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Simulation of Living Behavior
- A Cardiovascular Model for Predicting Blood Pressure and Heart Rate -

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Abstract: We have developed a simulation tool that can evaluate the comfort using a computer Mannequin. We also have developed a cardiovascular model that can predict blood pressure and heart rate as determined by physical activity. The predicted blood pressure and heart rate were well agreed with the actual blood pressure and heart rate in the experiments.

Keywords: digital human, cardiovascular model

INTRODUCTION

A digital human is a kind of software that can check the conformity between humans and the surrounding spaces including equipment by simulating human behavior. Conventional methods may use human subjects and build up mock-ups in order to evaluate its usability and its goodness based on actual human senses. This design process is sometimes repeated until the designer has a satisfactory result, which is very time-consuming and expensive. Since the digital human can handle this iterative process on the computer, it can attain rapid development and cost reduction.

Past research activities using the digital human include a new washroom design for the wheel-chaired person, bathroom development for the handicapped[1), 2)], and development of new functions for the digital human[3)]. However, there are three important functions lacking in evaluating residential spaces in our country. The first one is the function for generating motions in a simple way because it takes enormous time to simulate motions of the digital human with the conventional mouse operating method. The second one is the function for predicting blood pressure and heart rate during behavior since 70% of the accidents at home come from physiological burden in the cardiovascular system. The third one is the function which can evaluate conformity comprehensively from different evaluation items.

A residential space design tool, which we call "CUPS", has all the three important functions stated above. This paper describes an outline of CUPS and the concept of a cardiovascular model and its experimental results.

REDIDENTIAL SPACE DESIGN TOOL "CUPS"

Figure 1 shows the system outline of CUPS. This is the design support tool that can evaluate residential spaces

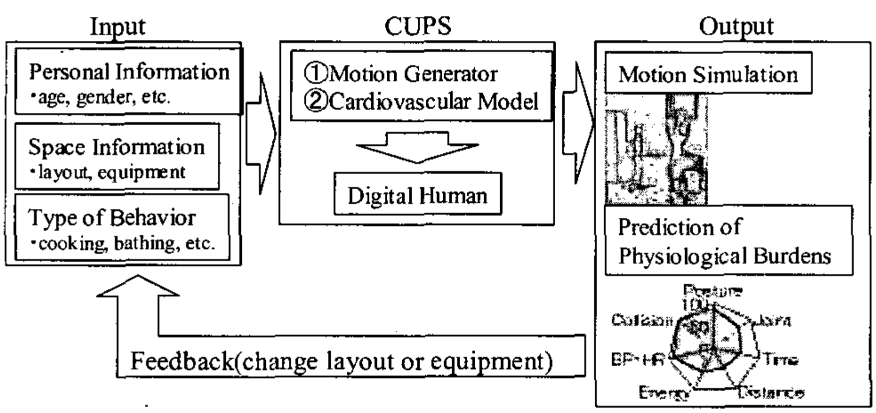

Fig.1 CUPS.

in terms of conformity between humans and the residential space. The features of CUPS are as follows.

1) Comprehensive evaluation from the points of comfort, usability, performance, and safety.

2) Rapid motion generation of the digital human for several of minutes.

3) Blood pressure and heart rate prediction during human behavior.

A CARDIOVASCULAR MODEL

Model Algorism

There are three types of exercise defined below.

-Isotonic Exercise : dynamic motions with joint movement such as walking or cycling

- Isometric Exercise : mainly static loading without joint movement as in weight lifting

- Stand up and Sit down : motion with rapid height change of a heart such as standing up or sitting down

At present application of the model shown in Fig.2 is limited to isotonic exercise.

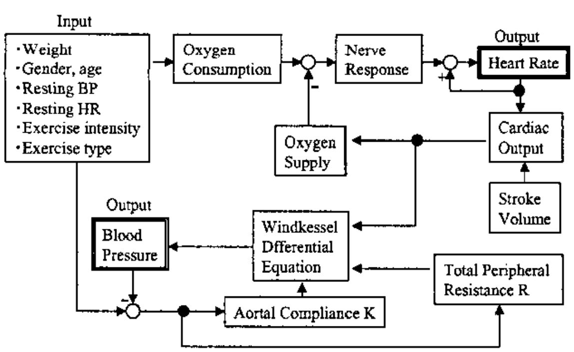

Fig.2 Cardiovascular model.

