Animation and Modelling of Cardiac Performance for Patient Monitoring

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Abstract

Many patients treated for heart problems do not follow correct rehabilitation procedures because they have a poor understanding of their disease and how it is affected by their behaviour and lifestyle. In this paper we present an animated heart model for improving patients' rehabilitation. The model visualises the changes in cardiac performance during rehabilitation, rather than the correct heart physiology and anatomy. The proposed tool, when fully developed, will enable patients to gain a better understanding of their disease and will help them to understand why correct rehabilitation procedures are imperative. In addition the animated heart model will enable a patient to visually monitor the rehabilitation process which might lead to several psychological benefits such as increased motivation to follow the rehabilitation procedures and a more positive attitude towards life after a heart attack.

Keywords: biomedical visualisation, heart modelling, non-photorealistic rendering, rehabilitation

1 Introduction

The goal of cardiac rehabilitation is to reduce the risk of another cardiac event and to control the current heart condition of a patient and to stop it from deteriorating [1]. Most current cardiac rehabilitation procedures include counselling, to help the patient understand their disease more clearly and manage the disease process. In addition counselling aims to help the patient to be aware of (and hopefully modify) risk factors, such as high cholesterol, diabetes, smoking, lack of physical activity and high blood pressure. Development of exercise programs and lending emotional support are also standard components of most cardiac rehabilitation procedures.

Studies have shown that early intervention in the rehabilitation process can result in improved functional outcomes after myocardial infarction [2]. However, many patients treated for heart problems do not follow correct rehabilitation procedures because they have a poor understanding of their disease and how it is affected by their behaviour and lifestyle. In this paper we present a novel tool for use in cardiac rehabilitation programs. By providing an animated model of a heart which reflects the cardiac disease of the patient it is hoped that patients will gain a better understanding of their disease and its consequences and allow them to gain more insight into why correct rehabilitation procedures are imperative. In addition the animated heart model will enable the patient to visually monitor the rehabilitation process which might lead to several psychological benefits such as increased motivation to follow the rehabilitation procedures and a more positive attitude towards life after a heart attack.

The impetus of the project is to design a model of the human heart that visualises changes in cardiac performance and rehabilitation, rather than to design a physiologically and anatomically correct model.

2 The Human Heart

The human heart is a hollow muscular organ weighting approximately 325 ± 75g in men and $275 \pm 75g$ in women [3]. It has approximately the shape of an half-ellipsoid and contains two large chambers called the *ventricles* which are divided by the *inter-ventricular septum*. The heart beats (contracts and expands) about 60-100 times a minute and pumps oxygen-poor blood to the lungs where red blood cells extract oxygen from air. The blood then flows back to the heart and is pumped through *arteries* to all parts of the body (including the heart muscle) from where it flows back through the *veins* to the heart chambers.

2.1 Heart Diseases and Heart Failure

One or multiple heart diseases can result in heart failure, which is a clinical syndrome that arises when the heart is unable to pump sufficient blood to meet the metabolic needs of the body at normal filling pressures [3]. Causes of heart failure are differentiated into mechanical, myocardial, and rhythmic abnormalities. Mechanical abnormalities include increased pressure or volume load (e.g., due to a dysfunctional valve) and bulging of the heart wall (*ventricular aneurysm*). Myocardial abnormalities include metabolic disorders (e.g., diabetes), inflammation, and *ischemia* (blockage of the coronary artery). Abnormalities of the cardiac rhythm or conduction disturbances include standstill, irregular heart beat (*fibrillation*), and abnormally rapid heart beat (*tachycardia*).

Atherosclerosis is the narrowing of an artery due to a build-up of substances on the inner lining (*intima*) of the artery walls. It results in a reduced blood flow and hence decreased delivery of oxygen and other nutrients to the body tissues. The formation of a blood clot (*thrombus*) in the narrowed area can block the artery completely. Atherosclerosis in the coronary artery causes *coronary artery occlusive disease* (*ischemic heart disease*).

