Modeling Mechanical Properties of the Chest During the Cardiopulmonary Resuscitation Procedure

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Abstract

The first step in improving the cardiopulmonary resuscitation (CPR) procedure is to understand how the force applied on the chest relates to the resulting blood pressure. In order to capture the mechanical properties of the chest and abdomen accurately, in this paper we proposed a nonlinear mass spring and damper model which consists of nonlinear spring up to 5th order, a combination of viscous and hysteresis damper. We then nondimensionalized the proposed model in order to enhance parametric study of the model for future use. In the next step we used gradient decent optimization method to identify the model parameters for force-compression data of 10273 CPR cycles collected from different pigs at the Children's Hospital of Philadelphia (CHOP). We used the mean square error (RMSE) between the estimated force and actual force for each cycle as an objective function to be minimized. Using the above method we were able to estimate the model parameters for each cycle seperately. In order to find a best set of estimated parameters we used K-nearest neighbor (K-NN) method. K-NN is an unsupervised learning technique which clusters the data into different groups based on the distance metric. The cluster center with lowest RMSE is selected as the estimated parameters for the entire cycles. The resulted MSE of testing entire cycles with the estimated parameters are 0.12 mean and 0.04 SD. Results show that the proposed model is the most accurate model of pig chest during the CPR.

1. Introduction

The main focus of this paper is to seek to characterize the mechanical properties of the chest during the cardiopulmonary resuscitation (CPR) in order to increase CPR performance and consequently the survival rate in patients suffering form cardiac arrest.

Sudden cardiac death remain the main cause of out-of-hospital death in united states, according to [1] cardiovascular disease was responsible for 30.6% of total death in US from 1998 to 2008. The CPR is a procedure which is performed in an emergency condition on patients who are suffering from different types of cardiac arrest. The main goals of CPR procedure are to maintain blood flow and oxygen delivery to the brain and other vital organs in the case of asphyxial cardiac arrest, and to effectively remove carbon dioxide in the presence of ventricular fibrilation (VF). Since 1966 the American Heart Association (AHA) has been providing and developing guidelines for step by step procedures of the cardiopulmonary resuscitation (CPR) to increase the quality of CPR. The developed guidelines have been saving many lives; however, in spite of a relative success, survival rates for in-hospital patients remains very low, generally $5-10\%$ [2]. Using a model developed by Babbs [3] we have shown the the brain oxygen delivery [4] and end tidal carbon dioxide $ETCO_2$ [5] can be maximized by varying different CPR parameters such as number of compressions per minute or compression depth.

The CPR procedure involves two main steps: chest compressions and artificial respiration. Chest compressions help to pump blood from the heart to restore blood circulation in the body and mouth-to-mouth ventilation provides manual respiration. During the chest compression phase rescuer pushes the chest to create the desired blood pressure and circulation in the body. The exact mechanism which is responsible for blood flow is still not understood and needs to be addressed.

Modeling the response of the chest to the applied force during chest compression phase of the CPR is the first step in understanding the complicated nature of the CPR procedure which consequently will result in improving the performance of the CPR procedure. Accurate analysis of force-chest compression depth relationship will certainly provide a major step in modifying the CPR procedure for both in and out hospital patients by advancing both understanding of the CPR procedure and improving training procedure for rescuers.

Despite the fact that previously proposed models establish a strong foundation to study the thoracic behavior during the CPR, these models fail to fully capture the dynamic behavior of the chest such as hardening properties, nonlinear damping or hysteresis phenomenon. Moreover, since there is fundamental difference between anatomy of dog chest and human chest, the canine studies are not prefect to study thoracic behavior.

In this paper we are interested in characterizing the mechanical properties of the chest during the CPR procedure and how these characteristics are changing over time using porcine data collected at the Children's Hospital of Philadelphia (CHOP). A modified model of human chest proposed in [6] has been used to study thoracic behavior in porcines during the CPR procedure. We believe that the results of this study can be used to improve the quality of the CPR and potentially save many lives.

