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Invention of Device for Measuring Cardiac Compression Rates and the Depth for the Cardio-Pulmonary Resuscitation Manikin

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Abstract: Manikins that simulate cardiopulmonary resuscitation (CPR) are used to teach personnel how to execute it. Modern cardiac resuscitation manikins are still low-fidelity designs in terms of anatomy and physiology. Designing a manikin with a cardiac and respiratory system, as well as integrated flow sensors to track cardiac output and air displacement in response to cardiopulmonary resuscitation, was the main goal of this research. A polyoxy-methylene rib cage joined to a vertebral column from an anatomical female model was used to create this manikin in line with anatomical proportions. The respiratory system was made up of a polyvinyl chloride bronchus, a latex trachea, and silicon-coated memory foam that mimicked lungs. The pulmonary and aortic arteries were represented by two sets of latex tubing, while the ventricles and aggregated abdominal volumes were represented by latex balloons, respectively. These components made up the cardiovascular system. These balloons were inserted into polyether foam and filled with blood from a life/form simulation. Flow sensors were installed in the respiratory and cardiovascular systems to collect data in reaction to chest compressions. On this manikin, three non-medical individuals applied chest compressions that produced data proportional to force-displacement while the flow sensors supplied feedback. The force-displacement experiments performed on this manikin demonstrate an advantageous nonlinear behavior that mimics the chest compressions used during cardiopulmonary resuscitation in humans. A considerable amount of information on the internal effects of cardiopulmonary resuscitation is also provided by the flow sensors. To sum up, scientifically developed and anatomically accurate designs of cardiopulmonary resuscitation manikins that incorporate flow sensors can enhance physiological fidelity and offer helpful feedback data.

Keywords: Cardio-Pulmonary Resuscitation, Chest Compression, Medical Simulation, Medical Training, Feedback System, Manikin, CPR, Innovation, Patent

1. Introduction

Cardio-Pulmonary Resuscitation (CPR) is an emergency technique used on individuals who are experiencing cardiac and respiratory arrest. Through the application of chest compressions and artificial ventilation, this therapy externally activates the cardiovascular and respiratory systems. These steps are intended to get oxygen to the body's critical organs until breathing and spontaneous circulation can be recovered.

Several organizations, including the American Health Association (AHA) [1], offer CPR guidelines. According to these recommendations, adults should perform thoracic compressions at a rate of at least 100 compressions per minute with a depth of 5 cm or more at the sternum's center. According to these recommendations, every 30 chest compressions should be followed by two rescue breaths (with a visible chest raise). Manikins are used as surrogate patients to instruct staff members how to conduct CPR.

In order to increase training realism and clinical performance of CPR administration, manikins should ideally be created based on knowledge of the physiological and mechanical impacts of doing CPR. The theoretical underpinnings of simulation in healthcare [2],[3], physiological modeling of the cardiovascular and respiratory systems [4],[6], force-displacement testing of the human thorax, improving tactile experience of CPR manikins [7], [9], effectiveness of using simulation in clinical practice, and incorporating clinical recommendations [11], [13] for manikin design are among the current fields of research in this area [14].

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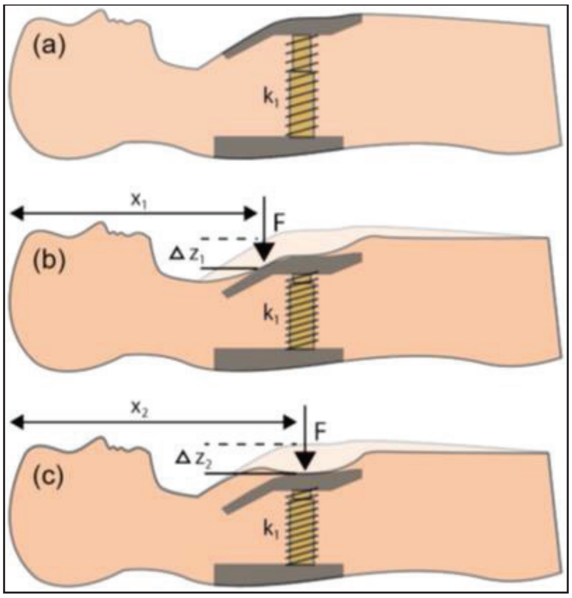

Figure 1 - (a) An example of a manikin for doing traditional, uncompressed CPR, (b) Left of center, there is a constriction of the chest, and (c) central thoracic compression of the chest. In both examples of compression, $\Delta z_1 = \Delta z_2$ which is unrealistic when compared to the human body.

