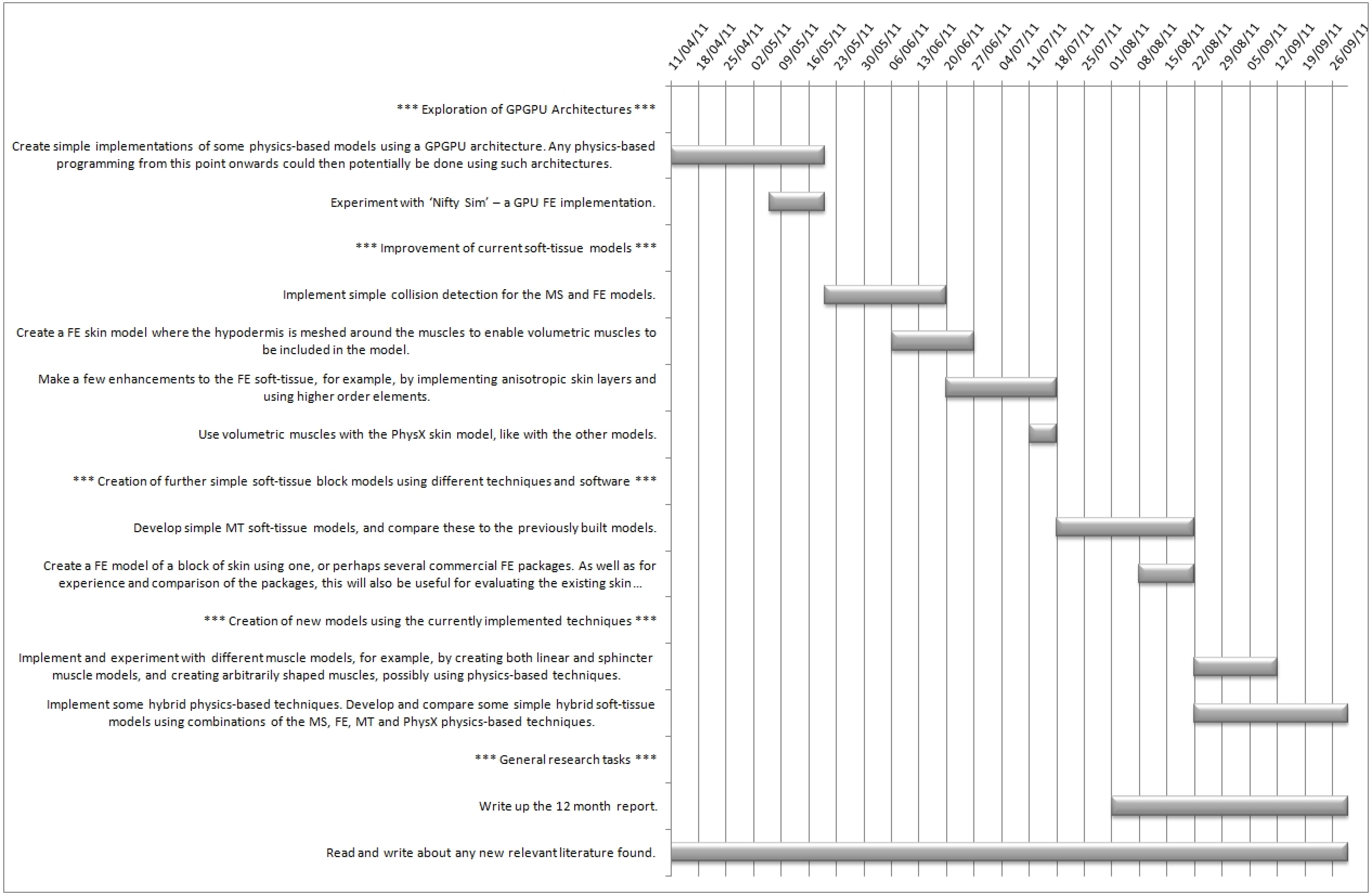

Figure 7: A project plan for the next 6 months of the project.

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A Head Anatomy Images

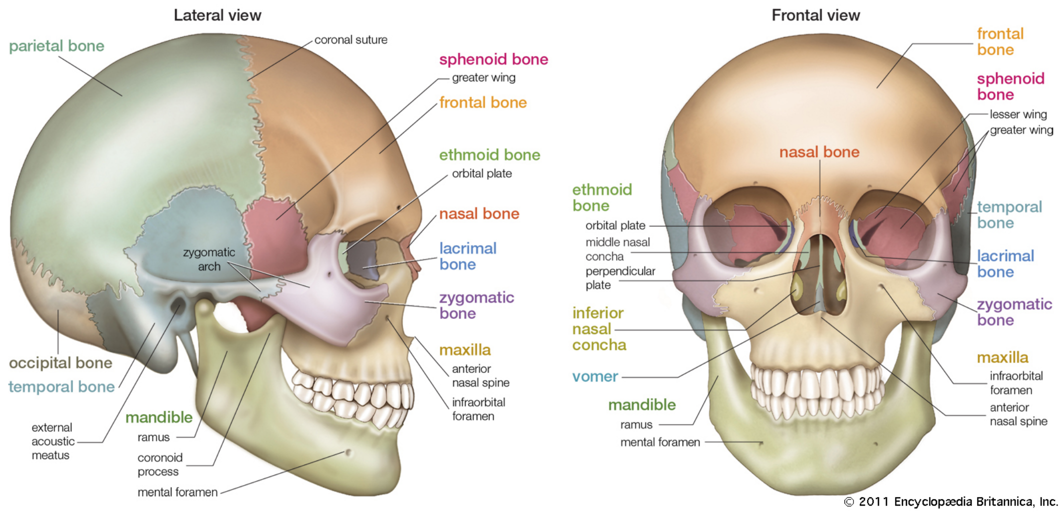

Figure 8: Diagram showing the bones of the skull [Enc11a].