The data for the current study were collected at the Children's Hospital of Philadelphia (CHOP). The predefined experimental protocol was approved by The University of Pennsylvania Institutional Animal Care and Use Committee. 15 healthy 3-month-old female domestic swine $(32.4 \pm 2.0kg)$ were anesthetized and mechanically ventilated using a Datex Ohmeda anesthesia machine (Modulus SE) on a mixture of room air and titrated isoflurane $(\sim 1.0 - 2.5\%)$ [7].

To ensure the consistency of the results and removing artifacts, two criteria have been applied for the inclusion of cycles. These two criteria are compression depth minimum and compression frequency minimum. The cycle with compression depth of less than 30 *mm* and more than 55 *mm* has been removed from the analysis. Moreover, the cycles that are shorter than 0.4 *s* (150 cycles/min) or longer than 1 *s* (60 cycles/min) have been excluded from the analysis. A total of 10273 cycles from 15 pigs have met two criteria and been included in the analysis.

2. Mathematical Modeling

Mechanical behavior of sternum during chest compression-release state of CPR can be described using lumped parameter viscoelastic model [8, 9]. A basic viscoelastic model consisting a linear spring and a viscose damper has been proposed by [9].

To develop our proposed model, we have first started by looking at the collected data. By plotting real collected data of force against displacement for consecutive compression-release cycles during the CPR which presented in Figure 1, we can observe the hysteresis loop which causes energy dissipation. Hysteresis or material damping is caused by internal frictions and is frequency dependent [10]. We believe that hysteresis is an important feature for characterizing the mechanical properties of the chest and is not captured in the previously developed models.

In this paper, a new nonlinear viscoelastic model with

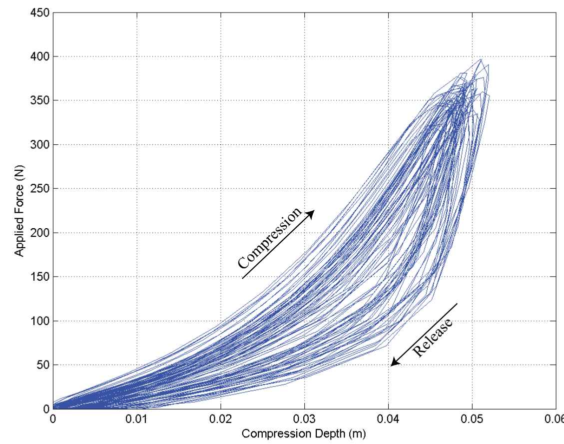

Figure 1. Plot of force vs compression depth for different cycles. The hysteresis loop can be observed as a gap between compression and release phases.

hysteresis damping component has been developed to capture the complex behavior of thorax during chest compression and provide a better understanding of the chest during CPR procedure, the developed model can be described by Equation (1)

$$\begin{aligned} F &= F_s + F_d + F_h + F_i \\ F_s &= k_1 X + k_2 X^2 + k_3 X^3 + k_4 X^4 + K_5 X^5 \\ F_d &= c_1 \dot{X} + c_2 \dot{X}^2 \\ F_h &= c_h \frac{\dot{X} sgn(\dot{X})}{\omega} \\ F_i &= M\ddot{X} \end{aligned} \quad (1)$$

where, X is compression depth, F_s is spring or elastic force, F_d is damping force, F_h is hysteresis force, F_i is inertial force and ω is the compression rate. The term $\dot{X}sgn\dot{X}$ ensures that the hysteresis force remains positive during the CPR. The main differences between the current model and the previously developed model are: (i) addition of hysteresis force component F_h which is frequency dependent (ii) addition of nonlinear viscous damping term $\dot{X}^2$. Moreover, in this study we have used porcines model of cardiac arrest instead of canine model. Since the anatomy of porcine chest is closer to human chest anatomy, it will provide a better analogy to human sternum during the CPR.

In order to make a better analysis of the proposed model and decrease uncertainties associated with estimating the model parameters we have nondimensionalized the proposed model. The nondimensionalization will make parametric study of the nonlinear model for future use easier [11].

We proceed by defining a set of nondimensionalized variables x, τ, m as presented in Equation (2):

$$x = \frac{X}{X_0} \quad \tau = \frac{t}{T} \quad m = \frac{M}{M_0} \tag{2}$$

where, lower case letters indicate nondimensionalized variables and X_0, T and M_0 are characteristic length, time and mass scales to be chosen later. The X_0, T, and M_0 are user defined parameters and can be adjusted to change the order of magnitudes of the original parameters. The selected values are 0.05, 0.06 and 3 respectively.