Despite the aforementioned suggestions and a clinical need for physiologically and anatomically high-fidelity manikin designs, even the most technologically advanced manikins, like the SimMan 3G (Laerdal, Stavanger, Norway) and Apollo (CAE healthcare, Sarasota, FL, USA), do not completely meet these specifications. This is partially because these manikins, like other traditional designs, only had one spring-damper combination, as seen in the illustration in Figure 1(a), where the spring is represented by the diagonal stripes and the damper by the yellow cylinder. The behaviour of the spring with spring constant k_1 is that a vertical force F leads to a vertical displacement $\Delta z_1 = F/k_1$ (Figure 1(b)). The manikin sternum is stiff and does not tilt, which is a behavior that is unrealistic when compared to the human body, so this displacement is independent of the axial location (Figure 1(c)) of the applied force. Furthermore, while the majority of traditional manikins give depth detection and the rate of chest compression, hence revealing compliance with CPR recommendations, they do not offer feedback on the physiological and mechanical implications of conducting CPR, such as oxygen saturation and cardiac output.

For the purpose of providing feedback information for evaluating CPR performance, there is a critical clinical need for CPR manikins that replicate human physiology and monitor cardiac output, artificial breathing, and oxygen saturation [15], [16]. Manikins must have real cardiovascular and respiratory systems so that the required sensors can be placed inside. In order to improve tactile realism, manikins also require an anatomically accurate skeletal system. Since physicians will be able to adjust their CPR procedures to meet physiological needs, a design that includes these features will be more valuable than the existing designs.

This article describes how to create a manikin with an anatomically accurate thorax, a circulatory system, and a respiratory system with built-in flow sensors to track their output. Additionally, we contrast our design's force-displacement performance with that of people and traditional manikin designs. The cardiac output determined by the integrated sensors is then compared to physiological and clinical investigations.

2. Resources and Techniques

2.1 Modelling the Thorax

We demonstrate a theoretical advancement over a single spring-damper manikin design in Figure 2(a). Three spring-damper setup is given for demonstration purposes. An infinite of

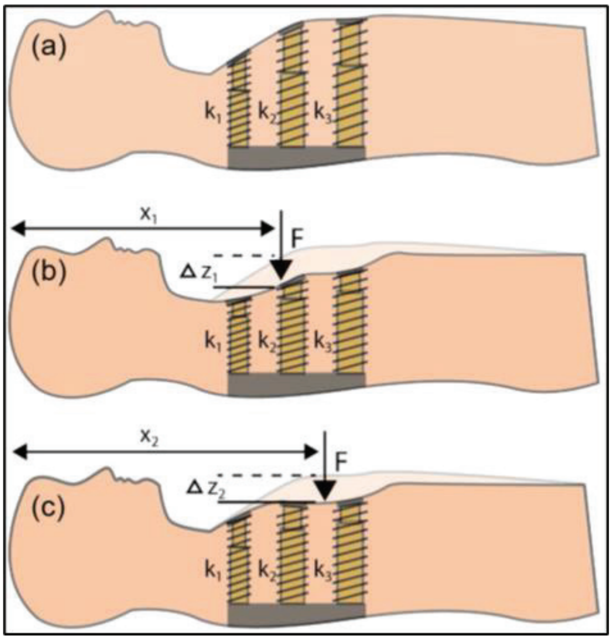

Figure 2 - (a) A theoretical improvement over a single spring - damper configuration. (b and c) The same force at different locations will lead to different displacements, $\Delta z_1 \neq \Delta z_2$.

these spring-dampers would closely resemble the human thorax. The placement of the force determines how the thorax responds like a spring in such a configuration. Various displacements will result from the same force being applied in different places (Figures 2(b) and (c)), $\Delta z_1 \neq \Delta z_2$.

