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Determination of Heart Rate Changes using Simulated Head Up Tilt Test for Syncope Patient Assessment

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Abstract— **Home-based self-training can be beneficial to neurocardiogenic patients, particularly for those who experience a decreased heart rate during the clinical head up tilt test (HUT). Many patients, however, may not be able to attend a clinic and/or attend clinics which lack HUT devices. Individualized heart rate prediction based on a simulated HUT (sHUT) model may address this gap in clinical practice. The proposed sHUT model aims to predict whether home-based self-training is an appropriate beneficial intervention based on the calculated decrease in heart rate from the model. The results obtained with the model are in agreement with previous clinical findings with greater than 80% accuracy in identifying patients who could benefit from home training. The predicted home-based training efficacy of syncope against the control group had a corresponding p-value of p<0.0001. Based on these results, physicians may be able to recommend home training as part of online or telemedicine consultation.**

Clinical Relevance— The simulated Head Up Tilt model predicts the patient-specific efficacy of tilt-training for patients at home diagnosed with syncope.

I. Introduction

Vasovagal syncope (VVS) accounts for 60–70% of the causes of syncope [1]. Patients with recurrent syncope episodes are typically assessed by a head-up tilt (HUT) test to determine possible pathophysiology and decide treatment options [2]. However, HUT is time consuming, is not available in all clinics and carries the risk of inducing cardiac arrest [3]. HUT changes the position of the patient from a supine position to a maximum angle of 80°. The degree of tilt causes lower extremity blood pooling due to gravity. Consequently, the reduced venous return leads to a drop in blood pressure above the center of gravity (COG) [4]. Baroreceptors sense the decrease in blood pressure and activate a sympathetic response leading to an increase in heart rate. In healthy individuals, although the blood pressure initially increases. the heart rate quickly goes back to normal. In contrast, a sustained increase in heart rate is observed in syncope patients [5]. Abe and his team identified syncope patients where heart rate decreased during the early stages of HUT and proposed an orthostatic self-training exercise for patients with neurocardiogenic syncope [2].

This paper discusses a novel personalized at-home simulated HUT (sHUT) heart rate prediction model with justification of parameters and variables. The aim is to provide clinicians/patients with means of assessing whether extended standing posture is effective in decreasing syncopal episodes based on subsequent 5 minute heart rate recordings.

II. Methods

A. ECG data, demographics, and HRV analysis

Data were collected at the Wangaratta Cardiology and Respiratory Centre (WCRC) in Wangaratta, Australia from a group of 10 syncope patients and 20 palpitation patients, which were designated as the control group. All data were de-identified and ethics approval obtained from the Charles Sturt University Human Ethics Committee. All participants signed a consent form following an information session. The study included 18 females (6 syncope) and 12 males (4 syncope) with 43% of the cohort above 60 years of age, the oldest patient being 92 (syncope group), and the youngest 20 years old (control group). The average age of participants was 57±25. The leg-to-body ratio for men was set as 1.123 and for women as 1.124, and were used to calculate the gender specific estimated peripheral body resistance. The raw ECG data was preprocessed using a Librow MATLAB code for ECG filtering via fast Fourier transform to eliminate lower frequencies using a threshold which filters anything under 4Hz and a first pass filter which used window sizes of 102.78 (571 multiplied by the sampling rate of 180 per second and divided by 1000). The second pass filter was dependent on the QR distance subtracted from the distance between peaks, which varied with different ECG signals [6].

The simulated HUT (sHUT) model uses the heart as the main component, where the heart rate modelled as velocity (quantified by Bernoulli's principle), and the total peripheral resistance added as an inversely-related component to blood flow. Moreover, an average lower body height is considered. The starting tilt angle of 0° used in this study is the upright

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position in order to be comparable with the angle used in [2]. sHUT attempts to predict heart rate change for ECG data retrieved from 5-minute intervals captured every 10 minutes of recording from the 24-hour Holter recording. The obtained heart rate provides an indicator of the possible efficacy of an at-home upright training program for reducing syncope. The data for the model includes heart rate change of healthy individuals following sHUT, which is then retrofitted into the model to determine the resulting blood flow and the patient's initial heart rate to predict patient-specific heart rate decrease based on [2]. The remaining input variables are constants and include gravitational acceleration, blood density, and peripheral resistance. The output of the model is then compared to the results presented in [2]. Home-based training efficacy based on the sHUT compared between syncope and palpitation patients was assessed using a Chi-squared test and significance set at $p<0.05$.