A *myocardial infarction* (heart attack) occurs when a coronary artery is completely blocked (*stenosis*) and an area of the heart muscle dies because it is completely deprived of oxygen for an extended period of time. If the blood supply can be restored before the heart cells die, the patient will have a limited heart attack. Sometimes the body will do this on its own, by supplying blood through a system of alternate, un-blocked arteries (*collateralization*). Permanently damaged muscle is replaced by scar tissue, which does not contract like healthy heart tissue, and sometimes becomes very thin and bulges during each heart beat (*aneurysm*) [4, 3].

2.2 Heart Modelling

The literature contains a large variety of heart models developed for medical applications. Physically realistic finite element models of the heart can be obtained either directly from biomedical imaging data or from mathematical simulations. For example, Young et al. developed a finite element model for reconstructing the 3D motion and strain of the left ventricle from tagged MR images [5, 6].

A three-dimensional finite element model of the mechanical and electrical behaviour of a porcine heart has been developed by the Bioengineering Institute at the University of Auckland [7]. The model is based on the theory of large deformation elasticity and is solved using Galerkin and collocation techniques [8, 9]. We adapted this model for our research.

The literature offers a variety of alternative mathematical heart models and a good overview is given in [10]. However, we are not aware of any 3D heart models used in cardiac rehabilitation programs.

3 A Perceptually-Based Heart Model

Our aim is to create a heart model which visualises the changes in cardiac performance based on the patient's perception of disease processes rather than their physiologically and anatomically correct simulation. Our model uses the heart geometry of an anatomically correct model developed by Stevens et al. [7].

Several psychological studies have investigated patients' perception of cardiac diseases. Cameron et al. report that fatigue, chest pain, loss of strength and increased perspiration are the symptoms most commonly experienced during the initial days following myocardial infarction [11]. Broadbent et al. show that patient drawings can give a better prediction of their long-term recovery than medical diagnosis of the damage [12]. So far no studies have been performed associating cardiac performance measures with a patients' mental image of their heart.

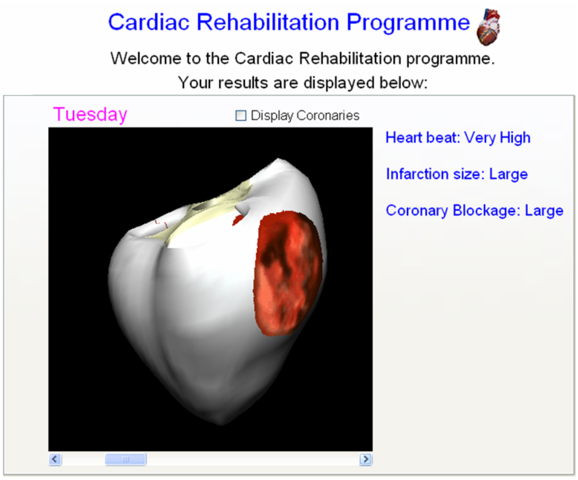

Figure 1: The size and position of the infarcted area is influenced by patient data.

We therefore design our model such that it incorporates a range of visually easily identifiable features. In future research we will investigate which visual features patients associate with different disease processes and lifestyle choices. For example, patients might associate eating lots of fatty food with an increased size of their heart and