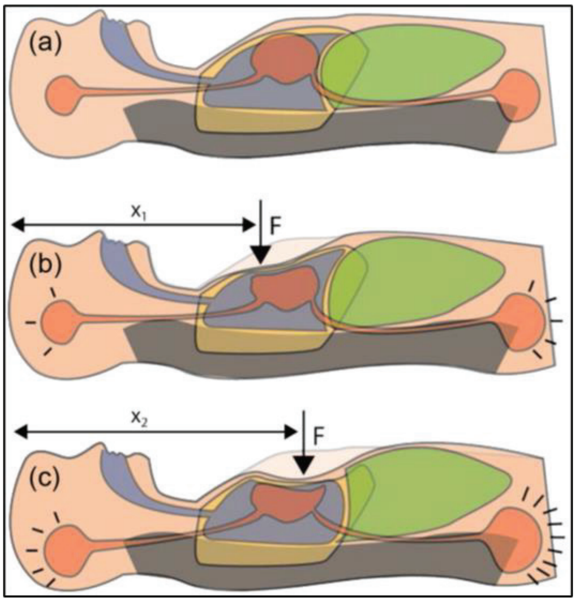

Figure 3 - (a) Illustration of the Human Body. (b and c) Cardiac Output is Position-Dependent (e.g., x_1 or x_2).

We show the human body in anatomical detail in Figure 3(a), which includes a flexible sternum/rib cage, along with the respiratory and cardiovascular systems. The spinal column in *grey*, with the rib cage (*yellow*) linked to it, is shown. The rib cage houses the cardiovascular (*red*) and respiratory (*blue*) systems. The cardiovascular system's blood arteries are divided into cranial and abdominal blood volumes (shown as two *red* circles at the far ends of the body). The abdomen is seen in the *green* area. Chest compressions have internal repercussions, which are seen in Figures 3(b) and (c). The effects of compression modulate cardiac output and are position-dependent (clearly apparent) [17].

The models from Figures 2 and 3 were combined to create the manikin created for this study (Figure 4). Here, a configuration of numerous spring-damper systems is mimicked by the rib cage, respiratory, and cardiovascular systems. The design of this manikin is covered in the following section.

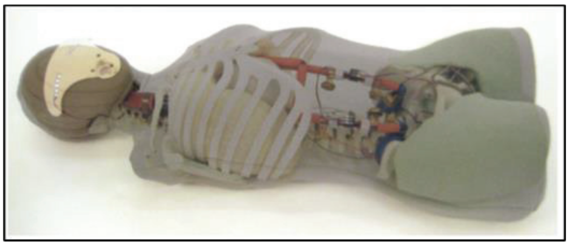

Figure 4 - A Transparent Representation of a Novel Manikin Design with a Human-Like Internal Structure.

2.2 The New Manikin's Design and Sensor Integration

A vertebral column (78 cm in height from the pelvis to the C1 vertebra) from an anatomical female model (vertebral column for the demonstration of malpositions; Erler-Zimmer, Lauf, Germany) served as the basis for the creation of the manikin. Using the Illustrator program, the rib cage of this model was taken out and copied at a 1:1 scale (Adobe, San Jose, CA, USA). This design was carved from a sheet of polyoxymethylene (POM) material using a Speedy 300 laser engraver (Trotec, Canton, MI, USA) (dimensions: 700 mm X 400 mm X 4 mm). Heat was used to bend the rib cage into the proper anatomical position (Figure 5(a)), and the original reference model was taken out of the spinal column. The T1-T10 vertebrae of the skeletal model's spine were then socketed into place and fastened with bolts (Figure 5(b)). The anticipation of powerful compressions [18] served as the driving reason for the selection of POM, which was chosen for its high rigidity attribute. Additionally, POM exhibits excellent resilience to repeated loads [19] and high abrasion resistance, which are essential material properties for a model exposed to prolonged compressions.

