ANNA MEMPEL

FACIAL ANIMATION USING MUSCLES TO CONTROL THE MIMIC ARTICULATION OF PHONEMES

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MASTER THESIS

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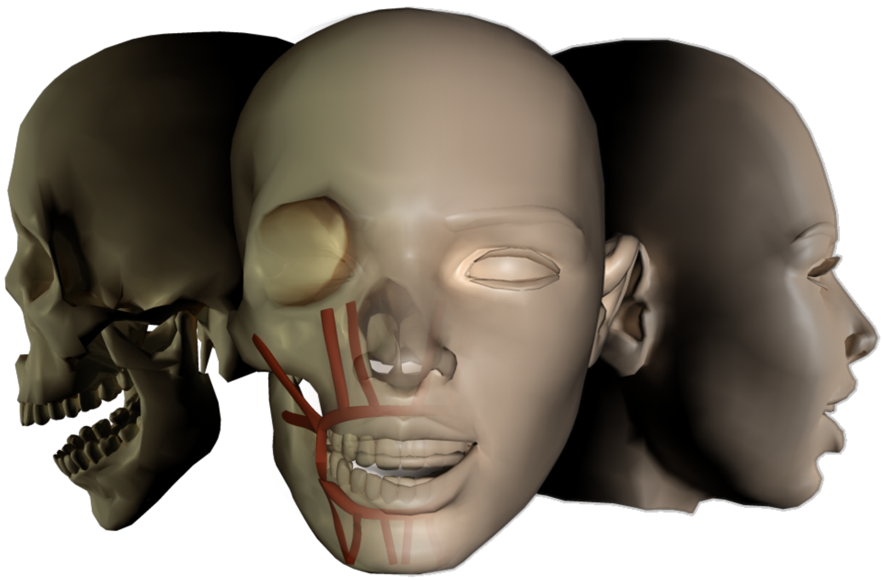

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To my Mom and Dad

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ABSTRACT

This master thesis describes an approach to facial animation using the muscle feature of Autodesk Maya. The skeletal, muscular and skin anatomy of the human head is abstracted from nature. The muscular structure is modelled to act as a highly reusable interface between any skull and skin model. The muscle actions are based on the *Facial Action Coding System* and are implemented using weights painted on the skin mesh. By combining several muscle actions it is possible to animate facial expressions, e.g. emotions or phonemes. By animating the mimic articulation of several visemes, the accuracy, usability and performance of the developed approach is determined.

ZUSAMMENFASSUNG

Diese Master Thesis stellt einen Ansatz zur Gesichtsanimation mit Autodesk Mayas Muskel-Funktion vor. Die Anatomie der menschlichen Gesichtsknochen und -muskeln, sowie der Haut wird von der Realität abstrahiert. Das Muskel-Modell wird als wiederverwendbare Schnittstelle zwischen beliebigen Schädel- und Haut-Modellen implementiert. Basierend auf dem *Facial Action Coding System* werden die Muskelaktionen durch Gewichtung des Haut-Modells modelliert. Das kombinierte Aktivieren einzelner Muskeln ermöglicht die Animation von Gesichtsausdrücken, wie Emotionen oder Phoneme. Die Genauigkeit, Nutzbarkeit und Leistungsfähigkeit des Ansatzes werden nachgewiesen, indem verschiedene Viseme mimisch artikuliert werden.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Because of the nature of Moore's law, anything that an extremely clever graphics programmer can do at one point can be replicated by a merely competent programmer some number of years later.
- John Carmack

The field of *computer graphics* (CG) deals with the creation and manipulation of 2D or 3D images by a computer. It comprises many areas of which the most prominent ones are *modelling*, *rendering*, and *animation*. Modelling is about the mathematical specification of the shape and appearance of an object, for example a human head, which can be described as a set of connected points inside a three dimensional space, plus information about the interaction of light with the head. Rendering is about creating shaded images from the 3D model of the head. Animation is the illusion of motion, like changing facial expressions, through a sequence of rendered images [SM09].

Computer Graphics

Facial animation has been a topic of research since computer technology got available for a wider range of people back in the 1970s. In 1972 Parke approximated the surface of a face with a polygonal skin [Par72]. He was one of the first who reproduced realistic facial motion [Käh07]. The skin contained about 400 vertices defining 250 polygons. Rendering was a complex process, involving two PDP-10 computers, which can be classified as mainframe computers in those days. Three D/A-converters were used to display the output on a high precision display with a resolution of 1024×1024 pixel (cf. Fig. 1.1). The rendering of a single black-and-white picture required about two and a half minutes. Pictures were recorded using a 35 mm camera. It took one hour to produce an animation sequence of the face, containing 20 frames.

The Beginnings of Facial Animation

According to Moore's Law the available computational power and graphics capabilities increase exponentially over time. Besides Carmacks remark, more complex simulation techniques are a consequence of this development. They enable extremely realistic facial animation in an acceptable time these days.

Moore's Law

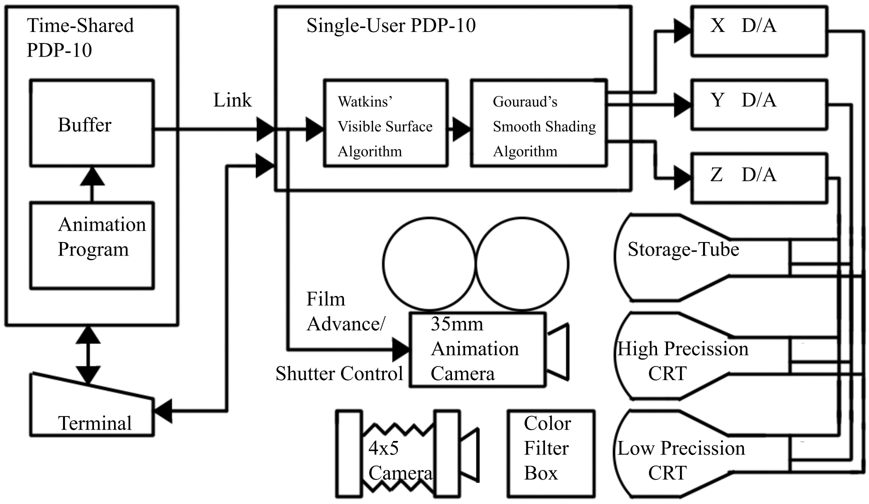


Figure 1.1: Rendering and Animation System in 1972 [Par72]

5 Steps of Facial Animation

Facial animation in general deals with several steps. Each step itself can become very complex depending on the desired target achievement of the animation [Käh07]:

1. Language units — so called *phonemes* — and their duration and intensity are specified.
2. The phonemes are mapped to *visemes*, their visual counterparts.
3. The simulation is done using a geometric model that may base on exact anatomy.
4. The model is updated based on the simulation results.
5. The images are rendered.

Mastering Facial Animation now and then

All steps on their own have been mastered in different ways during the past 40 years. For example steps one and two require knowledge about characteristics of a given language, e.g. phonemes and visemes. There are different concepts of finding the right base for the animation (cf. Chap. 4). Step three and four require knowledge about anatomy. A skull model is usually the basis to start with. It often gets covered by computer recreations of the facial muscles. Different approaches exist that simulate muscles using springs, others use the finite element method (cf. Chap. 2). Since the beginning of facial animation up to today there are also approaches that do not rely on muscles at all. When a form of muscles is involved, the skin is layered over the muscle model and connected to it in order to respond to manipulations of the muscles. Several different approaches address this connection task. The last step of facial animation highly depends on the soft- and hardware used for animation and is therefore (together withs steps three and four) the one that profits most from the technological progress in computer power since the 1970s.

Facial Animation Today

Today facial animation as done for the character Shrek from computer animated movies of the same name (cf. Fig. 1.2) has set the standards. The level of detail is extremely high. Hundreds of nerves and other controls are connected to the skin. Combinations of controls produce very human facial expressions that also lead to wrinkles and laugh lines. Rendering a whole movie, that contains much more than one character with facial animation of this quality, takes millions of CPU hours on a cluster of thousands of servers with multiple cores [Shr12a].

Figure 1.2: Facial Animation Details on Shrek [Shr12b]

The realism of the visual and motion accuracy of animated characters has improved so much over the past 40 years, that it is sometimes hard to tell, whether an image sequence shows a real face or not. But there is a point when the human perception identifies something odd-looking, for example when the motion lacks fluidity. This point is called *believability flip*

Believability Flip (cf. Fig. 1.3). Once the flip occurs a re-calibration to lower expectations happens and the behavior of the person towards the character changes. Since this flip is irreversible, animators try to overcome this point when animating characters [PW08].

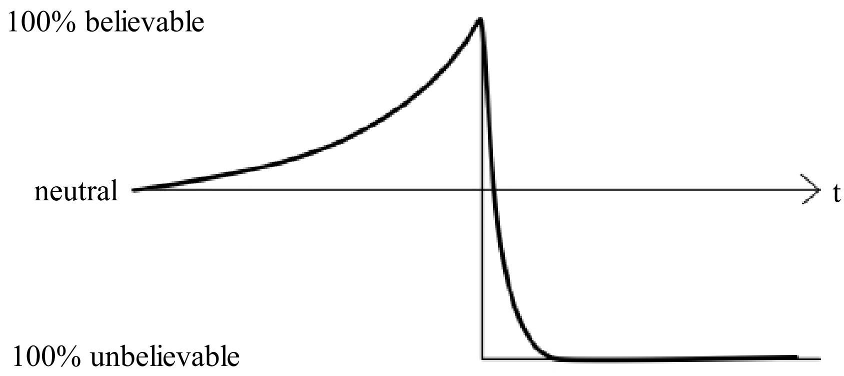


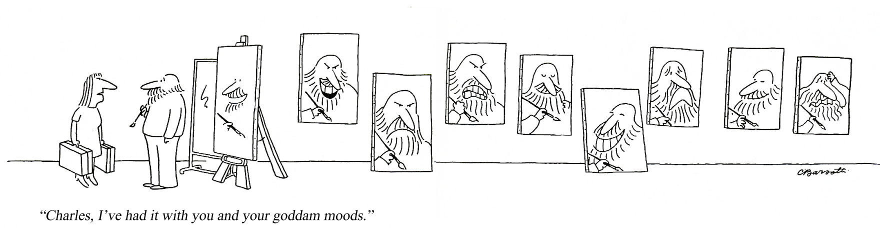
Figure 1.3: Believability Flip [PW08]

This thesis presents an approach on using Autodesk Maya's muscle feature to build a model of human facial muscles that enables animation of realistic facial expressions. The goal is the implementation of this muscle layer as an interface between random models of skull and skin. In this way the model becomes highly reusable. By animating the mimic articulation of phonemes the quality of the model is tested. All steps of facial animation are solved within this approach.

Chapter 2 introduces the current state of facial animation and Chapter 3 gives an overview on the application areas. Chapter 4 deals with steps one and two of facial animation. Chapter 5 covers the anatomical background that is important for understanding facial animation. An overview on the presented approach is given in Chapter 6. Chapter 7 and 8 show how the muscle model is created and animated based on steps three and four of facial animation. Finalising these steps, Chapter 9 deals with the application of the model to mimic articulation of phonemes and shows the results of step five of facial animation.

2

FACIAL ANIMATION — STATE OF THE ART



- Out-take of a Drawing by C. Barsotti

Facial animation is an active area of research since more than 40 years. Several initial questions are important when dealing with this topic. It is important to decide how the geometric head model and its animation should be controlled in general. Also there are several possibilities to morph from one facial expression into another. And last but not least one has to decide how and to what extent the anatomy is simulated.

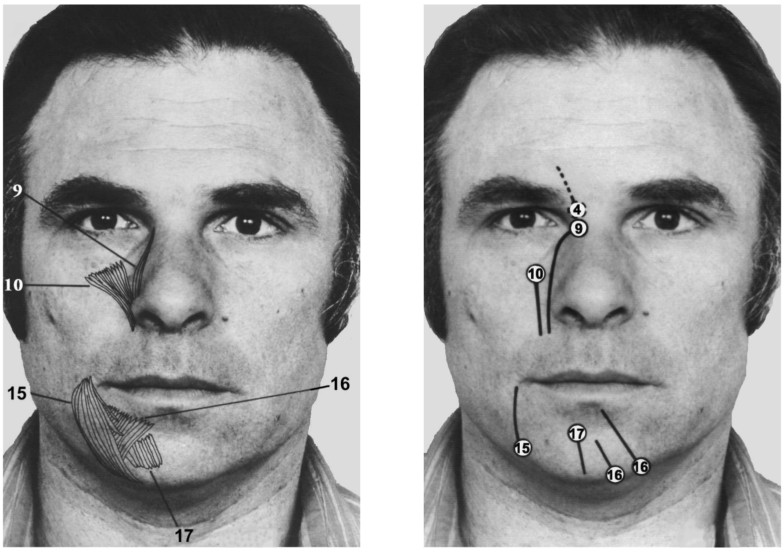
2.1 CONTROLLING THE ANIMATION

Feature-Based Parametrisation

One possibility to control the animation is to directly manipulate the parameters of the face geometry, for example the vertices of a polygon mesh. This approach is called feature-based parametrisation and is used since the beginnings in 1972 [Par72]. The face geometry is formed by parameter adjustments. Each parameter determines an interpolation between two extreme poses of vertices of the model. With this approach the possibilities of configurations are infinite. Therefore meaningful configurations need to be figured out.

Muscle-Based Parametrisation

Another approach is the muscle-based parametrisation where the underlying muscle structure is manipulated. The muscle geometry and the influenced skin are not necessarily separated. For muscle-based parametrisation one can use the *Facial Action Coding System* (FACS). Ekman and Friesen [EFH02] collected momental changes in facial appearance and the respective muscle activity. Expressions are modelled abstractly in *Action Units* (AU) which are grouped by muscle location, direction and special actions (e.g. eye rotation). These units are independent of a particular face and form a simple base for facial



(a) Muscular Anatomy (b) Muscular Actions

Figure 2.1: (a) Muscular Anatomy and (b) Muscular Actions that underlie Action Units responsible for Appearance Changes of the Lower Face. Numbers on (a) refer to the Action Unit that makes Use of the Muscle. Numbers on (b) indicate the Origin and the End of each Line indicates the Insertion of the Muscle [EFH02]

Facial Action Coding System

animation. Figure 2.1 shows the muscles and their actions involved in vertical expressions of the lower face. Numbers on Figure 2.1(a) indicate the number of the action unit that makes use of the specific muscle. Numbers on Figure 2.1(b) refer to the *origin* of the specific muscle and the end of each line indicates the *insertion* (cf. section 5.2). The muscles underlying action unit 16 (Lower Lip Depressor) emerge from the sides of the chin and attach to the lower lip; they pull the lip downwards. A similar approach is presented by Magnenat-Thalmann et al. [TPT88], who model facial animation with *Abstract Muscle Action* (AMA) procedures. Other approaches are more complex, like the one by Chen and Zeltzer [CZ92], which is based on the finite element method, or by Scheepers et al. [SPCM97], which considers the underlying skeleton.

Physics-Based Parametrisation

As an extension of muscle-based parametrisation, physics-based approaches include separate layers for muscle and skin. The skin is deformed with virtual muscles that are attached to the mesh, e.g. modelled with virtual fibres by Platt and Badler [PB81], where muscles are vectors. In the approaches by Böttcher [Böt07] and Kazakow [Kaz07], muscles are modelled as polygons. All three approaches use springs to attach muscle points to skin points.

2.2 TRANSITIONS BETWEEN FACIAL EXPRESSIONS

Switching from one facial expression to another is a complex task. If all parameters used to control the animation change at the same speed, the resulting interpolation won't look natural.

Keyframing

In a keyframing system one manually specifies individual parameter values for points in time. In order to have smooth motion, spline functions are often used for interpolation. With this approach it is not easy to combine the animation of e.g. lips and eyebrows, since their movement is not correlated. As an extenuated kind of keyframing many approaches are based on blend shapes: Single vertices of a face mesh are translated and keyframed in order to capture different shapes and morph between them. Such approaches are often very labour-intensive and custom-built as explained by Seol et al. [SSK+11] in their approach on speeding up keyframe animation. The approach of Smith [Smi08] tries to overcome other blend shape limitations, like interferences caused by overlapping shapes.

Performance-Based

To overcome these problems and limitations, approaches exist, that capture facial motion from a real actor. Terzopoulos and Waters [TW90] present a technique for estimating muscle actions from video sequences. Yuencheng Lee et al. [LTW95] present a methodology for automating the process of digitising facial geometries via scanning range sensors.

Synthesised

When actors or hardware are not present and keyframing is too ineffective, synthesised animation may be the alternative. In such approaches one works with phonemes and visemes in order to achieve realistic movement of the lips for a text sequence. Such visemes are created manually or in an automated fashion from analysed video material.

2.3 ANATOMICAL SIMULATION

The human skin consists of several tissue layers that interact with each other to lead to visual changes, e.g. facial expressions. Many approaches address this fact by simulating these layers for facial animation. Chadwick et al. [CHP89] propose a methodology for animation based on several layers including bones and fat tissue. Scheepers et al. [SPCM97] focus on bones and muscles. Böttcher [Böt07] and Kazakow [Kaz07] both present

Springs approaches with mass-spring models. Differential equations are used to animate the skin that is connected to elastic springs. Such approaches are still common these days and used for example to realise the cloth feature of Autodesk Maya.

Finite Elements Other approaches use finite element methods where a stiffness matrix contains material properties. It relates forces on element nodes to respective displacements of the nodes. This is a computational expensive task and mostly used for surgery. For example Koch et al. [KGC+96] present a prototype system for surgical planning and facial shape prediction using finite element analysis.

Muscle Vectors The approach of Bibliowicz [Bib05] shows, that it is possible to simulate facial muscles with Autodesk Maya's character rigging tools. In this approach muscles can be seen as vectors. In order to overcome the lack of curvature and to produce skin deformation each muscle is connected to single vertices via constraints.

3 APPLICATION OF COMPUTER FACIAL ANIMATION

Clearly, if we'd had the kind of computer graphics capability then that we have now, the Star Gate sequence would be much more complex than flat planes of light and color.
- Douglas Trumbull

Computer facial animation has a large number of application areas and the number increases with increasing computational power and graphics capabilities. Some of the main areas are briefly discussed in the following sections.

3.1 ANIMATION INDUSTRY

The animation industry is the largest motivator, consumer, and developer of computer facial animation. Modern computer animated films like the Shrek trilogy (2001, 2004, and 2007) or Avatar (2009) make use of the latest technological process (like 3D filming capability) and animation studios push research for new technology at the same time to implement new ideas [PW08].

Computer Animated Films

3.2 VIDEO GAME INDUSTRY

Today's video game industry benefits from real-time performance. The animation of speech and facial expressions follows a script and is computed offline. In contrast to that, hair, skin reflectance, environment mapping, motion dynamics, etc. can be rendered on the fly. These effects enable very realistic characters, however their computation may require the latest hardware. The improvement can be seen best in game series like *Gothic*, as shown in Figure 3.1. Every few years a new part of the series is released, taking advantage of the technological progress. In part one of the Gothic series, mouth opening was not implemented in character animation at all. Such details were roughly included in the second part for the first time and improved for the next parts. Further progress of the gaming industry can be expected in the future, especially in non-verbal

On-The-Fly Rendering

Non-Verbal Communication

(a) Gothic 1 (2001)

(b) Gothic 2 (2002)

(c) Gothic 3 (2006)

(d) Arcania (Gothic 4) (2010)

Figure 3.1: Game Industry Improvements over the last Years using the Computer Game Gothic as an Example [got12]

communication, e.g. eye contact, which involves a camera that is included in the display [PW08].