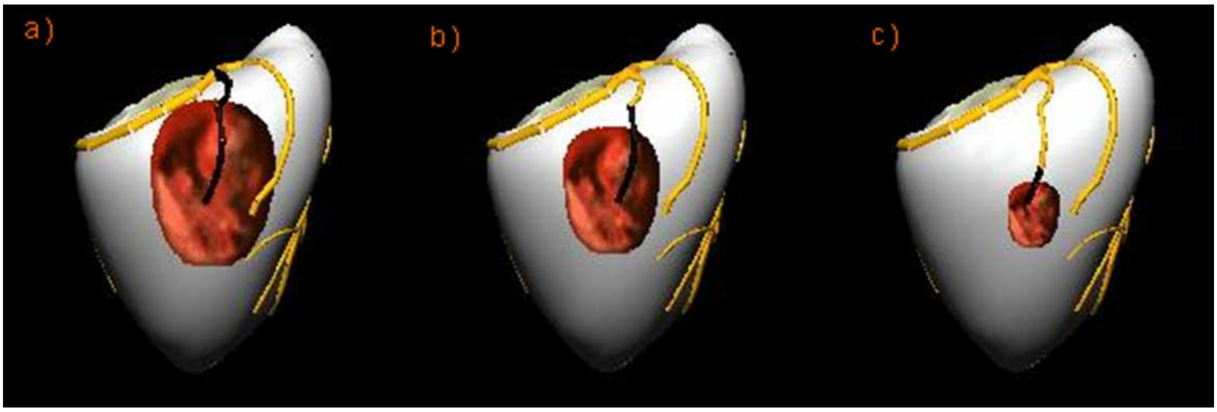

Figure 2: The left ventricle and differently sized infarcted areas and arterial blockages.

a slower heart beat (since “fat” is often associated with “sluggishness”).

3.1 Perceptual Attributes

In order to visualise the effect of the patient behaviour we want to use easily identifiable perceptual attributes. Research from cognitive science suggests that colour, texture, size and motion are all suitable [13].

In order to represent the infarcted area we use a texture map which is perceptually easily differentiated from the heart’s surface texture. The type of infarction can be “Left Ventricular Infarction”, “Right Ventricular Infarction” or “Mid Section Infarction”. Infarcted areas are always represented by surface textures rather than by the anatomical correct 3D regions within the heart muscle. The size of the infarcted area can be changed by scaling the texture map. Furthermore the rehabilitation supervisor can modify the exact position of the infarcted area. An example is shown in figure 1

The size of the heart can be scaled as well and different texture maps for the heart and the infarcted area can be loaded. The heart beat can be changed by changing the time steps in the animation sequence of the heart model. The size of the heart can be scaled up or down in order to indicate “strengthening” or “weakening” of the heart muscle. In order to emphasise the damage done by a cardiac infarct it is possible to display part of the arterial tree. A blocked artery is indicated by black colour, The position and size of the blockage changes with the position and size of the infarcted area as demonstrated in figure 2.

In order to obtain more convincing effects we have started to incorporate techniques from computer animation. Examples are exaggeration and visualisation of weight by using inertia and momentum [14]. In future we might also investigate stylised rendering techniques [15].

3.2 Visualisation of Monitoring Data

Changes in cardiac performance during rehabilitation are visualised by animating the model. This is achieved by obtaining daily monitoring data from the patient, which is then used to affect the look and behaviour of our heart model. Currently the state of the patient’s heart is represented by the size and location of infarcted regions, the patient’s approximate heart beat and the damage to the heart’s coronary system.

A web based user interface enables cardiac rehabilitation patients to input general information and daily monitoring data. The daily data includes the patient’s average heart beat and blood pressure and, if the patient is a smoker, the amount of cigarettes smoked. The amount of exercise a patient receives and the patient’s alcohol intake is also recorded. Once the data are input into the system they all contribute to the final visualisation the patient sees describing the state of their heart. Figure 3 shows a screen shot of the current prototype prompting the user for the general and daily monitoring information.

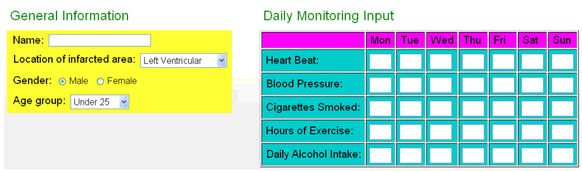

Figure 3: A web-interface for patient monitoring showing general patient information (left) and the interface for entering daily monitoring data (right).