Figure 2 shows a schematic diagram of the cardiovascular model. The features of the cardiovascular model are as follows.

1) Consideration on personal information such as weight, age, and resting blood pressure.

2) Consideration on exercise level and type.

Inputs of this system are individual parameters (weight, gender, and resting blood pressure etc.), exercise intensity, and exercise type. From the information the cardiovascular model calculates oxygen consumption required for the exercise. In parallel with the calculation, the cardiovascular model calculates cardiac output (CO) from heart rate (HR) and stroke volume (SV). Oxygen supply is calculated by cardiac output. If oxygen supply is larger (smaller) than oxygen consumption, HR decreases (increases) by the nerve response. On the other hand, blood pressure (BP) is determined by being inputted CO, total peripheral resistance (TPR), and aortal compliance (K) into Windkessel model. By repeating above calculation, BP and HR can be simulated in time series.

Exercise intensity is given in a unit of MET, which is a metabolic measure equivalent to 3.5 ml of oxygen per kilogram of body mass per minute (3.5ml/kg/min). 1 MET is the resting level of metabolic activity for the average person. It is possible to predict blood pressure during the transition period from resting to exercise and from exercise to resting as well as during steady-state exercise. For example, walking at 4 km/h is about 4 METs isotonic exercise

Otto Frank's Windkessel model likens the human cardiovascular system to a type of hand-operated water pump. In the water pump, water is periodically pulsed into a high-pressure air chamber. The water exits the air chamber at a higher average pressure, but with pulses of a lower amplitude. The human cardiovascular system is very similar, with the elastic aorta translating pulses into a more steady flow. The solution to the differential equation representing pressure p is shown as Eq. (1) below:

$$p(t) = \frac{1}{K} e^{-t/(RK)} \int_0^t \dot{Q}(\tau) e^{-t/(RK)} d\tau + p_o e^{-t/(RK)} \quad (1)$$

R represents the total peripheral resistance (TPR) and cardiac output is represented by $\dot{Q}$[4]. Given variables K and R, the Windkessel equation essentially translates cardiac output into pressure. K generally affects the pulse pressure, or difference between systolic and diastolic blood pressure. R affects the mean blood pressure. K is assumed to be constant within the pressure range it experiences during light exercise, but R changes significantly. During exercise, capillaries dilate to allow more blood to flow through.

The above is the outline of the cardiovascular model. Four elements which are the features of this model are explained below.

Dynamic Oxygen Consumption: When transitioning from rest to exercise, or from exercise to rest, it is evident that changes in heart rate and blood pressure do not occur instantly. Testing shows that oxygen consumption gradually increases even though the output level of work increases immediately [5].

To explain the decoupling of exercise and oxygen uptake, it must be understood that there are two categories of ways the body can metabolize energy, aerobic and anaerobic. Aerobic metabolism is always present, and provides sustained energy for moderate exercise. Aerobic metabolism is the basis of the cardiovascular model. For short bursts of energy, the anaerobic system is used. As the name suggests, the anaerobic system does not require oxygen to produce energy. When exercise is first started, both systems are used simultaneously. Until the aerobic system increases to steady-state, the anaerobic system makes up for the difference in energy[6]. This is modeled as a simple time based linear relation.

At high levels of exercise (above 6 METs) there exists a VO_2 Drift, where oxygen uptake rises gradually with time while exercise remains constant. The mechanisms behind this are not fully understood, but it appears to be related to changes in blood lactate[7]. This is also modeled linearly.

After exercise, oxygen uptake and heart rate remain elevated for a period of time. This is known as "Excess post-exercise oxygen consumption" (EPOC). EPOC occurs due to several factors, including the need to replenish anaerobic chemical reserves, re-oxygenate the blood, and to cool the body[8]. There appear to be two components to EPOC, a fast component which lasts only for minutes, and a slow component which can last for hours. The slow component appears to be related to VO_2 Drift, and is currently modeled the same way. The fast component is an exponential function of time[9].