3.3 MEDICINE AND THERAPY

Surgery

Facial animation is a very important topic in surgery, especially when it comes to the surgical simulation of skin, bone, and muscle tissues. Models of the facial tissues can be generated from computer tomography scans and used for surgical planning [PW08]. Such models have to be very detailed and anatomically correct.

Models of the human face that come with detailed mouth dynamics are used in therapy to train pronunciation [Kal03].

3.4 LIP-READING AND SPEECH ANIMATION

Co-Articulation

Speech animation often uses a rough approximation to anatomically correct speech dynamics, for example by modelling viseme based key poses (cf. Chap. 4). One of the main topics of speech animation deals with the simulation of co-articulation, which happens during fluent speech. Facial movements that occur when a phoneme or viseme is articulated are influenced by the previous and the next phoneme or viseme. This process is automatically done by the brain, but the transitions are hard to do artificially. However they are very important for realistic speech animation [DN08]. The animation pipeline of Kalberer solves co-articulation within several steps and can be included as plugin into animation software to support the facial animation progress [Kal03].

Lip-Reading

In the area of lip-reading, computer facial animation can be used to animate lip-readable conversations, e.g. as a communication aid for deaf people on a mobile phone [TTB+06].

3.5 VIDEO TELECONFERENCING AND PHOTOGRAPHY

Recognition of Facial Expressions

The importance of video teleconferencing systems has increased over the last years. Methods have been developed that recognise faces within the pictures of the video stream. Eyes and mouth can be tracked and the faces can be analysed for various purposes, for example to evaluate the emotional state of a face and provide conversation context depending on it [DN08]. The same principles apply to digital photography. Today's digital cameras analyse the scene and faces continuously and notify the photographer when everyone is smiling, to take the picture in the perfect moment.

Signal Coding

Another aspect of this area is the compression of the data, that is transmitted in video conferences. As compared to pixel-based data compression the facial expressions can be extracted from the image and get parametrised. The resulting parameters are compressed and transmitted.

3.6 AVATARS AND SOCIAL AGENTS

Real-Time Rendering

Avatars and social agents are widely used on the Internet these days. They provide information and answers within a dialogue system, based on an FAQ system, in real time and act like a real person. The personification of such virtual humans is very important for their believability. It is therefore important to design the physical attributes, expressions, and emotions carefully [DN08, PW08]. The speech and facial expressions of virtual agents, that interact in real time, need to be computed and rendered in real time. The system of Neto et al. [NCVMa06] receives spoken phonemes, maps them to visemes and sequences of emotions and behaviors, and transforms these sequences into keyframes. These keyframes are used as reference to interpolate frames for live agent animation. Real-time computation and rendering form a contrast to characters in animation or video game industry, where the animation of speech and facial expressions follows a script.

4

PHONETICS AND PHONOLOGY

A phoneme can be regarded as an element in an abstract linguistic system, an element which has to be realized in the physical world by an acoustic signal produced by vocal activity.
- International Phonetic Association [Ass99]

As a subject of linguistics, *phonetics* deals with the sound and signs of human speech. It is about the production, physical transmission, reception and perception of speech sounds. In contrast to that, *phonology* deals with systems of phonemes. A phoneme is "the smallest phonetic unit in a language that is capable of conveying a distinction in meaning" [pho12]. For example the *m* of the English word *mat* and the *b* of the English word *bat* are two separate phonemes. For the phonetic transcription of speech, phonemes are notated between slashes, for example /m/ and /b/. The symbols correspond to the *International Phonetic Alphabet* (IPA) of the *International Phonetic Association* [IPA12]. The alphabet is based on the Latin alphabet and each phoneme of a language is assigned a corresponding symbol. The IPA defines several types of phonemes, for example different kinds of consonants and vowels. Figure 4.1 shows *pulmonic consonants* of the English language. Consonants in general are articulated with a closed or partial closed vocal tract (cf. Fig. 4.2). Pulmonic consonants involve air pressure provided by the lungs. Each column represents a different type

Phonemes

Types of Phonemes

	Bilabial	Labiodental	Dental	Alveolar	Postalveolar	Retroflex	Palatal	Velar	Uvular	Pharyngeal	Glottal
Plosive	p b			t d		ʈ ɖ	c ɟ	k ɡ	q ɢ		ʔ
Nasal	m	ɱ		n		ɳ	ɲ	ŋ	ɴ		
Trill	ʙ			r					ʀ		
Tap or Flap		ⱱ		ɾ		ɽ					
Fricative	ɸ β	f v	θ ð	s z	ʃ ʒ	ʂ ʐ	ç ʝ	x ɣ	χ ʁ	ħ ʕ	h ɦ
Lateral fricative				ɬ ɮ							
Approximant		ʋ		ɹ		ɻ	j	ɰ			
Lateral approximant				l		ɭ	ʎ	ʟ			

Figure 4.1: Consonants of the IPA [IPA12]

of consonant. When symbols appear in pairs, the right one represents a *voiced consonant*.

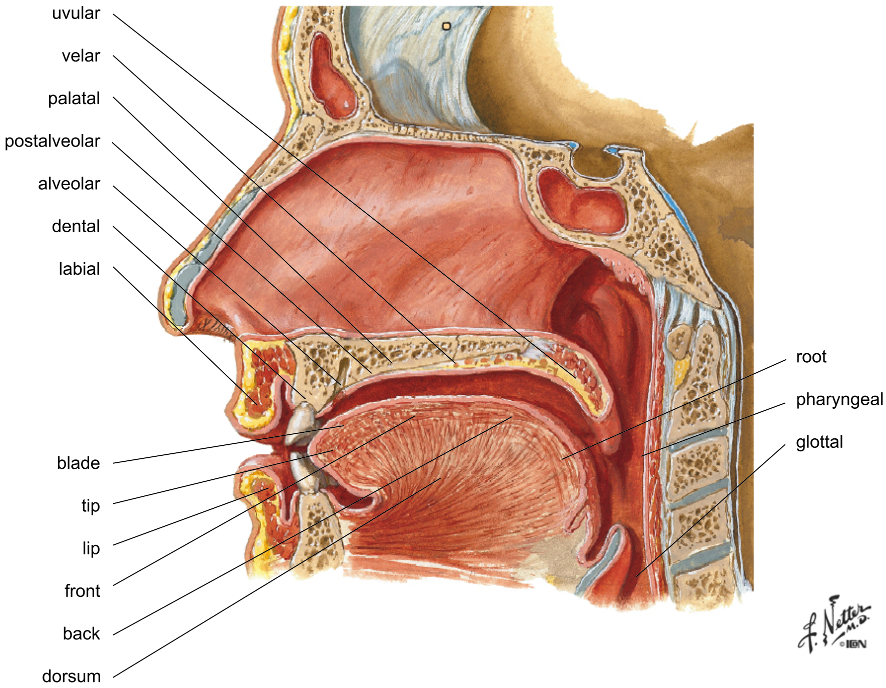


Figure 4.2: Places of Articulation in the Vocal Tract [Net10, Ass99]

Articulating different Types of Consonants

Bilabial consonants are the ones articulated with both lips. *Labiodental consonants* are articulated with the lower lip and the upper teeth. *Dental consonants* are articulated with the tongue against the upper teeth. When articulating *alveolar consonants*, the tongue is close to the sockets of the upper teeth (*alveolar ridge*) and for *postalveolar consonants* the tongue is near or touching the back of it. When articulating *retroflex consonants*, the tongue has a flat or concave shape and is between the alveolar ridge and the bony plate in the roof of the mouth (*hard plate*). For *palatal consonants* the tongue is raised against the hard plate. When articulating *velar consonants* the back part of the tongue is raised against the soft plate in the back of the roof of the mouth (*velum*) and *uvular consonants* are articulated even further back in the mouth. *Pharyngeal consonants* are articulated with the tongue root against the throat. *Glottal consonants* are articulated with the vocal folds and the space in between (*glottis*). When articulating a *plosive consonant*, the vocal tract is blocked and the airflow stops. A *nasal consonant* is produced with a lowered velum that allows the air to flow through the nose. When articulating a *trill consonant*, a vibration occurs between the (active) *articulator* (e.g. tongue) and the (passive) point of articulation (e.g. roof of the mouth). *Flap* or *tap con-*

sonants are produced with a muscle contraction that causes one articulator to be thrown against an other articulator. When articulating a *fricative* or a *lateral fricative consonant* the air flows through a narrow channel of articulators (e.g. lip and teeth). Articulating *approximant consonants* produces turbulent airflow with two articulators approaching each other. For *lateral approximant consonants* the middle of the tongue touches the roof of the mouth and the sides approach the teeth.

Articulating different Types of Vowels

In contrast to consonants, vowels are articulated with an open vocal tract (cf. Fig. 4.2). The IPA declares a range of vowels from open to close and from front to back. The vowels of the English language are shown in Figure 4.3. When symbols appear in pairs, the right one represents a *rounded vowel* [IPA12], which are vowels articulated with the lip corners drawn together. When articulating *close vowels*, the tongue is positioned as close as possible to the roof of the mouth. For *open vowels* the tongue is located as far as possible from the roof of the mouth. When articulating *front vowels*, the tongue is positioned in the mouth as far in front as possible and for *back vowels* the tongue is placed as far back as possible.

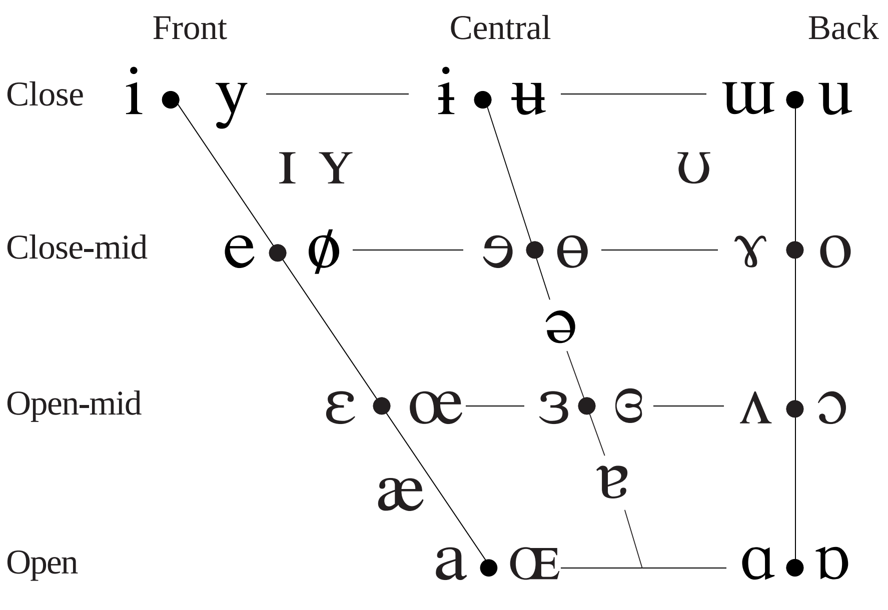


Figure 4.3: Vowels of the IPA [IPA12]

4.1 PHONEMES VERSUS VISEMES

The different types of consonants and vowels explained above can be grouped by the approximate place of articulation: lips, tongue and throat. All three kinds are combined in phoneme-based approaches, which is why phonemes are not considered to be the best choice for lip-sync and speech animation [Osi10]. Tongue and throat sounds are unnecessary overhead, since only sounds made with lips can be seen by a viewer. Therefore phonemes are good in classical animation where each frame is drawn, but they should not be used as actual shapes or poses respectively because the synchronisation animation will seem very clipped. Phonemes should rather work as an idea than a strong physical target. Because of that it is common to focus on visual phonemes, also called *visemes*. In contrast to phonemes, which are sounds, visemes are shapes.

Lip-Sync

Visemes

4.2 MAPPING PHONEMES TO VISEMES

Since visemes are the visual counterpart of phonemes, each viseme can be derived from a group of phonemes that have the same visual appearance. Several approaches exist that map phonemes of the English language to visemes. Such maps usually show a many-to-one relation and can be built either through linguistic knowledge of which phonemes might have the same shape or by clustering phonemes based on several features [CH12]. Neti et al. propose a map based on both approaches [NPL+00]. It is composed by 48 phonemes and 10 viseme classes (cf. Tab. 1(a)). The chosen class names are based on the phoneme types that the IPA introduced for consonants (cf. Fig. 4.1) and vowels (cf. Fig. 4.3).

Many-to-One Relation

The map of Lee and Yook (cf. Tab. 1(b)) shows a many-to-many relationship [LY02]. It contains 14 viseme classes and 41 phonemes. The ambiguity can be removed by only using the first association of a phoneme to a viseme.

The MPEG-4 standard for compression of digital audio and video data [PF02], as used by Yau et al. [YKA06], also specifies a mapping. The standard contains *Face Animation Parameters* (FAP) which represent movements of the face and head. One group of FAPs are visemes and expressions [PF02]. The phoneme-to-viseme map includes 25 phonemes grouped in 15 viseme classes as shown in Table 1(c).

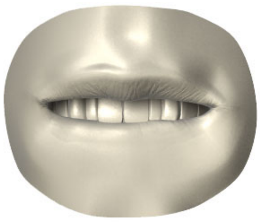
MPEG-4

When it comes to facial animation and speech, Preston Blair, who was an American character animator for Walt Disney and popularised basic phoneme mouth shapes, is often referred. Figure 4.4 shows the standard Preston Blair mapping of phonemes to visemes as published by Martin [Pre12].

Preston Blair Visemes

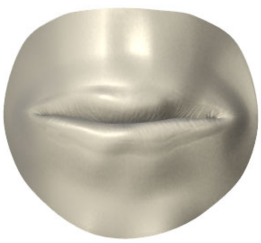
(a) E, like in egg, free, peach, dream, tree

(b) A and I, like in apple, day, hat, happy, rat, act, plait, dive, aisl



(c) V and F, like in forest, daft, life, fear, very, endeavour

(d) L, like in election, alone, elicit, elm, leg, pull



(e) M, B, P, like in embark, bear, best, put, plan, imagine, mad, mine

(f) U, like in fund, universe, you runner, jump, fudge, treasure

Figure 4.4: Preston Blair Phoneme-to-Viseme Mapping [Pre12]

(g) O, like in honk, hot, off, odd, fetlock, exotic, goat

(h) W and Q, like in cower, quick, wish, skewer, how

(i) C, D, G, K, N, R, S, Th, Y and Z, like in sit, expend, act, pig, sacked, bang, key, band, buzz, dig, sing

(j) Th, like in the, that, then, they, this, brother

(k) C, D, G, J, K, N, R, S, Y and Z, like in grouch, rod, zoo, kill, car, sheep, pun, dug, jaw, void, roach, lodge

(l) Default Shape used when no corresponding Viseme exists

Figure 4.4: Preston Blair Phoneme-to-Viseme Mapping [Pre12]

Similarities

The four phoneme-to-viseme mappings have several conformities in mapping. The number of viseme classes is similar and all mappings consider a silent viseme, which represents the default mouth shape. Which set to use depends on the approach and the intended goal. Using the MPEG-4 viseme set as a base for facial animation has the advantage of global awareness and standardisation and therefore reusability. For example the voiceless speech recognition technique by Yau et al. [YKA06] could be coupled with any MPEG-4 supported facial animation system.

Table 1: Phoneme-to-Viseme Maps

Viseme Class	Phonemes
Lip-rounding based vowels	/ao/ /ah/ /aa/ /er/ /oy/ /aw/ /hh/ /uw/ /uh/ /ow/ /ae/ /eh/ /ey/ /ay/ /ae/ /eh/ /ey/ /ay/ /ih/ /iy/ /ax/
Alveolar-semivowels	/l/ /el/ /r/ /y/
Alveolar-fricatives	/s/ /z/
Alveolar	/t/ /d/ /n/ /en/
Palato-alveolar	/sh/ /zh/ /ch/ /jh/
Bilabial	/p/ /b/ /m/
Dental	/th/ /dh/
Labio-dental	/f/ /v/
Velar	/ng/ /k/ /g/ /w/
Silence	/sil/ /sp/

(a) Neti et al. [NPL+00]

Viseme Class	Phonemes
P	/b/ /p/ /m/
T	/d/ /t/ /s/ /z/ /th/ /dh/
K	/g/ /k/ /n/ /ng/ /l/ /y/ /hh/
CH	/jh/ /ch/ /sh/ /zh/
F	/f/ /v/
W	/r/ /w/
IY	/iy/ /ih/
EH	/eh/ /ey/ /ae/
AA	/aa/ /aw/ /ay/ /ah/
AH	/ah/
AO	/ao/ /oy/ /ow/
UH	/uh/ /uw/
ER	/er/
S	/sil/

(b) Lee and Yook [LY02]

Viseme Class	Phonemes
0	Silence
1	/b/ /p/ /m/
2	/f/ /v/
3	/th/ /dh/
4	/t/ /d/
5	/g/ /k/
6	/sh/ /j/ /ch/
7	/s/ /z/
8	/n/ /l/
9	/r/
10	/a/
11	/e/
12	/i/
13	/o/
14	/u/

(c) MPEG-4 Standard [YKA06]

5 ANATOMY OF THE HUMAN FACE AND SKULL

There is no landscape that we know as well as the human face.
- Gary Faigin [Fai08]

The visual identity of a face can be mostly reconstructed by the skull. It is for example possible to distinguish between Asian and European origin just by considering a skull. To understand the appearances, behaviors, and functions of the human head and face it is important to consider skeletal and muscular anatomy. Anatomy of muscles is a main fact when it comes to facial expressions and their changes in appearance, but not less important is the structure of the skin with its different components. Figure 5.1 shows areas and sections of the human face that are important in the presented approach.

