Motion analysis of the left ventricle of a human heart for realization in a cardiovascular mock-loop

S. Kurtenbach[1], F. Wieja[1], I. Müller[2], M. Neidlin[2], S. J. Sonntag[2], P. Bruns[3], C. Hopmann[3], F. Chuembou Pekam[4], M. de la Fuente Klein[4], K. Radermacher[4], U. Steinseifer[2], M. Hüsing[1], B. Corves[1]

[1] *RWTH Aachen University, Department of Mechanism Theory and Dynamics of Machines (IGM), Aachen, Germany,*
e-mail: {kurtenbach, wieja, huesing, corves}@igm.rwth-aachen.de

[2] *RWTH Aachen University, Department of Cardiovascular Engineering (CVE), Aachen, Germany,*
e-mail: {mueller, neidlin, sonntag, steinseifer}@ame.rwth-aachen.de

[3] *RWTH Aachen University, Institute of Plastics Processing (IKV) in Industry and the Skilled Crafts at RWTH Aachen Universit, Aachen, Germany,*
e-mail: {philipp.bruns, Christian.hopmann}@ikv.rwth-aachen.de

[4] *RWTH Aachen University, Chair of Medical Engineering (MediTec), Aachen, Germany,*
e-mail: {chuembou, fuente, Radermacher}@hia.rwth-aachen.de

Abstract. Within the further development of a special mechanical representation of the human circulatory system the CVELoop at the Department of Cardiovascular Engineering at RWTH Aachen University, a contractive MockHeart was developed. This MockHeart simulates a healthy heart in the CVELoop. In opposition to all previous cardiovascular system simulators, the left ventricle is externally driven by several cam mechanisms. These cam mechanisms provide the necessary power to create the pressure-volume-work for the fluid circulation but also the important time dependent radial contraction, which is the most influential degree of Freedom in the human heart. The aim is to produce a MockHeart providing valid boundary conditions for the connected VAD (Ventricular Assist Device). The systematic approach of the development of the mechanism is performed based on an accurate measurement of the kinematic properties of a healthy human heart at RWTH Aachen University with the speckle tracking echocardiography-procedure.

Key words: MockHeart, CVE Loop, Left Ventricle, Left ventricular assist device (LVAD)

1 Introduction

Realistic simulators for the cardiovascular system provide the opportunity to perform in examinations under laboratory conditions ahead of testing and researching ventricular support systems in living organisms. That way, animal experiments, which still provide the most meaningful test results, can be reduced [1]. Since this reduces costs in most cases as well as time expense and efforts during the development of a cardiac support system, numerous different cardiovascular simulators have been developed. The fact that animal experiments are not always viable and ethically questionable contributes to the effort of developing new systems. So far, it was not possible to reproduce every single part of the cardiovascular system realistically [2]. The models, which have been developed up to this point, not only differ in the number of simulated parts of the cardiovascular system, but also in their specific execution [2].

Basically, the number of actuators that have been implemented for the simulation of ventricles distinguish between three main categories: single-chamber-system, double-chamber-system and multi-chamber-system. Single-chamber-systems, usually controlled using a pneumatic drive, yield cost-efficient results due to their simple design. Their general goal is to simulate the pressure-volume-work of a native heart [3-9]. They are capable of reproducing the contraction of a human ventricle considering the Frank-Starling-mechanism; however they do not involve the systematic effects of the pulmonary circulation [2]. As an example the independently developed simulators by Colacino et al. [10] and Ferrari et al. [11] should be mentioned. Double-chamber-systems with two ventricles or alternatively one ventricle and one atrium can be used to develop further aspects of the circulatory systems [2]. This is exemplified by the cardiovascular simulator CVELoop by the Department of cardiovascular at RWTH Aachen University [12, 22, 23].

Weak spot of the double-chamber-systems is the poor illustration of the interaction between the atrium and the ventricle as well as the interaction between the ventricle and the artery in both the systemic and pulmonary circulation. Multi-chamber-systems that usually consist of four chambers are capable of replicating the diastolic and systolic pressure as well as the flow rate. However, until the development of the cardiovascular simulator by Paula Ruiz et al. [2] they were not suited to depict the filling phase of the chambers reliably. Ruiz considered the cause to be the use of multiphase motors and pneumatic drives. Multiphase motors in particular are unsuitable for the emulation of pathophysiologic conditions, because of their disadvantages according to controlling possibilities. Pneumatic drives admittedly are able to illustrate the contraction phase realistically by injecting air into a flexible membrane, but they also generate a vacuum due to the necessary ventilation during the diastole. This limits the simulation of the faster and slower filling phases [2].