Stroke Volume: Stroke volume increases with blood pressure and preload according to the Frank-Starling Mechanism[10]. By using experimental data, it was possible to fit a piecewise linear function to stroke volume varying with the intensity of exercise. At 4 METs, nearly all test subjects had a stroke volume roughly double their resting stroke volume. There are two stroke volume functions, one for walking, and one for cycling. Direct measurement of stroke volume requires a catheter to be inserted into the pulmonary artery. As this is highly invasive, stroke volume was estimated based on oxygen consumption and heart rate. By assuming linear behavior of arteriovenous oxygen content difference (see below) cardiac output can be estimated from oxygen uptake. Stroke volume is then estimated by dividing the cardiac output by heart rate.

Arteriovenous Oxygen Content Difference: In the cardiovascular model, heart rate is driven by oxygen need. That is, the level of exercise combined with the body mass of the subject determines how much oxygen is needed, and heart rate will increase or decrease to meet this need. Oxygen supply is determined by cardiac output multiplied by the arteriovenous oxygen content difference (C_{av}). C_{av} varies linearly with the volume of oxygen consumed (VO_2) as a percentage of maximum volume of oxygen consumed (VO_2 max) [11]. It would be impractical to determine VO_2 max for each test subject, therefore the average VO_2 max of the age and gender group is used[12]. This is shown as Eq. (2) below:

$$C_{av} = 5.72 + 0.105 * \%VO_2 \max \frac{ml\,O_2}{100\,ml\,blood} \quad (2)$$

Automatic Fitting: Aortal compliance varies significantly between individuals. As well as age, smoking, exercise, and genetic factors are strong determinants in compliance. The result of this was an accurate prediction of mean resting blood pressure, but systolic and diastolic blood pressure would often be very different from the actual subject. In the cardiovascular model, parameters K and R are automatically fitted to input systolic and diastolic blood pressure. The Windkessel equation cannot be solved analytically, therefore this is done by independently altering K and R in steps until the difference between predicted and actual resting blood pressure is acceptably small. This usually takes 15 seconds or less.

Experimental Testing

We conducted experiments in order to verify the cardiovascular model in isotonic exercise.

Subjects: eight young, healthy male

Exercise: Walking at 4km/h, 6km/h

Cycling at 25W, 50W, 90W, and 170W

(The final cycling trial of 170W was reduced to 130W for the last three subjects.)

Equipment: Portapres Model2 (Finapres Medical

Systems), Aeromonitor AE-280S(Minato Medical Science)

Procedure: rest (10min) – standing or sitting on the cycle (3min) – exercise (5min) – rest (5min)
(The final cycling trial was occasionally stopped early due to subject exhaustion, and 10 minutes of rest afterwards was recorded.)

RESULTS AND DISCUSSION

The goal of our research is to predict diastolic and systolic blood pressure within 15 mmHg, and heart rate within 15 beats per minute during exercise up to a level of 5 METs. To simplify analysis, the waveforms were reduced to data points averaged over the steady-state periods. Systolic blood pressure, diastolic blood pressure, and heart rate during a time period are considered as one data point. Of the eight subjects, 96 data points were collected under 5 METs (excluding resting data). The cardiovascular model meet these design goals for 71of the data points, giving a success rate of 74%. It should be noted that in many cases the cardiovascular model met the design parameters at levels of exercise as high as 9 METs. Figures 3 and 4 show the average of all test data compared to the average of all the simulation data. There will always be a degree of variance with individuals, but the cardiovascular model now appears to be accurate for predicting blood pressure of an average member of a group. The difference in blood pressure and heart rate is smaller than the design parameters.The cardiovascular model has a

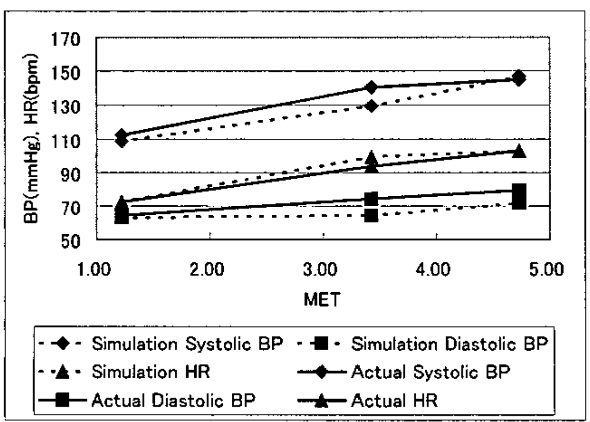

Fig.3 Comparison of blood pressure and heart rate between simulation and experimental data during treadmill exercise.