B. Mathematical Model

This section explains the proposed cardiovascular model used to find the approximate heart rate of each patient while using at-home sHUT. In our model, the heart rate was derived from the approximate blood flow equation based on Darcy's Law. Darcy's law describes the relation between flow rate (Q) in ml/s, pressure gradient over a tube ($P_1 - P_2$) and the total peripheral resistance (R) :

$$Q = KA\frac{h_1 - h_2}{L} \; or \; q = \frac{Q}{A} = -K\frac{dh}{dl} \qquad (1)$$

where: K is the permeability, h is the hydraulic head, $h = p/(\rho g) + z$, A (m^2) is area, L (m) is the length

The linear proportionality in Ohms law between voltage and current are substituted for in Eqn. 2 with the pressure and volumetric flow rate q (ml/s) between compartments in cardiovascular regulation respectively. Flow rate is computed as Eqn (2):

$$q = \frac{p_{out} - p_{in}}{R} \qquad (2)$$

Based on the assumption that blood flow behaves as a continuum [7]. The flow (given as velocity) is then converted to heart rate using Bernoulli's Principle. In fluid dynamics, Bernoulli's principle relates velocity, pressure, fluid elevation, and fluid density (accounting for internal friction) as shown in Eqn. 3 [6]:

$$\frac{1}{2}\rho v_1^2 + \rho g h_1 + P_1 = \frac{1}{2}\rho v_2^2 + \rho g h_2 + P_2 \quad (3)$$

Rearranging Eqn. (3), the final velocity can be calculated as:

$$V_1 = \sqrt{{V_2}^2 + 2 \cdot g \cdot (h_2 - h_1) + \frac{2}{\rho}(P_2 - P_1)} \qquad (4)$$

where: v_1 is the velocity at elevation 1, P_1 is the pressure at elevation 1 based on Bernoulli's Equation, h_1 is the height of elevation 1, P_2 is the pressure at elevation 2, V_2 is the velocity at elevation 2, h_2 is the height of elevation 2, ρ is the density of the fluid, and g is the acceleration due to gravity.

When considering the heart as a dynamic system, the velocity pertains to the heart rate. Therefore in this model, pressure (blood pressure) will be substituted with velocity (heart rate), allowing for heart rate to be the main input for the model, which matches the data from [2]. The model can produce realistic flow fields that may appear under normal conditions in healthy blood vessels; as well as flow that could appear during abnormal conditions [8].

C. Modelling HUT.

The sHUT model utilizes blood flow by replacing hydrostatic pressure in Bernoulli's equation with heart rate as velocity (as derived previously) to simulate the HUT response when blood pressure data is not available. Angle manipulation is available for the model and allows this model to work for both the supine and upright positions. However, this study will only provide results for the upright position at 80 degrees. Gravity is considered and added to the flow equation due to the pooling effect of blood with head-up tilt. This would fit naturally in the gravitational potential energy factor at specific elevations in Bernoulli's equation. The calculated gravitational effects and the modified inverse flow equations are shown as Eqns (5) and (6):

$$q = \frac{\left(\rho \cdot g \cdot h \cdot \sin\theta(t) + \frac{1}{2} \cdot \rho \cdot ({v_2}^2 - {v_1}^2\right)}{R} \qquad (5)$$

$$v_2 = \sqrt{\frac{2 \cdot R \cdot q}{d} - (2 \cdot g \cdot h \cdot sin\,\theta(t) + {v_1}^2} \quad (6)$$

where: q is the blood flow, ρ (g/cm^3) is the blood density, $\theta(t)$ is the tilt angle (in radians), v_1 is the heart rate before training in liter/sec, v_2 is the heart rate after training in liter/sec, g (cm/s^2) is the constant of gravitational acceleration, h (cm) is the absolute patient height, $\rho g h \sin\theta(t)$ represents the hydrostatic pressure between the lower and upper body parts.

