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Literature Review: Biomedical Information of Animal Treadmill Speed Control Using Proportional Integral Derivative Controller

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ABSTRACT: The use of treadmill exercise in cardiovascular research played a vital role in assessing heart health and determining appropriate exercise regimens for patients. Before applying these regimens to humans, experiments on animals, such as white rats or mice, were conducted to simulate human cardiovascular responses. A specialized treadmill designed for experimental animals was required to determine exercise doses based on individual abilities. This process involved controlling the treadmill speed, which was generated by a conveyor driven by a DC motor. The motor speed was regulated through PID (Proportional Integral Derivative) control, while encoder sensors monitored the motor's rotation speed, and limit switch sensors determined the exercise duration. This article reviewed the design and implementation of treadmill systems used for animal-based cardiovascular research, focusing on the control of DC motor speed using PID controllers. Previous studies that contributed to the development of such systems were discussed, with an emphasis on the precise control mechanisms required to simulate exercise conditions tailored to the subject's abilities. The treadmill system also incorporated sensors to accurately adjust motor speed and track exercise duration, ensuring alignment with the physiological capabilities of the test subjects. Furthermore, this review explored the potential for advancing research on treadmill control systems, offering insights into how this technology could support medical experts in determining optimal exercise regimens for white rats. These developments helped bridge the gap between animal-based studies and human applications, facilitating improved cardiovascular research outcomes.

KEYWORDS: Heart; rat; treadmill; DC motor; encoder sensor; PID control

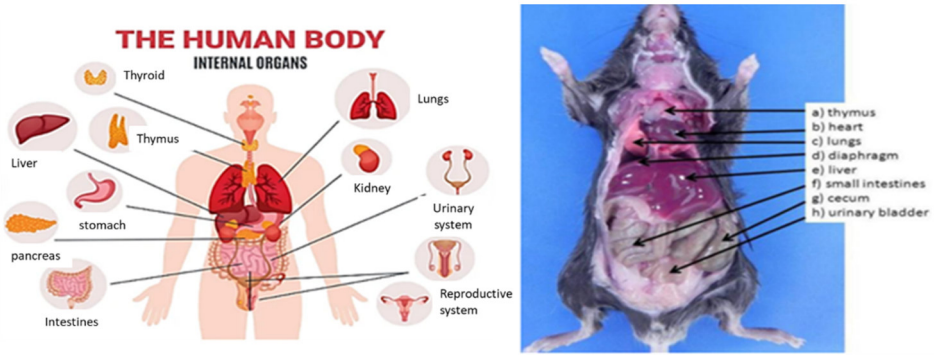
1. Introduction

The heart is an important organ that worked reflexively to determine the health of a person's body from the heartbeat [1]. To nourish the heart, it was recommended to engage in exercise that triggered muscle movement and improved the body's metabolism [2]. One such exercise involved using a treadmill. A treadmill was an ergometer or piece of sports equipment with a controllable work system [3]. The advanced features found on treadmills included heart rate monitoring, timers, speed control, calorie tracking, distance measurement, massagers, dumbbells, twisters, and MP3 and speaker features connected via Bluetooth or USB [4]. The

health code of ethics in exercise dosing stated that one of the basic principles of biomedical research with humans as subjects was to adhere to scientific principles based on robust laboratory experiments and experimental animals, as well as complete knowledge from scientific literature [5]. The administration of exercise for rats using a treadmill tool, categorized by duration and frequency, had to follow a physical exercise protocol [6]. The study was conducted on albino rats or mice selected according to the study's requirements [7–21]. Previous research by Dandi Irawan simulated an electric treadmill tool for fitness using a microcontroller-based PWM technique, employing the "hex" language, Code Vision AVR (CVAVR) software, and implementing control through a push button and a one-way DC motor [22]. The contribution of this research lay in controlling the motor speed on a specialized treadmill for experimental animals using PID control (Proportional Integrative Derivative). This study reviewed standard literature explaining the anatomy of mice and described the method of design. It also provided an explanation of the PID control concept, including research on the application of PID to treadmills and the implementation of rat exercise protocols using treadmills that had been conducted previously.