We also need to define dimensionless frequency as:

$$\Omega = \frac{\omega}{\omega_n} \tag{3}$$

where, $\omega_n = \frac{2\pi}{T}$.

By doing some algebra we can convert our proposed model which represented in Equation (1) to the dimensionless from shown in by Equation (4).

$$\begin{aligned} f &= f_s + f_d + f_h + f_i \\ f_s &= \alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3 + \alpha_4 x^4 + \alpha_5 x^5 \\ f_d &= \beta_1 x' + \beta_1 x'^2 \\ f_h &= \beta_h \frac{x' sgn(x')}{\Omega} \\ f_i &= x''. \end{aligned} \tag{4}$$

where, α_i, β_i and β_h are nondimensionalized coefficients.

2.1. Parameter Estimation

To estimate the set of model parameters we have used a gradient decent optimization method. We have defined the root mean squared error (RMSE) between estimated force and measurement force as the objective function.

After finding the set of parameters which minimizes RMSE for each compression-release cycle and since these parameters are different for different cycles, we need to find the best set of parameters which describe the chest mechanical properties for all pigs and all cycles not for each cycle separately.

In order to find a best set of estimated parameters we used K-nearest neighbor (K-NN) method. K-NN is an unsupervised learning technique which clusters the data into different groups based on the distance metric. The cluster center with lowest RMSE is selected as the estimated parameters for the entire cycles.

To apply the clustering method we first paired each set of estimated parameters with its corresponding error or in mathematical term $y = \{\theta, e\}$ then we find the cluster centers using the clustering algorithm with euclidian distance as distance measure. The cluster center with has the lowest error is selected as the estimated parameters for the entire cycles.

3. Results and Discussion

The final estimated parameters of the model are presented in the Table (1). We used this set of parameters to estimate force for all cycles and then we calculated the RMSE for each cycle. The calculated RSME value is 0.12 ± 0.05. The reported RMSE are mean $\pm$ SD, where SD is the standard deviation.

Table 1. Estimated nondimensionalizes model coefficients for two time periods, until 10 minutes after the start of the CPR and more than 10 minutes from the start of the CPR.

Parameter	Value
α_1	1.51
α_2	-0.12
α_3	12.38
α_4	-16.99
α_5	10.94
β_1	0.08
β_2	1.15
β_h	0.17

A glance at the Table (1) reveals interesting information regarding the mechanical properties of the chest during the CPR. Results show a very strong nonlinearity in the spring component or elastic part of the model particularly third, fourth and fifth order components. Results also show a relatively strong nonlinearity in the damper. The presented results in this paper show that the current CPR manikins which are based on the linear viscoelastic model are not fully representative of the sternum during the CPR and consequently will fail to mimic real conditions.

Figure (2) is the plot of the estimated force versus measured force for 10 consecutive cycles. Please note that this is a nondimensionalized force plot. As it can be seen from this figure and this is a very good estimation especially considering the fact that the force amplitude is varying cycle by cycle.

4. Conclusions

Characterizing mechanical properties of the chest during the CPR, will help us to better understand the underlying mechanism that relates chest compression and resulting blood pressure. Consequently it will facilitate the optimization of the CPR procedure and improving CPR outcomes. The results of estimating model parameters show that while the elastic properties of chest are dominant, the damping components including viscous and hysteresis damping are still very important to fully capture the mechanical properties of the sternum during the CPR.

