

A Physiological Torso Model for Realistic Breathing Simulation

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Abstract. For the convincing modeling of virtual humans, realistic breathing is an important aspect. This paper is about the simulation of breathing, based on anatomical and physiological principles. We have built a torso, including a thorax, a deformable belly, and muscles. This results in a model with two independent breathing systems, namely abdominal and chest breathing, which gives a high degree of realism in simulating breathing. The generated spirograms, diagrams of lung volume changes, are comparable to normal human ones according to a medical expert. The generated videos show convincing breathing sequences at various frequencies. The model itself is made available for public use.

1 Introduction

That non-verbal communication is the most important aspect of communication is, is a statement dating back to 1972 [6]. While verbal communication is based on spoken words, the non-verbal communication is based on body language: pose, gestures, facial expressions, and breathing, as well as a number of non-visual aspects.

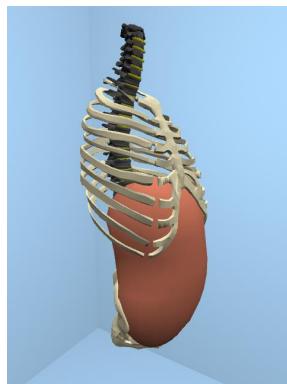


Fig. 1. Frame from the breathing animation

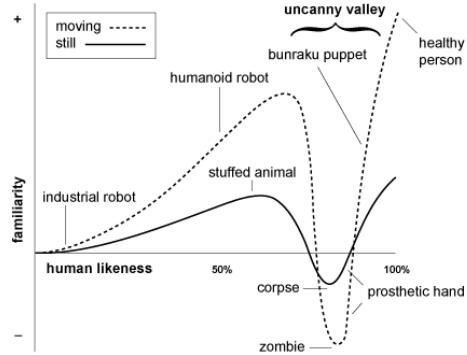


Fig. 2. The Uncanny Valley [9]

In virtual reality, gaming, simulation, animation, and medical applications, the modeling and animation of the human torso received less attention than many other aspects of character modeling such as lip synchronization, eye movement, and facial expressions. The game engine Source, developed by Valve Corporation, and used in games such as Half Life 2, is an example of a game engine that support such aspects. Using the FacePoser SDK tool, it synthesizes an animation of a spoken sentence, including lip movement, facial expressions, and head movement. Yet, the movement of the chest, caused by breathing is not well developed and supported. Figure 1 shows one frame from our video of animated chest movement.

The human visual system is very good in making a distinction between natural and unnatural animations, especially of humans. In fact, when a character is modeled that has a high degree of realism, but is not completely realistic, it is considered robot like, rather than human. This phenomenon is called the 'Uncanny Valley' [9], see figure 2. It describes the feeling people have when seeing a robot. Initially, a more human like robot is considered more pleasant. However, when the robot gets close to realistically human, people find the robot scaring and repelling. Suddenly, the little discrepancy between almost and fully realistic gives a strong negative feeling. In contrast, animated toys and monsters are not considered unrealistic, such as in movies like Toy Story, Monsters & Co., and The Incredibles.

1.1 Related Work

In the past, characters that didn't do anything specifically, were put on hold during the animation, yielding a frozen pose. This is very unrealistic, so subtle arbitrary movements of arms and body were introduced [4].

A lot of research has already been done on the simulation of muscles, although more on the deformation than on the way they exhibit force. Muscles are often modeled as mass-spring systems [10] or finite element systems [3]. Alternatively, [13] models muscles only those structures that have a visual effect

on the appearance of the body, which is more similar to an artistic approach than a physiological approach.

Simulation of the abdominal breathing is done by [11]. It is done by constraint resolution on a physical model. Accuracy of elastic spring meshes was researched by [5]; the conclusion was that an exact solution is not possible. Modeling an incompressible free form solid was performed by [12].

Breathe Easy [16] is an anatomy based physiological model of the human torso built from rigid and deformable parts. The simulation is done using ODE, the Open Dynamics Engine [14]. They simulate four frequencies of breathing: slow deep breathing, calm breathing, normal breathing, and panting. The spirograms shown in [16] are not realistic according to a lung physiologist at the Utrecht Medical Centre [15]. For example the shown tidal volume of 60 ml at a frequency of 15 normal breathings per minute, is far too small for a normal person. Their accompanying video [2] shows little if any abdominal breathing, which is unrealistic, because abdominal breathing is the most efficient way of breathing.

Different types of breathing model are developed in the medical image domain, for medical applications such as multi modal image registration, see for example [8].