In our current prototype system the daily patient data is evaluated using a scoring formula which calculates for each day the improvement or damage the patient is doing to their health through their lifestyle choices. This information is then portrayed to the patient through the heart model by affecting the state of an infarcted region on the heart surface. A daily comparison of models is made available to the patient through the web interface in order to visualise the cardiac rehabilitation process. If the patient has made harmful lifestyle choices this is currently depicted in the model by enlarging the infarcted region, increasing the patient's heart beat and/or increasing the damage to the coronary system whereas if the patient has been living a healthy lifestyle then this is visualised by decreasing the infarcted region et cetera. The rehabilitation supervisor can customise the visual feedback in order to take into account patient specific requirements.

4 Implementation

The 3D heart model interface is implemented using the visualisation component of the CMISS software package, called CMGUI. CMISS, a mathematical modelling and simulation environment for solving complex bioengineering problems [16], is developed by the Bioengineering Institute of the University of Auckland.

CMGUI is embedded directly into web based applications through the ZINC extension developed for the Mozilla Platform web-browsers by Carey Stevens of the Bioengineering Institute. This environment is supported on most platforms including Linux, MacOSX and Microsoft Windows.

CMGUI 3D scene viewers are embedded into web based interfaces through the ZINC extension by including the appropriate tags in the markup that describes the web page e.g. html or xml. The format that has been used for the current project uses the XML User Interface Language (XUL) to build the interface [17]. XUL is part of the Mozilla browser, is portable across operating systems, and can be combined with Javascript in order to create the dynamic interfaces used in our application.

Javascript is used to connect the web interface and CMGUI and makes it possible to call CMGUI functions for loading models, modifying and animating them.

We have implemented the display of several heart models (one for each day) through the scrollbar object in the web application. The scrollbar has an event handler associated with it which calls the `dayChanged()` function whenever an event occurs. This function checks which day it should be displaying and calls the `controlHeartBeat()` and `controlInfarctionSize()` functions with the various input information the user entered into the index page as their parameters.

A very simple scoring system has been devised which calculates a health score based on the amount of cigarettes smoked, exercise done, alcohol intake etc. for each day. For the final system we will consult with medical professionals in order to develop formulas linking patient's behaviour to their cardiac health. Once a score is calculated the corresponding size and location of the infarcted area is displayed on the heart model by calling functions which are exposed by CMGUI.

In order to represent coronary blockages the existing finite element model was extended with three extra groups of nodes describing different parts of the damaged area. Depending on the intended damage these regions are coloured differently.

In order to texture map the heart's surface rectangular Cartesian coordinates must be transformed into cylindrical coordinates which is achieved by defining extra fields in CMGUI. Translation of the infarcted area is achieved by shifting the texture coordinates which are associated with the heart's surface. The scaling of texture maps is directly supported by CMGUI.

5 Results

Our system allows the recording of daily monitoring data, such as average heart beat, exercise, cigarettes smoked and alcohol intake. The system processes this data and produces a 3D visualisation of a patient's heart with various visual cues describing the cardiac health of the patient. The visual cues include the speed of the animation describing the patients average heart beat rate, the location and size of an infarcted region on the heart's surface and damage to the coronary system of the heart by displaying blockages which have occurred at various areas in the heart's coronaries.

In the current system a separate model is displayed for each day that data is collected. This enables patients to compare and monitor their heart's health and to understand the impact of different lifestyle choices as illustrated in figure 4.

It is important to note that the visualisation provided to the patient is not meant to describe an anatomically correct heart, but rather it provides various visual cues which the patient can interpret as harmful or beneficial. It is hoped that this will increase patient motivation to get healthy and stay healthy. Our tool will not replace traditional cardiac rehabilitation methods, but we hope that it will become a worthwhile addition to standard car-