This rib cage served as the structure for the respiratory system, which included the lungs, bronchi, and trachea. Polyurethane (PU) memory foam (density, ρ= 45 kg/m^3) was used to construct the lungs. This substance was picked to resemble the porous nature of lung tissue [20],[22]. A coating of Ecoflex 00-30 silicon (Smooth-On, Macungie, PA, USA) was applied to two foam blocks that had been cut into the anatomical shape of lungs (Figure 6) to produce closed chambers. These chambers were connected to PVC (polyvinyl chloride) bronchi, which in turn were connected to a latex tube trachea (inner diameter, 2 cm). The manikin's oral cavity was where this trachea came to a stop.

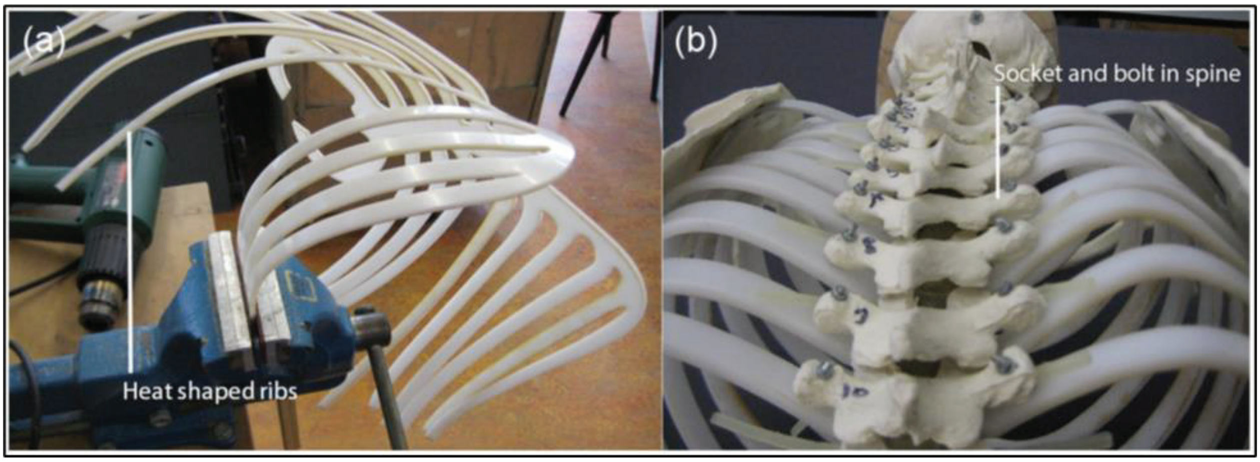

Figure 5 - (a) A 4-mm-thick POM Piece is bent into the Shape of an Anatomically Perfect Rib Cage. (b) The Rib Cage was Bolted to the Spine and Socketed into Place

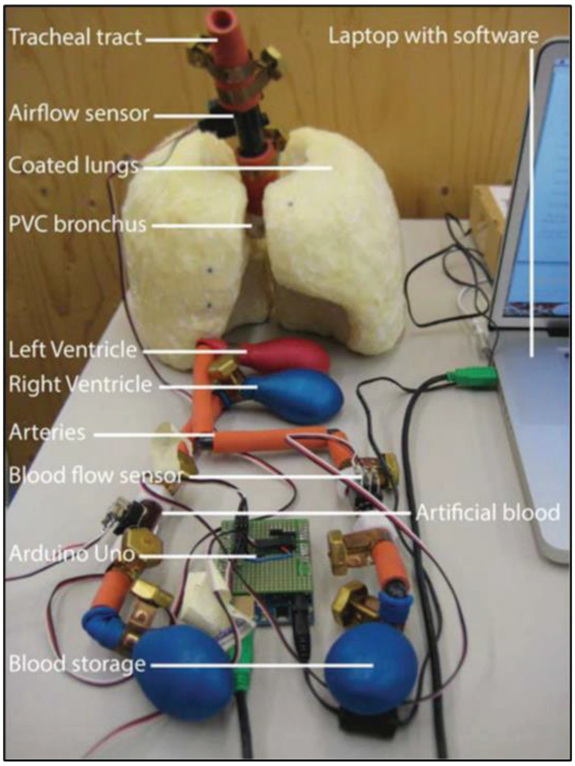

Figure 6 - The manikin's assortment of artificial organs and body components. Trachea, airflow sensor, lungs, bronchi, left and right ventricles, pulmonary and aortic arteries, liquid flow turbine sensors, Arduino Uno microcontroller connected to laptop, and aggregated abdominal blood volumes are shown in order from top to bottom.

