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Mechanical simulation model of the systemic circulation

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ABSTRACT

The simulation of different physiological systems is very useful as a pedagogical tool, allowing a better understanding of the mechanisms and the functions thereof. Thus, the observation of physiological phenomena through mechanical simulators represents a great asset. Furthermore, the development of these simulators allows for the reinterpretation of physiological systems. The cardiovascular system is one of the most important systems of the human body and has been the target of several biomedical studies. The present work describes a computational approach for a mechanical model of the systemic circulation, capable of reproducing with high accuracy the physiological haemodynamic function. The model was developed in the *Automation Studio*™ software. Despite this software is widely used in hydraulic and electro-hydraulic conventional simulations – among others, as pneumatics simulations, industrial controllers behaviour simulations – it is not commonly used for physiological functions. Therefore, this work represents a step ahead in physiological simulations, once the different cardiac conditions were simulated with flexibility, versatility and accuracy in a current and accessible commercial software. The model allows the individual alteration of the vascular parameters, the simulation of various physiological conditions, as well as the construction of pressure-blood flow curves in various components of the system. This work also presents a systematic method for the model validation, allowing simulating the system under any operating conditions. This modelling will allow for the extrapolation of the virtual hydraulic system to a physical model, which should lead an improvement in understanding the behaviour of the physiological system.

1. Introduction

The functioning of the cardiovascular system is vital to human survival, and it comprises complex interactions and mechanisms underlying various physiological and pathological processes. The simulation of the blood circulation is of particular relevance for understanding its functioning under normal and abnormal conditions. Moreover, such simulation has been and will continue to be applicable for teaching and research purposes.

Mechanical simulation is an interesting approach in this context as it allows for the observation and interpretation of various phenomena and, consequently, for a better understanding of physiological processes. Furthermore, mechanical simulation allows for the identification of cause-and-effect relationships through the simulation of different case studies. One of the greatest advantage of this type of simulation is the use of sensors and transducers similar to those employed in diagnostic procedures to acquire haemodynamic parameters.

Due to their relevance for biomedical research, the mechanical modelling and simulation of the cardiovascular system have been the subject of several studies over the

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years. Through this modelling the mechanical properties, the blood flow and structure interactions have been studied experimentally in order to improve, for instance, the development of artificial vessels [1]. Some of these studies have focused on the simulation of the systemic circulation, reproducing with accuracy haemodynamic parameters such as arterial pressure, volume and flow. Reul et al. developed a physical model whose geometrical dimensions and working fluid were similar to those observed *in vivo* [2]. Other physical models allowing for the study of the unsteadiness of physiological flows have been presented, many of which have been directed toward cardiac valve testing and towards the study of vascular bifurcations [3]. Other simulations have been developed for ventricular assist device testing, which also replicate the main characteristics of the human circulatory system, based on mathematical models [4–8]. In 2009, Zannoli et al. developed a mechanical simulator for teaching purposes, using a 1:20 scale factor, capable of simulating certain complex physiological processes [9].

The present work describes the model of a systemic circulation mechanical simulator, whose main objective is to reproduce, with high accuracy, physiological haemodynamic parameters. The model was developed in the *Automation Studio*™ software for a hydraulic-oil system. This software is used in the design and troubleshooting of, for instance, hydraulic systems. Because the devised model operates under pressure and flow conditions unlike those encountered in *in vivo* systems, a systematic method for the model validation is also presented, which relies on assumptions and theories derived from fluid mechanics. The model was developed in the *Automation Studio*™ software. Despite this software is widely used in hydraulic and electro-hydraulic conventional simulations it is not commonly used for physiological functions. Therefore, this work represents a step ahead in physiological simulations, once the different cardiac conditions were simulated with flexibility, versatility and accuracy in a current and accessible commercial software using fluid mechanics theory for obtaining similarities of models. This approach was needed because pressure and flow rate of human cardiovascular system are very different from those that can be simulated in a normal hydraulic system simulated by *Automation Studio*™ software. Therefore, the model can be simulated under any desired conditions using the *Automation Studio*™ software. Important mechanical parameters for the functioning of the cardiovascular system can be extracted from the detailed analysis of the simulation results, under any conditions, as ensured by the systematic validation of the model.

2. Cardiovascular system

The cardiovascular system comprises the heart and the circulatory system, which supply nutrients to body tissues. Therefore, the cardiovascular system is one of the most important physiological systems. The blood pumped by the heart circulates through the vessels, carrying nutrients and oxygen and waste products away from all body tissues. The intensity of blood flow is controlled in response to the amount of nutrients required. The heart and the circulation are controlled, in turn, to produce sufficient cardiac output and arterial pressure required to generate the blood flow [10].

The circulation is divided into systemic and pulmonary circulation (Fig. 1A), the first of which represents the major part of the overall system and is responsible for providing flow to all parts of the body, except the lungs. Given the relevance of the systemic circulation, the model developed was restricted to the left side of the heart.

2.1. Systemic circulation

The mechanical work performed by cardiac muscle depends on two variables: the blood volume and pressure. Cardiac muscle contraction causes a rise in pressure in the chambers of the heart (atria and ventricles), and cardiac muscle relaxation induces a decrease in pressure. Differences in pressure cause the opening and the closing of the mitral (MV) and the aortic (AoV) valves on the left side of the heart during a cardiac cycle (Fig. 1B) [10,12].

In the systemic circulation, blood flows continuously from the pulmonary veins to the left atrium. Approximately 80% of the blood contained in the atrium passes to the left ventricle before the atrium's contraction and the remaining 20% after. The atrium is considered a primer pump that allows for high ventricular pumping efficiency. Immediately following the beginning of the ventricle's contraction (systole), the pressure inside the ventricle increases sharply, powering mitral valve closing (MVc). This phase is called isovolumetric contraction, during which the blood volume does not change (Fig. 2). Approximately 0.03 s later, the ventricle exerts sufficient pressure to open the aortic valve (AoVo), initiating blood ejection. The opening of the AoV occurs when the intraventricular pressure reaches 80 mmHg. This is the ejection phase (Fig. 2). During the ventricular systole, the atrium accumulates large blood quantities because the MV is closed. After the contraction, the ventricle relaxes (diastole) suddenly, causing the intraventricular pressure to decrease rapidly to diastolic values. This event is called isovolumic relaxation (Fig. 2). After the intraventricular pressure decreases and blood accumulates in the atrium, the pressure increases, forcing MV opening (MVo) and thus starting a new pumping cycle with the filling phase (Fig. 2.), when the blood passes to the left ventricle [10,12].

2.2. Haemodynamics

The cardiovascular system can be described in terms of its haemodynamic parameters, such as blood pressure, volume, cardiac output, and vasculature resistance or compliance [14].

The blood flow rate is called the cardiac output and generally corresponds to the total blood volume ejected per minute by the left ventricle to the aorta. The blood flow rate is determined by two factors: the pressure gradient in vessels, which is the force that drives blood, and vessels' resistance to flow. This resistance increases with the contraction of the vessels and decreases with the dilation of the vessels. The instantaneous flow rate measured in the