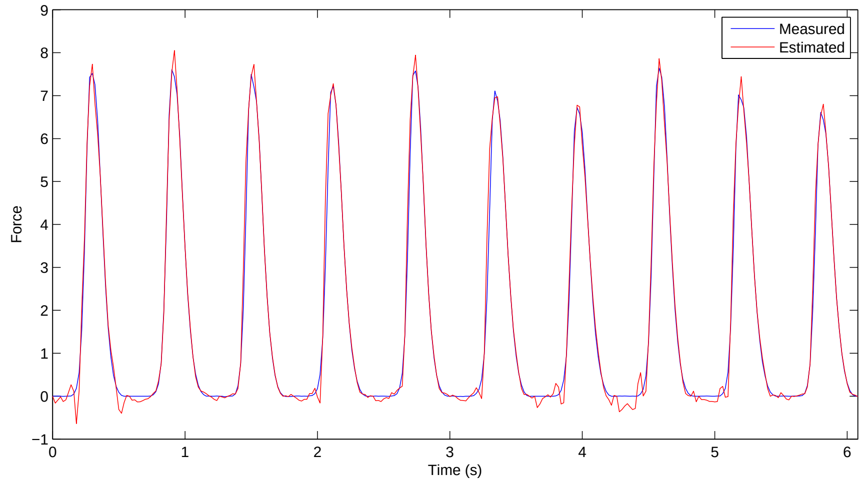

Figure 2. Plot of estimated force versus measured force for 10 cycles.

The result show that the chest has very strong nonlinear elastic properties, these properties starts after $1cm$ of the chest compression. The results also indicate that the elastic properties remains fairly constant for the first 20 minutes of the CPR.

References

[1] Go AS, Mozaffarian D, Roger VL, Benjamin EJ, Berry JD, Borden WB, Bravata DM, Dai S, Ford ES, Fox CS, Franco S, Fullerton HJ, Gillespie C, Hailpern SM, Heit JA, Howard VJ, Huffman MD, Kissela BM, Kittner SJ, Lackland DT, Lichtman JH, Lisabeth LD, Magid D, Marcus GM, Marelli A, Matchar DB, McGuire DK, Mohler ER, Moy CS, Mussolino ME, Nichol G, Paynter NP, Schreiner PJ, Sorlie PD, Stein J, Turan TN, Virani SS, Wong ND, Woo D, Turner MB, A. Executive summary: heart disease and stroke statistics–2013 update: a report from the American Heart Association. Circulation Jan 2013;127(1):143–152.

[2] Zheng ZJ, Croft JB, Giles WH, Mensah GA. Sudden cardiac death in the United States, 1989 to 1998. Circulation Oct 2001;104(18):2158–2163.

[3] Babbs CF. Effects of an impedance threshold valve upon hemodynamics in standard CPR: studies in a refined computational model. Resuscitation Sep 2005;66(3):335–345.

[4] Jalali A, Berg RA, Nadkarni V, Nataraj C. Model based optimization of the cardiopulmonary resuscitation (CPR) procedure. Conference Proceedings of IEEE Engineering in Medicine and Biology 2012;2012:715–718.

[5] Jalali A, Berg R, Nadkarni V, Nataraj C. Improving cardiopulmonary resuscitation (CPR) by dynamic variation of CPR parameters. In ASME Dynamic Systems and Control Conference (DSCC). 2013; .

[6] Gruben KG, Halperin HR, Popel AS, Tsitlik JE. Canine sternal force-displacement relationship during cardiopulmonary resuscitation. IEEE Transactions on Biomedical Engineering Jul 1999;46(7):788–796.

[7] Sutton RM, Friess SH, Bhalala U, Maltese MR, Naim MY, Bratinov G, Niles D, Nadkarni VM, Becker LB, Berg RA. Hemodynamic directed CPR improves short-term survival from asphyxia-associated cardiac arrest. Resuscitation May 2013;84(5):696–701.

[8] Bankman IN, Gruben KG, Halperin HR, Popel AS, Guerci AD, Tsitlik JE. Identification of dynamic mechanical parameters of the human chest during manual cardiopulmonary resuscitation. IEEE Transactions on Biomedical Engineering Feb 1990;37(2):211–217.

[9] Neurauter A, Nysaether J, Kramer-Johansen J, Eilevstjnn J, Paal P, Myklebust H, Wenzel V, Lindner KH, Schmlz W, Pytte M, Steen PA, Strohmenger HU. Comparison of mechanical characteristics of the human and porcine chest during cardiopulmonary resuscitation. Resuscitation Apr 2009; 80(4):463–469.

[10] Nataraj C. Vibration of Mechanical Systems. Cengage Learning, 2012.

[11] Samadani M, Kitio Kwuimy C, Nataraj C. Model-based fault diagnostics of nonlinear systems using the features of the phase space response. Communications in Nonlinear Science and Numerical Simulation 2014;.

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