This rib cage also contained a cardiovascular system in addition to the breathing system. The pulmonary and aortic arteries were represented by two sets of latex tubing with inner diameters of 1 cm in the system. The ends of these tubes were joined to four latex balloons, two of which simulated ventricles and two of which simulated aggregated abdominal blood contents (Figure 6). A total of 75 mL of Life/form simulation blood was used to fill each balloon (Nasco, Fort Atkinson, WI, USA). This volume is consistent with the typical blood volume seen in the female human body's ventricles [23].

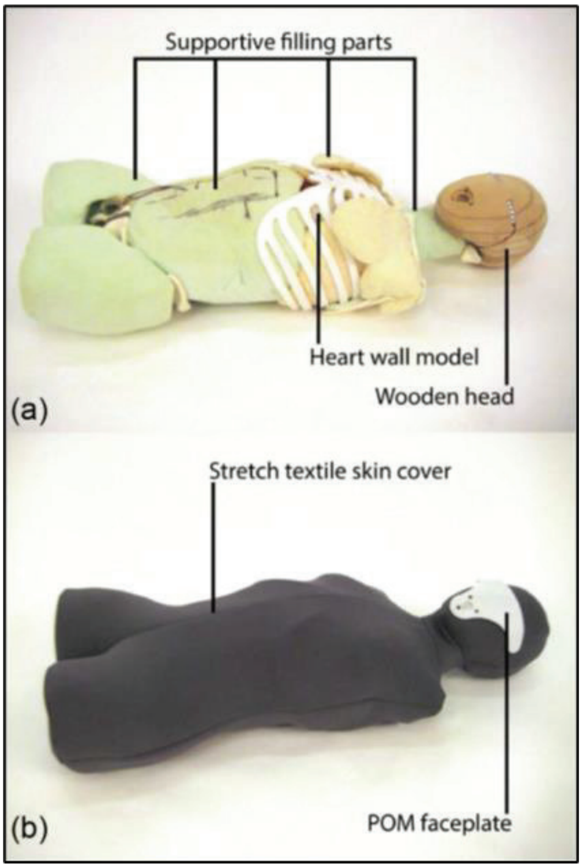

Figure 7 - (a) The Manikin with Padded Muscles on the Head, Abdomen, and Body. (b) The Faceplate and Outer Skin Cover.

A two-pocket, single polyether (PE) foam model of the heart walls (density, ρ= 25 kg/m^3) was used to place both ventricles (Figure 7(a)). The coronal cardiac axis of 45° slightly left of the sternum was used to position the heart model inside the thorax, between the fourth and seventh ribs.

The respiratory and cardiovascular systems were equipped with flow sensors to gather data in response to chest compressions. An AMW720P1 airflow sensor (Honeywell, Morris Plains, NJ, USA) was embedded into the trachea. Two Vision 2000 flow sensors (B.I.O - TECH, Vilshofen, Germany) were embedded in the aortic and pulmonary arteries (Figure 6). An Arduino Uno microprocessor platform was used (ARDUINO LLC, Somerville, MA, USA) for collecting and processing the data from sensors. These data were displayed on a laptop (Figure 6) in real-time using Processing software (Creative Commons, Mountain View, CA, USA).

The manikin was finished by adding a wooden head and muscle structures made of foam for the thighs, shoulders, abdominal wall and neck respectively. While the other body components were developed to enhance the manikin's appearance, the abdominal muscles were developed to protect the thoracic organs (Figure 7(a)). In order to hold everything on the manikin in place, a stretch-textile cover (skin) and POM faceplate were developed (Figure 7(b)).