Since the native cardiovascular system and therefore basically the function of the heart cannot be illustrated by the controlling of multiphase motors or pneumatic drives, there is a demand for a suitable drive concept for ventricles simulated through flexible membranes.

The goal of the following concept is not just to provide the necessary pressure-volume-work for the fluid circulation, but rather in particular to realize the significant radial contraction of the human left ventricle realistically, so that the cardiovascular simulator yields valid test conditions for the connected cardiac support system. In order to realize this radial movement of the left ventricle, an unevenly transmitting mechanism is developed using methods commonly utilized in mechanical engineering.

2 Contraction of the human heart

The contraction of the left ventricle happens through the excitation of the heart muscle cells, which are constructed in a unique pattern. Their structure through the three layers of the myocardium results in a complex deformation of the left ventricle during contraction [4, 7]. The heart starts contracting along the longitudinal axis and the wall of the ventricle thickens radially. The valve plane moves towards the cardiac apex and the additional shift of the valve plane facilitates the ejection of blood into the aorta. At the same time this movement generates a pull into the atrium in favor of the blood flow from the pulmonary vein. During diastole the valve plane moves back. Besides the aforementioned radial contraction and the axial movement, the contraction also causes an opposed torsion between the base and apex of the heart. Figuratively speaking, the left ventricle is “wrung out”. During the relaxation phase the torsion regresses. Its movement between base and apex facilitates the inflow of blood into the ventricle. In addition to that, the contraction of the atrium contributes to the filling of the ventricle during diastole [13-15].

2.1 The radial contraction

The foundation for the development of a mechanism is the result of an extensive study on the radial contractions of a healthy grown heart at the medical center of RWTH Aachen University. The study has been performed with the aid of the Speckle tracking echocardiography (STE) using the software 4D LV Function™ by TomTec Imaging Systems GmbH. STE is a three-dimensional parametric ultrasound measuring procedure that, compared to the conventional two-dimensional echocardiography, should enable an, as far as possible, examiner independent, objective and quantitative analysis of the “myocardial functions” [16]. With the aid of this parametric method it is possible, depending on the problem, to analyze tissue velocity and deformation rate as well as forms of contractions and even derived parameters. That way the myocardial radial strain, which describes the contraction, or deformation respectively, relative to a reference length or reference point in radial direction, can be determined [16]. This determination takes place in the center transverse sectional plane of the left ventricle (**Fig. 1**).

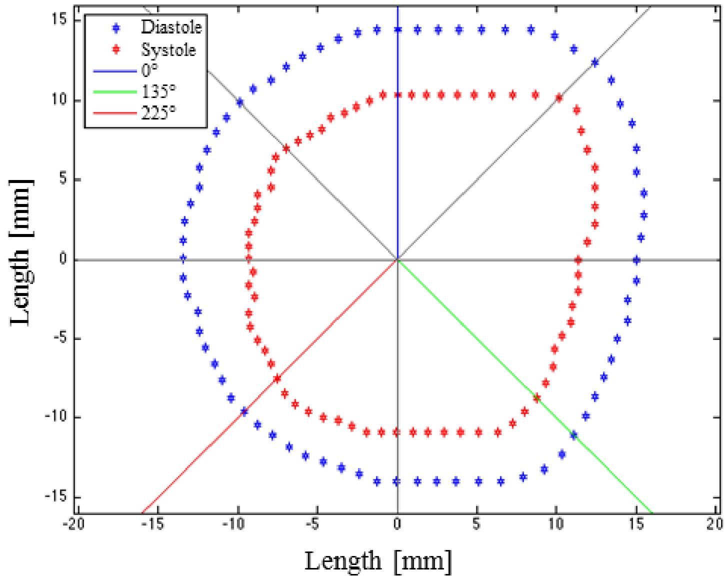

Fig. 1 Determined measurement data from the end-systole and end-diastole

Fig. 1 displays the followed pixels in the end-systolic and end-diastolic condition. The shortening of endocardial pixels to lines by steps of 5° was monitored using the software mentioned above. The measuring was executed, beginning in the end-diastolic state, in steps of 34ms of a 893ms long cardiac cycle.

The radial path of motion of the examined pixels on one beam is shown as an example in **Fig. 2** by reference to the 135° line. The radial back-and-forth motion follows the typical phases of a cardiac cycle [15, 17]. One cardiac cycle consists of the systole with the tension and ejection phase as well as the diastole with the relaxation and filling phase.

