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Applied Fluid-Structure Interaction Technique to Initial Insight into the Effect of Exercise on the Aortic Valve Stroke Work

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Abstract

The left ventricular stroke work is a measure of the work done by the left ventricle during the ejection of blood throughout per cardiac cycle. The aim of this investigation was to propose a model to numerically evaluate the stroke work for a healthy subject using a fluid-structure interaction (FSI) simulation during exercise protocol. Aortic valve dimensions were calculated using an imaging technique of echocardiography. A FSI simulation was performed using an Arbitrary Lagrangian-Eulerian (ALE) mesh. Boundary conditions were defined by pressure loads on ventricular and aortic sides. Stroke work was predicted to increase to 121% from 60 bpm to 125 bpm, and it did not increase much above 125 bpm. Based on derived regression equations of our FSI results of stroke work and comparing them with clinical ones, numerically-predicted stroke work values are in good agreements with published clinical data. The slope of stroke work changes to mean arterial pressure, while exercise protocol, is 168.08 ml which is 12.2% less than the average slope of clinical data. The y-axis intercepted of stroke work changes to mean arterial pressure, while exercise protocol, is -11186 which is 15% less than the average y-axis intercept of clinical data. Our results of the specific patient show that numerical methods can be proposed to predict good estimates of patient specific stroke work at different heart rates.

Keywords: Aortic valve, Finite element method, Fluid solid interaction, Stroke work

1. Introduction

Measurement of stroke work is a crucial factor in understanding the development of heart problems and subsequent clinical diagnosis [1]. For example, the stroke work index is a reliable criterion of left ventricle performance which requires an invasive procedure, and has been usually measured and utilized in the settings of intensive care units and operation rooms [2-4]. While invasive methods have been used to measure stroke work, such techniques are expensive and include risks to patients [5]. Computational procedures, however, have the potential to determine stroke work but bypassing such limitations.

Invasive, and cost intensive techniques have been used so far [5-7]. For example, Loeb et al. assessed left ventricular function after acute myocardial infarction using stroke volume calculation [8]. They plotted left ventricular stroke-work index (LVSWI) versus left ventricular end-diastolic pressure (LVEDP). Linhart, investigated pacing-induced alterations in stroke volume in the appraisal of myocardial function [9]. They performed right atrial pacing in 16 subjects while right and left heart catheterizations. They concluded when pacing ventricular function curves were performed relating left ventricular stroke work (SW) to LVEDP, normal patients demonstrated a steep curve. Hamosh, P., & Cohn, J. N. studied acute myocardial infarction with measuring left ventricular stroke volume [10] in 40 healthy patients. Kamoi, S. et al. estimated accuracy of stroke volume via reservoir pressure concept and three element windkessel model [11]. Also, due to the fact that invasive experiments could be risky for human subject, there have been some studies on animals; although, no data related to stroke work was found in some of them but it can be derived from their hemodynamic results [12-18].

Simultaneous simulations of Fluid-Structure Interaction (FSI) have the potential for non-invasive prediction of stroke work. Recently, FSI has been utilized to investigate heart and heart valve mechanics [19-35]. Studies include use of a two-dimensional model to evaluate the stroke volume and cardiac output for a healthy subject [29]. That was done by coupling the FSI simulation with an echo-Doppler method at rest and while exercise. Detailed attention was taken into account to validate the simulation against cardiac function measures that can be reliably computed by using clinical protocols, with varying heart rates [29]. Moreover, it was possible to predict the effect of heart rate increment while exercising on blood hemodynamics through the aortic valve, and strains and stresses experienced by the valve leaflets [29]. Developing such models to enable stroke work would potentially be of clinical value because they are supposed to perform it more readily. However, so far FSI and clinical measurements have not been jointed to predict a patient's stroke work. Effect of heart rate changes (e.g. due to exercise) on stroke work of the patient have not been analyzed either. Heart rate would be a significant parameter to consider because it brings about large differences in stroke work.