Visual Identity

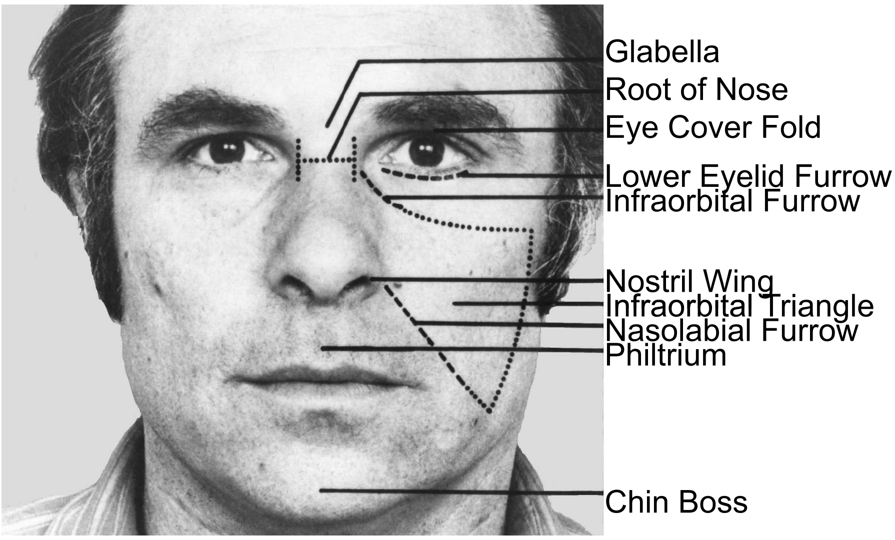


Figure 5.1: Important Areas and Sections of the Face [EFH02]

5.1 SKELETAL ANATOMY OF THE HUMAN FACE

The visible appearance of the head depends on the shapes of the *neurocranium*, which is the part of the skull that protects the brain, and the *ciscerocranium*, which is the part that builds the face. The *frontal bone* is the most important cranial bone when it comes to the appearance of the face. It is located above the

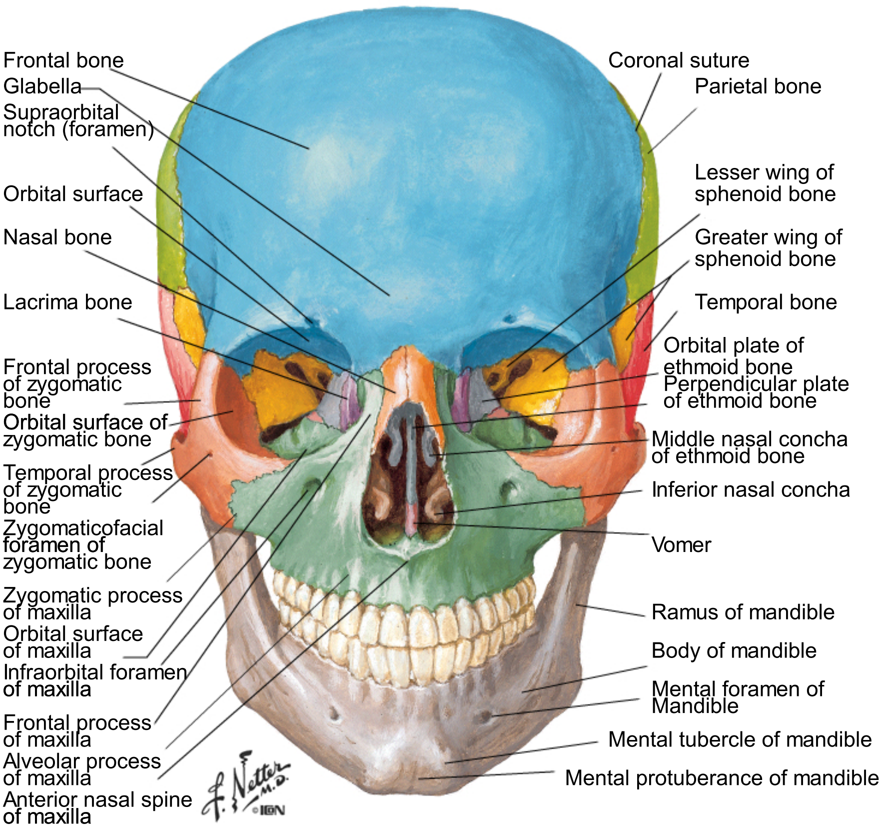


Figure 5.2: Human Skull, Front View [Net10]

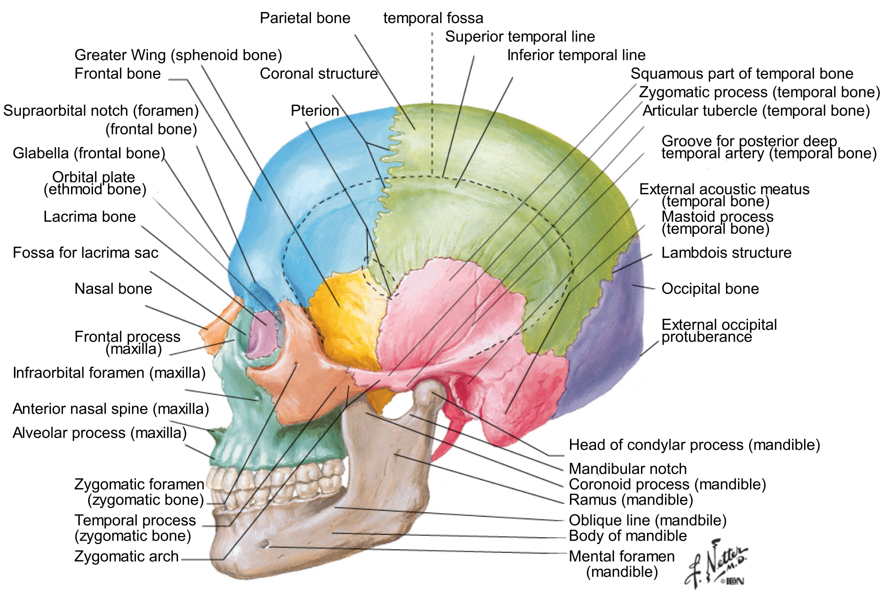


Figure 5.3: Human Skull, Side View [Net10]

eyeballs. The lower front of the skull is built from several facial bones: the *nasal bone*, the *lacrima bone*, the *zygomatic bone*, the *mandible*, the *maxilla* and the *volmer*. All bones of the human skull are shown in Figures 5.2 and 5.3. The facial bones have outgrowths (*processes*) to hold muscles and ligaments and holes through which nerves and blood vessels pass (*foramina*). They also have signs of development processes (*lines*) and empty spaces (*sinuses*) that make the bone lighter. These and other features can vary in location, size, shape, thickness etc. and can give information about personal or character attributes of the person the skull belongs to (*physiognomy*) [ana12].

Bones of the Skull

5.2 muscular anatomy of the human face

When it comes to facial expressions the anatomy of muscles is a key fact. In general there are three types of muscles: *skeletal*, *smooth* and *cardiac* (heart). Facial muscles belong to the skeletal muscles and since they can merge together there exists no official number of muscles. The structure of such a muscle is shown in Figure 5.4. A muscle is covered by the *epimysium*, a connective tissue, that protects the muscle from friction. Inside the muscle there are bundles (*fasciculi*) of ten to 100 fibres surrounded by *perimysium* (another tissue).

Muscle Types

Muscle Structure

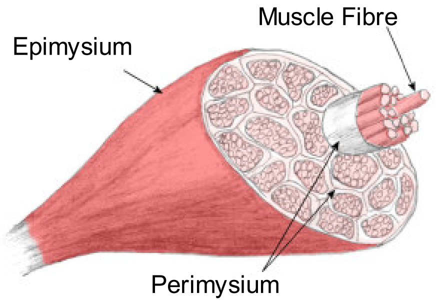


Figure 5.4: Muscle Structure [mus12]

Figure 5.5 shows muscles of the human face and head that are involved in facial expressions. The fascia is depicted. Figure 5.6(a) shows the muscles of the mouth in detail and Figure 5.6(b) shows muscles of the lips from behind. Both views are very helpful for understanding the complex muscle structure of this part of the human head.

In reality one differentiates between muscles of mastication and muscles of expression, but since some muscles belong to both groups, this distinction is not relevant in the following.

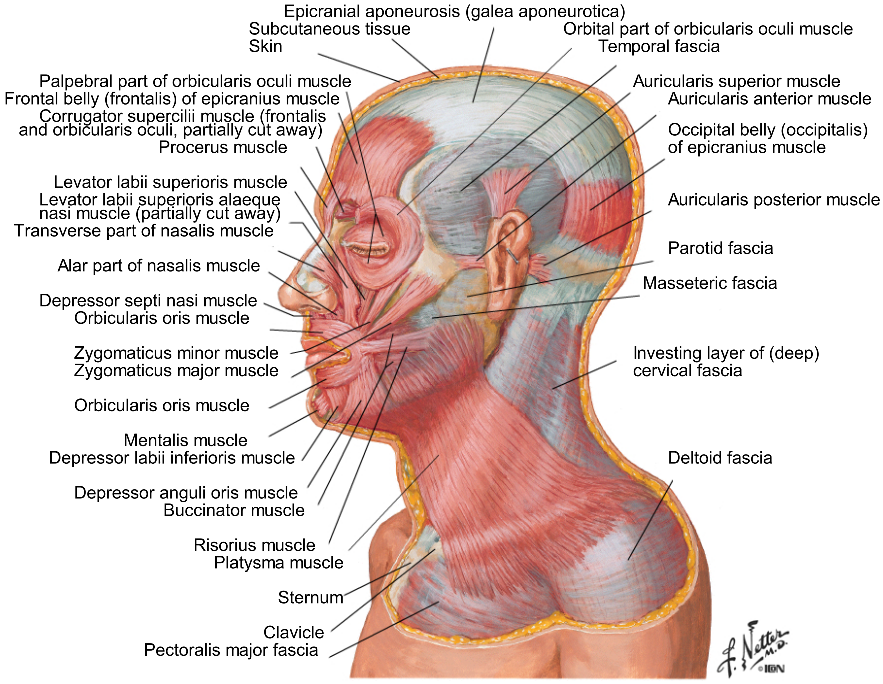
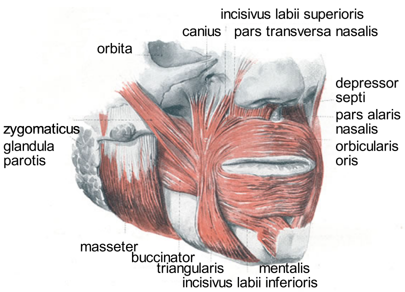
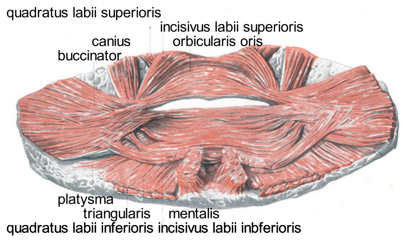


Figure 5.5: Muscles of the Face and the Head [Net10]



(a) Muscles of the Mouth



(b) Muscles of the Lips seen from behind

Figure 5.6: Muscles of (a) the Mouth and (b) the Lips [ana12]

Muscle Categories

Furthermore the muscles can be grouped into the categories *linear*, *sphincter*, and *sheet*. When linear muscles contract, the surrounding skin is contracted toward the static attachment to the bone, until the force dissipates to zero at a finite distance (cf. Sect. 7.1). Sphincter muscles squeeze the skin towards an imaginary center (cf. Sect. 7.2). Sheet muscles act similar to linear muscles, but they consist of several parallel fibres [PW08]. When a facial muscle contracts it often causes distinct and recognisable wrinkles, which are very important for understanding facial expressions [Fai08].

Wrinkles

Origin and Insertion

In order to get a detailed insight into the function of the muscles of a human face it is important to determine the origin and the insertion of each muscle. The origin is an anatomical concept that describes the point at which a muscle is attached to e.g. a bone. The structure that the origin is attached to is not influenced by muscle contraction. The insertion also describes a point at which a muscle is attached. The attached structure (e.g. skin) has less mass then the structure of the origin and therefore is influenced by muscle contraction. When the muscle contracts, the insertion draws towards the origin and pulls the connected tissues. Insertion and origin are a key fact when it comes to modelling muscles (cf. Chap. 7). Figure 5.7 shows the origins of the muscles on the skull. Figure 5.8 shows in detail the origins of the muscles on the maxillary bone and part of the zygomatic bone.

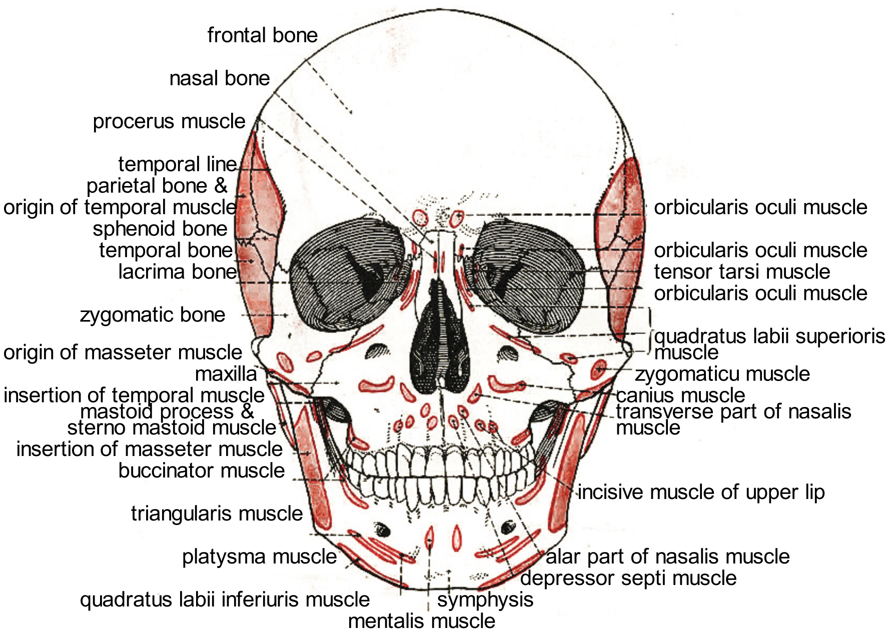


Figure 5.7: Origins of Muscles on the Skull [ana12]

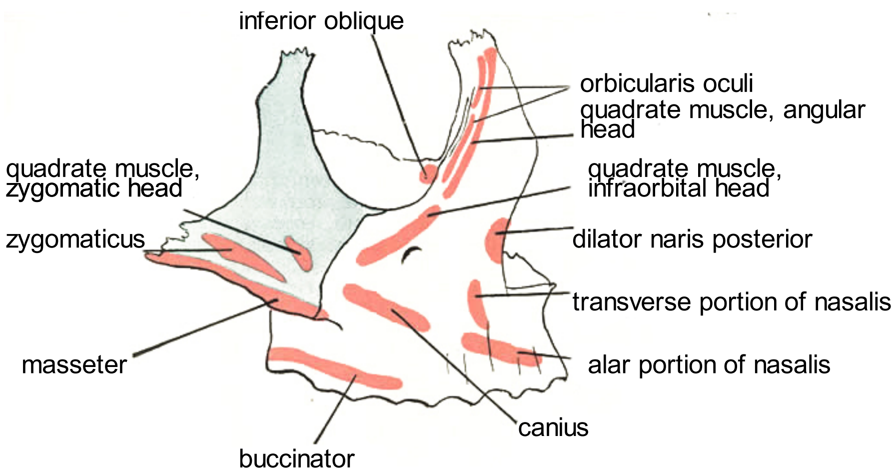


Figure 5.8: Origins of Muscles on the Maxillary Bone and Part of the Zygomatic Bone [ana12]

In the following, function, origin, and insertion of the facial muscles that are furthermore important are described.

LEVATOR LABII SUPERIORIS ALAEQUE NASI The *levator labii superioris alaeque nasi* is responsible for lifting the wing of the nose and elevating the upper lip. It has its origin at the upper frontal process of the maxillary bone and inserts into the lateral nostril and the skin of the the upper lip. The levator labii superioris alaeque nasi is also known as "the muscle of crying with hot tears" [dBC90] and its action can be described best by action unit 9 of FACS (cf. Fig. 5.9) [ana12]:

Levator Labii Superioris Alaeque Nasi in Action — Nose Wrinkler

- The skin along the sides of the nose is pulled upwards, causing wrinkles.
- The *infraorbital triangle* is pulled upwards and the skin around the lower eyelid is bunched.
- The upper lip center is pulled upwards and the lips may part.
- The wings of the nostril may be widened [EFH02].

LEVATOR LABII SUPERIORIS The *levator labii superioris*, also known as "the muscle of crying" [dBC90] has its origin at the *medial infraorbital margin* under the eye. The orbit is the cavity in which the eye is situated (cf. Fig. 5.10). The zygomatic bone and the maxillary bone form the infraorbital margin. Figure 5.7 shows the levator labii superioris as the middle spot of the *quadratus labii superioris* muscle. The insertions of the levator labii superioris are the skin

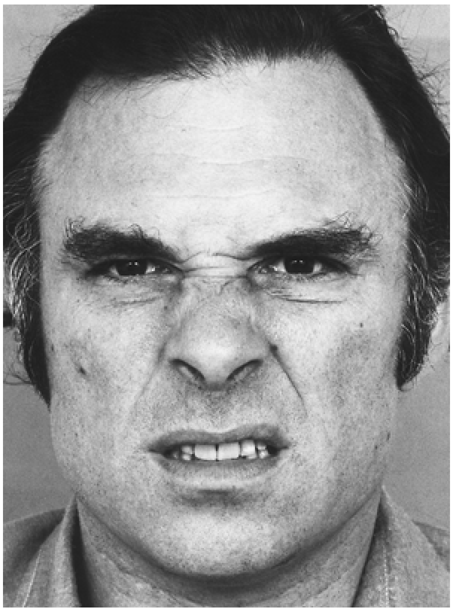


Figure 5.9: AU 9 (Nose Wrinkler) [EFH02]

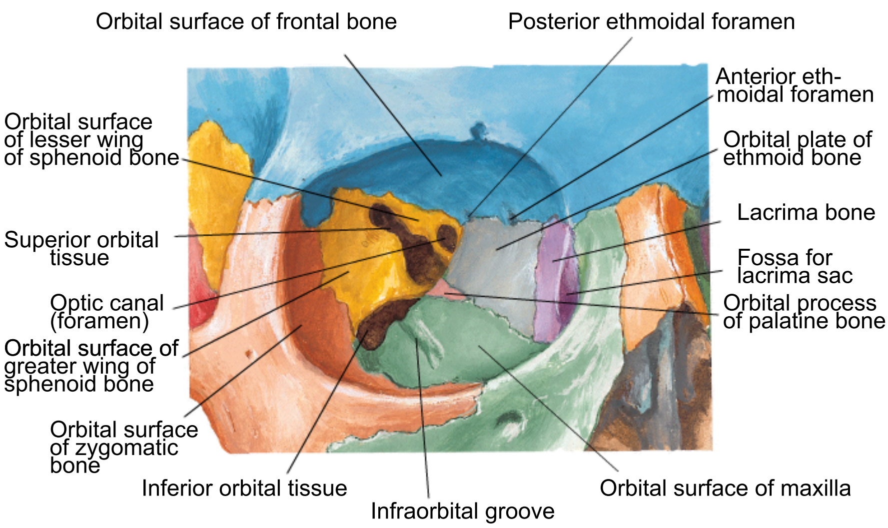


Figure 5.10: Bones that form the Orbit [Net10]

and muscles of the upper lip [ori12]. The muscle aids the upper lip to elevate and evert. The action can be described best with the corresponding action unit of FACS, AU 10 (cf. Fig. 5.11) [ana12]:

Levator Labii Superioris in Action — Upper Lip Raiser

- The center of the upper lip is drawn straight up, the outer portions are drawn up less.
- An angular bend in the upper lip shape is caused.
- The infraorbital triangle is pushed up and the *infraorbital furrow* may wrinkle.
- The *nasolabial furrow* is deepened and raised.
- The nostril wings are raised and widened.
- The lips may part [EFH02].