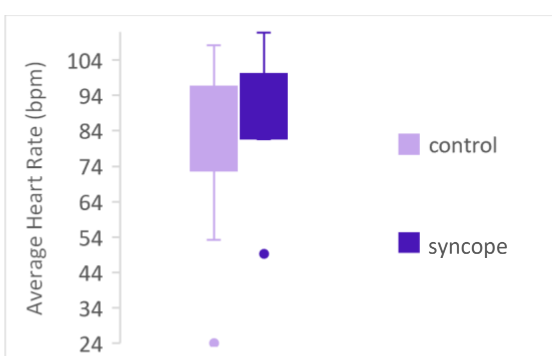

Figure 1. Box and whisker plot for average heart rates corresponding to the control group and syncope group.

According to [9], patients undergoing standing exercises respond better when they have higher starting heart rates. The results seen in the following box and whisker plot of the average heart rate over the 24 hour Holter recording (Fig. 1) imply that syncope patients should respond better compared to non-syncope. Using Eqn (5), a decrease in blood flow of -254.31 ml/s was calculated for the early stage of the sHUT test, possibly suggesting that blood flow decrease may be an important factor in predicting rehabilitation outcome of syncope patients.

Fig. 2 indicates that the syncope patient cohort has a significantly higher rehabilitation efficacy rate due to an ideal heart rate decrease that matches the data from [2]. The results indicate that 8 of the 10 patients would benefit from the at-home program with percentage likelihood above 84%. The efficacy percentage was found by comparing the heart rate decrease in patients to those seen in [2].

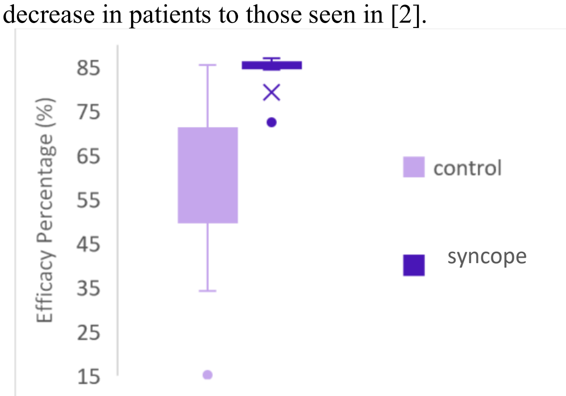

Figure 2. Box and whisker plot for efficacy percentage for control and syncope group.

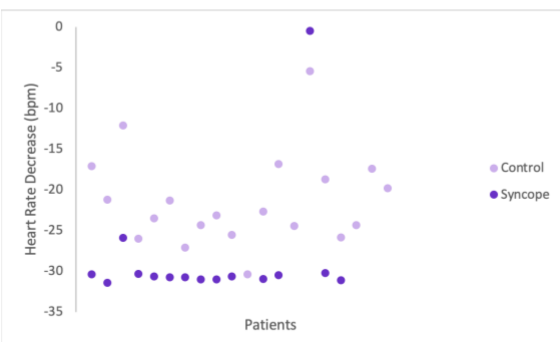

Figure 3. Scatter plot for heart decrease for control and syncope group

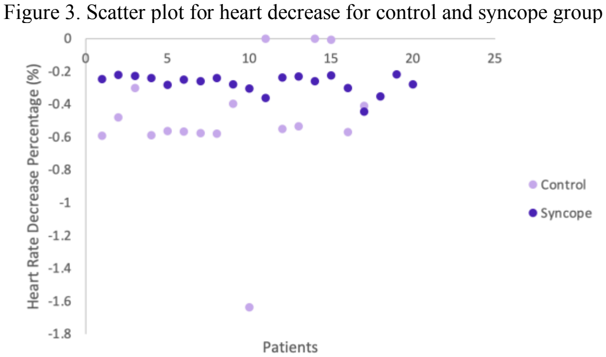

Figure 4. Scatter plot for heart decrease percentage for control and syncope group

In Fig. 3, the syncope and control groups are presented with an average of 30.5±1 bpm and 21.4±5bpm heart rate decrease respectively over 5 minute intervals of the 24-hour Holter recording. Fig. 4 shows the average heart rate percentage decrease for each group. There was one outlier from each group which deviated by 4bpm. Outliers require a follow-up with the aim to review any underlying conditions that could have caused this heart rate deviation from expected. Fig. 3 indicates the utility of the sHUT as it indicates a consistent decrease in heart rate for the syncope group as expected for vasovagal syncope compared to the heart rate decrease for the control group, which showed a random pattern indicating no consistent effect of sHUT for the control / palpitation group.