Based on the end-diastolic condition the ascertained pixels stagnate initially for about 120 ms. During this isovolumetric tension phase the ventricular pressure of about 4-6 mmHg increases to about 80 mmHg [17]. Since the mitral valve as well as the aortic valve is closed, the tensioning takes place under constant volume. Once the intraventricular pressure exceeds the pressure of the aorta (about 80 mmHg) the aortic valve opens and blood flows into the aorta. This marks the beginning ejection phase that lasts for about 200 ms. As soon as the intraventricular pressure falls below the pressure of the aorta, the aortic valve closes and the ejection of blood comes to a stop. This is followed by a relaxation phase that lasts about 70 ms. During this phase, the pressure of the ventricle under constant volume decreases further. Once it falls below the pressure of the left atrium, the mitral valve opens and the filling phase begins. The volume of the ventricle increases steadily until the ventricular pressure equals the atrium pressure when the valve opens. Towards the end of the diastolic filling, the atrium excited by sinoatrial node cells contracts, which causes the ventricular pressure to increase slightly and the volume to grow until the end-diastolic filling volume is reached and the cardiac cycle begins all over again [15,17]. During the diastole the heart itself is supplied with blood through the coronary vessels [15].

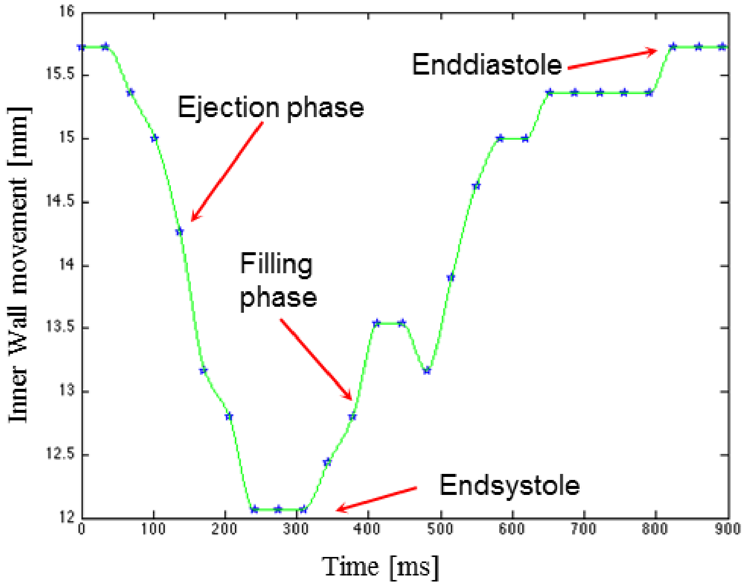

Fig. 2 The radial movement of the 135° line

The radial path of movement of the pixels on all examined lines does not coincide temporally. As an example, **Fig. 3** shows the path of movement of three different lines. During the plateau phase of the action potential, every cell of the working myocardium is absolutely refractory and within that time not excitable again. As soon as the myocardia cells polarize towards negative potentials, action potentials can be triggered again [17, 18]. These are initially short-lived and in between neighboring cells they are only transmitted slowly. For a short while during this phase the excitability of the working myocardium is inhomogeneous [18].

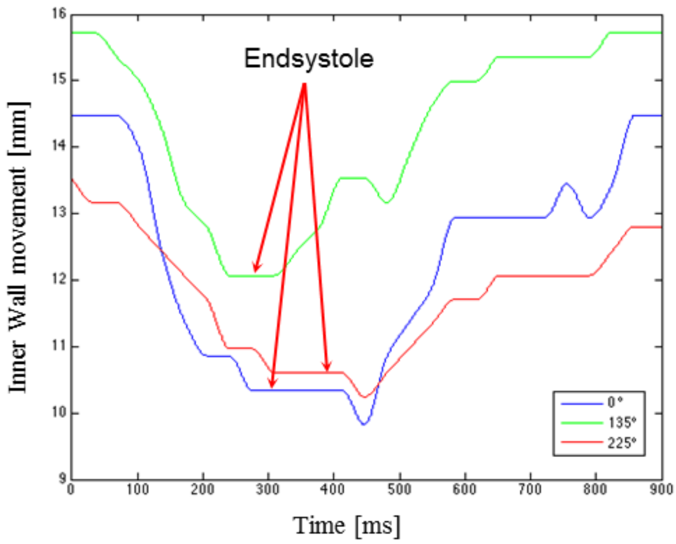

Fig. 3 The inner wall movement compared for three different beams

The left ventricle of the heart fulfills its function by temporally contracting single muscle cells and therefore neither a superposition of single twitches nor muscle cramps can occur [18]. As part of a motion study by Alkhadi et al. [19] the following images originated from a computer tomographic examination (**Fig. 4**).