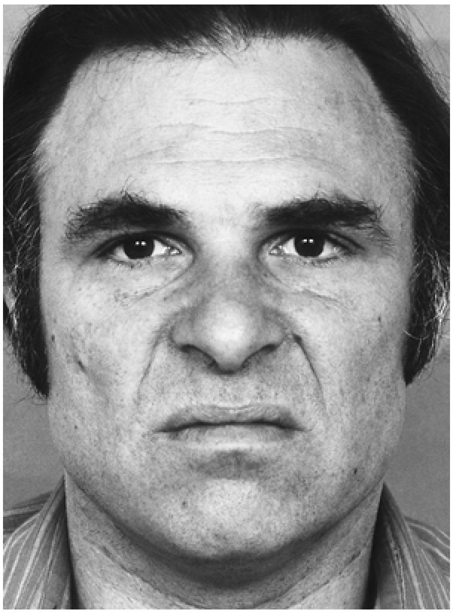


Figure 5.11: AU 10 (Upper Lip Raiser) [EFH02]

ZYGOMATICUS MAJOR The *zygomaticus major* has its origin at the anterior surface of the zygomatic bone and inserts into the *modiolus*, a chiasma of muscles at the corner of the mouth [ori12]. The muscle is shown as zygomatic muscle in Figures 5.7 and 5.8. It elevates and draws the mouth corner in a lateral way. The zygomaticus major is "the muscle of joy" [dBC90], its action can be described best with action unit 12 of FACS (cf. Fig. 5.12) [ana12]:

Zygomaticus Major in Action — Lip Corner Puller

- The corners of the lips get pulled back and upwards.
- The infraorbital triangle is raised.
- The nostrils may be raised and widened.
- The skin of the chin may be flattened [EFH02].

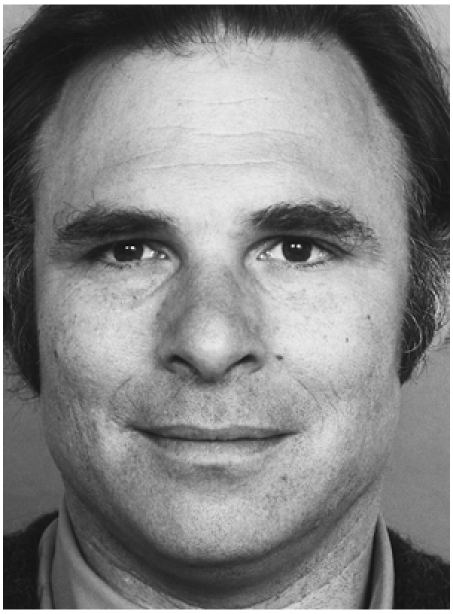


Figure 5.12: AU 12 (Lip Corner Puller) [EFH02]

LEVATOR ANGULI ORIS The *levator anguli oris*, alias *canius*, elevates the corner of the mouth. Its action can be described with the action unit 13 of FACS (cf. Fig. 5.13) [ana12]:

Canius in Action — Sharp Lip Puller

- The corners of the lips are pulled up and appear tightened and narrowed.
- The red parts of the lips do not move [EFH02].

The canius has its origin at the anterior surface of the maxilla below the *infraorbital foramen* — an opening in the skull (cf. Fig. 5.2), as shown in Figures 5.7 and 5.8. It inserts into the outer end of the upper lip and the modiolus. [ori12]

BUCCINATOR The *buccinator*, "the muscle of irony" [dBC90], starts at the external *alveolar margins* of the maxillary bone, shown as the respective left or right upper spots in Figure 5.7. It also starts at the mandible at the back tooth, shown

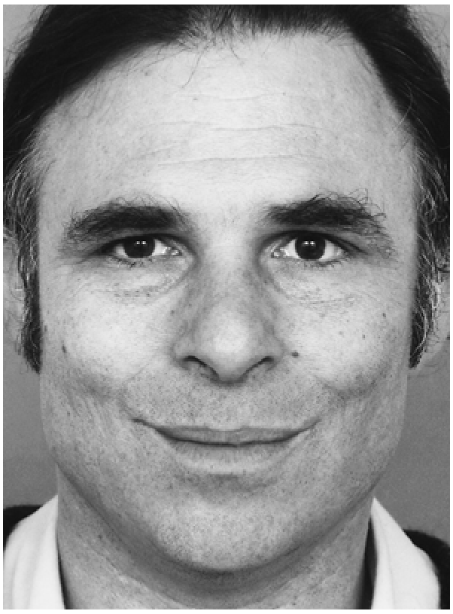


Figure 5.13: AU 13 (Sharp Lip Puller) [EFH02]

as the lower spots. It is connected to the *maxillary tubercle*, a part of the maxillary bone, and also to the *pterygoid hamulus* and the *mylohyoid line*. It is also attached to the *pterygomandibular raphe*. The muscle decussates at the modiolus and interdigitates with the opposite side [ori12]. The buccinator aids the closing of the mouth, chewing, and tenses the cheeks for blowing and whistling. Its action can be described best with action unit 14 of FACS (cf. Fig. 5.14) [ana12]:

Buccinator in Action — Dimpler

- The corners of the mouth are tightened, and pulled inwards.
- Wrinkles at the lip corners are caused.
- Lip corners may angle up or down [EFH02].

DEPRESSOR ANGULI ORIS The *depressor anguli oris*, alias *triangularis*, is "the muscle of sadness and disgust" [dBC90]. It does not start on the skull, but at the *oblique line* of the outer surface of the mandible and inserts into the modiolus. It is capable of lateral depression and draws of the corner of the mouth [ori12]. Its action can be described best with action unit 15 of FACS (cf. Fig. 5.15) [ana12]:

Depressor Anguli Oris in Action — Lip Corner Depressor

- The corners of the lips are pulled down.
- The skin below the lower lip corners is wrinkled or bagged [EFH02].

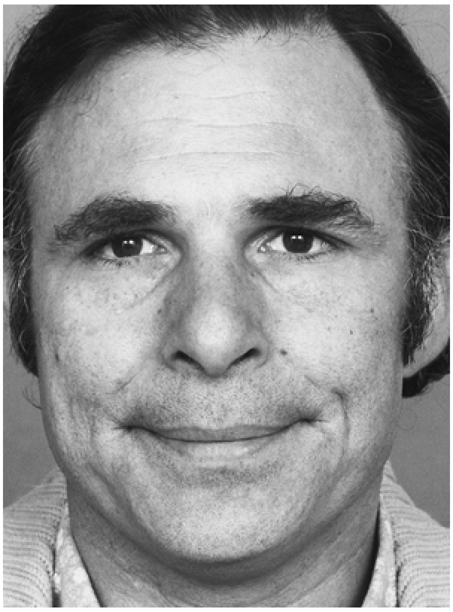


Figure 5.14: AU 14 (Dimpler) [EFH02]

DEPRESSOR LABII INFERIORIS The origin of the *depressor labii inferioris* is placed on the outer surface of the mandible along the oblique line and the insertion is located in the skin of the lower lip. It is capable of lateral depression and therefore "the muscle complementary to irony and aggressive feelings" [dBC90]. Its action can be described best with action unit 16 of FACS [ana12] (cf. Fig. 5.16):

Depressor Labii Inferioris in Action — Lower Lip Depressor

- The lower lip is pulled down and stretched.
- The lips are parted and the lower teeth exposed.
- The chin boss is stretched laterally and down [EFH02].

MENTALIS The *mentalis* is associated with thinking, since it wrinkles and elevates the chin and protrudes the lower lip, but it is also called "the muscle of disdain and doubt" [dBC90]. Its action can be described best by action unit 17 of FACS (cf. Fig. 5.17) [ana12]:

Mentalis in Action — Chin Raiser

- The chin boss is pushed upwards.
- The lower lip is pushed upwards.
- Wrinkles may appear on the chin boss.
- The mouth is shaped like an inverted U [EFH02].

The originn is the *incisive fossa* on the anterior aspect of the mandible, which is below the teeth and can be seen on Figure 5.7. The insertion is the skin of the chin [ori12].

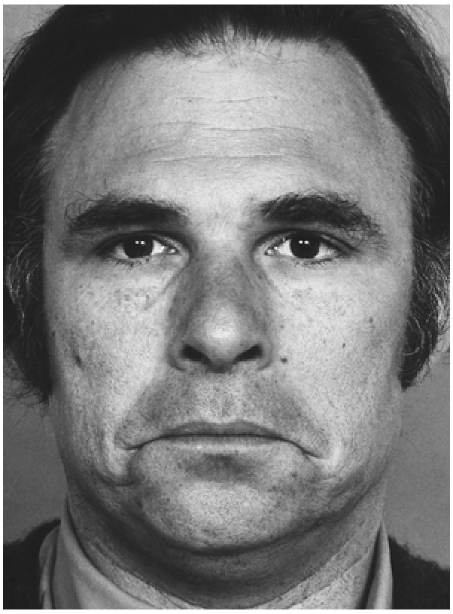


Figure 5.15: AU 15 (Lip Corner Depressor) [EFH02]

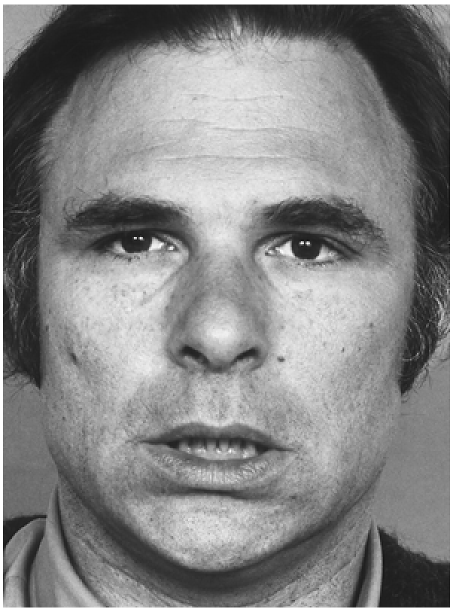


Figure 5.16: AU 16 (Lower Lip Depressor) [EFH02]

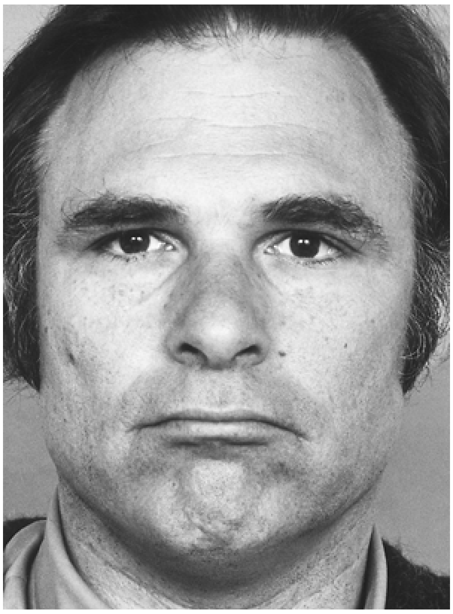


Figure 5.17: AU 17 (Chin Raiser) [EFH02]

ZYGOMATICUS MINOR The *zygomaticus minor* is "the muscle of moderate crying or weeping" [dBC90]. It starts at the lateral infraorbital margin and ends in the skin of the upper lip. It is shown in Figure 5.7 as the right muscle of the quadratus labii superioris muscle and as zygomatic head in Figure 5.8. It is capable of elevating and everting the upper lip.

RISORIUS The *risorius* muscle is used to retract the corner of the mouth. The action can be best described by action unit 20 of FACS (cf. Fig. 5.18) [ana12]:

Risorius in Action — Lip Stretcher

- The lips are pulled back laterally.
- The mouth is elongated.
- The lips are flattened and stretched.
- The skin beyond the lips is pulled laterally.
- The skin of the chin boss is stretched in a lateral manner [EFH02].

The risorius starts at the deep fascia of the *masseter muscle* and the *parotid gland*. It inserts at the corner of the mouth into the modiolus.

ORBICULARIS ORIS This muscle encircles the lips. The origin of the *orbicularis oris* is near the midline on the anterior

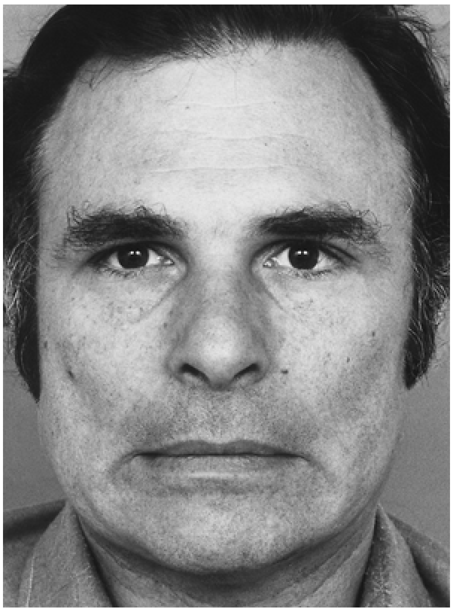


Figure 5.18: AU 20 (Lip Stretcher) [EFH02]

surface of the maxillary bone and the mandible and the modiolus at the angle of the mouth. It inserts into the *mucous membrane* of the margin of the lips. With the buccinator it also inserts into the modiolus [ori12]. Since origin and insertion are not on the skull they are not shown in Figure 5.7. The orbicularis oris narrows mouth opening. It is used for pursing lips and to pucker the lip edges. Several action units of FACS base on this muscle, like AU 22 (cf. Fig. 5.19) [ana12]:

Orbicularis Oris in Action — Lip Funneler

- The lips funnel outwards.
- The lip corners are pulled in medially.
- The teeth are exposed.
- The red part of the lips is exposed [EFH02].

PLATYSMA The *platysma* has its origin in the skin over the lower neck and the upper lateral chest. It inserts into the inferior border of the mandible (cf. Fig. 5.7), into the skin of the lower face, and into the modiolus. The platysma wrinkles and depresses the lower face and the mouth. It is used for forced depression of the underjaw.

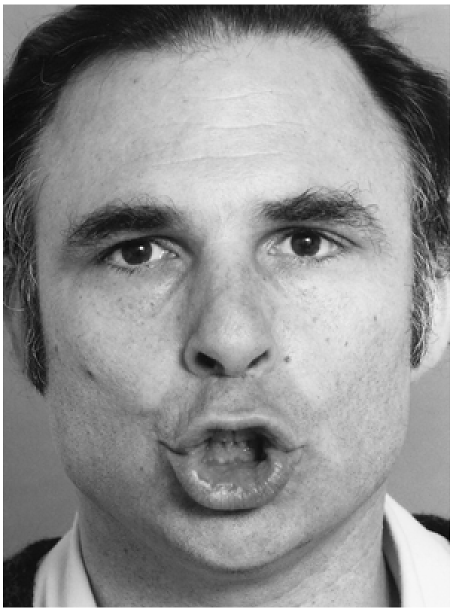


Figure 5.19: AU 22 (Lip Funneler) [EFH02]

5.3 SKIN STRUCTURE OF THE HUMAN FACE

Human skin consists of three layers as shown in Figure 5.20: *epidermis*, *dermis* and *hypoderm*.

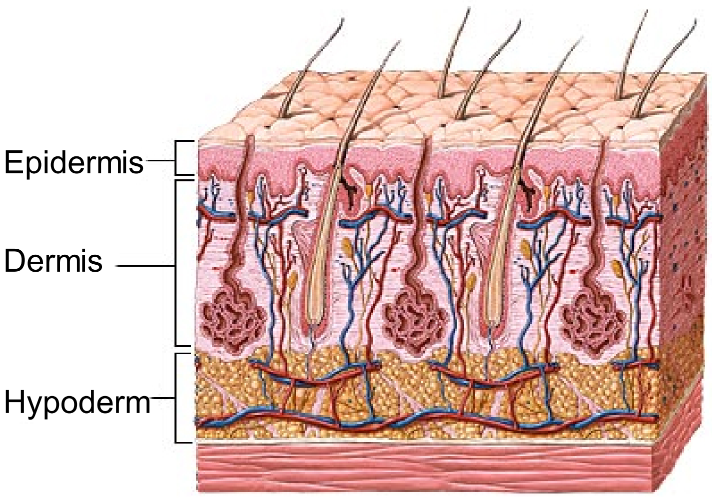


Figure 5.20: Layers of the Skin [ski12a]

The epidermis contains several sublayers and at the thinnest point (eyelids) it is about 0.05 mm thick. The top layer is made of dead, flat skin cells.

Layers

The dermis is composed of tissues and 0.3 mm thick at the thinnest point (eyelids).

The hypoderm is a tissue rich of fat and blood that bolsters muscles, bones and organs and shields from cold. The thickness of this layer varies from person to person [ski12a].

6 SOLUTION OVERVIEW

The mouth, however, has no fixed attachment whatsoever. This, combined with the fact that there are a host of muscles specifically aimed at stretching and moving the mouth around, makes the mouth the most variable feature in the face.

- Gary Faigin [Fai08]

The approach we present in this thesis makes use of state-of-the-art muscle-based (physics-based) parametrisation in order to control the animation of facial expressions. Phonemes and visemes, respectively, are created as poses of realistic mouth shapes and interpolations between them. The phonemes and visemes used are explained hereafter. The modelled muscular anatomy is an abstraction of the real human anatomy and will be explained in the following, as well as Autodesk Maya's new muscle feature that is used to model these anatomical details. This feature enables realistic skin deformation, the computational costs are lower than for finite elements and it is less abstract than the spring approach (cf. Chap. 2). The different renderers, that come along with Autodesk Maya, are briefly discussed in the following to explain, how the rendering task of step five of facial animation is solved in the approach.

6.1 SELECTING PHONEMES AND VISEMES

Step one of facial animation deals with selecting phonemes and in step two these are mapped to visemes (cf. Chap. 4). In the chosen approach one does not decide on a specific viseme set. In order to prove the usability of the muscle model, visemes are selected that occur in all of the maps presented in Section 4.2. Additionally one selects these visemes based on the phoneme types they represent, to obtain a diverse set.

The selected phonemes */m/*, */b/*, and */p/*, are classified as bilabial consonants by the IPA. These phonemes are mapped to the bilabial viseme class in the map of Neti et al. (cf. Tab. 1(a)), classified as P by Lee and Yook (cf. Tab. 1(b)), and mapped to class 1 of the MPEG-4 standard (cf. Tab. 1(c)). These phonemes correspond to the Preston Blair mouth shape in Figure 4.4(e). *Consonants*

Also selected are the labiodental consonants */f/* and */v/*, which belong to the same named viseme group of the map of Neti et al. (cf. Tab. 1(a)), to class F in the mapping of Lee and Yook (cf. Tab. 1(b)), and to class 2 of the MPEG-4 standard (cf. Tab. 1(c)). The Preston Blair mouth shape in Figure 4.4(c) shows the corresponding mouth shape.

Vowels

In addition the following three front-vowels are selected: */i/*, */a/* and */e/*. */i/* is a close-front vowel whereas */a/* is an open-front vowel and */e/* is a close-mid-front vowel. All three are classified as lip-rounding based vowels by Neti et al. (cf. Tab. 1(a)) whereby they are only mentioned as combined phonemes (e.g. */ih/*, */ah/*, or */eh/*). The same applies to the map of Lee and Yook, where each vowel is mapped as a combined phoneme to one ore more classes (e.g. class IY, EH, AA, etc., cf. Tab. 1(b)). In the map of the MPEG-4 standard each vowel is mapped to its own class (cf. Tab. 1(c)). The Preston Blair mapping associates */i/* and */a/* to the same mouth shape, shown in Figure 4.4(b). The mouth shape corresponding to */e/* is shown in Figure 4.4(a).

Furthermore the close-mid back-vowel */o/* is selected, which is part of the lip-rounding based vowel viseme class by Neti et al. (cf. Tab. 1(a)), combined with */a/* in the AO class of the map of Lee and Yook (cf. Tab. 1(b)), and mapped to class 13 of the MPEG-4 standard (cf. Tab. 1(c)). The corresponding Preston Blair mouth shape is shown in Figure 4.4(g).

6.2 ABSTRACTING ANATOMY

Step three of facial animation deals with transferring anatomical conditions of the human face into a 3D model. In order to do this, one needs to simplify. This is achieved by focusing on the muscular anatomy of the face, and confining the skeletal anatomy and the skin layer to the basics (cf. Chap. 5).