2. Study Background

In the development of biomedical research, the role of animal models was very important. The white rat was one of the most widely used experimental animals in research related to medicine, pharmacy, medicinal plants, nutrition, and other scientific fields [9]. White rats (*Rattus norvegicus*) were commonly chosen because they were easily obtained in large quantities, exhibited fast responses, and provided a scientific representation of conditions that might occur in humans, as illustrated in Figure 1. A physiological comparison between rats and humans was presented in Table 1, while Table 2 showed the age comparison of rats and humans.Anatomically, the heart was located in the left chest cavity, composed of four chambers: two atria and two ventricles. The lungs were situated in the right chest cavity, consisting of four lobes, while the left lung had one lobe.



(a) (b)

Figure 1. Anatomical structure Human Being [25] (a); Rat [26] (b).

The morphological structure has a small head, approximately 12-20 cm long, with long whiskers and a hairy tail. The hind legs have a size of 16 mm, the size of the ears is 12 mm, and the size of the skull is 19 mm [23]. In controlling the treadmill tool used for this exercise, rats are given adaptation first. Adaptation is given in the form of 800 mg/kg grain food for 8 weeks, exercise at a speed of 18 m/min, and given an angle of 32o for 2 hours/day for 5 days/week in 8 weeks [24]. With this behavior, rats are expected to be able to follow the

treadmill to get an exercise dose. They can be applied to individual humans (taking into account age, body weight, and activity level).

Table 1. Comparison of rats and humans [27–40].

Physiology	Rat	Normal adult human
Heartbeat	250-450 time/minute	60-100 time/minute
Blood pressure	Systol 84-134 mmHg Diastole 60 mmHg	Systol 95-120 mmHg Diastole 60-80 mmHg
Respiratory rate	70-115 time/minute	12-20 time/minute
Protein (g/dl)	5.6-7.6 g/dl	Male 65 g/dl Female 60 g/dl
Albumin (g/dl)	3.8-4.8 g/dl	3.5-5.9 g/dl
Globulin (g/dl)	1.8-3 g/dl	1.3-2.7 g/dl
Glucose (mg/dl)	50-135 mg/dl	70-140 mg/dl
Blood urea nitrogen (mg/dl)	15-21 mg/dl	6-20 mg/dl
Creatinine (mg/dl)	0.2-0.8 mg/dl	Male 0.6-1.2 mg/dl Female 0.5-1.1 mg/dl
Total bilirubin (mg/dl)	0.2-0.55 mg/dl	0.3-1.0 mg/dl

Table 2. Age comparison of rat and humans [6]

No	Age of rats	Age of human
1	6 (months)	18 (years)
2	12 (months)	30 (years)
3	18 (months)	45 (years)
4	24 (months)	60 (years)
5	30 (months)	75 (years)
6	36 (months)	90 (years)
7	42 (months)	105 (years)

3. Methods

3.1. Design of treadmill prototype.

A treadmill is an ergometer or sports equipment whose work process is quantitative and can be controlled [3]. This tool provides facilities that can determine the speed and duration of exercise, and the design uses a DC motor as a conveyor drive, as shown in Figure 2.

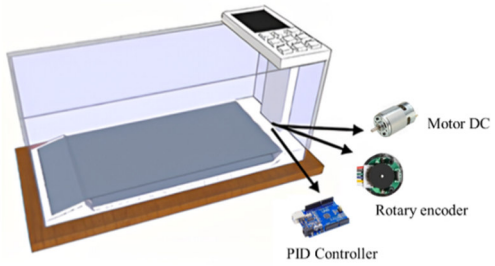


Figure 2. Experimental animal treadmill with PID control.

3.2. DC motor.

A DC motor was a device that converted DC electrical energy into mechanical energy, requiring direct current to operate [41]. The average rotational speed of a DC motor was estimated to be between 3000–8000 rpm, with an operational voltage ranging from 1.5 to 24 V [42]. DC motors functioned as actuators controlled by PWM (Pulse Width Modulation), which

had a value ranging from 0 to 255 based on fixed frequency and period parameters. When a DC motor was subjected to a load, the current increased, and a stall current was required to stop the motor if the load reached its maximum.

3.3. Speed Encoder.

A speed encoder was a speed sensor component, also known as a rotary encoder sensor, that acquired speed data from the controlled DC motor [43]. The magnetic rotary encoder calculated the DC motor's angular velocity, with the rotary encoder having specifications of 211.2 CPR.

