Fractional Order Cardiovascular System Model with Baroreflex Control - An Optimization Approach

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by

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Abstract

The Cardiovascular System (CVS) is an intricate and essential part of human physiology which maintains oxygen transport, blood flow and homeostasis throughout the body. Understanding the dynamics and regulation of the CVS is important in clinical medicine, biomedical research and healthcare innovation. Experimentation with the human body to understand physiology is a challenging research area in the modern world. The mechanisms postulated to explain the human system can be easily studied using mathematical expressions in computer simulation due to the extremely complex structure of the human system. These mathematical representations involve creating dynamical equations and computational simulations to describe the physiological process of the human system.

During the initial phase of the research work, a lumped parameter model for CVS is developed using the pressure voltage analogy. In the existing arterial Windkessel models, the viscoelasticity characteristics are not considered, leading to error in the model and hence false prediction is unavoidable. To incorporate this characteristic, improved Fractional Order (FO) Windkessel models are developed by introducing fractionality in the existing 2-element, 3-element and 4-element Windkessel models (Wk4). The MATLAB function fmincon() is used to optimize the model parameters and fractionality of the differential equation by minimizing the error between the clinical data and the model output considered as an objective function. The simulation results indicate that the FO models provide least error index than the existing Integer Order (IO) Windkessel models. In specific, the FO Wk4 model provides better closeness to the clinical data than other FO Windkessel models. Hence, FO Wk4 model is further used to study the behavior of system subjected to abnormalities like atherosclerosis and arterial stiffness.

The Windkessel model is a single compartment representation which simplifies the complex arterial system into a series of resistive and compliant elements, neglecting the intricate branching and geometry of the chambers and the valve functionality. A more complex model is required to address the limitations of Windkessel model for specific applications or studies which need better accuracy. Hence, a FO geometric model is presented which includes four chambers of the heart, systemic and pulmonary circulation. The heart chambers are modeled based on the geometry and systemic and pulmonary circulation are modeled using the Windkessel approach. To include the viscoelastic property, a fractionality is included in the dynamics of the chambers. An optimization method is presented to

obtain the fractionality of different chambers by minimizing the error index between clinical data of healthy human and model output using heuristic algorithms such as Cuckoo search, Firefly and Accelerated particle swarm optimization.

Baroreflex dysfunction is one of the common causes associated with the CVS. The buffering capability and baroreflex gain influence large variation in blood pressure for short term control. For regulating the blood pressure, a model with the baroreflex control is proposed to study the complex interactions between the autonomic nervous system and CVS. Initially, baroreflex control is designed for the IO extended windkessel model which handles the distribution of total blood volume changes under the influence of postural changes by means of short term baroreflex control utilizing the sympathetic and parasympathetic nerve activities. To show the efficiency of the proposed model, the simulation is carried out further for orthostatic hypotension and hypertension conditions. The existing IO model will not consider the viscoelastic property of CVS. Hence to get the realistic anatomy and better accuracy, the baroreflex control is designed for the proposed FO geometric model and validated with clinical data. Also, the proposed model is studied for different abnormality conditions like orthostatic intolerance, hemorrhage, atherosclerosis and arterial stiffness.