1.2 Contribution

Because breathing is an essential distinction between humans and robots, a realistic modeling of breathing is an important aspect of making animation of virtual humans convincing. In this paper we present a torso model and breathing simulation, based on anatomical and physiological principles. We have built a torso, including a thorax, a deformable belly, and muscles. In contrast to previous work, our model has two independent breathing systems, namely abdominal and chest breathing, which gives a high degree of realism in simulating breathing. The model, built in Alias Maya and Maya Embedded Language scripts, is made available for public use.

The generated spirograms, diagrams of lung volume changes, are comparable to normal human ones according to a medical expert. The generated videos show convincing breathing sequences at various frequencies. See figure 1 for a frame from one of the videos of animations that accompany this paper.

2 A Physiological Torso Model

In order to alleviate the shortcomings of previous models, we have designed a new model that better combines the abdominal and chest breathing, resulting in more natural spirograms and animations. We have built our model with Alias Maya and MEL (Maya Embedded Language) scripting. As an initial basis we used a torso from 3D Cafe [1]. We have divided this polygonal model into its constituent parts: ribs, dorsal vertebra, hip, shoulder blade, and collarbone, which are made rigid, so that constraints can be applied to them. We have assigned physiology based masses to these objects as provided by Zordan et al. [16]. Also, the model

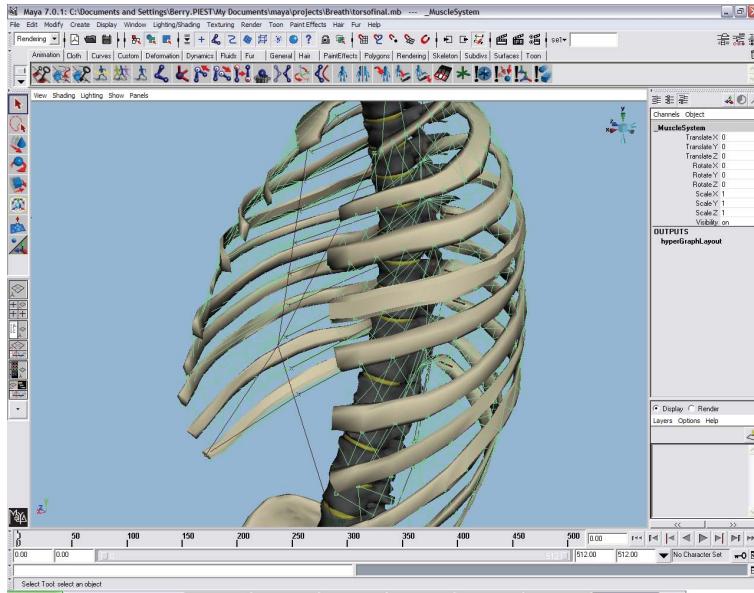


Fig. 3. Modeling the intercostal muscles between the ribs (green lines)

is scaled to give it a realistic size, i.e. the size of one the authors (a sternum of 220 mm, measured by a physiotherapist).

2.1 Thorax

The ribs must be able to move, and should not be fixed to the spine. Since during the breathing the ribs move up and sideways, we don't model the joint as a ball and socket, but as two hinges. The intercostal muscles are modeled anatomically correct as follows. Since Maya springs can only connect to the center of a rigid object, boxes are attached to polygon vertices with a Pin Constraint, on top of the rib polygon. Between boxes of adjacent ribs, strings are placed crossways, see figure 3. The first rib is also attached to cervical vertebra C6. This muscle helps lifting the ribs.

2.2 Abdominal Cavity

The abdominal cavity is modeled as one volume, following the shape of the belly. At all times the belly tries to maintain the same volume. If the diaphragm is pushed, the front of the belly will expand. If the pressure is released the belly will return to its original state, because the belly muscles will relax. The surface is polygonal, the volume consist of a number of tetrahedra, equal to the number of triangles. A central point inside the cavity is the common top of all tetrahedra, the base of these tetrahedra are the triangles of the polygonal surface. The bottom and back side of the abdominal cavity are passive, the front (belly) and