The aim of this research was to assess the influence of exercise on stroke work at different heart rates from rest to exercise. Using FSI model and our two-dimensional aortic valve geometry, we evaluate stroke work during exercise. The key valves of dimensions and boundary conditions for our study were acquired from a single volunteer, enabling an initial assessment of the applicability of the model for personalized healthcare.

2. Materials and Methods

2.1 Overview

A healthy human male adult, 33 years old (80 kg, 175 cm, BMI: 26.1) , participated in this study. His healthy cardiovascular function was confirmed by clinical protocols. The informed consent was obtained. The workflow of the study is provided in Figure 1.

1- Velocity integration, stroke volume and cardiac output are recorded by Doppler imaging.
2- Brachial systolic and diastolic pressures are recorded by blood pressure cuff.
3- Aortic valve geometry is measured by echo-Doppler.
4- Systolic ejection time at different heart rates are measured by echo-Doppler.
5- Equations of Fluid–Solid interaction is applied to the geometry concerning boundary conditions provided in stage 2, 3 and 4.
6- Computing numerical velocity integration by equation 2.
7- Computing numerical stroke volume by equation 3.
8- Computing numerical stroke work by equation 4.
9- Comparing Literature and our numerical results at discussion, section of comparison to the literature.

Figure 1: The workflow of the study

2.2 Numerical Approach

Systolic and diastolic pressures were recorded during the test via a brachial pressure cuff (Figure. 2). Using echo-cardiography, the aortic valve geometry (Figure.3) and its dimensions were obtained (Table 1). The computer aided design (CAD) model of the aortic valve geometry were created with Solidworks package based on the clinically-measured data. The leaflet mechanical properties were considered as homogenous, isotropic with linear stress-strain relationship [22, 24, 25, 36]. Blood was presumed to be Newtonian and an incompressible fluid [37]. All material properties are given in Table 2 [38, 39].

The CAD model then discritized and imported into the finite element analysis package, Comsol Multi-physics (v4.2, Comsol Ltd). The fluid and strucure governing equations were applied and the material geometries were introduced. Pressure boundary condition was used at the inflow (the ventricular side) and outflow (the aortic side) boundaries for the fluid mechanics module (Figure. 3). The use of a moving ALE mesh enabled the deformation of the fluid mesh to be tracked without the need for re-meshing [36]. The second order Lagrangian elements were utilized to define the mesh. The model is capable to solve time-dependent

FSI model [23, 40]. The model then validated to ensure its independency from mesh resolutions [29].

2.3 Analysis of Fluid Dynamics

The aortic area was calculated utilizing:

$$\text{Area} = \pi \left(\frac{D}{2}\right)^2 \qquad (1)$$

where D is the calculated ascending aortic diameter after the sinotubular junction (Table 1). For FSI simulations, the mean velocity numerically was obtained at each time step of the ejection period:

$$\text{Velocity integration} = \oint_0^{\text{ejection time}} V.dt \qquad (2)$$

where V is the mean fluid velocity through the outlet boundary. Comparison of measurements of velocity integration, cardiac output and stroke volume enabled quantitative validation of the FSI model.

Knowing the velocity integration and aortic area, one can calculate the strock volume as Eq. (5):

$$\text{Stroke volume} = \text{Velocity integration} \times \text{Aortic area} \quad (3)$$

The total left ventricular stroke work (SW) is calculated by the product of left ventricular pressur during ejection and the ejected volume of blood integrated over the ejection interval.

$$\text{Stroke work} = \int_0^{\text{ejection time}} \text{Pressure} \times d(\text{stroke volume}) \quad (4)$$