2.3 Configuration for a Test

Force-displacement tests were carried out on the CPR manikin utilizing the Q-CPR measurement and feedback tool to assess the mechanical behavior of the thorax (Philips, Eindhoven, The Netherlands). Three non-medical professionals compressed the manikin's chest repeatedly for 30 seconds. These compressions were carried out in accordance with the AHA's recommendations for compression depth and speed. Utilizing MATLAB, the depth of the thoracic displacement (in cm) and the force of compressions (in Newton) were measured with regard to time (MathWorks, Natick, MA, USA). The integrated sensors were used to record cardiac output and breathing volume during one of the force-displacement tests. These sensors measured ventricular blood flow and air displacement. The Arduino microcontroller was used to collect these sensor data, and processing was used to show it.

2.4 Data on Force-Displacement and Previous Study Comparison

The force-displacement test results that we achieved in our test setup were compared to those of Gruben and colleagues' thoracic displacement studies on normal humans and typical classical CPR manikins. Gruben et al. (1990), fit the following polynomial equation to the data in their study:

$$F = F_e + F_d \quad \ldots(1)$$

$$F_e = k(\mathrm{z}).\mathrm{z} \quad \ldots(2)$$

$$k(\mathrm{z}) = k_1 + k_2.\mathrm{z} + k_3.\mathrm{z}^2 + k_4.\mathrm{z}^3 \quad \ldots(3)$$

$$F_d = \mu(\mathrm{z}).\dot{\mathrm{z}} \quad \ldots(4)$$

$$\mu(\mathrm{z}) = d_0 + d_1.\mathrm{z} \quad \ldots(5)$$

where the elastic component of the compression force, F_e, and the damping component, F_d, are both present in equation (1). Since the stiffness coefficient, k(z), depends on displacement (equations (2) and (3)), the elastic component (F_e) is nonlinear. Equations (4) and (5) describe how the displacement-dependent damping coefficient μ(z) affects the damping component (F_d).

Equation (6) illustrates how Gruben et al. (1990) computed k(z) and μ(z) by fitting them to polynomials with four and two coefficients, respectively.

$$F = k_1 \cdot \mathrm{z} + k_2 \cdot \mathrm{z}^2 + k_3 \cdot \mathrm{z}^3 + k_4 \cdot \mathrm{z}^4 + d_0\dot{\mathrm{z}} + d_1 \cdot \mathrm{z} \cdot \dot{\mathrm{z}} \quad \ldots(6)$$

The linear least squares method was used to fit the findings of the compression force and the associated vertical displacement (depth) from our experiments to the aforementioned equation.

2.5 Comparing Flow Sensor Data to Study already done

In reaction to chest compressions, flow sensors were used to detect the average cardiac output and air displacement (L/min). These data are contrasted with the physiological model created by Koeken et al. (2011) [6] to study the cardiac output during CPR. We proportionally scaled the obtained cardiac output because the ventricular volumes of the manikin created for this study (150 mL) and those of Koeken et al. (2011), (262 mL) differ. The outcomes of the cardiac output study are also contrasted with those of Fodden et al. (1996) [24], who calculated the cardiac output during CPR in people by utilizing Doppler ultrasound.