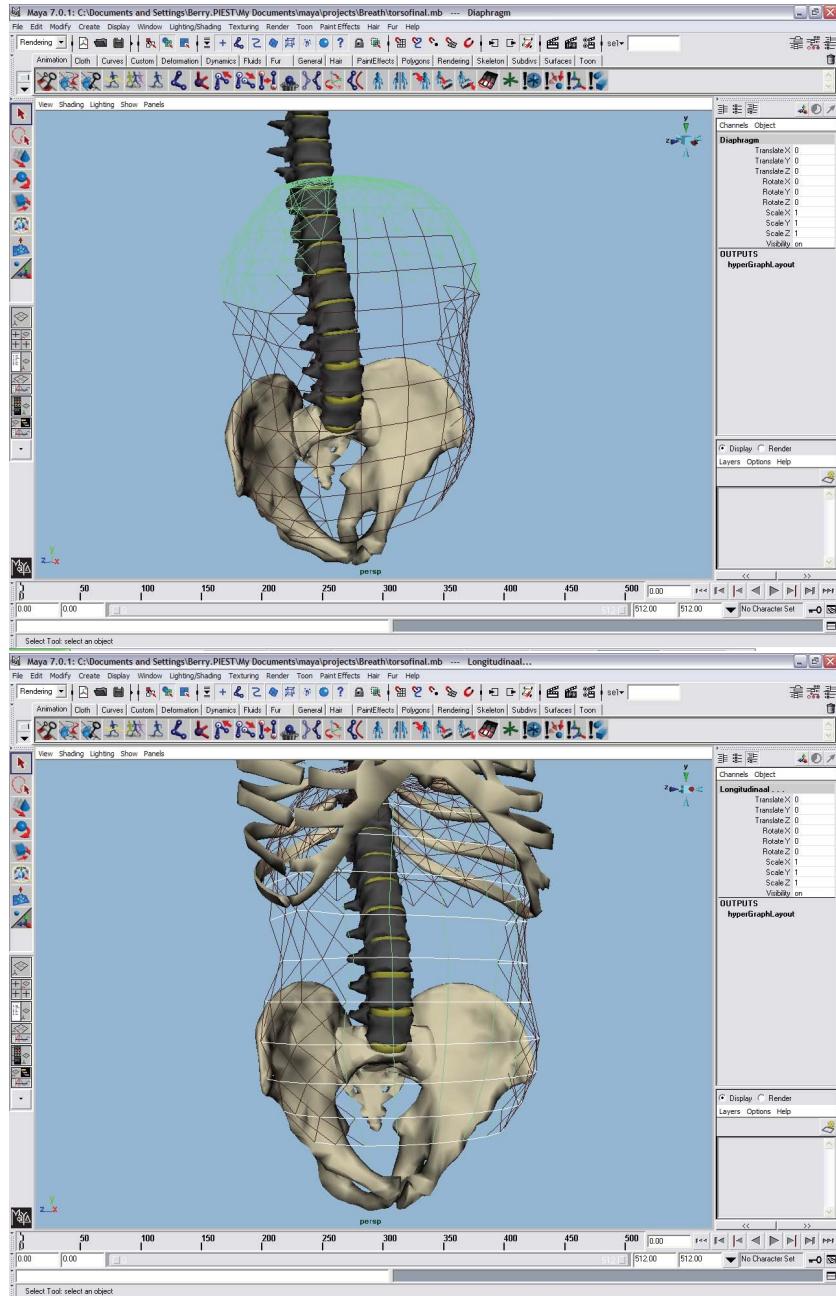


Fig. 4. Abdominal cavity. Top: diaphragm in green. Bottom: longitudinal (green) and transverse (white) muscles. (The obliques are not shown here).

top (diaphragm) are active. A mass of 8 kilos (cf. [16]) is divided over the active vertices. To these vertices, boxes and mass-springs are attached. The force F applied by these springs are proportional to the pressure P times the area A of each triangle:

$$F = n(P \cdot A)/3, \quad (1)$$

where n is the direction vector of the force perpendicular to the triangle, the division by 3 accounts for the three vertices, and the pressure is determined by Hooke's law:

$$P \propto (V_0/V - 1), \quad (2)$$

where V_0 is the original volume, and V the current volume. For each spring the length in rest is determined; the initial distance between the vertices is set to this length, to make the model go back to its original shape.

The diaphragm is a curved plate, where muscles radiate from the center. A relaxed diaphragm rests on top of the bowels. When the diaphragm contracts, it becomes flatter, pushing away (forward) the bowels, enlarging the chest cavity, giving more room for the lungs.

The diaphragm is modeled as the top of the polygonal surface of the abdominal cavity. In order to make the diaphragm move like a plate, vertices in a square layout are connected by side and diagonal strings, see figure 4 (top). The abdominals, the belly muscles, are modeled anatomically correct, so the strings follow the direction of the actual muscles: longitudinal, transverse, and oblique, see figure 4 (bottom).