3.4. Treadmill speed control technique.

Some techniques are carried out by researchers who design hardware and software to control the speed of DC motors. Using a program with the "hex" language with Code Vision AVR (CVAVR) software by controlling the device using a button and the results are displayed on the LCD screen [22]. Motor speed control was achieved using an accelerometer sensor to measure foot speed (m/s). The data collected was transmitted wirelessly to an ATMega128 microcontroller. The measured data was then compared with readings from a stroboscope to measure motor speed, yielding an error value of 1.21%, which was within a tolerable range [44]. Another method utilized PID control techniques to regulate the speed of a DC motor on a treadmill.

4. Results and Discussion

4.1. PID control technique.

PID control was a feedback mechanism controller frequently used in industrial equipment systems [45]. PID systems had the potential for errors in maintaining setpoints. Figure 3 illustrated the block diagram of PID control on a DC motor system in a closed-loop configuration. The first Ziegler-Nichols method regulated the response of a motor with a unit-step input characterized as a first-order type, incorporating a time delay (L) and constant-time (T) response, which were derived from the inflection point of a tangent line c(t)=Kc(t) = Kc(t)=K on an S-shaped curve [46], as depicted in Figure 4. The tangent line was determined by identifying a straight line that coincided with the response at the point of maximum slope and intersected the value of γγγ, representing the response time to reach the steady-state value [46]. The parameters for the first Ziegler-Nichols method were summarized in Table 3. The second Ziegler-Nichols method began by setting the values of Ti=∞T_i = ∞Ti=∞ and Td=0T_d = 0Td=0, then gradually increasing the proportional gain (KpK_pKp) from 0 until it reached the critical value (KcrK_{cr}Kcr), where the system output oscillated consistently, as shown in Figure 5 [46]. The PID controller utilized a transfer function (GcG_cGc) that resulted from summing the proportional gain (KpK_pKp), the integral gain (KiK_iKi) divided by the integral time constant, and the derivative gain (KdK_dKd) multiplied by the derivative time constant, forming Equation (1).

$$G_c = K_p(1 + \frac{1}{T_i s} + T_d s)$$

(1)

Kp is a proportional gain that will produce an output directly proportional to the error. Ki is an integral gain that reduces or eliminates the error value. Kd is a derivative gain used to stabilize a system [47].

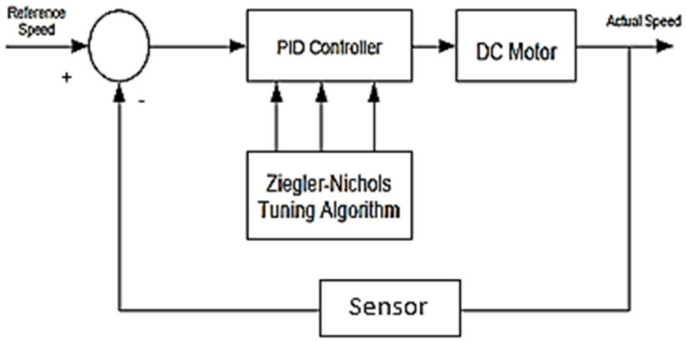


Figure 3. Block Diagram of DC Motor Control [46].

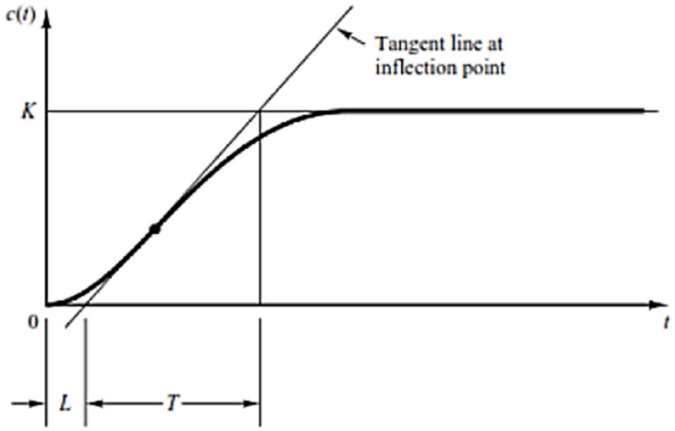


Figure 4. Block Diagram of DC Motor Control [46]

Table 3. First Ziegler-Nichols Rule [46]