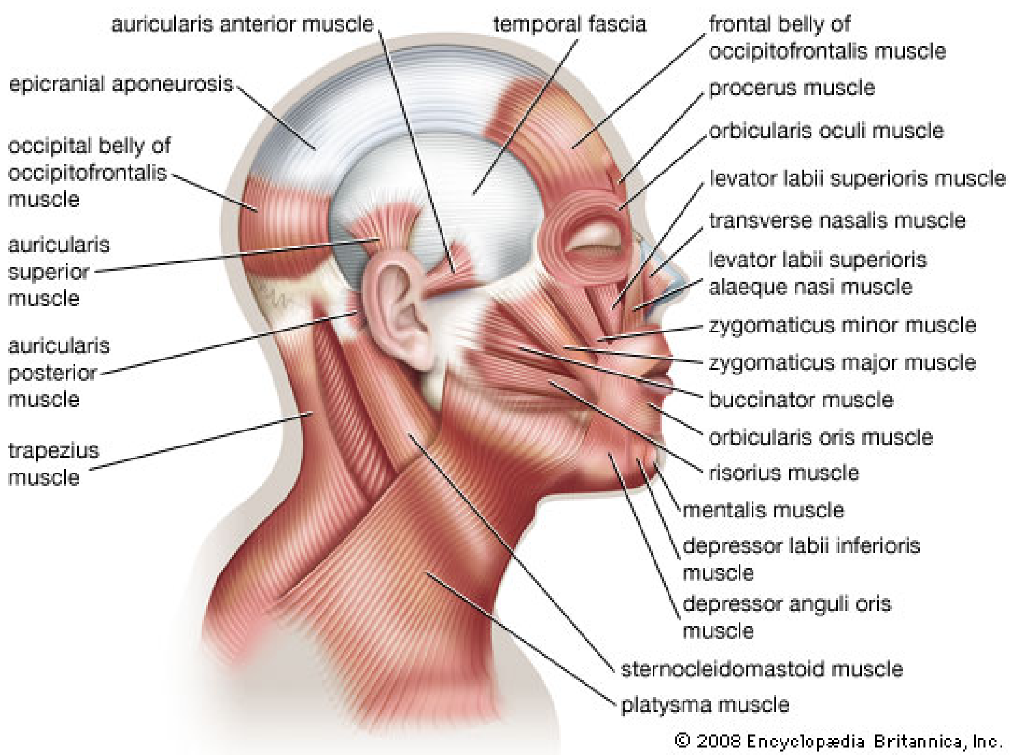

Figure 9: Diagram showing some of the most significant muscles of the head [Enc11b].

B Wrinkle Images

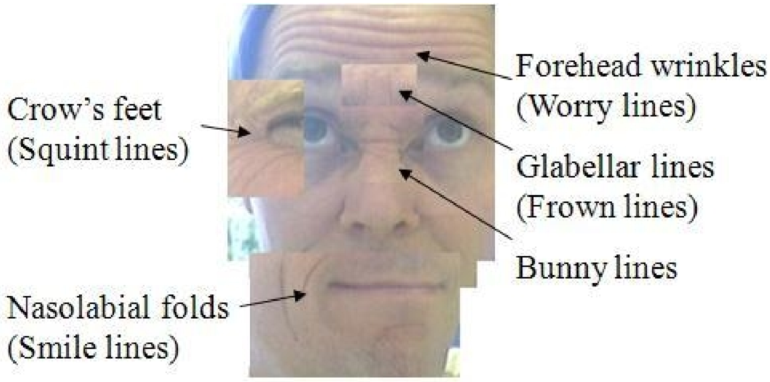

Figure 10: Diagram showing different types of facial wrinkles [Mad09].

Figure 11: An image illustrating the development of aging wrinkles [Far10]. The wrinkles around the eyes created by smiling (middle image) have been morphed onto the neutral pose of the young face (left) to predict the future aging wrinkles for that individual (right). This therefore illustrates how aging wrinkles form at skin locations that have been affected by a lot of stress, causing expression wrinkles to become permanently visible with age.

C DDP Progress

Following the plan of the DDP, various activities have been completed:

- Several activities relating to teaching and demonstrating have been completed:
  - Did 10 hours demonstrating in lab classes for module COM4230/COM6340 (3D Computer Graphics).
  - Took DDP course GSC611 (Introduction to Laboratory-Based Demonstrating in Higher Education) to help improve demonstrating-related skills, including teaching and question answering in a laboratory-based context, and assignment marking.
- Attended the following two seminars so far to improve research skills:
  - Freely Available Academic Research Sources on the Open Web
  - Introduction to Referencing Styles
- Helped to redevelop and update the Graphics Intranet - a useful information resource for the Computer Graphics and Virtual Reality Research Group.
- Continuously maintaining a personal website detailing any research, experiments and demos that have been made.
- Made contact with experts from a different department. Met with Dr Pat Lawford and Dr Andrew Narracott from the Department of Medical Physics to discuss facial and skin anatomy, and the finite element method. Also arranged to meet Dr Stephanie Davy-Jow, a forensic anthropologist at Liverpool John Moores University.
- Almost completed a paid project developing a website for a research group. This mainly involved using and extending the MediaWiki engine, requiring a lot of PHP and MySQL coding.
- Reading, understanding and writing about previous relevant research, and implementing simple physically-based models while starting to develop a research hypothesis has greatly improved research-related skills.