Skin Abstraction

Skeletal Abstraction

The different skin layers shown in Section 5.3 are neglected and merged into one layer, represented by a polygon mesh. Furthermore one does not distinguish the different bones of the skull explained above, except for the mandible. The mandible is the only bone involved in movement and it supports facial expressions. The skull model used therefore consists of a separate mandible mesh and a mesh containing all other bones. The skin and the skull models are described in detail in Section 6.3.

Muscular Abstraction...

The muscle model created in this approach is abstracted in the following ways: Firstly, it is not necessary to consider the complex internal structure of muscles, as explained above, in order to model muscle action. The abstraction of the muscle structure and actions is done by Maya (cf. Sect. 6.4). Secondly, it is necessary to abstract insertions and origins of muscles in a way that the muscle model is accurate enough to enable realistic facial expression while it is not too detailed and complex to enable efficient modelling, animation, and rendering. Taking these limitations into account the origins of all linear muscles in the model are placed at the approximate region of the real origin (cf. Sect. 7.1). The insertions of all linear muscles are abstracted in order to insert into the orbicularis oris, which enables control of this muscle (cf. Sect. 7.5). Origin and insertion of the orbicularis oris are abstracted due to limitations of Maya's muscle feature (cf. Sect. 7.2). Thirdly, it is not necessary, to model all the muscles of the face, since some muscles have a supportive function. From Figures 5.12, 5.13 and 5.14 one can conclude, that the zygomaticus major muscle, the canius muscle and the buccinator muscle produce similar facial expressions. The same applies to the zygomaticus minor muscle. It is possible to map these actions to one muscle and therefore not necessary to model all four muscles. One could also assume, that the actions of the mentalis muscle and the risorius muscle could be modelled with one muscle. Nevertheless one decides to distinguish them in order to have two muscles that connect to the same point of the orbicularis oris (cf. Sect. 7.5). Thus one can neglect the platysma muscle, since its action is similar to the risorius muscle.

. . . of internal Structure

. . . of Insertion and Origin

. . . of Responsibility

Table 2 gives an overview over all muscles of the chosen approach including their type. It contains only linear and sphincter muscles. The origins and insertions are given in the abstract way described above. Figure 6.1 indicates the desired position of each muscle in the model.

6.3 THE SKIN AND THE SKULL MODEL

The approach makes use of detailed 3D models of human skin and skull that are available on the Internet.

The skull that forms the basis for the approach is part of a very detailed skeleton model created by Andrew Klein [Ske12]. The mesh contains 18,651 polygons of which 1,376 build the mandible and 3,531 build the rest of the skull (cf. sect. 5.1). These polygons are mostly three-sided. 13,744 mostly four-sided polygons build the teeth. The model contains separate meshes for the mandible, the teeth and the rest of the skull.

Skull Model

Table 2: Overview of the Muscles of the Model, their Category and the abstracted Origin and Insertion.

Muscle	Type	Origin	Insertion
Levator Labii Superioris	Linear	Lower Edge of Eye Socket	Orbicularis Oris
Levator Labii Superioris Alaeque Nasi	Linear	Maxilla Bone	Orbicularis Oris
Zygomaticus Major	Linear	Zygomatic Bone	Orbicularis Oris
Risorius	Linear	Parotid Gland	Orbicularis Oris
Triangularis	Linear	Mandible	Orbicularis Oris
Depressor Labii Inferioris	Linear	Oblique Line of Mandible	Orbicularis Oris
Mentalis	Linear	Bottom of Mandible	Orbicularis Oris
Orbicularis Oris	Sphincter	Orbicularis Oris	Orbicularis Oris

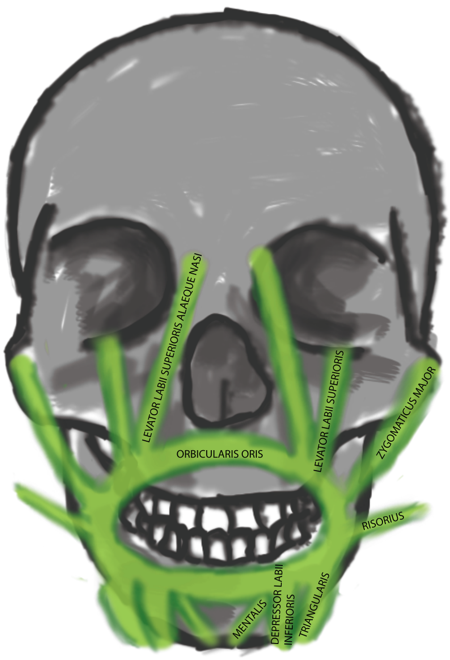


Figure 6.1: Sketch of the Muscle Position

The reference skull mesh contains 42,621 four-sided polygons (quads), but does not contain details like separate meshes [Ref12].

The skin mesh is going to be deformed by muscle actions, therefore a mesh with only quads would be perfect. Other shapes (e.g. triangles or n-gons) cause a central pinch and their flow and bend is harder to handle, since they tend to cause artifacts. Such shapes also cause problems when adding edge loops or trying to smooth the mesh [Cho11]. Moreover the paint weights tool used works better with quads.

Quads or Triangles

The mainly used skin mesh consists of 4,362 polygons, which are mostly four-sided, and about 600 are three-sided. This is an acceptable amount and will not cause problems, since only a few triangles are used in the important mouth area (cf. Fig. 6.2). The model contains many details, like eyeballs, eyelids, teeth,

Skin Model

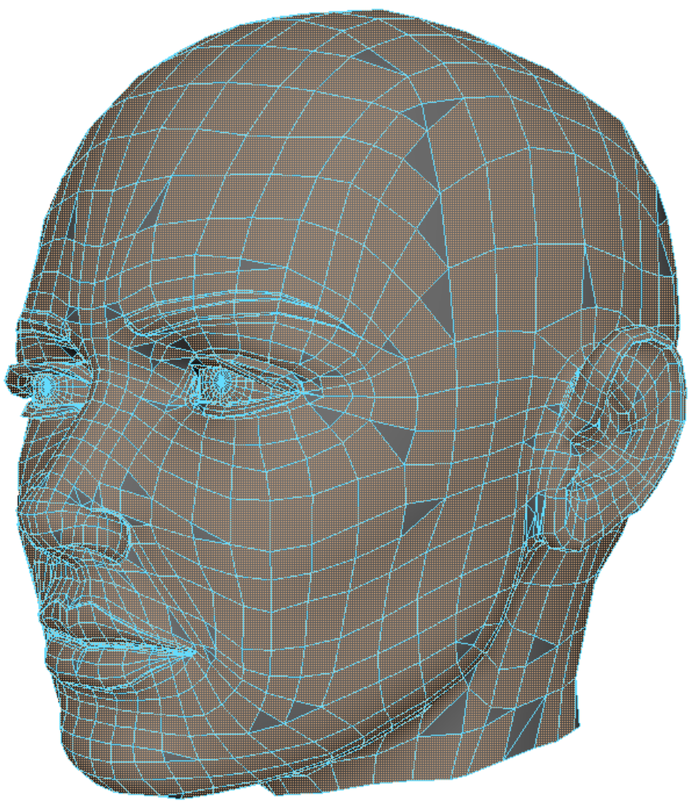


Figure 6.2: Quads (highlighted) and Triangles of the Skin Mesh

and tongue, but there is no differentiation between the single layers of the skin (cf. Sect. 5.3) [Ski12b].

The reference skin mesh is the male counterpart of the described mesh. It has the same structure and a similar amount of triangles and quads.

Independence The models were built independently, so the proportions of the skin do not match any of the skulls perfectly. One goal of the chosen approach is to perform the matching by modelling a muscle layer based on the skull mesh and applying influences to the muscles based on the skin mesh. The muscle layer will act as an interface that could match any skin model to any skull model.

6.4 AUTODESK MAYA

Animation Software Autodesk Maya is the 3D animation software used to complete steps three to five of the described facial animation method. The software is based on an extensible production platform and comes along with tools for modelling, simulation, animation, rendering, etc. It is used in a wide range of 3D animation projects such as game development. The current software version (2013) enables parallel workflows and complex tasks [May12a]. Bibliowicz has shown that facial animation is solvable with Maya. He uses joints of Maya's character rigging feature to model facial muscles. These muscles are attached to parts of the skin mesh by point constraints in order to cause deformation [Bib05]. The new muscle feature can be seen as an advancement of character rigging. It is more flexible and powerful as will be shown in the following chapters.

6.4.1 *Deformers of the Maya Muscle System*

Since 2009 Autodesk Maya comes with a muscle system that enables sophisticated character rigging and realistic skin deformation. Used in concert or independently the tools can deform geometries in order to simulate muscle bulging and stretching.

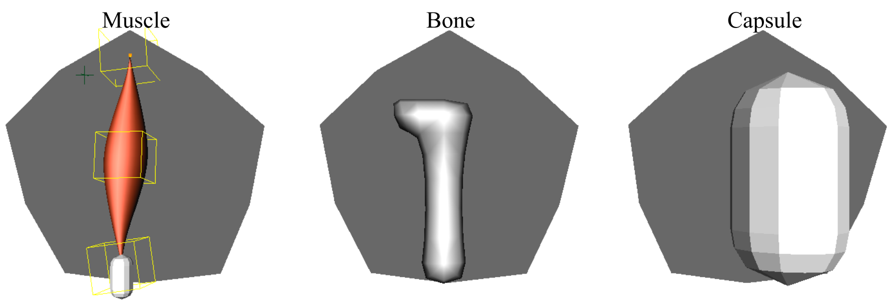


Figure 6.3: Maya Muscle, Bone and Capsule [DTM08]

The muscle system includes three main deformers: Muscles, bones and capsules (cf. Fig. 6.3). Muscles are the most powerful component. They are created from NURBS and have one connection point per end. It is possible to flex, extend, bounce, etc. a muscle.

Bones are derived from polygons and can have any shape. They are used for simulating bone sliding beneath the skin and do not necessarily refer to Maya bones, that connect joints in skeletal rigging.

Muscles, Capsules, and Bones

Capsules are like joints and shaped like a pill. In conjunction with a skin deformer and skin geometry they can produce fast sliding effects. The shape of the capsule is driven by a formula and therefore fast to solve.

Muscles, bones and capsules are used together with skin deformers, which are binding systems. This causes deformation to geometry and enables weighting (e.g. sticky, sliding, jiggle, cf. Sect. 8.1) [DTM08, PK11, May12b].

6.4.2 *Muscle Types*

As described above, muscle objects are created from NURBS surfaces. Maya knows two different types of muscles, (new) *Muscles* and *Simple Muscles*. Simple muscles use regular NURBS surfaces with a spline and a special spline deformer used to bend them. New muscles are parametric-style NURBS shapes that can deform and pose.

Creating Simple Muscles

There are different ways to create a simple (spline-based) muscle. One can apply a spline- or stretch-deformer and a muscle object to a NURBS surface in order to create the muscle. The muscle gets a number of controls applied that cannot be changed once the muscle is created. This approach is straightforward and works well for simple shaped muscles. Simple muscles can also be created using the muscle builder tool. One can specify two objects that the muscle will attach to. Within this tool one can specify *cross sections* and *segments* of the muscle. The cross sections are used to control the muscle, while the segments are used to shape it. In the finalisation step a deformer is selected. Muscle parameters like fat, jiggle, etc. or poses for stretch and squash can also be modified.

In order to create (new) muscles one makes use of the muscle creator tool, which is quite similar to the muscle builder. Within this tool one can specify cross sections and segments of the muscle. The muscle attaches to a selected start object and an

Creating New Muscles

end object. The tool also enables sculpting of the muscle. Controls can be easily adjusted and poses can be specified e.g. for stretch and squash. It is also possible to grow muscles to surfaces in order to get the right shape [MMA12, May12b].

6.4.3 *Renderers*

To illustrate steps three and four of facial animation within the next chapters, step five is anticipated by explaining the render options of Autodesk Maya.

Software Renderer

Several renderers are provided in the current software version (2013). One of them is the software renderer, which enables ray tracing, particles, fluids, paint effects, etc.

Vector Renderer

The Maya vector renderer can be used to create artificial renderings, like cartoons or wireframes, that do not need special effects like bump maps, fluid effects, particles, post-render effects, etc.

Mental Ray

In the following most of the time the *mental ray* renderer is used, which enables 3D rendering of photorealistic and unrealistic scenes likewise. It provides the largest set of features, like special materials and shaders, global illumination, ray tracing, depth of field, motion blur etc. [Ren12].

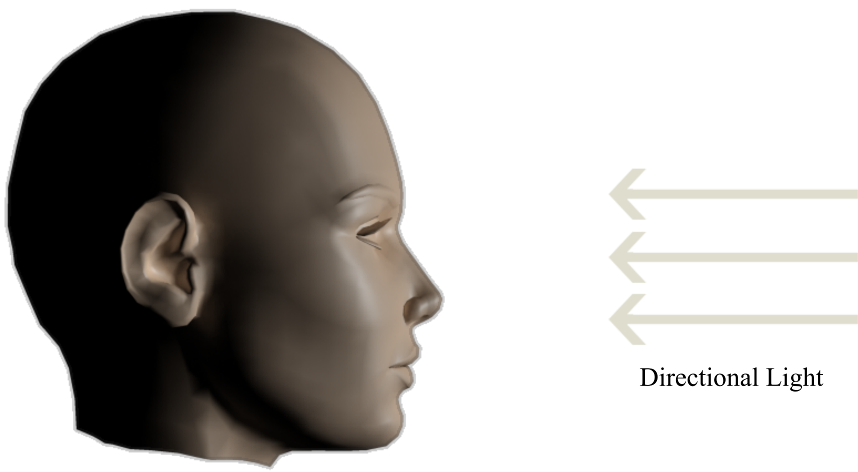


Figure 6.4: Directional Light illuminating the Material and Skin Shader of the Skin Mesh

Setting

In order to render images of the skin mesh that is deformed by muscle actions with mental ray, several features are combined. The goal is to produce a simple image structure with highlights on the features caused by facial expressions. First of all, a shiny mental ray material, combined with a mental ray skin shader is applied to the skin mesh, in order to achieve a natural look of the skin. Next, a directional light with a white color and an average intensity is added to the scene, pointing towards the head as shown in Figure 6.4. The light rays are parallel and simulate illumination from a far distance. Finally, contour rendering is enabled to produce a glow around the head, similar to the glow that occurs in three-point illumination. The contour intensifies the contrast between the head and the background of the scene.

For rendering images of the skull mesh with mental ray, the same light setup is used, but contour rendering is disabled. The mesh gets a shiny material applied that simulates bone texture with a bump map and is available on the Internet [Bon12].

Hardware Renderer

The Maya hardware renderer makes use of the computational power of today's graphic cards. It enables displacement mapping, shader translucency, specular lights, reflections, shadows, etc. The hardware renderer 2.0 also enables real-time rendering. This real-time renderer together with the light setup and materials mentioned above is used to render images of the skull and the skin that also show the mesh structure.

6.5 Prospective Application Areas

The approach does not provide a 100% anatomical correct and complete model of the human musculature. It's rather an abstraction based on the basic muscles that are necessary to model facial animation. Therefore it cannot be applied in the area of medicine. Since one goal of the discussed approach is reusability, one could apply the derived model in situations, where the visual appearance of a face might change often, but the underlying logic stays the same. Another goal is the mimic articulation of phonemes or visemes. A lip-reading application, where one can select between a female social agent and a male equivalent, is just another example of an application.

7 CREATING A MODEL OF FACIAL MUSCLES

Facial expressions come and go. They pass over the surface of the face like ripples on the surface of a pond.
- Gary Faigin [Fai08]

In Section 5.2 it has been shown that facial muscles have a complex outer structure, consisting of origin, the muscle itself and the insertion. On the inside muscles consist of bundles of fibres (cf. Sect. 5.2). This level of detail is not relevant for models dedicated to facial animation. In this scope a muscle consists of the insertion, the origin, and the belly, which is the part that does the tightening and contraction. The size and the shape of a muscle are in addition almost neglectable for animating facial expressions. Instead, the motion of each muscle is the important aspect [Pal11]. This simplification a of a muscle can be described as a direction and magnitude in two and three dimensions. The direction is toward the origin at the bone. The displacement depends on the muscle contraction [PW08].

Direction and Magnitude

7.1 LINEAR MUSCLES

Except for the orbicularis oris muscle, all muscles in the presented approach are linear muscles.

7.1.1 *Mathematical Description*

For linear muscles one can describe the effect of a muscle vector contraction on an arbitrary point P on the skin. Figure 7.1 shows a vector representation of a muscle with the origin O and the insertion I. O and I are located on a two-dimensional plane. The maximum influence of the muscle is denoted as ω. It is assumed that no displacement happens at the origin and that the deflection increases to a maximum right before the point of insertion. Therefore, a decline of the displacement runs through the skin [Wat87]. R_s denotes the fall-off start radius and R_f the finish radius. The point P is located on the skin mesh. The

Muscle Vector Contraction

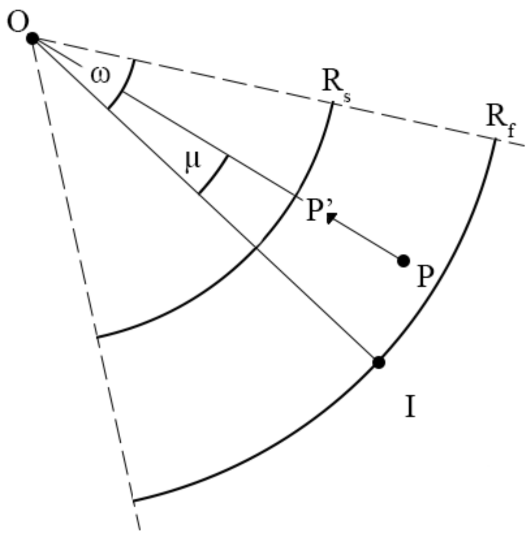


Figure 7.1: Linear Muscle Description: The displacement of P to P′ is calculated

displacement of this point to a point P' towards O along the vector $\overrightarrow{PO}$, can be written as:

$$P' = P + AKR\overrightarrow{PO} \tag{7.1}$$

Angular Displacement

The angular displacement factor A is defined as:

$$A = \cos\left(\frac{\mu}{\omega} \cdot \frac{\pi}{2}\right) \tag{7.2}$$

Radial Displacement

where μ denotes the angle between the vectors $\overrightarrow{OI}$ and $\overrightarrow{OP}$. The radial displacement factor R is defined as:

$$R = \begin{cases} \cos\left(\left(1 - \frac{D}{R_s}\right) \cdot \frac{\pi}{2}\right) & \text{for } D < R_s \\ \cos\left(\frac{D - R_s}{R_f - R_s} \cdot \frac{\pi}{2}\right) & \text{for } R_s < D < R_f \end{cases} \tag{7.3}$$

where $D = \|P - O\|$. K is a constant factor that represents the elasticity of the skin [PW08].