These muscles work autonomously, trying to preserve the pressure in the abdominal cavity. Another force is needed to stretch them. During simulations, for each active vertex a force on the mass point is calculated with formula (1).

2.3 Rythmogenesis

We have grouped the muscles into groups, so that they don't have to be steered individually. For a normal respiration, we use a timed vital capacity, the volume of breath per minute, of 6 litres per minute. This can be achieved by a breathing frequency of 12 times per minutes, and a tidal volume of 500 ml. This means that per breath, which lasts for 5 seconds, 500 ml is refreshed. For an animation of 40 frames per second, a full breath takes 200 frames.

Some muscles, such as the abdominals, are elastic, and need some time to return to a rest situation. For both abdominal and chest breathing we need a periodic function that are synchronized. We have used sinusoidal functions. When the abdominal breathing sine function is larger than zero, we let the diaphragm contract. The contraction duration leaves sufficient time to return to a rest situation.

To model the chest breathing, three group of muscles must be controlled, the outer intercostals, the inner intercostals, and the longitudinal muscles. During inhalation, the outer intercostals contract, so that the ribs lift. Meanwhile, the diaphragm contracts, so that the pressure in the belly increases, and the belly moves forward. As a result, the abdominal cavity volume increases, giving an

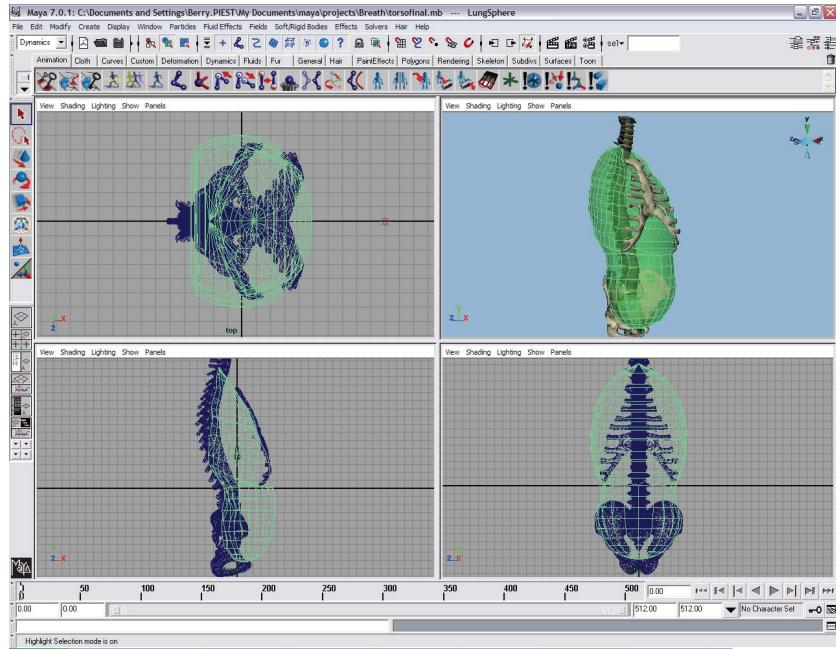


Fig. 5. The torso volume

under-pressure in the lungs, leading to an inflow of fresh air. While breathing out, the tension in the outer intercostals is released, the inner intercostals slowly contract, and the diaphragm relaxes, so that the bellow moves back, and the air is pushed out of the lungs. During the activation, a new length of each muscle is calculated as the initial length times the value of the sine function times the fraction the muscle can shorten. The derivative of the sine function also controls the speed of contraction.

2.4 Volumes

The volume of the abdominal cavity is the total volume of its constituent tetrahedra. Similarly, the volume of the whole torso is the total volume of its constituent tetrahedra, see figure 5. The lung volume is then the torso volume minus the volume of the abdominal cavity.