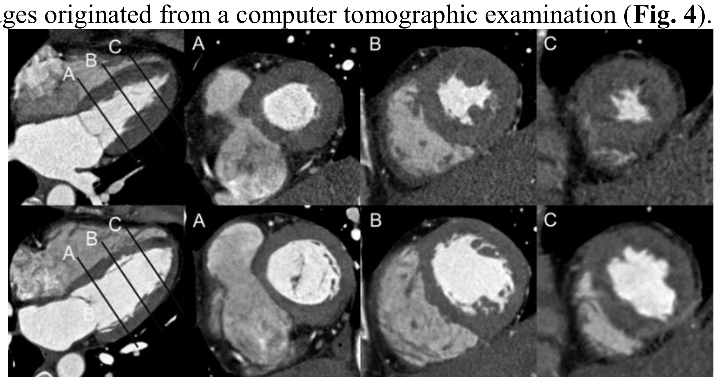

Fig. 4 Transversal sections of the left ventricle during heart contractions

In three transversal sections parallel to the valve plane the end-systolic (top) and the end-diastolic (bottom) conditions have been determined. Here as well the irregular and temporally shifted radial contractions of single muscle cells of the left ventricle are visible. While the intraventricular area in the end-diastolic state in Fig. 4 is approximately elliptical, it resembles a circle in the end-systolic state. The increase in thickness of >5 mm as well as the characteristic relief in the inside of the ventricle is also obvious [19].

3 Structural and Dimensional synthesis

In order to realize the contraction motion of the left ventricle and its fluid-mechanical properties realistically, a suitable mechanism following the VDI-guideline 2221 has been developed. In doing so, the steps planning, structural synthesis, dimensional synthesis and the preliminary design of the mechanism have been completed [20, 21].

The radial contractions of the left ventricle (LV) are realized through a mechanism that has a ring structure and is mounted horizontally to the flexible main chamber. The dynamic motion of the mechanism is controlled by a drive. Several pressure forces caused by the mechanism, which externally act onto the main chamber, cause the pulsating cyclical contractions of the MockHeart. The evenly distributed pressure forces acting onto the main chamber overcome the inner pressure of the chamber, which is equal to intraventricular pressure. The amount of blood extruded by the MockHeart during this process equals the stroke volume of the left ventricle.

During the structural synthesis, planar structures have been developed that can ensure the guidance of work components according to the provided measurement data. These structures are based on quadrinomial and six-membered kinematic chains. The systematic variation of joint types, frames or arrangement of the mechanism elements to one another lead to kinematic structures, that allow different designs and movement patterns of posterior mechanisms. The solution field generated using construction technology approaches and is expanded using heuristic methods and techniques from analogy observation. The results of the structural synthesis are a multitude of planar ring structures that are composed of basic kinematic structures. After an evaluation of the ring structures, those structures, which are either rigid or do not enable a parallel guide due to their arrangement, were eliminated. Additionally the structures that cannot be controlled using a drive were disqualified. The structures shown in **Fig. 5** are pursued further in the subsequent dimensional synthesis.

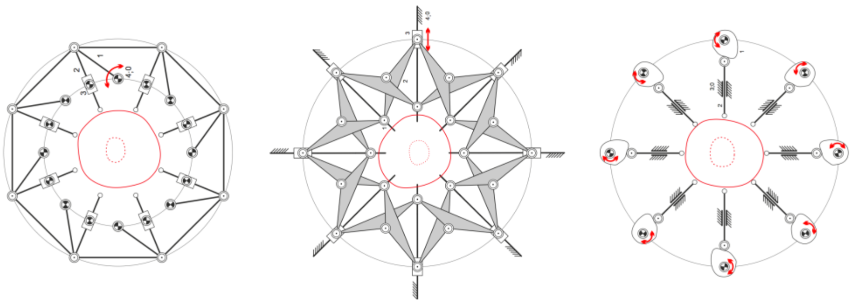

Fig. 5 Kinematic structures to be pursued further

The first ring structure consists of basic crankshafts and it is controlled by a rotary driven component. The second structure is composed of basic crossing over linkages and is driven linearly by a thrust component. In contrast, the third structure is composed of basic cam mechanisms in their original form with roller tappets mounted centrically. During the design phase, the main kinematic dimensions of the pursued kinematic structures have been determined.