7.1.2 *Modelling Linear Muscles*

When modelling muscles of a linear shape Maya's straightforward approach for muscle creation can be used. In the following the modelling process is explained for the zygomaticus major muscle on the left side of the face. As mentioned before the base of a Maya muscle is a NURBS surface. One does not start with a NURBS but a polygonal cylinder, in order to make use of nDynamics features as follows: The cylinder is translated and scaled into the desired position and form. Its bottom and top need to get shrunken by merging the respective vertices to a point. Next, the vertices are aligned to the approximate position at the zygomatic bone and a dummy orbicularis oris object. In order to get the muscle as close to the skull as possible one could either use the soft select tool or the nDynamics features. The latter enables the geometry to be placed at an exact distance from the skull. To achieve this, one makes the skull mesh a passive collider. Passive objects do not take part in interaction with forces, but in collisions. The muscle becomes an nCloth object, which is also part of the dynamic simulation framework. In order to attach the muscle to its origin and insertion, a dynamic point constraint is applied. Now, a gravity field can be applied to influence the nCloth object. The gravity needs to act towards the skull. For the case of left zygomaticus major muscle, gravity in negative X and Y axes will force the muscle to nestle to the shape of the skull as shown in Figure 7.2. The pressure value determines the distance from the skull. Since the nDynamics feature calculates natural forces in an iterative manner, one needs to run the animation until the desired influence on the shape is calculated.

Shaping with Polygons

nDynamics

Figure 7.2: Modelling Zygomaticus Major as Polygonal Muscle

After deleting the dynamic information, the polygon muscle is converted to a NURBS object and a spline deformer is applied, resulting in a simple muscle. For a linear muscle the following three cross sections are sufficient: origin, insertion, and

Conversion

body. The cross sections of the insertion can be constrained to any other object, like a control point of the orbicularis oris.

7.2 SPHINCTER MUSCLES

The orbicularis oris is the only sphincter muscle that is modeled in the chosen approach. The squeezing that occurs on contraction can be considered to be uniform around the mouth [PW08].

7.2.1 *Mathematical Description*

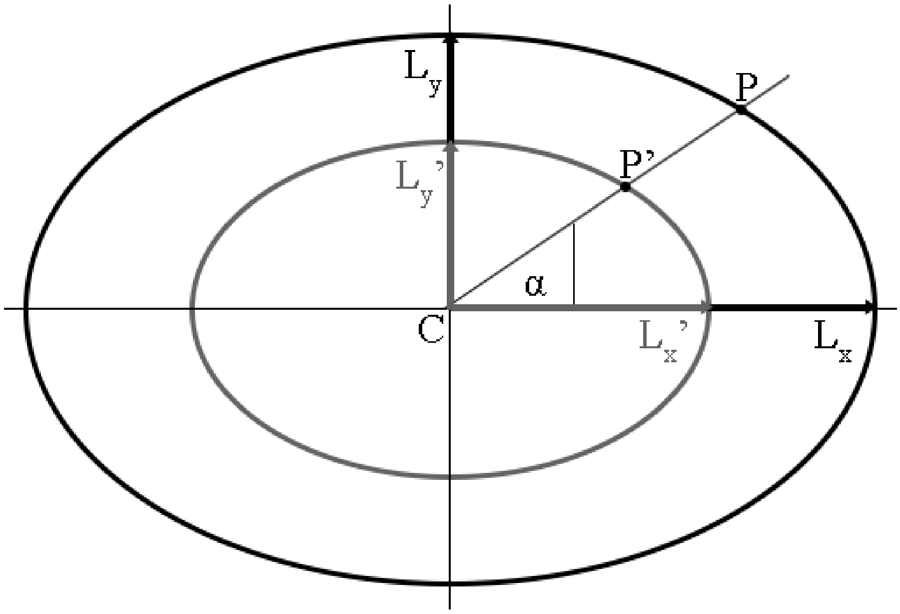


Figure 7.3: Sphincter Muscle Description: The displacement of P to P′ is calculated

Ellipse

A sphincter muscle has an approximately elliptical shape. When such a muscle contracts, the surface around the imaginary central point is contracted. Therefore, the angular displacement needed for linear muscles is no longer required [Wat87]. An elliptical representation of a sphincter muscle is shown in Figure 7.3. Let L_x denote the semi-major axis and L_y its semi-minor axis. The displacement of a point P to a point P' can be described by the ellipse equation:

$$0 = 1 - \frac{\sqrt{L_y^2 P_x^2 + L_x^2 P_y^2}}{L_x L_y} \tag{7.4}$$

which describes the possible locations of P on the ellipse. Since P, L_x and L_y are given, one can calculate the angle between the vector $\overrightarrow{CP}$ and the semi-major axis, which results in:

$$\begin{pmatrix} P_x \\ P_y \end{pmatrix} = \begin{pmatrix} L_x \cos\alpha \\ L_y \sin\alpha \end{pmatrix}. \tag{7.5}$$

When the muscle contracts, the ellipse shrinks uniformly by the factor K, resulting in L'_x and L'_y. A displacement of P occurs along the vector $\overrightarrow{CP}$ and the displaced point P' moves to the grey-colored ellipse described by L'_x and L'_y. Since α does not change, P' can be written as:

$$\begin{pmatrix} P'_x \\ P'_y \end{pmatrix} = \begin{pmatrix} K \cdot L_x \cos\alpha \\ K \cdot L_y \sin\alpha \end{pmatrix} \tag{7.6}$$

where K denotes the elasticity of the skin as a constant.

7.2.2 *Modelling Sphincter Muscles*

In 2005 Bibliowicz presented his model of facial muscles. At this time it was not possible to model sphincter muscles with help of the character rigging feature of Maya and led to limitations of his approach [Bib05]. With Maya's new muscle feature sphincter muscles are still not built-in. Maya muscles are designed to represent linear muscles, therefore modelling a sphincter muscle is a challenge. A straightforward approach would be to create a NURBS curve for the inner and one for the outer edge of the muscle, and then loft the curves. For the resulting NURBS surface an offset is created to generate thickness. This approach can lead to a very detailed orbicularis oris muscle shape, but a spline deformer applied to this NURBS object is resulting in an inappropriate simple muscle. Maya does not apply the muscle controls in an elliptic way, but very close around a point on the surface. Due to this the muscle could never contract or tighten correctly.

Converting NURBS to Muscle

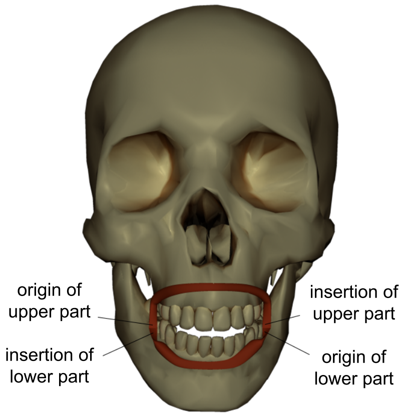
Another approach would be to use Maya's muscle creator to create a muscle with a start and end point and then form the muscle into the desired elliptical shape. The initial start and end would be connected. Bringing the muscle into a flat circular shape is hard. The shape is controlled by several segments and adjusting one segment influences a wide range of the shape. If one segment is shaped correctly and one tries to

Made of one Muscle Object

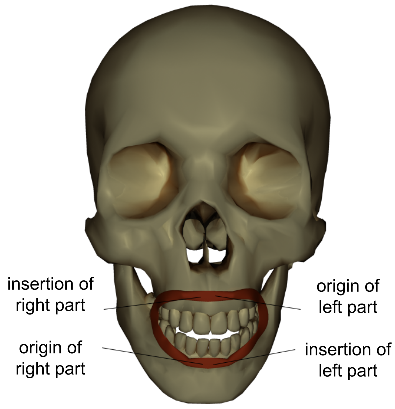
adjust the next segment, the shape of the first segment might get worse.

Made of two Parts

A more promising way would be to split the orbicularis oris into two parts: an upper and a lower part or a left and a right part (cf. Fig. 7.4). Both parts share an origin and an insertion. Modelling the orbicularis oris as a left and a right part seems



(a) Upper and Lower Part



(b) Left and Right Part

Figure 7.4: Modelling Orbicularis Oris (a) as upper and lower Part and (b) as left and right Part

Left and Right Part

Upper and Lower Part

to be more sensible at first glance, since this would be close to the real anatomy. Each corner of the mouth would be formed and controlled by a solid muscle. All muscles that insert into the modiolus would have a solid base to attach to. The connection of both muscle parts happens in the center line of the skull. Almost no muscle attaches there, so the resulting force of the connection points is low. But due to the functional principle of Maya's muscle feature, modelling a left and a right part of the muscle is not feasible. Muscle movement deforms skin according to the weights that are painted to the corresponding faces of the skin mesh. The left part of the orbicularis oris influences the left part of the upper lip and the left part of the lower lip. Therefore one has to paint weights to both lips. It is not possible to distinguish them. The consequence is that pulling the muscle upwards will lift upper and lower lip at the same time. Opening the mouth is not possible. This fact leads to the conclusion that the orbicularis oris muscle needs to be modelled as an upper and a lower part. The upper part influences the upper lip and the lower part influences the lower lip. Lip opening can be achieved easily. In the discussed approach each part of the muscle is modelled as (new) muscle with six cross sections and segments in order to get a sufficient amount of attachment points to attach other muscles (cf. Sect. 7.5).

7.3 Mirroring Muscles

All linear muscles that are modelled in the proposed approach exist twice in the human face — mirrored at the center line. Modelling just half of the muscles and mirroring them speeds up the modelling process. Since a 100% symmetric face cannot be found in nature, one should consider to slightly randomise the shape of the muscles after mirroring them. During this thesis this modification was predetermined, since the skull model itself was not 100% symmetric.

Symmetry

7.4 Finalising the Muscle Model

After modelling seven linear muscles, mirroring and slightly modifying them, the final muscle model is obtained as shown in Figure 7.5. It contains 14 "real" linear muscles and one sphincter muscle made of two linear muscles. Before starting

Figure 7.5: Final Muscle Model

to animate the muscle model, a "snapshot" is taken. Based on the final shape of the muscles, a *base pose* is created for each

Creating Base Poses

of them. The base pose enables adjustment of the muscle at a later point in time without having to delete or recreate skin deformation information. This is a key fact for the reusability of the whole model (cf. Sect. 7.6 and 8.4).

7.5 CONNECTING MUSCLES

Considering the muscular anatomy of the human face, one might conclude that the linear muscles around the mouth insert into the orbicularis oris. This approximation is used in the following.

Point Constraints

The connection is done by point-constraining the cross section of the insertion of each linear muscle to a cross section of the orbicularis oris. The linear muscles act as drivers, the cross sections of the orbicularis oris act as driven. This results in the orbicularis oris being moved indirectly when other muscles move. This approach is more powerful than connecting the muscles to single vertices of the skin mesh, like Bibliowicz proposed in his approach [Bib05]. The reason is that painting weights to the skin has the same effect: the muscles are quasi connected to the skin, but their influence is controllable and easy to refine.

Connecting Linear Muscles to the Sphincter Muscle

The orbicularis oris contains 12 cross sections, but 14 linear muscles are modelled. Thus, two linear muscles on each side of the face need to share an attachment point. As mentioned in Section 5.2 the zygomaticus major muscle and the risorius muscle both insert into the modiolus, which is located at the corner of the mouth. This fact is simplified by allowing both muscles to attach to one cross section of the upper part of the orbicularis oris. Furthermore the levator labii superioris and levator labii superioris alaeque nasi are attached to the upper part. The triangularis, mentalis and depressor labii inferioris are constrained to the lower part.

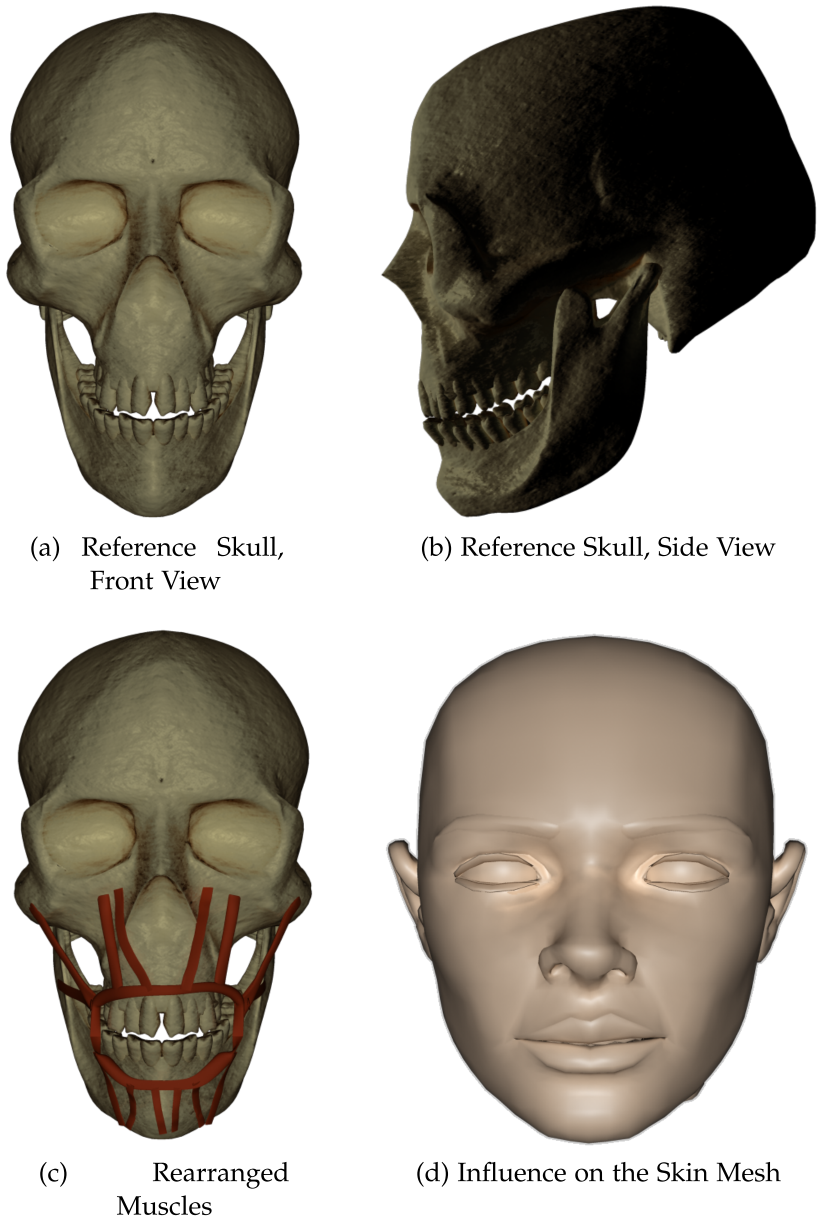
7.6 REUSING THE MUSCLE MODEL

A major advantage of the approach developed in this thesis is the reusability of the created muscle model.

Once the base pose for each muscle is created, the muscles can be exported and imported again to any skull model. In case the muscle shape needs to be changed in order to match a new skull, it is possible to set the new shape as base pose.

Exchanging the Skull

In order to test the reusability, a reference skull model [Ref12] is imported (cf. Fig. 7.6(a) and (b)) and the origins of all muscles are translated to match the new mesh as shown in Figure 7.6(c). It is also possible to rearrange the muscles when their influences on the skin mesh are already painted (cf. Chap. 8). In this case the skin deforms during rearrangement (cf. Fig. 7.6(d)), but as soon as the new base poses are set, the initial pose is adopted.



(a) Reference Skull, Front View

(b) Reference Skull, Side View

(c) Rearranged Muscles

(d) Influence on the Skin Mesh

Figure 7.6: Reference Skull Model requires Rearrangement of Muscles

8 IMPLEMENTING MUSCLE BEHAVIOR

When you feel worried and depressed, consciously form a smile on your face and act upbeat until the happy feeling becomes genuine.
- Jonathan Lockwood Huie

Once the base pose for each muscle is specified one can start to animate correct muscle behavior. As explained in Chapter 6, Autodesk Maya's muscles are controlled by deformers. In order to declare which part of the skin should deform when a muscle action occurs, weights are painted. There are several types of weights available. Their usage for the linear and sphincter muscles of the presented approach is explained in the following.

8.1 MODELLING LINEAR MUSCLE ACTION

Sticky Weights

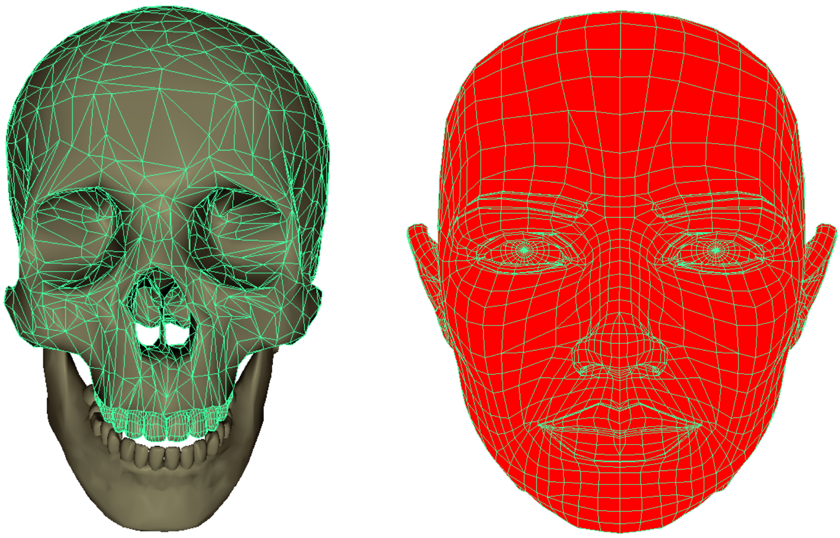
The most important weights are sticky weights, which allow the direct attachment of the skin mesh to Maya's muscles, bones or capsules. The weights are normalised, i. e. the weights of all muscles, bones and capsules that influence a vertex of the skin add up to one:

$$1 = \sum_{i=1}^{n} W_{B_i} + \sum_{j=1}^{l} W_{C_j} + \sum_{k=1}^{o} W_{M_k}. \tag{8.1}$$

W_{B_i} denotes the weight of a bone i, W_{C_j} is the weight of a capsule j, and W_{M_K} represents the weight of muscle k that is painted for a vertex of the skin mesh. If the overall influence would be less than one, the vertex would be left behind when moving a muscle. If the influence would be greater, the vertex would move too much. It is important to consider this fact at the beginning of the weighting process since it is recommended to start with a root object with a weight of one in order to prevent displaced vertices [May12b]. In the presented model the upper skull is selected as root bone (cf. Fig. 8.1(a)), since it is the only part of the skull that cannot cause deformation of the skin. The polygon representation of the upper skull gets converted to a bone object and connected to the muscle system

Root Object

of the skin. The sticky weight is flooded to one as shown by the red color in Figure 8.1(b).