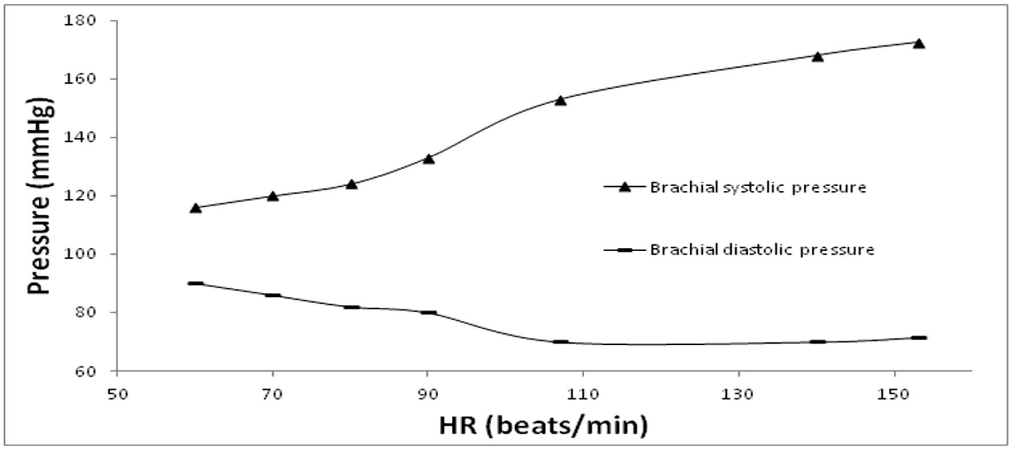

Figure 2: Systolic and diastolic pressures

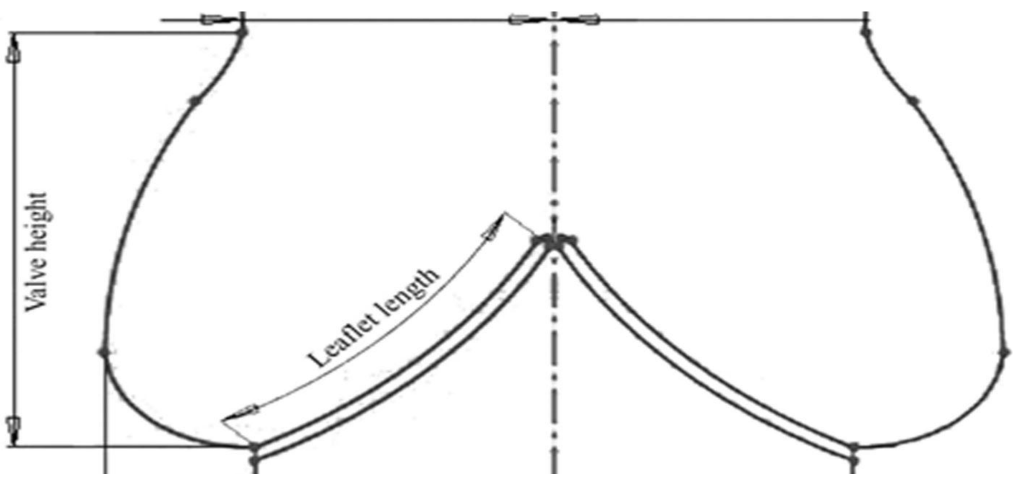

Figure 3: Two-dimentional aortic valve geometry

Table 1: Parameters of the aortic valve geometry

Aortic side radius (mm)	Leaflet's length (mm)	Ascending aorta radius after sinotubular junction (mm)	Valve's height (mm)	Maximum radius of normal aortic root (mm)	Leaflet's thickness (mm)	Ventricular side radius (mm)
11.5	16.6	11.75	20.36	16.65	0.6	11.1

Table 2: Mechanical properties of fluid and solid

Viscosity (Pa.s)	Density (kg/m^3)	Young's modulus (N/m^2)	Poisson ratio
3.5×10^{-3}	1056	6.8×10^6	0.49

3. Results

Systolic Pressure Changes to Stroke Volume.