The basic dimensions of the mechanism elements of both crank mechanisms were both determined using the three-pose-synthesis, whereas the preset of three positions on a trajectory is sufficient [21]. The selection of the positions, which correspond with the positions of the LV in the end positions of the diastole and systole and also an additional position in between, ensures that the entire radial movement of the simulated LV can be reproduced on one beam.

The basic dimensions of the basic mechanism elements of the crank mechanism were determined using the zero-order transfer function of the radial motion as well as the approximation method by Flocke [21]. The transfer function of the single cam elements were predefined through the measurement results of the previous echocardiographic examination at discrete positions. One cardiac cycle, beginning with the systole, is passed through within 893.63 ms and corresponds with one revolution of the cam. The radial distance covered by the point, which matches the output motion of the roller tappet, amounts to an average of 4-6 mm. The discrete measurement results need to be interpolated in a way that the measuring points are reproduced exactly and high-quality operating characteristics of the cam mechanism are aspired. These high-quality operating characteristics feature a minimization of harmful oscillatory phenomena, a reduced noise emission and a decrease of wear. Furthermore, shocks and jolts are avoided. Since the cyclical excitation of the human cardiac muscle is equivalent to a sinus rhythm, the periodic measurement data can be interpolated most conveniently through an approximation with trigonometric functions.

The basic dimension of the respective cam discs were eventually selected in a way that all discs can be fixed to a circle, which does not fall below the minimum transmission angle and at the same time ensures the same length for all roller tappets.

4 Evaluation

The mechanism based on the pursued mechanism design must not only enable the radial back-and-forth motion of the simulated left ventricle, but also transfer the force, that is necessary to drive out the fluid.

After the structural and dimensional synthesis, a last comparative evaluation of the mechanism designs is performed to decide which concept is suited for the realization of the radial movements and therefore should be pursued.

The crank mechanism, which is easy to manufacture, can enable the radial movement through three given positions. However, neither their transmission can be changed nor a correct time response for the temporal contractions of the single muscle cells of the simulated left ventricle can be realized through a required drive. Furthermore, it is not possible to generate the necessary even pressure force with the aid of their output link. Even though the necessary force can be generated at the drive, there is loss of energy due to the arrangement of the elements and the resulting division of the acting forces into their radial and tangential components towards the MockHeart. The loss of energy can be amplified by prismatic joints liable to wear and potential tolerances in the bearing of both mechanisms. That is why the energy provided at the drive component cannot generate the same force in radial direction at the eight interfaces to realize the necessary pressure force. In contrast, the designed cam mechanism can realize the zero-order transfer function at the 24 predefined discrete positions exactly. Besides the radial contractions required for the fluid circulation during the ejection and the filling phase, a further contraction, necessary for self-sufficiency of the heart, is realized. However, this contraction is not relevant to the provided pressure-volume-work within the cardiovascular simulator. Through the selection of trigonometric transfer functions jolts and shocks of the cam mechanism are avoided and the operability is enabled. Besides the radial contractions, the synchronously controlled cam mechanism also generates the even pressure force, necessary for the pressure-volume-work of the MockHeart, provided that a contraction of the simulated left atrium facilitates the opening of the atrioventricular valve as well as the following filling of the ventricle. In order to realize the pressure-volume-work as well as the radial movement of a potential pathological heart, cam discs can easily be dismantled or exchanged to suit the problem. Since the cam mechanism has crucial advantages compared to the crank mechanism, the following cardiovascular simulator CVELoop is controlled using a cam mechanism.

5 Design

The scaled rough design of the cam mechanism is mainly geared to the kinematic main dimensions attained during the dimensional synthesis.

The simple structure is composed of a basic frame, a round base plate and eight basic cam mechanisms mounted to the frame in their original form including a roller tappet. By selecting an evenly transmitted drive concept, the eight basic cam mechanisms can be controlled synchronously using only one drive application. The function of synchronous controls can be realized by using belt drives or even gear pairs. Thus, an identical force is induced into every one of the eight cam mechanisms, which simultaneously provides a basis for an even radial movement of the MockHeart. For the purposes of this project this drive concept has been chosen due to the space saving installation. The rough design of the cam mechanism is displayed in **Fig. 6**.