(a) Geometry (b) Initial Sticky Weight

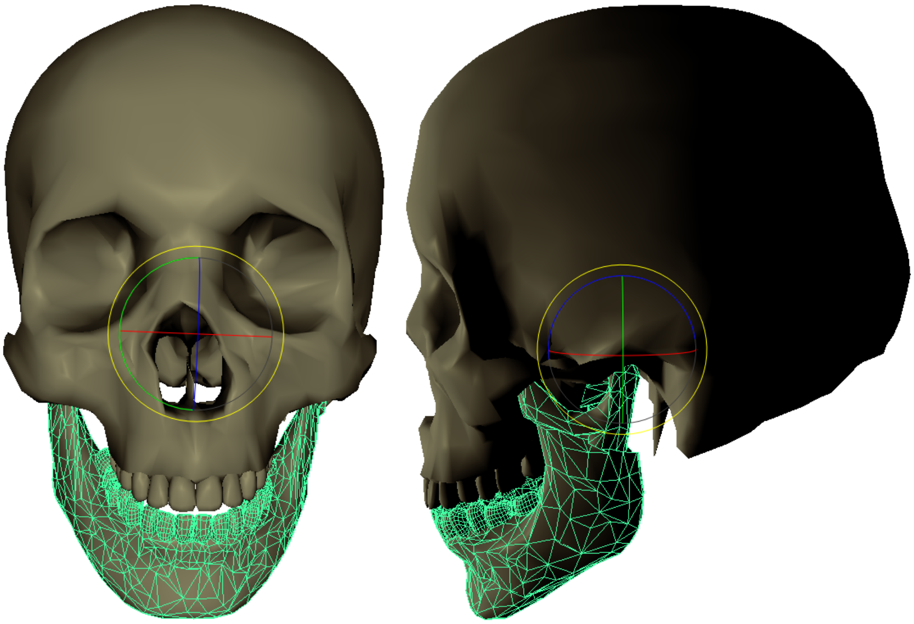
Figure 8.1: (a) Geometry and (b) initial Sticky Weight of the Upper Skull

Polygonal Bone

When sticky weights are painted to a polygonal bone, skin deformation is caused by translating, rotating or scaling the whole bone. This fact is useful when dealing with the mandible. The mandible rotates around a pivot point approximately in the middle of the skull (cf. Fig. 8.2). Besides the rotation there is also protrusion and retrusion possible, which translate the mandible forwards, backwards or sidewards. Combinations of these transformations cause the mouth to open. By painting sticky weights for the polygon representation of the mandible bone it is possible to achieve this behavior in the presented model. Figure 8.3(a) shows the influence of the mandible to the skin of the lower face. The yellow and green colors represent medium and low influence, black areas are not influenced by the mandible bone at all.

NURBS Muscles

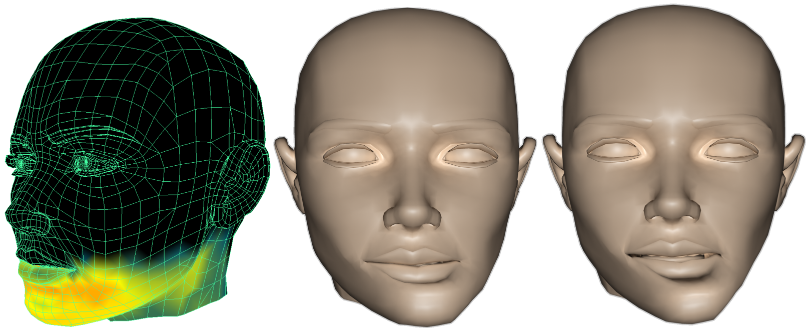
As stated above, the muscles of Maya's muscle system are built from NURBS. When painting sticky weights to NURBS muscles, the points of the skin mesh are actually attached to the muscle surface. As a consequence the skin will move even if the pivot point of the muscle stays and only the shape of the muscle changes or some point is transformed. This fact is very useful when reproducing the anatomical behavior of real muscles (cf. Sect. 5.2). For example the levator labii superioris



(a) Front View

(b) Side View

Figure 8.2: Pivot Point of the Mandible seen from (a) Front and (b) Side.



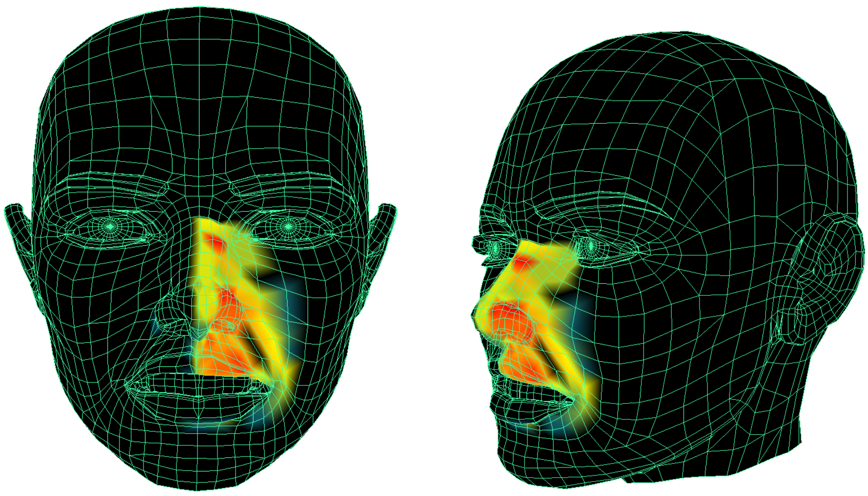
(a) Sticky Weight

(b) Sidewards Translation

(c) Translation & Rotation

Figure 8.3: (a) Sticky Weight of the Mandible. (b) Translation, Rotation and (c) Combinations of them enable Mouth Opening

alaeque nasi muscle pulls up the skin along the sides of the nose as shown in Figure 5.9. Wrinkles are caused, the upper lip center is pulled upwards, the lips may part, and the wings of the nostril widen, too. In order to apply this description to the model, sticky weights are increasingly painted to the upper lip and the nostril as shown in Figures 8.4(a) and (b). The heavy weights are indicated by a reddish color whereas blue illustrates a weight close to zero. When the skin mesh



(a) Front View (b) 45° View

Figure 8.4: Painting Sticky Weights for Levator Labii Superioris Alaeque Nasi (left Side).

is very detailed, it is possible to paint weights in more detail. This way one could force fine wrinkles of the skin of the nose by applying heavy weights to small areas of the nose as indicated by the upper red part. Figure 8.4(b) shows that the skin mesh used in this approach is not detailed enough to produce fine wrinkles. However Maya allows to split faces of a mesh in order to get a higher level of detail, but it is not recommended when painting weights, since it degrades performance. Nevertheless the mesh is detailed enough to give weight to the nasolabial furrow. Since this furrow is pointed out most by actions of the levator labii superioris the weights are increasingly painted for this muscle (cf. Fig. 8.5).

Wrinkles

Another type of weights are sliding weights. They enable muscles, bones or capsules to push out the skin mesh for sliding effects. Sliding weights are not normalised, so multiple muscles may affect a vertex for 100% each. They can be controlled with direction weights in order to get better results in regions where skin movement may cause penetration. Calcu-

Sliding Weights

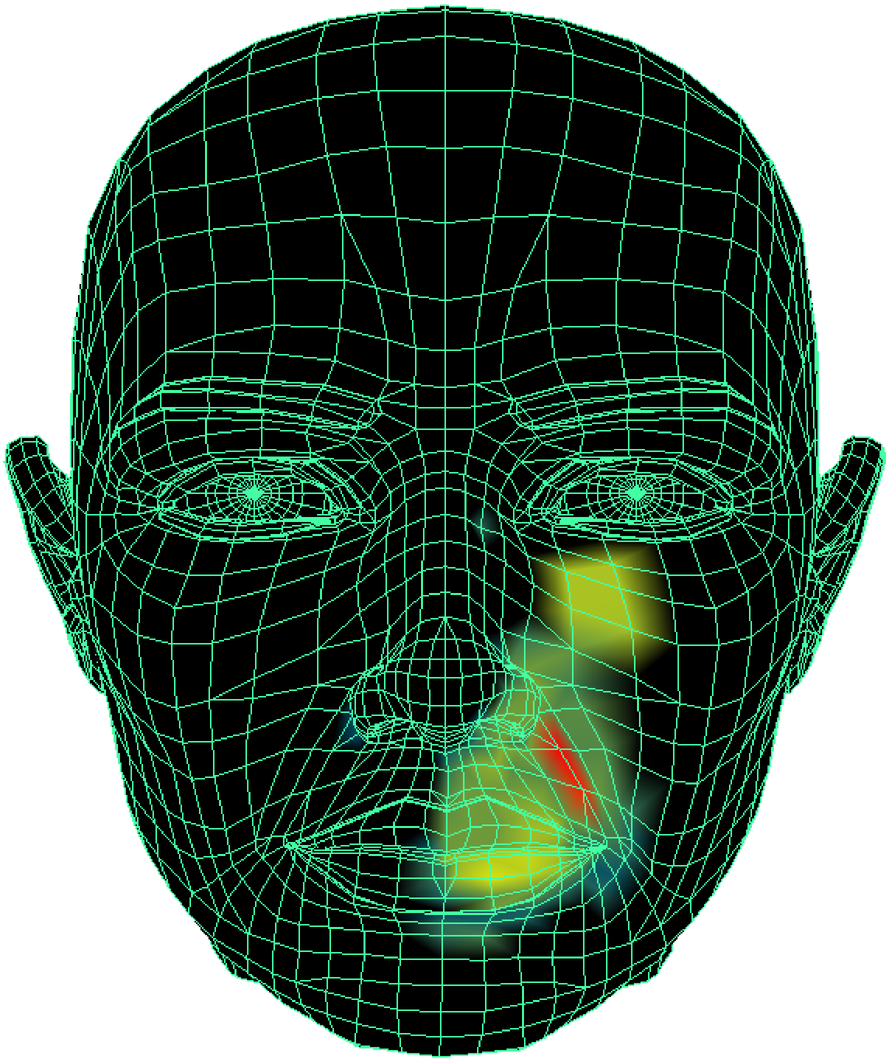


Figure 8.5: Painting Sticky Weights for Levator Labii Superioris (left Side) focusing on the Nasolabial Furrow.

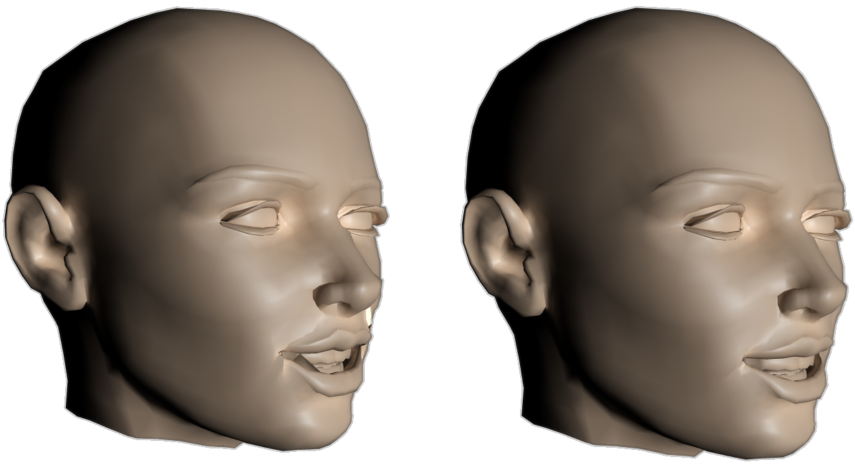
lating sliding information takes a lot of time, especially for NURBS muscles. Because of this, sliding weights are rarely used in the presented approach. This is not a problem at all, since the muscle and bone layers are not displayed when rendering [May12b].

Jiggle Weights

Jiggle weights are used to apply jiggle effects to vertices. They support a realistic inertia of the skin in movement, but the calculations are very expensive. As with sticky weights, the points of the skin mesh are attached to the muscle surface when painting jiggle weights. The presented model does not make use of jiggle weights, since jiggling effects are less pronounced in facial expressions and therefore negligible [May12b].

Relaxing Weights

Relaxing weights are useful to apply wrinkle effects to the skin without causing artifacts. When vertices get further apart, relaxed areas are kept at their original relative distance. When they get close, wrinkles are caused. It is also possible to specify relax and wrinkle weights for each muscle in detail. The skin mesh of the presented muscle model makes use of relaxing weights globally set to one, in order to produce smooth deformations of the skin as shown in Figure 8.6 [May12b].



(a) Without Relaxing Weights

(b) With Relaxing Weights

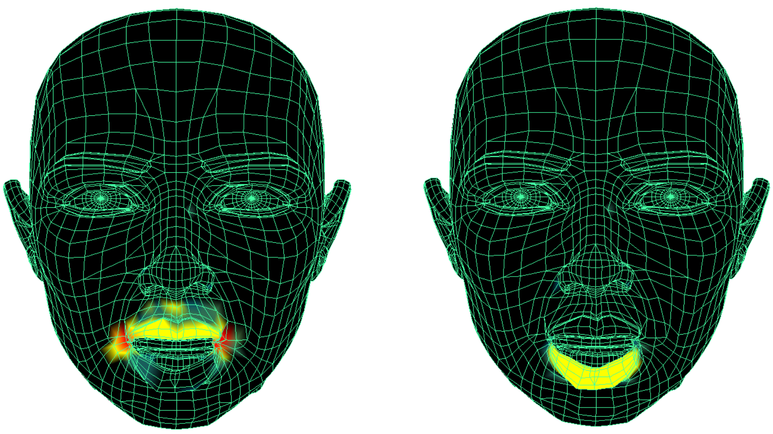
Figure 8.6: Same Mouth Shape (a) without and (b) with Relaxing Weights enabled

8.2 MODELLING SPHINCTER MUSCLE ACTION

Modelling the behavior of the orbicularis oris muscle is a challenge. As explained above, the action of linear muscles is different from the action of sphincter muscles. Linear muscles displace a point on the skin mesh towards the static origin. As an abstraction from nature in the presented approach sphincter muscles do not have a static origin. Admittedly the orbicularis oris is modelled with two linear muscles, which have a defined origin and insertion, however upper and lower part arise from and insert into each other as the corners of the mouth. There is no static attachment to the skull. This design enables the translation of *all* control points, comprising cross sections, and insertion and origin. Thus it is possible to model sphincter muscle behavior by combining translation and the painting of weights.

Combination of Weights and Translation

In order to implement an action of the orbicularis oris, sticky weights are applied to both parts of the muscle (cf. Fig. 8.7). Next, the translations of control points required to achieve a lip funneling pose (cf. Fig. 8.8) are identified. Finally, the cross sections of the orbicularis oris are translated by the action of the respective linear muscle which is attached. The mouth corners are translated independently.



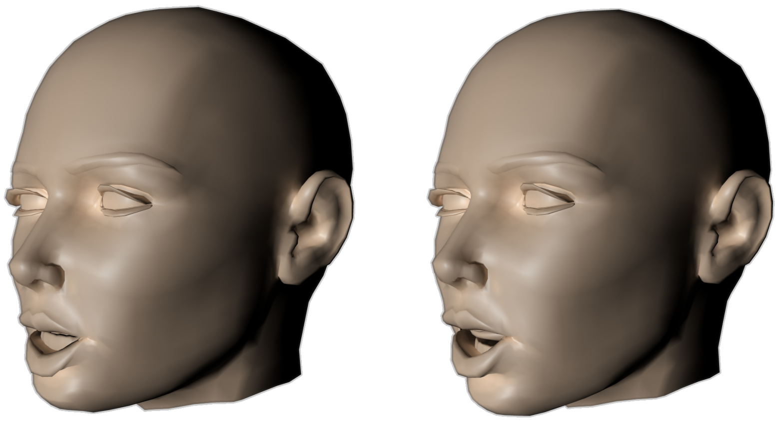
(a) Upper Part of Orbicularis Oris

(b) Lower Part of orbicularis Oris

Figure 8.7: Sticky Weights applied to (a) the upper and (b) the lower Part of Orbicularis Oris

On the one hand it is difficult to model realistic lip funneling with an orbicularis oris made of two linear muscles, since linear muscles are not meant to squeeze and cause wrinkles around a center point. On the other hand orbicularis oris actions involve the upper and lower lip. Therefore a mesh of high quality is important. A mesh that is not very detailed or built from triangles can cause artifacts when a funneling action squeezes the lips to much. Thus the funneling action is limited to a soft bulging of

Limitations



(a) Funneling Pose with Jaw closed

(b) Funneling Pose with Jaw opened

Figure 8.8: Funneling Pose with (a) Jaw closed and (b) Jaw opened.

the two muscle parts in order to adumbrate the pose. In this way wrong skin squeezing and wrinkling as well as artifacts in the corners of the mouth caused by a small amount of triangles (cf. Sect. 6.3) are prevented.

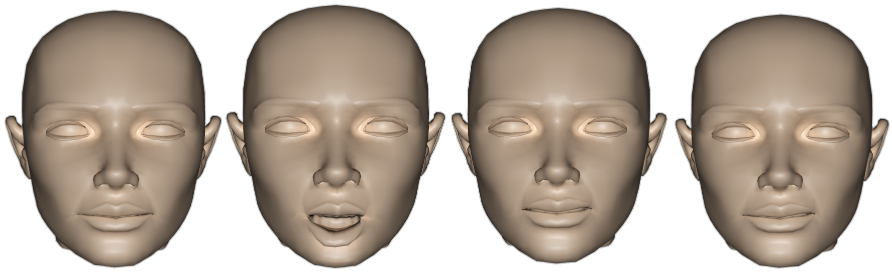
8.3 RESULTING MUSCLE ACTIONS

After painting the sticky weights for all muscles and defining possible translations for the control points of all muscles, the muscle model is ready for facial animation. The possible single muscle actions are illustrated in Figure 8.9(a-p). By combining several of these muscle actions the articulation of visemes or expressions is possible.