3 Breathing Simulation

We have simulated different types of breathing at a number of frequencies: abdominal breathing at 12 times per minutes, and combined abdominal and chest breathing at 12, 15, 20, and 24 times per minute. Figures 6, 7, and 8 each show 3 curves in a single graphic: the height of the sternum (blue) to illustrate the

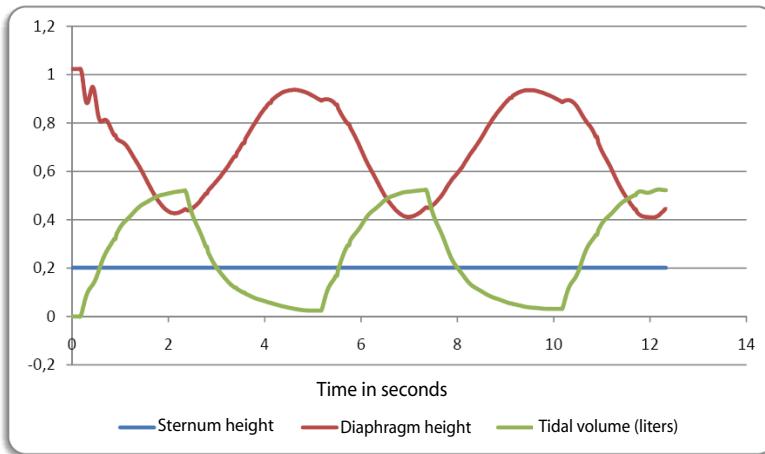


Fig. 6. Slow breathing, 12 times per minute, abdominal breathing only

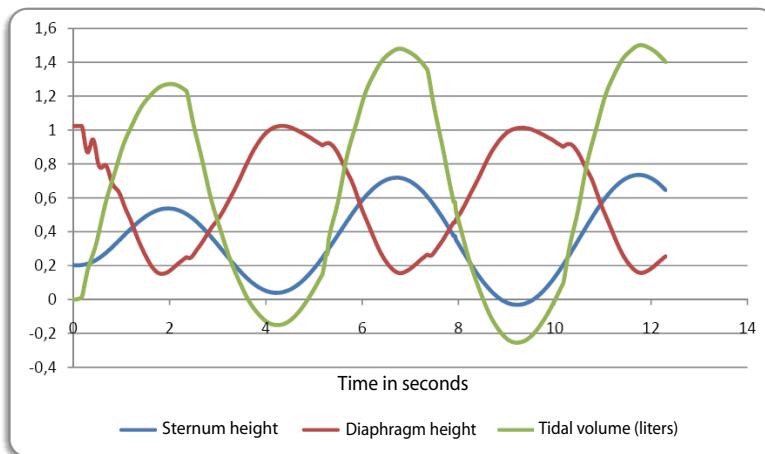


Fig. 7. Slow breathing, 12 times per minute, combined abdominal and chest breathing

moving of the thorax, the height of the diaphragm (red), and the tidal volume (green). The vertical axis is multifunctional, for the blue and red lines it is the height of the sternum and diaphragm in the model coordinates, the green one is the breath volume which is relative to the initial torso volume, which is in liters.

Figures 6 and 7 show spirograms of slow breathing, at a frequency of 12 times per minute. In the case of abdominal breathing (figure 6), the thorax remains still, and the sternum is not moving. The tidal volume is about 500 ml, which results in a timed vital capacity, the volume of breath per minute, of about 6 litres. In combination with chest breathing (figure 7), the sternum is also moving. The resulting slow, deep breathing gives a much higher timed vital capacity of