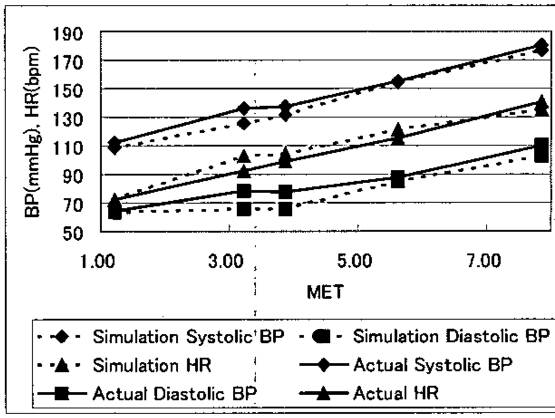

Fig.4 Comparison of blood pressure and heart rate between simulation and experimental data during cycle ergometer exercise.

tendency to underestimate blood pressure, especially around 4 METs. Greater inaccuracy at 4 METs is unavoidable due to the inflection point in the stroke volume algorithm, but it may be possible to reduce the underestimation tendency by taking into account the changes in posture. All resting blood pressure measurements were taken while sitting.

Since one of the main features of this model is the ability to simulate individual difference, error for each individual test subject must be looked at as well. We use the term "error" as the difference between simulation data and experimental data. The average absolute error of the eight individuals for each of the five tests is shown in Table 1.

Table 1 Average absolute error

	4 km/h	6 km/h	
Systole error (mmHg)	12.9±15.0	15.0±8.99	
Diastole error (mmHg)	10.8±8.71	15.1±6.88	
Heart rate error (bpm)	7.75±6.04	7.75±2.74	
	25W	50W	90W
Systole error (mmHg)	12.0±9.79	14.3±8.87	10.0±10.5
Diastole error (mmHg)	12.6±11.13	14.5±10.1	10.0±6.91
Heart rate error (bpm)	10.8±7.15	7.13±6.09	9.38±6.93

The average diastole error during a 6 km/h brisk walk does slightly exceed the 15mmHg design goal, but overall error can be considered small given the limited input parameters. For example, two of the subjects had near identical weights, resting blood pressures, heart rates and ages. Even for the subjects whose weights, resting blood pressure, heart rates, and ages are regarded as identical, there was nearly 25 mmHg of difference in blood pressure.

The main causes for these errors are considered to be 1) smoking habit, 2) obesity, and 3) lifestyle and exercise habit. Only one subject in this test smoked, and only occasionally. Error was quite small for this individual, and well within the acceptable bounds of error. Since obesity is a common factor in high blood pressure, it would be logical to assume this would have an effect on the accuracy of the program. We verified a correlation between prediction error and obesity using body mass index (BMI), body fat percentage (BFP), and body mass. The results are shown in Fig.5, Fig.6, Fig.7, and Table2. Note that a positive relative error means that the simulation data is higher than the experimental data. As can be seen, heart rate and diastole error tend to increase with BMI, BFP and body mass. Though not as obvious, there is a downward trend to systole error. The reasons for these errors are considered as follows. The larger individuals have a greater volume of blood. In order to move this greater volume of blood without placing undue strain on the heart, stroke volume tends to be greater during exercise than in a smaller individual. If the stroke volume were increased, heart rate would be lowered. If the heart rate were lowered, the result would be a greater pulse pressure, lowering diastole and heighten systole. Thus, changing the heart rate should have the effect of also changing systole and diastole blood pressure errors. Currently there is not enough data to change stroke volume curve based on body mass. Accuracy is acceptable within the healthy range of BMI(18-25), so this is not a priority.