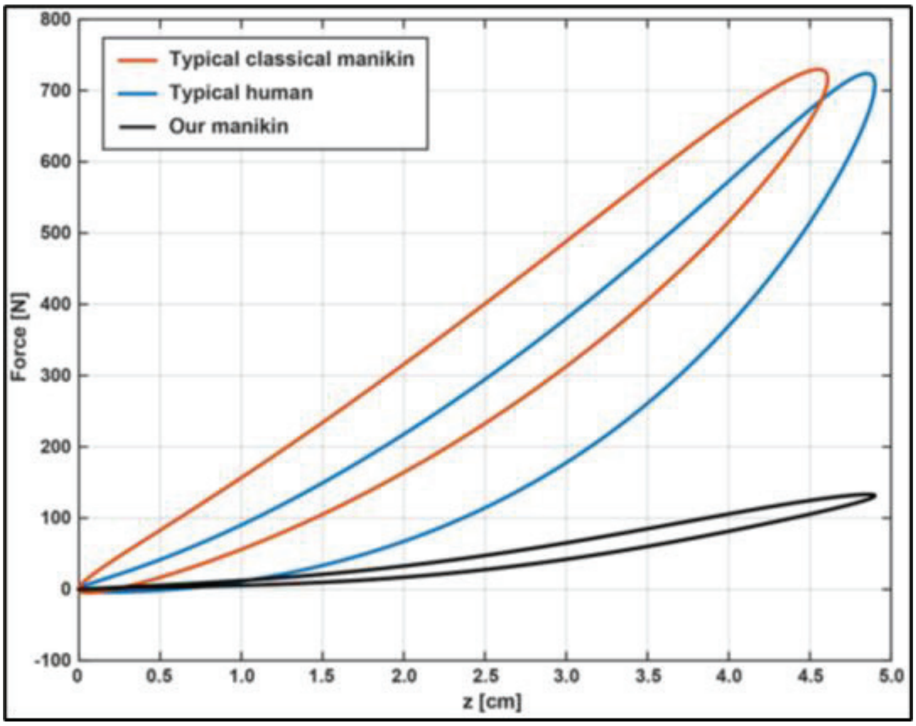

Figure 8 - The force-displacement graphs for a standard classical manikin (red), a standard human (blue), and the manikin created for this study (black). My manikin exhibits a nice nonlinear behavior that resembles that of humans when the compression depth approaches 5 cm (as specified by the AHA standards).

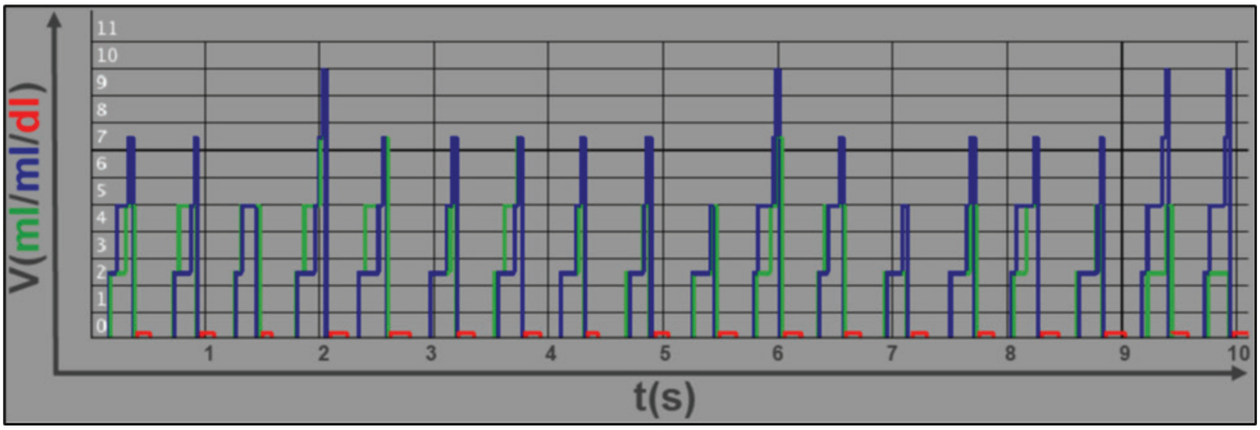

Figure 9 - The air displacement volume (red) and cardiac output of the left and right ventricles, measured during 18 successive chest compressions at 120 compressions per minute (CPM), in accordance with AHA recommendations.

3. Results

3.1 Comparing Force-Displacement Findings

Figure 8 depicts the force-displacement graphs for the standard classical manikins (red), standard humans (blue), and the manikin created for this study (black). Both the elastic (compression) and damping components make up each curve (release). The energy transferred into the manikin/body during chest compressions is represented by the areas under the curve (the work (*W*)). As the compression depth approaches 5 cm (as needed by the AHA standards), our manikin exhibits a desired nonlinear behavior that resembles human behavior (blue). The force needed to achieve comparable compression depths is significantly less, though.

3.2 Comparing Sensor Data Readings Collected

Figure 9 depicts the left and right ventricles' cardiac outputs as well as the air displacement volume during 18 successive chest compressions carried out at 120 CPM in accordance with AHA recommendations.