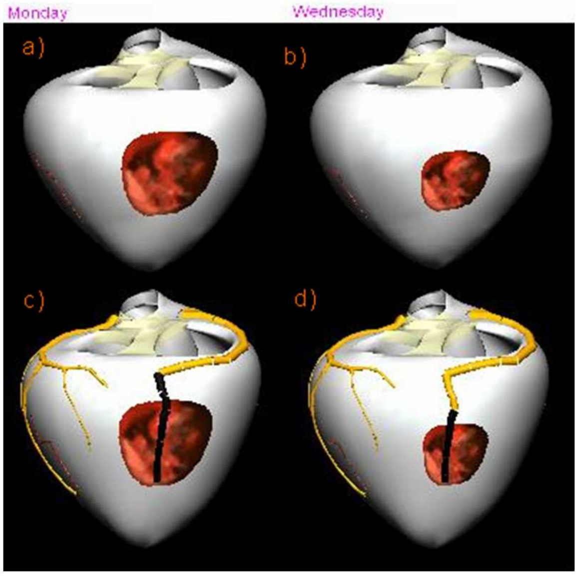

Figure 4: Comparison of the heart model for two different days. The changes in the appearance are caused by positive lifestyle choices reflected in the daily patient monitoring data and give the patient visual feedback about the success of the rehabilitation procedure.

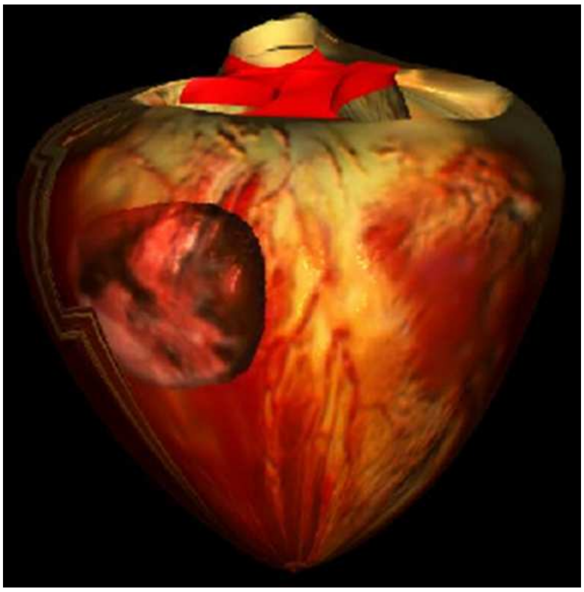

Figure 5: The heart model rendered using multi-texturing, per pixel lighting and bump mapping for increased realism.

diac rehabilitation procedures such as counselling, exercise and lending emotional support.

One drawback of the current system is that at the present it does not provide multi-texturing capabilities which would allow the infarction to be translated and scaled on top of a general heart texture. This feature will be implemented shortly and an example using the stand-alone CMGUI application with per pixel lighting and bump mapping for increased realism is shown in figure 5.

6 Conclusion

We have implemented a heart model with easily perceived visual features such as size and location of infarcted area and coronary blockages, heart beat, and size of the heart. The representation of the heart can be changed over time in order to indicate the influence of the patient's behaviour on cardiac performance.

Currently we haven't investigated which perceptual features are most suitable for which type of cardiac damage and patient behaviour. Special care must be taken in order to avoid discouraging the patient or giving the patient a wrong sense of security.

We have implemented a web-based interface which allows the patient to input daily monitoring data such as blood pressure, alcohol intake and the amount of daily exercises. Using the data the heart model is animated in order to indicate to the patient the success/failure of the rehabilitation process.

7 Future Work

Currently the visual quality of our results suffers from the lack of multi-texturing which will, however, be available shortly. In order to guarantee the success of our tool it is necessary to perform psychological studies researching the effect of various perceptual features on the patient's behaviour. We also want to determine optimal models for different patient groups. For example, the heart model should reflect the age, gender, and potentially the race, size and body mass index of a patient. The aim is to generate positive feedback which encourages the patient to strictly adhere to the rehabilitation regime.

In future we plan to incorporate additional monitoring equipment and to give the user a "what-if" scenario by extrapolating the effects of the patient's current behaviour over time. We plan to implement and evaluate additional visual cues such as enlarging selected areas of the heart, changing the thickness of the cardiac wall and implementing a narrowing of the heart's arteries.

At the moment the ZINC extension, which allows the CMGUI environment to be embedded into web based applications, can only be used with Mozilla based browsers, such as Firefox. We would like to provide plug-ins for other web browsers such as Internet Explorer.

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