Figure 4 provides systolic pressure changes to stroke volume at different heart rates. Overall, in terms of ascending and descending heart rates, all the curves follow the same trend. However, as heart rate increases, the curve size becomes larger. It can be observed that at the end of each curve, a stroke volume decreases. This reduction in stroke volume can indicate the blood backflow towards left ventricle [29]. As seen in figure 4, the changes from heart rate of 60 to 80 bpm are much lower than those between heart rate of 98 to 147 bpm and the next ones.

Figure 5 provides the stroke work values during the ejection period while increasing the heart rate. A quadratic polynomial equation with a high accuracy ($R^2 = 0.983$) was fitted to the calculated data. The stroke work through exercise protocol increased by 121% from 60 to 125 bpm, and it did not increase much above 125 bpm. In a healthy subject, at higher heart rates the filling time of the left ventricle during diastole will decrease which brings down the preload and as a result of this the stroke volume will not show appropriate incrimination. This is because of the fact that the stroke volume does not increase considerably at the heart rate over 125 bpm [28]. Stroke volume changes were followed by bigger increment after heart of 80 (Figure 4).

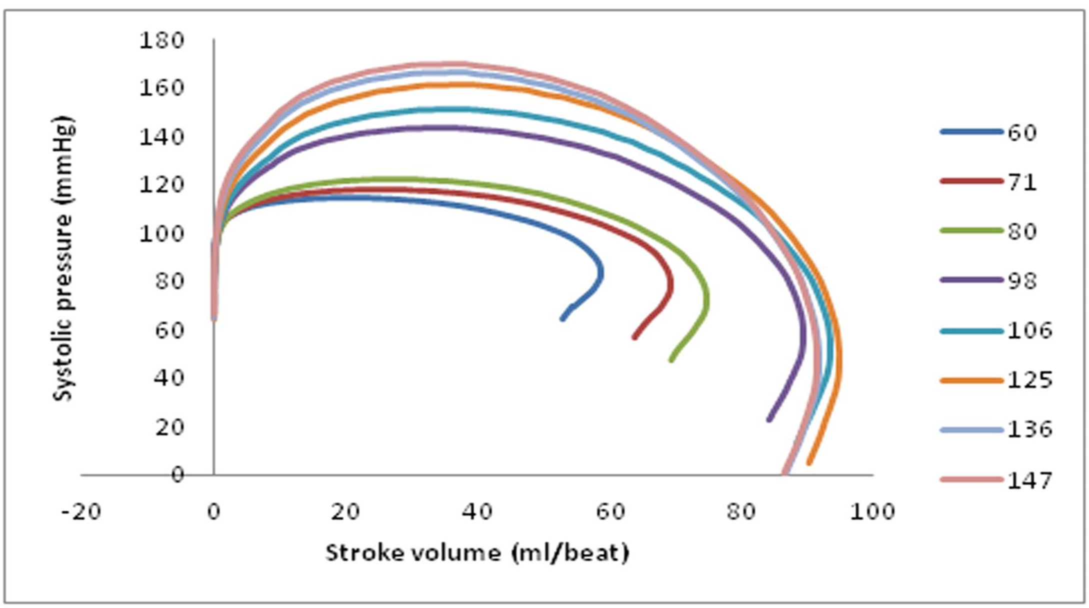

Figure 4: Systolic pressure changes to stroke volume at different heart rates

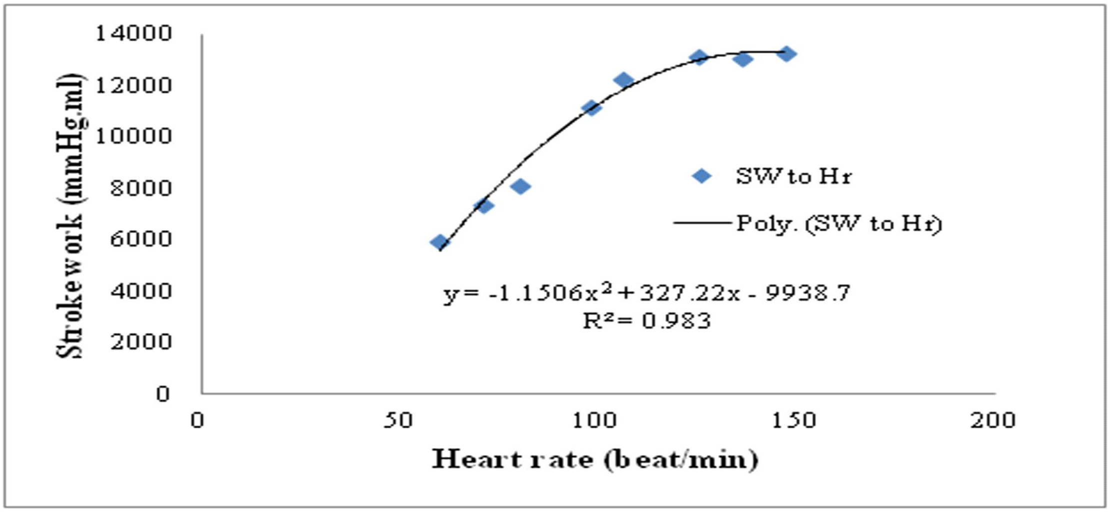

Figure 5: Stroke work changes to heart rate

4. Discussion

4.1 Study Findings

The study has investigated the initial use of a fluid-structure interaction model to calculate the stroke work done by the left ventricle by calculating the pressures and blood flow volume through the aortic valve. The hemodynamic data was acquired from a healthy subject while exercising. Echo-Doppler-derived data provided essential information for simulation including aortic valve geometry and pressure boundary conditions. To the authors' knowledge, this would be the first time that exercise protocol measurements and FSI technique have been combined together to enable numerical estimations of stroke work. All the curves of systolic pressure changes to stroke volume at each heart follow the same pattern at different heart rates in terms of ascending and descending orders (Figure. 4). To all appearances, stroke volume variations after heart rate 80, is followed by an abrupt increase.