8.4 REUSING THE MUSCLE BEHAVIOR

In addition to reusing the muscle model on another skull mesh (cf. Sect. 7.6) the painted weights can be saved and imported to influence any other skin. In order to test this part of the reusability the sticky weights that were painted to the muscles, the upper skull, and the mandible get saved. Then the skin is detached from all deformers and removed from the model. The initial skull model and the muscles remain without function. As a new skin model the male counterpart of the initial model is imported. Since both models have the same source, a similar level of detail of the mesh can be assumed. It is tried to

Exchanging the Skin

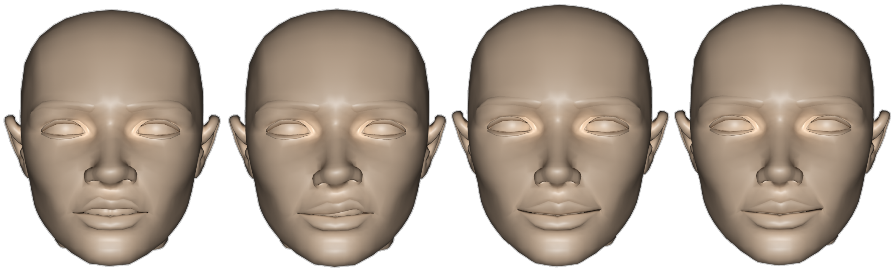


(a) No Action

(b) Orbicularis Oris

(c) Levator Labii Superioris, Left and Right

(d) Levator Labii Superioris, Left

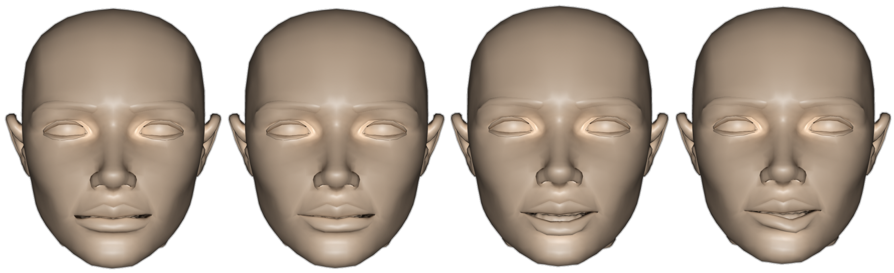


(e) Levator Labii Superioris Alaeque Nasi, Left and Right

(f) Levator Labii Superioris Alaeque Nasi, Left

(g) Zygomaticus Major, Left and Right

(h) Zygomaticus Major, Left

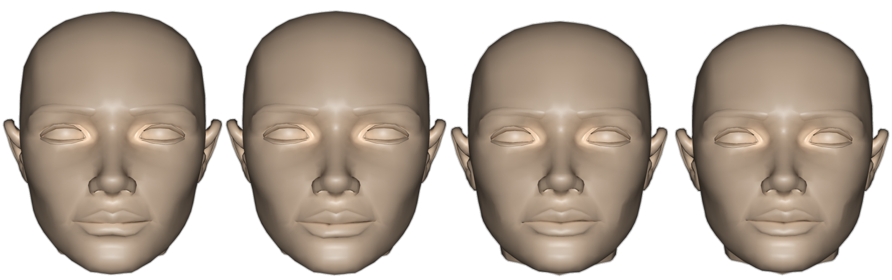


(i) Triangularis, Left and Right

(j) Triangularis, Left

(k) Depressor Labii Inferioris, Left and Right

(l) Depressor Labii Inferioris, Left



(m) Mentalis, Left and Right

(n) Mentalis, Left

(o) Risorius, Left and Right

(p) Risorius, Left

Figure 8.9: Mouth Shapes resulting from single Muscle Action

place the new skin at the same location. The more the old skin model resembles the new skin model in proportions, detail and position, the better results can be expected. The new skin is attached to the muscles, the upper skull, and the mandible. Then the saved weights can be loaded to the skin. Having a look at

Loading Weights

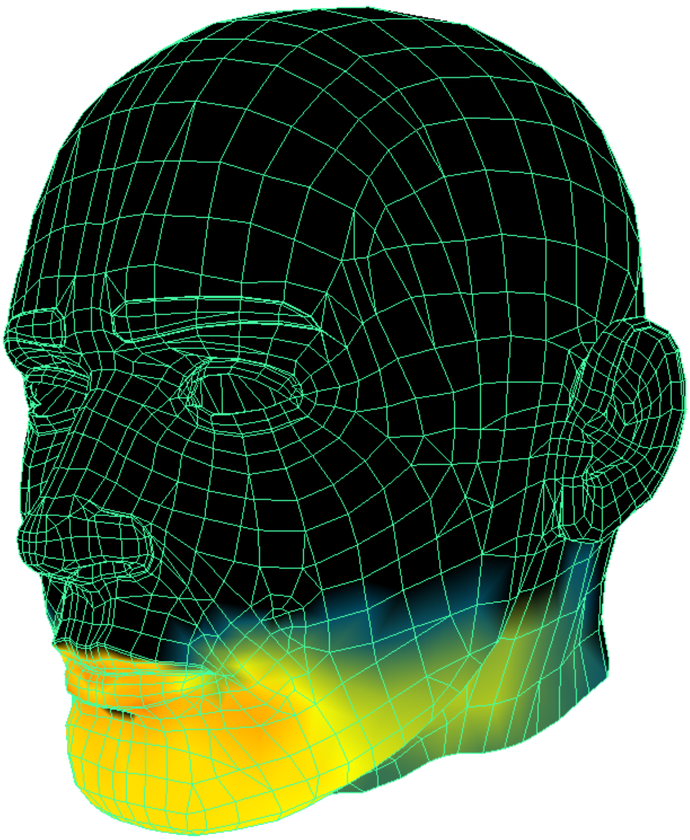


Figure 8.10: Reference Skin Mesh influenced by the reused Mandible Weights.

the painted weights shows that they are placed approximately correct. Figure 8.10 shows the influence of the mandible after copying it to the new skin. Subsequent work needs to be applied merely to parts of the lower lip. The same applies to the weights that were copied to the muscles. However this effort is just a small fraction of the effort that is needed to paint whole new weights for all muscles and bones to influence a new skin!

9 ANIMATING PHONEMES AND VISEMES

God has given you one face, and you make yourself another.
- William Shakespeare

When the muscle system is modelled and the muscle behavior is implemented, one can start to animate the actual facial expressions in order to test the muscle system. As mentioned in Section 6.1 two mouth shapes for sets of consonants and three mouth shapes for sets of vowels are selected for this test. Since applying such a shape to the model is an iterative process, composed of translating muscle cross sections and refining the weights that were painted in the last chapter, this process refers to steps three and four of facial animation. In the following this process and how the resulting shapes can be captured as poses are described.

Iterative Process

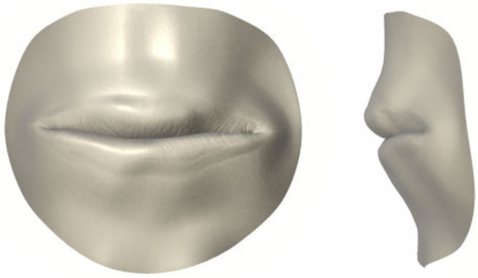
9.1 APPLYING MOUTH SHAPES FOR SELECTED PHONEMES

As described above all linear muscles insert into cross sections of the orbicularis oris. In order to implement a mouth shape these cross sections need to be translated by actions of the linear muscles, until a sufficient shape is reached. The Preston Blair visemes explained in Section 4.2 are used as reference mouth shapes.

9.1.1 *Bilabial Consonants /m/, /b/, /p/*

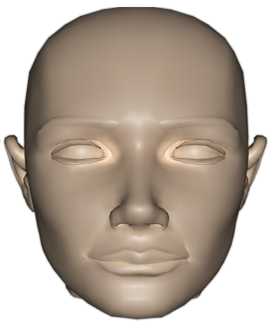
The bilabial consonants */m/*, */b/*, and */p/* — as in ***m**an*, ***b**ed*, and *s**p**in* — are articulated with both lips pinched. The red part of the lips gets narrowed and the shape of the mouth gets straightened. Considering the respective Preston Blair mouth shape, the upper lip might bulge a bit (cf. Fig. 9.1(a)). In order to produce this shape the levator labii superioris and levator labii superioris alaeque nasi are used to push the upper part of the orbicularis oris and therefore the upper lip down. Zygomaticus left and right are translated towards the middle of the mouth in order to narrow the upper lip. The mentalis muscle

Implementing /m/, /b/, and /p/



(a) Preston Blair Mouth Shape seen from the Front and the Side

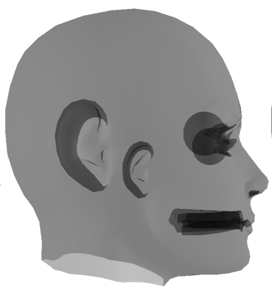
(b) Front View of Implementation without Self Collision



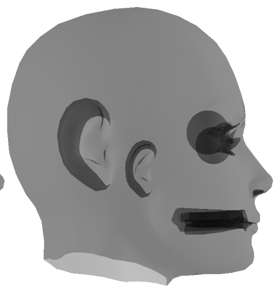
(c) Front View of Implementation with Self Collision

(d) 45° View of Implementation with Self Collision

(e) Side View of Implementation with Self Collision



(f) Side View (X-ray) of Implementation without Self Collision



(g) Side View (X-ray) of Implementation with Self Collision

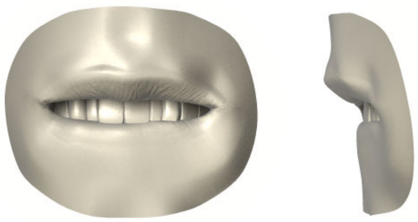
Figure 9.1: /m/, /b/, /p/ Viseme Pose

pushes the lower part of the orbicularis oris and therefore the lower lip upwards.

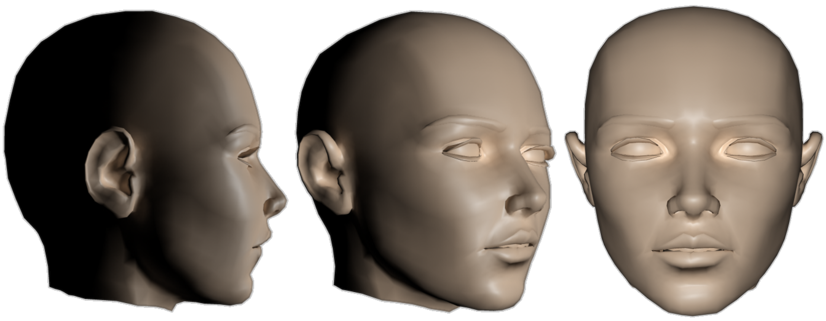
Muscle action alone is not sufficient to accomplish the desired mouth shape. By default Maya does not calculate any collision information when two parts of the mesh collide. Thus, the mesh parts of the upper and lower lip intersect instead of pressing against each other. In order to implement real lip compression, self collision of the skin needs to be enabled. Calculations for self collision are based on area groupings. In the presented approach the vertices of the skin mesh that define the upper lip are grouped into one area and the vertices of the lower lip into another area. Self Collisions are not based on time and can be refined by additional weights. Figure 9.1 shows the resulting mouth shape (b) without and (c-e) with self collision enabled. However the important difference is only visible at the lips region in Figures 9.1(f) and (g), that show an X-ray view of the skin mesh: with self collision enabled the mesh does not intersect.

Self Collision

9.1.2 *Labiodental Consonants /f/, /v/*



(a) Preston Blair Mouth Shape seen from the Front and the Side [Pre12]



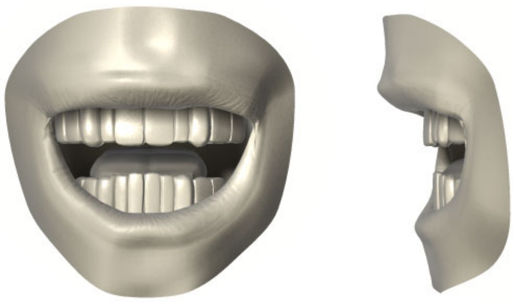
(b) Side View of Implementation (c) 45° View of Implementation (d) Front View of Implementation

Figure 9.2: /f/, /v/ Viseme Pose

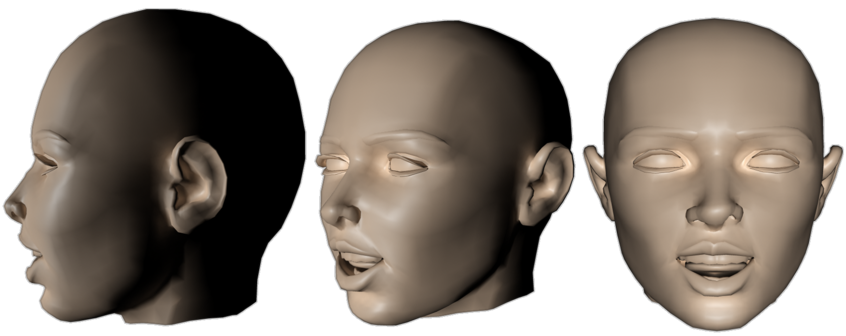
Implementing /f/ and /v/

When articulating the labiodental consonants */v/* — as in *valve* — and */f/* — as in *fly* — , the upper teeth are exposed and touch the lower lip as shown by the Preston Blair mouth shape in Figure 9.2(a). In order to achieve this pose, the mandible is rotated, resulting in mouth opening. The triangularis, mentalis and depressor labii inferioris muscles, that are attached to the lower part of the orbicularis oris, need to push that muscle in order to lift the lower lip slightly upwards and inwards until it touches the upper teeth. The vertices of the mesh that define the lower lip and the teeth are grouped for self collision in order to prevent the mesh to intersect. The resulting mouth shape is presented in Figures 9.2(b-d).

9.1.3 *Front Vowels /a/, /i/, and /e/*



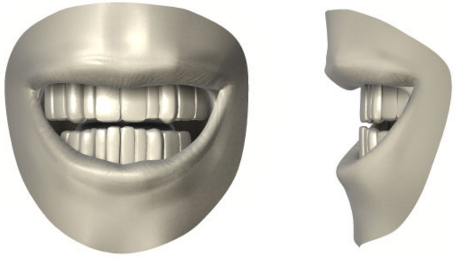
(a) Preston Blair Mouth Shape seen from the Front and the Side [Pre12]



(b) Side View of Implementation (c) 45° View of Implementation (d) Front View of Implementation

Figure 9.3: /a/, /i/ Viseme Pose

The shape for the front vowels */a/* and */i/* — as in *stack* and *five* — is similar to the shape for the front vowel */e/* — as in *lean* — as the Preston Blair mouth shapes in Figures 9.3(a) and 9.4(a) show. The biggest difference between the shapes is the



(a) Preston Blair Mouth Shape seen from the Front and the Side [Pre12]

(b) Side View of Implementation (c) 45° View of Implementation (d) Front View of Implementation

Figure 9.4: /e/ Viseme Pose

Implementing /a/ and /i/

mouth opening, which is slightly bigger for /a/ and /i/. Another difference is the shape of the upper lip, that is somewhat curved when articulating /a/ and /i/ and very straight for /e/. For articulating /a/ and /i/ the levator labii superioris and levator labii superioris alaeque nasi lift the upper part of the orbicularis oris and therefore the upper lip, resulting in exposed upper teeth. The zygomaticus major is used to lift the corners of the mouth and to narrow the mouth a bit. Depressor labii inferioris and mentalis muscle act together to pull the lower part of the orbicularis oris and the lower lip down. Mandible rotation ensures mouth opening. Figures 9.3(b-d) show the resulting mouth shape for /a/ and /i/.

Implementing /e/

When /e/ is articulated, the mouth opening is less extreme. Additionally zygomaticus major lifts the angles of the mouth a bit higher in order to achieve the straight shape of the upper lip. The resulting mouth shape is shown in Figure 9.4(b-d).

9.1.4 *Back Vowel /o/*

When articulating the back rounded vowel /o/ — as in *g**o*** — the corners of the lips are narrowed as shown in Figure 9.5. The

Limitations

mouth shape is similar to the funneling pose explained before (cf. Fig. 5.19) with the difference that articulating /o/ requires mouth opening. As stated before the funneling action of the orbicularis oris needs to be restricted in order to avoid artifacts and odd looking squeezing and wrinkling of the skin of the lips. As a result it is not possible to articulate the viseme /o/ with the presented approach in a realistic way.

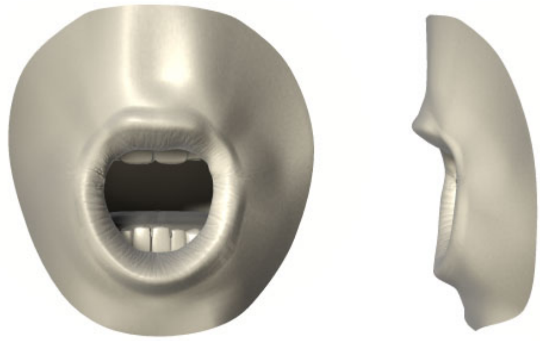


Figure 9.5: /o/ Viseme Pose

9.2 CAPTURING MOUTH SHAPES

Character

Pose

Clip

In order to reuse the mouth shapes, Maya's character features are used. Animated objects or attributes can be collected within a *character*. In the presented approach the character comprises the handles of all control points of the muscle model that were explained above. In order to implement mouth shapes, these handles need to be adjusted. When a mouth shape is finished it can be captured as a *pose*, which is a snapshot of the character's current position. Poses can be exported and imported for use with other characters. They can also be scaled, repeated, and combined with other poses in order to produce *clips*.

A pose for each implemented viseme and one for the basic mouth position is created. To test the reusability of the poses and the transitions between them, all poses are applied to the muscle model at an interval of 50 frames. Now Maya's default interpolation is used for animating the co-articulation. The resulting sequence is rendered with the setup described above (cf. Sect. 6.4).

10 CONCLUSION AND FUTURE WORK

In this master thesis an approach to facial animation using the muscle feature of Autodesk Maya has been described. Facial animation is an active research topic since the 1970s (cf. Chap. 1), which contains many different aspects (cf. Chap. 2) and extensive application areas (cf. Chap. 3).

Phonemes & Visemes

Treating the five steps of facial animation, it has been shown that the field of phonology deals with phonemes, which are language units that deliver a unique meaning. It has been shown that phonemes are not sufficient for speech animation and that it is common to map them to visemes, their visual counterparts. This mapping process groups phonemes that produce similar mouth shapes during articulation into the same class (cf. Chap. 4).

Anatomy of the Human Face

The skeletal, muscular and skin anatomy of the human face have been introduced to demonstrate their effect on facial expressions (cf. Chap. 5). It is not necessary to include all facial muscles into the 3D model, since some muscles produce similar actions by supporting each other. The anatomical structure of a muscle needs to be abstracted, as well as the origins and insertions of each muscle, in a way that the resulting model is detailed enough to produce realistic facial expressions and not too detailed to harm performance (cf. Chap. 6).

Modelling & Animating Muscles...

Autodesk Maya's new muscle feature has been introduced and evidence has been provided that it can be used to implement a model of facial muscles. Modelling linear muscles can be done straightforwardly, whereas sphincter muscles, like the orbicularis oris, pose a challenge (cf. Chap. 7). It has been shown that muscle behavior can be implemented by painting weights to the skin mesh and that the results are sufficient for linear muscles, but proved elusive when it comes to sphincter muscles (cf. Chap. 8). Since sphincter muscles are not provided by Maya, the orbicularis oris muscle has been modelled by composing two linear muscles — an upper and a lower part — and weights have been applied to both of them. This limits the present approach, since the linear muscles prevent the proper articulation of funneling poses or phonemes like /o/ that require mouth contraction. The lack of built-in sphincter muscles is a fact that could be the topic of future research. By implementing the mathematical description, a real contraction around the center of the mouth could be created, leading to more realistic orbicularis oris actions.

. . . Limitations

. . . Possibilities

Aside from this limitation it has been shown that the muscle model is capable of articulating visemes in an extremely realistic way, by applying mouth shapes for a diverse set of phonemes: the bilabial consonants */m/*, */b/*, and */p/*, the labiodental consonants */v/* and */f/*, as well as the front vowels */a/*, */i/* and */e/*. The implementation of further phoneme mouth shapes would be a meaningful extension of the presented approach.

Reusability

Furthermore it has been shown that the muscle model created in the presented approach is reusable. It can be applied to any skull model and any skin model. A few adaptions of the muscle shapes to the new skull or the skin weights to the new skin can be done easily. The effort is small compared to the effort caused by the creation of new muscles or the painting of new weights.

Co-Articulation

Further Animations

Additionally the visemes created have been captured as poses. In this way it is possible to reuse them and append them in an arbitrary order to animate speech. A simple interpolation, that is performed by Maya automatically, has been used to test the transitions from one mouth shape to the other. Of course these transitions are not lifelike and should be refined as part of the implementation of co-articulation for the presented model. Additional animation of the tongue would be worthwhile, since it would upgrade realistic speech animation. Animating other regions of the face (e.g. eyes) using Maya muscles is another imaginable extension of the model that would enable a broad set of facial expressions.

Real-Time Rendering

With real-time interaction of characters becoming more important (e.g. for social agents), real-time rendering is an important area of future research. A possible application is the interaction of a human being with a character based on the presented muscle model, that is integrated in a web application. It would be necessary to preprocess the interaction in order to prepare a response, then pass this information to Maya. In a next step Maya would append appropriate visemes to an animation sequence, calculate co-articulation, and render the image sequence on the fly. The output would be passed to the web front-end for display.

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INDEX

AFFIDAVIT

I hereby declare that this master thesis has been written only by the undersigned and without any assistance from third parties.

Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those indicated in the thesis itself.

Hamburg, 6 December 2012

Anna Mempel