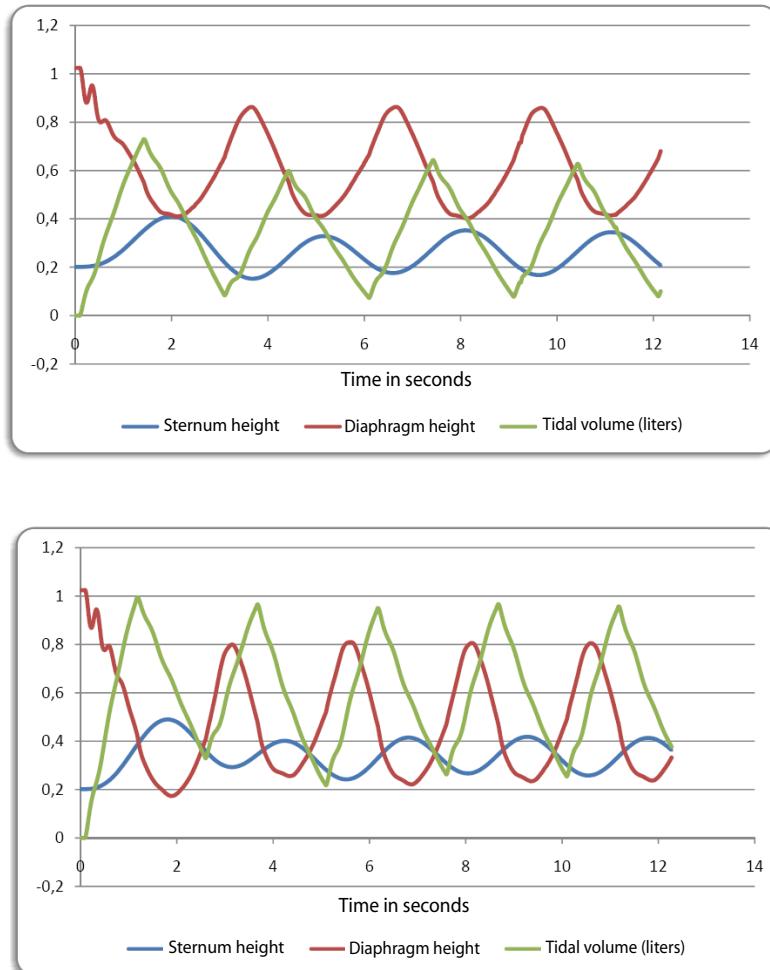


Fig. 8. Fast breathing. Above: 20 times per minute, below: 24 times per minute.

21 litres. It is clear that the tidal volume is minimal when the diaphragm is high and the sternum is low, and the tidal volume is maximal when the sternum is high and the diaphragm is low.

Figure 8 shows the spirograms for higher frequencies: 20 and 24 times per minute. Because of the higher frequency, the sternum does not move as much as with slow breathing, the blue line has a smaller amplitude than in figures 6 and 7. As a result, the timed vital capacity is 11 and 17 litres respectively. Because the torso is actively inhaling and exhaling, the muscles are actively used instead of passively. In slow breathing the thorax returns to the initial state passively, which uses the muscles' spring like effect for returning to its rest length. For fast

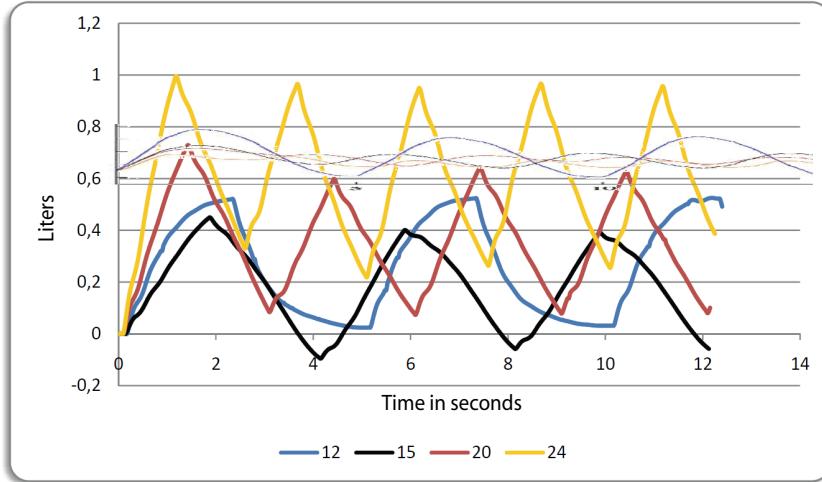


Fig. 9. Comparing our tidal volumes (large amplitudes) with other results (small amplitudes) at varying frequencies: 12, 15, 20, and 24 times per minute

breathing, the return to the initial state of the torso uses force to help returning to that state, which is why the graphs look triangular.

Looking at the physiology literature, these figures are realistic [7]. In order to make a direct comparison with [16], we overlay their results with our simulated tidal volume at different breathing frequencies: 12, 15, 20, and 24 times per minute, see figure 9. While the tidal volumes from [16] lie in the range 0.6-0.8 litres, our volumes have a much more realistic range for a normal person [7]. Also the curve shape is more realistic.

For animations of the simulated breathings, see the videos at <http://www.cs.uu.nl/groups/MG/gallery/Breathing/>

4 Concluding Remarks

Our model is more realistic than previous models, because the breathing in rest is based on abdominal breathing only, and at slightly higher frequencies on a combination of abdominal and chest breathing. Even though there is much variability between individuals, figure 9 shows that the tidal volumes of our model is much more realistic than previous models. The big advantage of our system is that abdominal and chest breathing are controlled independently. As a result, our spirogram values are realistic for normal persons.

We have modeled the torso in Maya, it can be used in any other Maya environment. The complete model is available at <http://www.cs.uu.nl/groups/MG/gallery/Breathing/>, and can be used by anyone for further modeling realistic avatars. An even more precise model would allow to simulate other actions such as blowing, whistling, and speaking.

Acknowledgment

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