The personalized predicted efficacy, obtained through comparing patient heart rate results from the sHUT with the heart rate results of successfully recovered syncope patients from [2], indicates that a higher efficacy for the syncope group averaging approximately around 85%, whereas the control group averaged approximately around 65%. The corresponding p-value between syncope and control efficacy was 3.16E-19. When the sHUT model using the 24-hour heart rate data was inserted into a modified Bernoulli's equation (Eqn 4), syncope patients were accurately distinguished from the control group, which were diagnosed with palpitations with $p<0.0001$. The findings suggest that the model not only accurately identified the group of patients for which a decrease in sHUT is expected but also that an at-home upright training program for reducing syncope is beneficial.

III. Discussion

In this study, average, instead of exact, values of lower body height and total physiological peripheral resistance were used in developing the model as these data were not provided by the clinic. Blood volume and blood pressure were also not modeled. However, heart rate prediction based on the impact of gravitational force and blood flow decrease for syncope patients provided the basis for developing a simulated HUT test. The advantage of the sHUT is that it can be used to determine heart rate changes at any time of the day using a 24 hour Holter recording, as vagally mediated and cardio-inhibition can occur during sleep [10].

A. Blood flow and heart rate correlation

The negative blood flow value seen in the results suggests that blood flow decrease may be an important factor in predicting rehabilitation outcome of syncope patients. Assuming recovery of syncope patients after decreased blood flow is observed in the early stages of the upright position during the sHUT test may be justified by the slower pooling of blood in the legs. If blood flow decreases early on during the sHUT test, it would not flow as fast as it normally would to the legs with the onset of gravity, leading to slowing the effects gravity during the sHUT test for some syncope patients [11].

Having heart rate as the only input for this model is recognized as a limitation since the output is reduced to sympathetic regulation efficiency. Future work includes more extensive analysis on the effects this model introduces to the patients' ECG signals. Moreover, this model can extend its variables to observation of time-specific measurements and/or include blood pressure as a parameter in order to measure the capabilities of the current model and judge whether blood pressure is a more effective parameter for this simulation. Future studies may also observe the applied efficacy of HUT exercises on the current patients included in the study to further confirm this model's accuracy. The research set out to propose a viable model for at-home assessment of syncope. The main limitation of the study was lack of additional physiological variables and a patient group to validate the findings in a clinical setting rather than comparing to results reported in the literature. Future studies are being undertaken that may identify other possible inputs to better validate the use of this sHUT model including blood pressure, measured arterial/pulmonary resistance and stroke volume as well as recruiting another syncope group for validation.

Finally, the objective of sHUT was to construct a simple model that is limited to essential elements. This allows for a clearer and focused observation on the specific system dynamics that are studied. This model may potentially be used to diagnose patients with syncope as an alternative to HUT tests, which may eliminate the unwanted side-effects associated with HUT tests experienced by patients. It may also be further studied to be used as an indicator of underlying conditions in syncope and palpitation. The results suggest that at-home orthostatic self-training exercises can be beneficial for some syncope patients as compared to patients with palpitations (control group). The heart rate decrease in the beginning of the sHUT observed in the syncope group reflects the potential success of the model. Moreover, a similar trend is seen when observing the decrease in heart rate results across the two groups. The syncope group exhibited a relatively higher decrease in heart rate (~30 bpm) averaged over the first, third, and fifth minute during the sHUT exercise, further confirming the possible efficacy of the proposed home training based on our model in line with the criteria outlined in [2]. The palpitation group (control) demonstrated a lesser decrease (~23 bpm) as compared to the syncope group. This indicates that the HUT exercises are more likely to be of benefit to syncope patients

IV. Conclusion

The main contribution of this study is providing a novel approach to predict heart rate changes in syncope patients that may indicate a beneficial outcome associated with a 30 minute bi-daily standing rehabilitation exercise. This was achieved by successfully combining blood flow parameters with heart rate as the velocity variable and the human heart as the dynamic system into one model. HUT was simulated by introducing an elevation factor of the upright position (80°) to the gravitational potential energy parameter with gravity and against the total peripheral resistance. The model then produced personalized results for the syncope study group that predicted recovery efficiency with respect to Abe et al. [2]. Moreover, more personalized and efficient program for distinctive syncope patients with lower predicted efficacy rates can be developed using the at home orthostatic self-training exercise for a duration of 30 minutes twice daily for 30 days.

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