Type of Controller	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\frac{T}{L}$	2 L	0.5 L

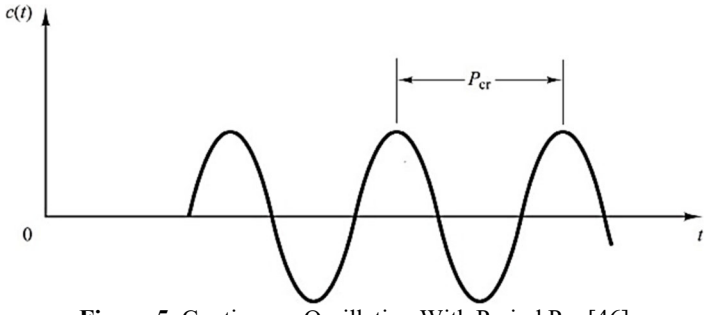


Figure 5. Continuous Oscillation With Period Pcr [46]

Table 4. Second Ziegler-Nichols Rule [46]

Type of Controller	K_p	T_i	T_d
P	$0.5\ K_{cr}$	∞	0
PI	$0.45\ K_{cr}$	$\frac{1}{1.2}\ P_{cr}$	0
PID	$0.6\ K_{cr}$	$0.5\ P_{cr}$	$0.125\ P_{cr}$

This method was applicable when the output of the KpK_pKp value exhibited continuous oscillation, as described above. The critical value (KcrK_{cr}Kcr) and the corresponding period (PcrP_{cr}Pcr) were determined by experimenting with various values [46]. The first Ziegler-Nichols rule was presented in Table 4. The application of PID control to DC motors, focusing on achieving the desired system specifications in speed control, included the following requirements [48]:

a) Rise time <1 s: The time required for the system response to rise from 10% to 90% (overdamped), 5% to 95%, or 0% to 100% (underdamped) of the final steady-state value of the desired response.
b) Settling time <2 s: The time required for the response to reach and remain within 2% of the final steady-state value.
c) Maximum overshoot <10%: The maximum peak value of the system response curve measured above the steady-state value.
d) Steady-state error = 0%: The difference between the final value of the system response and the desired input setpoint.

4.2. Speed control of DC treadmill motor using PID control.

In designing PID parameters with the Ziegler-Nichols method for DC motor speed control, previous research identified two approaches: the first Ziegler-Nichols method in an open-loop configuration and the second in a closed-loop configuration [42]. The PID control system designed for controlling the angular speed of a DC motor on a UGV (unmanned ground vehicle) drive wheel, using the trial-and-error method, successfully achieved the desired speed and ensured straight-line movement [45]. In testing the application of PID control to a spinner motor in the apple cider production process with a human-machine interface feature, the system response was faster and more stable compared to operation without the controller. As shown in Table 5, greater disturbances introduced into the system resulted in larger errors during the initial settling time when manual tuning was performed [49]. Another study utilized PID control in a MATLAB-based DC motor control system on a conveyor to optimize the DC motor's response [50]. Testing with the Ziegler-Nichols method was performed to regulate the rotation speed of the DC motor, ensuring precise control through PID [51].

Table 5. Research on the application of PID to DC motor speed control.

No	Ref.	Method	Technique
1	[42]	PID by Ziegler Nichols method	• Ziegler Nichols *open loop* and *close loop*
2	[45]	PID control for controlling angular speed of DC motor on UGV drive wheels	• Through trial and error successfully control the speed as desired and move in a straight track.
3	[49]	Speed Control Based PID Configuration of a DC Motor	• The PID controller was implemented using simulation software and a microcontroller-based controller to regulate the speed of the DC motor.
4	[50]	Development of PID in controlling the speed of Matlab-based DC motor on mini conveyor.	• Matlab and Arduino to analyze the data. • Encoder sensor to read the belt rotation speed with PWM input which is controlled according to the setpoint.
5	[51]	Ziegler Nichols method	• Obtain the rotation speed so that the system can be controlled using PID control.