1.65 L/min was determined to be the overall cardiac output, with the left ventricle producing 0.92 L/min and the right ventricle producing 0.73 L/min. It was discovered a 43% larger cardiac output in our manikin compared to the Koeken et al. (2011) [6] model. The cardiac output increased by 150% to 2.88 L/min after adjusting the output based on ventricular size. My manikin's 1.65 L/min cardiac output is 48% less than what Fodden et al. (1996) [24] predicted for real individuals. Additionally, during chest compressions, my manikin's tracheal air displacement during testing was 2.7 L/min.

4. Discussion

This article describes the construction of a unique CPR manikin with human-like anatomical features. The embodiment of essential organs with integrated flow sensors to assess cardiac output and air displacement is possible because to this human-like structure. The unique aspect of this design is how anatomically accurate it is, as demonstrated by Sawyer et al. (2016) [13] in training simulators for intubation. This is done in the hope that increasing physical accuracy will increase functional fidelity. Internal monitoring during CPR is made possible by the incorporation of flow sensors into the organs, which is highly clinically necessary [14]. With regard to adequate ventilation and blood flow, this biofeedback is anticipated to improve comprehension of the inside repercussions of doing CPR.

The force - displacement experiments used to investigate the mechanical behavior of the thorax reveal that the manikin created for our research exhibits a desirable nonlinear behavior similar to that of humans when the compression depth approaches 5 cm (as needed by the AHA standards). Since the polynomial estimate of the force-displacement connection (equation (6)) has three non-zero higher order components (k_2, k_3, and k_4) as opposed to the normal manikin's single higher order component, our manikin exhibits a stronger nonlinear relationship (k_2) [9].

In contrast, humans require a lot more force to accomplish identical compression depths [9]. This suggests that our manikin has a low degree of stiffness. The rib cage's stiffness can be increased by employing a different material (such ribs coated in fiberglass), adding more thickness, and/or using lungs made of more dense foam. Our manufacturing limitations (Speedy 300 laser engraver), along with the lack of greater density foams that mirror the density of lung tissue [25], prevented us from creating rib cages that were thicker. By connecting the lungs to the rib cage, simulating the pleural cavity, restricting flow, and improving the damping coefficient of the thorax, it is possible to increase the energy transmitted into the manikin (the work (W)). Along with increasing stiffness, this will more closely resemble the force-displacement behavior of the human thorax.

Since the CPR trainee can immediately see the results of their activities, the flow sensors measuring cardiac output and air displacement during CPR provide useful data. The cardiac output measurements produced here are 150 % more than predicted by physiological modeling but 48% lower than that recorded by Fodden et al [24]. Given that Fodden et al. (1996) samples was 70% male and may have had bigger ventricular sizes than our model subject, who was a female, it is likely that our results are different from theirs. Additionally, as shown by the force-displacement curves in Figure 8, less energy was transferred into the manikin's thorax during chest compressions. This manikin's cardiac output can be enhanced by substituting larger latex balloons for the ventricles and larger latex tubing for the pulmonary and aortic arteries. Before models can mimic physiologically accurate cardiac outputs, however, definitive clinical data on the human cardiac output during CPR are required.

Additionally, this design has several drawbacks. It can be enhanced, for instance, by using materials that more closely replicate the mechanical characteristics of human tissues. The difficulty in this situation is that the materials must not only have the required material qualities, but also be able to withstand the rigors of manufacturing processes including laser cutting, heat shaping, and injection moulding. The lack of valves and the separation of the pulmonary and systemic circulations further pose limitations to the design. Despite these drawbacks, this design advances anatomical and physiological integrity while also taking significant steps toward more realistic manikin design.

5. Conclusion

This paper describes a revolutionary manikin design with greater anatomical and physiological realism that integrates the heart and respiratory systems. This manikin exhibits a favorable nonlinear behavior in its force-displacement curve in response to CPR, which is also observed in humans. Internal flow sensors that keep track of cardiac output and air displacement can offer helpful input.

Acknowledgments

This study was carried out as part of obtaining a patent (Patent No. 19680) for a device that measures the depth and cardiac compression rate for a cardio-pulmonary resuscitation manikin which currently functions at the National Hospital of Colombo, Sri Lanka.

Declaration of Conflicting Interests
Regarding the research, writing, and/or publication of this work, the author discloses that there are no potential conflicts of interest.

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