The most serious factor affecting blood pressure during exercise is physical conditioning. Athletes were excluded from this test, but one of the eight subjects played soccer three times a week. Simply walking to work instead of using a car can have a significant effect on health, so regular soccer has a much greater effect. The simulation result for the soccer-playing subject was much smaller than the experimental data. This is due to a much greater VO_2 max than the average data and a lower heart rate. This effect is that the simulation significantly underestimated blood pressure. This is counter-intuitive, so an explanation is warranted: in an athlete, the heart beats slower, but larger strokes. This increases pulse pressure, but reduces strain on the heart. Athletes typically have cardiovascular systems better adapted for high blood flow, so overall blood pressure is not higher. The other factor is VO_2 max. Studies have shown that arteriovenous oxygen content difference (C_{av}) varies linearly with VO_2 as a percentage of VO_2 max[11]. As the athlete has a greater VO_2 max, C_{av} will be reduced, requiring a greater volume of blood flow for a given level of exercise. The goal of this project is to simulate ordinary people in the 1-4 METs range, so it is not deemed necessary to incorporate a function for athletes.

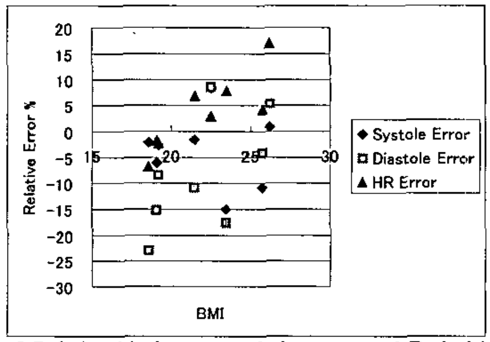

Fig.5 Relationship between relative error and Body Mass Index.

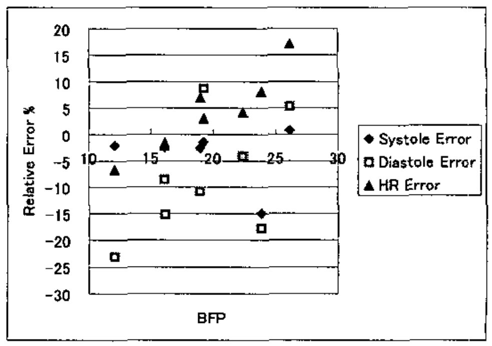

Fig.6 Relationship between relative error and Body Fat Percentage.

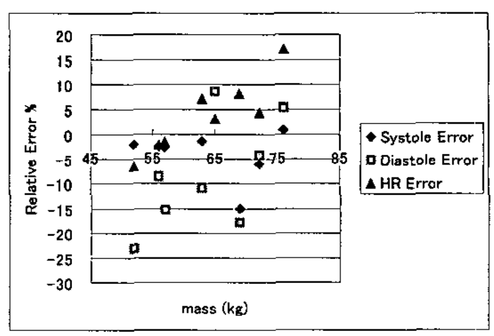

Fig.7 Relationship between relative error and body mass.

Table 2 Multiple correlation coefficient with relative error

	Systole	Diastole	HR
BMI	0.011	0.367	0.718
BFP	0.062	0.295	0.872
Mass	0.014	0.376	0.819

CONCLUSIONS

We have developed a residential space design tool "CUPS" and tried to validate the cardiovascular model for isotonic exercise.

A treadmill was used for the walking trials, and an ergometer was used for cycling trials. Each of the eight subjects underwent the same test procedure, which included walking at 4 km/h, 6 km/h, and cycling at 25 W, 50 W, and 90 W. Of the eight subjects, 96 data points were collected under 5 METs (excluding resting data). The design goals of model accuracy are within 15 mmHg in blood pressure and within 15 beats per minute in heart rate. The cardiovascular model meet these design goals for 71 of the data points, giving a success rate of 74%. The main causes for these errors are considered to be 1) smoking habit, 2) obesity, and 3) lifestyle and exercise habit. Only one subject in this test smoked, and only occasionally. The error was quite small for this individual, and well within the acceptable bounds of error. A correlation was accepted in obesity and prediction error of the heart rate. However, accuracy is acceptable within the healthy range of BMI (18-25). In this experiment one of the eight subjects played soccer three times a week. The soccer-playing subject had the greatest average level of error.

Future work may include experimental verification of 1) the cardiovascular model in isometric exercise and "standing and sitting motion", 2) CUPS as the integrated space design tool with the help of tens of aged subjects.

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