4.3. Administration of rat training using a treadmill.

A previous study examined the long-term angiogenic effects of *Nigella sativa* administration in mice combined with treadmill exercise. This exercise regimen was implemented to observe improvements in blood flow and the physiological health of blood vessels. The effects of *Nigella sativa* on angiogenesis required further investigation to develop new preventive measures and therapies for ischemic heart disease [24]. Another study evaluated the impact of treadmill activity on blood pressure and cardiac histopathology in rats (*Rattus norvegicus*) subjected to obesity induced by a 60% high-fructose diet (HFD). The study implemented a controlled and gradual exercise treatment, determining that 20 minutes of treadmill activity per day effectively reduced blood pressure in the rats [3]. In addition, research investigated treadmill exercise's influence on matrix metalloproteinase-9 expression in the rat hippocampus. This exercise induced a novel molecular mechanism of hippocampal plasticity, observed after 12 hours of treadmill activity [18]. Research on rat exercise using a treadmill is shown in Table 6.

Table 6. Research on rat exercise using a treadmill.

No	Ref.	Method	Technique
1	[24]	Long-term angiogenic effects by administering nigella sativa to mice exercising on a treadmill	• Improvement of blood flow and psychology of blood vessels. • Development of NS Effects on angiogenic and ischemic heart disease therapy
2	[3]	Effect of treadmill activity on blood pressure and cardiac histopathology in obese rats induced by 60% High Fructose Diet (HFD)	• Physical activity using a treadmill for 20 minutes/ day is an effective duration in reducing rat blood pressure
3	[18]	Providing treadmill exercise with matrix metalloproteinase-9 in rat hippocampus	• New molecular hippocampal plasticity from exercise results after 12 hours of treadmill exercise.
4	[19]	Forced treadmill exercise can cause stress and increase neuronal damage in ischemia rats	• Pre-exercise training is not beneficial if the training is forced and the rats respond to stress.
5	[12]	NLRP3 infalmmasone administered and microgial activation in MPTP mouse model of Parkinson's disease to reduce neuronal damage during treadmill exercise	• Treadmill exercise can effectively reduce neuronal damage due to NLRP3 inflummasoem inhibition and microglial activation in PD mice
6	[16]	*Spesies oksigen reaktif (ROS) dan pemulung pyrrolidine dithiocarbamet (PDTC)*	• Affects adaptations in rat exercise using a treadmill such as different effects on rat body mass, resting heart rate, and skeletal muscle fiber type composition
7	[11]	Effects of treadmill training and spinning wheel training on rats	• Lowered metabolic risk in mouse models with decreased body weight, fat mass, size and increased mitochondrial biogenesis

However, forced treadmill exercise was found to induce stress and exacerbate neuronal damage in ischemic rats. Pre-exercise administration did not mitigate these adverse effects, as forced exercise led to stress responses in the rats [19]. To minimize neuronal damage during treadmill exercise, studies administered NLRP3 inflammasome inhibitors and microglial activation in MPTP mouse models of Parkinson's disease. Results indicated that treadmill exercise reduced nerve damage through the inhibition of NLRP3 inflammasome activity and microglial activation in Parkinsonian rats [12]. Additionally, the reactive oxygen species (ROS) scavenger pyrrolidine dithiocarbamate (PDTC) was found to influence adaptations to treadmill exercise. PDTC produced varied effects on rat body mass, resting heart rate, and skeletal muscle fiber type composition [16]. Lastly, treadmill and spinning wheel exercises yielded favorable outcomes in rats, including reductions in body weight, fat mass, and size, alongside increased mitochondrial biogenesis. These findings suggested that such exercises could mitigate metabolic risks in rodent models [11].

5. Conclusions

Many studies have utilized albino mice as test subjects and trained them using a treadmill. To control the treadmill's speed, several previous studies have supported innovative approaches that can inform the latest developments. The use of treadmills in research offers a valuable tool for studying the human heart, allowing experiments to be conducted indirectly by using rats to investigate drug dosages for heart disease patients. The treadmill's speed control is achieved through a PID control system, which is widely used due to its effectiveness and ease of application. PID control operates by minimizing the error between the current motor speed and the desired motor speed (setpoint). The input for this controller is the motor speed, measured using an encoder sensor. This measurement is then converted into units of meters per minute (m/min), providing a reference to ensure a well-functioning control system.

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Author contribution

Conceptualization: Nurbadriani, Melinda, Roslidar; Methodology: Nurbadriani, Melinda, Roslidar; Supervision: Nurbadriani, Melinda, Roslidar

Competing Interest

The authors declare that there is no any financial or personal conflict of interest with others.

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