The FSI model predicted stroke work through exercise protocol to increase by 121% from 60 to 125 bpm, and then it did not increase much above 125 bpm. Our investigation provides initial insight as the feasibility of gaining a variety of conditions (e.g. changes due to exercise). The applicability of the modeling and it's privileges such as low computational time and less expensive as compared to currently available clinical approaches , make it usable to estimate the stroke work in patients. As well as aforesaid benefits, our mathematical model has the capability to analyses different aortic geometries. Also this model let patients to predict some situations which are not possible to clinically measure. To be more exact, based on the fact that the subject is human being applying such numerical model let physicians to understand and investigate probable conditions where patients could face in the future or on different circumstances.

Etiology of diseased states would be moreover assessable sine they may affect on shape and form (geometry) waveform and quantity of blood pressure (boundary conditions). On top of that, the vast majority of clinical techniques and research are not mechanical-based. Taking into consideration that the nature of heart valve functions are mostly mechanical-based, our discipline evidently steps toward to investigate the heart performance as it is a mechanical pump to a great extent.

4.2 Clinical Application and Reliability

Catheterization-Thermodilution is known as the golden method for measuring cardiac function [5]. This is, however, an invasive technique. This has been proved such strategies are associated with potential perils including heart failure, death, and even cardiac arrhythmia [5]. The FSI modeling can offer clinical team information that is clinically compatible with Catheterization-Thermodilution and provide such data earlier and in a safer approach than traditional methods. Noninvasive measurement of the hemodynamic parameters and knowing the normal values for these parameters, the hemodynamic status of each patient can be represented as percent changes from the norm. This can result in numerical modeling of the hemodynamic status, and clinicians may be able to more accurately react to the individual needs of the patient with appropriate treatment. Furthermore, numerical simulations are capable to precisely estimate cardiac hemodynamics. This is mostly due to the fact that it does not deal with inter- and intra-observer validity variables which are mainly the argument for performing ECG. This kind of unevenness is contingent upon personal expertise and the image capture ability of the user. Therefore, the fundamental matter is to prove the credibility of modeling methods for cardiac evaluations. Moreover, clinical experiments performed on animal subjects [12-18] to avoid any risks for human subjects, can glorify the merits of numerical approaches.