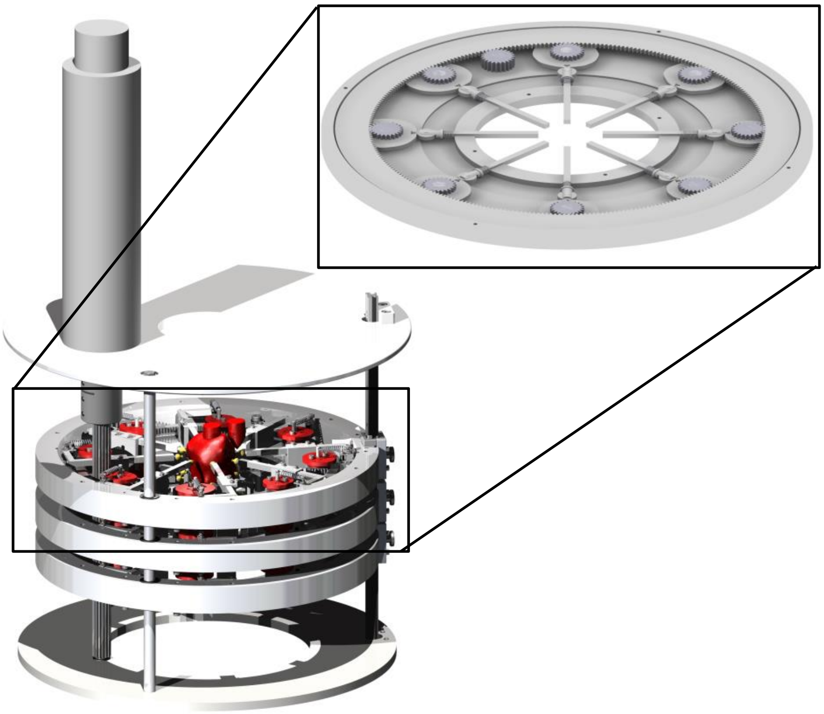

Fig. 6 Prototype with the three levels and a single level with eight cam mechanisms

6 Conclusions

As part of the further development of the cardiovascular simulator CVELoop at the Department of cardiovascular engineering of RWTH Aachen University a contractive MockHeart, which simulates the healthy heart of a human in the cardiovascular system, has been developed. In contrast to the numerous already developed simulators, the main component of the simulator is controlled by a mechanism. Starting from a healthy heart it is the long-term goal to simulate pathophysiological conditions and to develop and dimension VADs for these conditions.

The mechanism must not only enable the radial back-and-forth movement of the simulated left ventricle, but also transmit the force that is necessary for the ejection of the fluid.

The crank mechanisms, which are easy to manufacture, offer a realization of the radial movement through three predefined positions, however neither the transmission can be changed nor a correct time response through a required drive can be enabled. In addition to that, they cannot generate the necessary even pressure force, required for the fluid circulation, with their output components. On the other hand, the designed cam mechanisms can realize the zero-order transfer function at the 24 predefined discrete positions exactly. Besides the radial contractions, the synchronously controlled cam mechanism generates the even pressure force necessary for the pressure-volume-work of the MockHeart.

7 Outlook

A concept for the points of intersection between the output components of the cam mechanism and the MockHeart has to be acquired over the further course of the development. In doing so, it is important to consider that the silicone bags of the MockHeart deform evenly and without any „dents“.

In order to realize the radial movements in multiple transverse intersecting planes as well as the pressure-volume-work and the radial movements of a possible pathological heart, the determination of further radial strains through the Speckle-Tracking-echocardiography-method is necessary.

Furthermore, the installation of multiple mechanisms in the horizontal planes on top of each other needs to be facilitated. For example, these can be connected to each other through a shaft going through the cam disc pivot points, because hereby the mechanisms can be controlled dependently on each other using only one drive.

For a simulated holistic movement of the left ventricle an axial movement and a torsion need to be enabled aside from the radial movement. However, the cam mechanism cannot enable any torsion. In contrast, an axial movement is possible using Oldham or Schmidt clutches to connect the jointly driven shafts of the cam mechanisms, which are arranged on top of each other.

Moreover, it is important to take into account that the cam mechanisms connected to one another only enable the movement and fluid-mechanical properties of the left ventricle. In further work steps towards realization of the natively generated pressure-volume-work of the left heart, additional concepts for the realization of the contraction of the atrium as well as the fluid-mechanical properties of the left heart and the underlying simulated blood vessels need to be developed.

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