4.3 Comparison to the literature

Figure 6 performs stroke work changes to mean arterial pressure (for the exercise protocol). As it can be observed, slope of the results reported by this paper (168.08 mmHg • ml/ml) and are within the reported clinical data varied from 46.56 to 335.05 ml [1, 2, 4, 5 and 12]. The average slope of clinical data is 191.42 mmHg • ml/ml. The reported results of this paper is within12.2% with the literature reported data. The differences could be due to weight, sex, age and race of patients. It can be concluded that the reported data from the numerical model in this paper is in an acceptable range of reported clinical data.

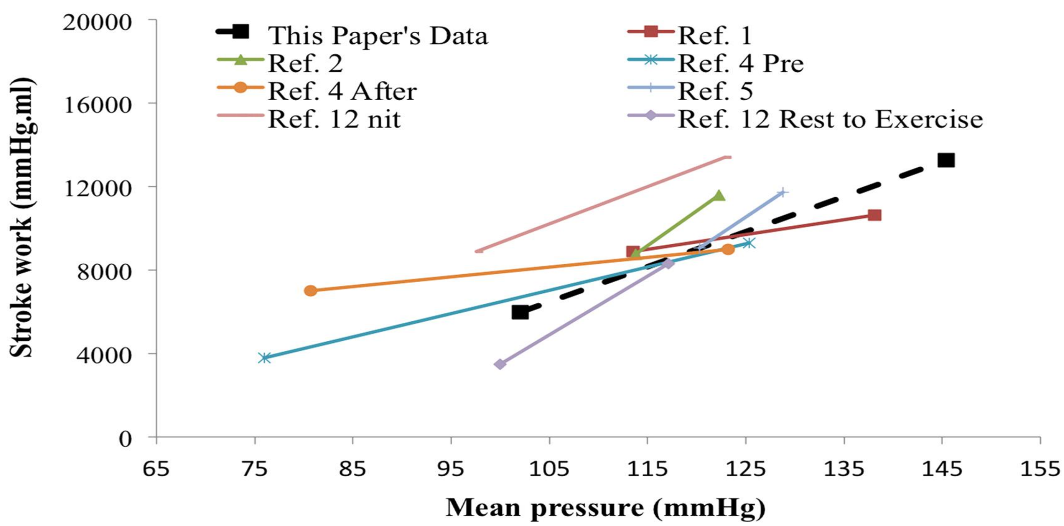

Figure 6: Fluid solid interaction and clinical stroke work changes to mean arterial pressure for the exercise protocol

4.4 Limitations and Future Trends

The limitations of this numerical study and future suggestions are listed as following:

1.Using two-dimensional rather than three-dimensional geometry.

2.Applying linear, homogenous and isotropic features for simplification of aortic valve's mechanical properties.

3.Mechanical properties are based on generalized information, and are not specific to the patient.

4.Considering blood as a Newtonian and incompressible fluid.

Despite model limitations, we fulfilled an acceptable consistency with the general literature.

Undoubtedly, a three-dimensional model may result in more precise predictions; however, it would also raising the processing time (that is less than 15 minutes for the two-dimensional model). This should hold shortcomings for clinical applications.

5. Conclusion

We have presented a two-dimensional fluid-structure interaction simulation of aortic valve having the ability to predict stroke work from rest to exercise stage. Derived regression for stroke work changes versus mean arterial pressure showed the averagely 15% difference between numerical and clinical data. Thus, this model provides initial insights as the potential for predicting stroke work for a specific individual within a 15-minute response time that matches with clinical data.

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