International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-6 Issue-5, October 2016

Design and Implementation of Mimicking Robotic Neck Improving Hyper-Flexion/Extension Movement and Lateral Bending using Linear Motor for Force Requirement Improvement

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Abstract: This paper presents a humanoid robot that has been developed to mimic human neck movement that can support the actual weight of human head using linear motor while performing the four degrees of freedom of the human neck. Linear motor is preferred to be used because of its ability to produce high force and lift heavy-weighted objects. The paper describes details of the mechanical design, control system and the controller design. The system has been developed in Arduino IDE platform and LabVIEW robotics. To demonstrate the mimicking capabilities of the robotic neck, we present accuracy test results, and the implementation of closed-loop control on the neck.

Index Terms: Degree of Freedom, Humanoid Robotics, Linear Motor, Mimicking, Robotic Neck

I. INTRODUCTION

Humanoid robots are similar to humans and can carry out human-like movements. Several humanoid heads, which include the neck, have been developed based on a variety of mechanisms with capability to meet requirements. In the field of robotics, challenges to the new mechanical solutions arise with mimicking the human movement. Existing robotic neck lacks some aspects like degrees of freedom (DOF) and range of motion. Some humanoid robots exhibit only 3 DOFs of the neck ([1],[2]) and only supports lesser weight than of the actual human head. With the complexity of robotic neck as part of the robotic head, the interest in its innovation became a mainstream. In line with this, the proponents studied the latest development of mimicking robotic neck [3] and focused on achieving the desired response. Their paper presented a humanoid neck featuring a ball joint mechanism integrated with revolute-like mechanism to support the head with the mass of 5 kg and a movement sensitive controller that uses a potentiometer.

Manuscript published on 30 October 2016.
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Servo motors were used as actuators for the system. The robotic neck can exhibit a normal four degrees of freedom but there is some deficiency. Torque needed to support the actual human head weight is thoroughly calculated.

Insufficient value of torque for the servo motor which has been used as the actuator resulted to the inaccurate movement of the robotic neck and this became the drawback of their study. Based on their study, torque of the servo motors greatly affects the movements due to the weight compensation. With high torque requirement to support the head, in which servo motors available in the market did not meet, some degrees of freedom has high percentage error.

With the aim to meet the force requirement to mimic lateral bending and hyper-flexion/extension movement, the proponents introduced the idea of using new actuator [4] that is related to the human neck anatomy which best suits in the design and applicable in the robotic industry. Linear motor is preferred to be used since the design requires lifting heavy weight and this actuator produces high force. The only disadvantage of the linear motor is that force is inversely proportional to speed. With this, the proponents used a roller connected to the linear motor to make larger angle as it extends, thus having the degree of freedom to move faster.

To mimic the neck movements, critical designs are created and compared with the help of different studies. The paper provides details about the mechanical design, motor control and sensor system. The result of the performed tests are presented and discussed.

II. METHODOLOGY

Figure 1 shows an overview of concepts and ideas and the flow of the system that is involved in the operation of the whole system. The concept of producing a human-like movement of the neck involves the necessary movement that will serve as the input to the position sensor in the wearable controller. The sensor in the controller will then provide the signal to the microcontroller unit. The microcontroller unit will provide the precise process to be made in the system, in which it interpret, converts and sends out the signal coming from the sensor. Since the provided signal by the controller is variable, it is then converted in varying outputs that dictates the actual movement to be performed by the motor that interprets the movements of the neck.

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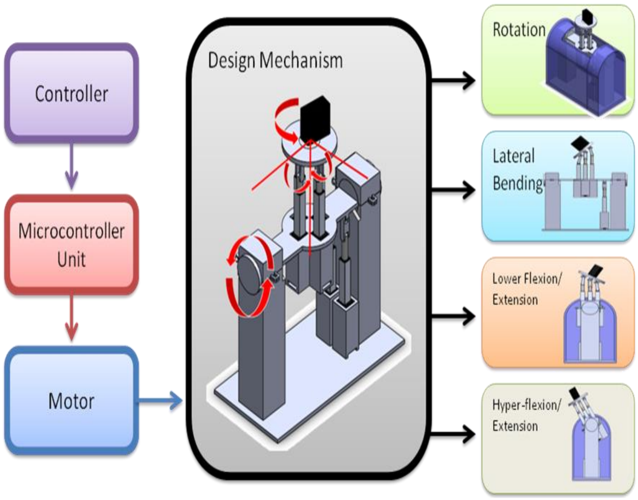

Figure 1. Conceptual Framework

A. *Designing of the Prototype and the Controller*

The system is composed of a robotic neck equipped with Arduino microcontroller and Motor Shield Driver, and actuated by three parallel linear motors and a servo motor. It is composed of a wearable device with four potentiometers to serve as an input sensor to know the angle produced by the user.

1. Representation and Dimension of Neck Bone

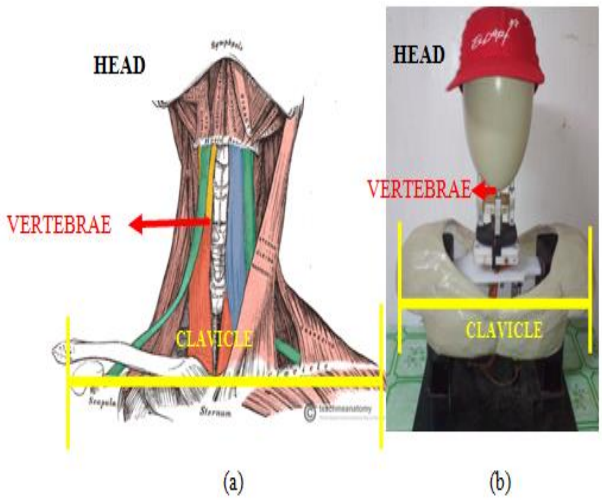

Figure 2. Comparison of (a) Human Neck Anatomy and (b) Robotic Neck

In designing the humanoid neck, design criteria were considered. The proponents based the mechanical design of the project on the skeletal structure and the muscles [5] responsible for each motion of the human neck. To be able to construct a design of the robotic neck, the proponents acquired all the necessary dimensions. The proponents based the dimensions of the robotic neck to the average size of a human neck. Based on the human neck anatomy, the proponents represented each muscles and bone according to its original structure as shown in Figure 2. Measuring the necessary parts of the human neck and head, the proponents created a robotic design using the gathered measurements as shown in Figure 3.

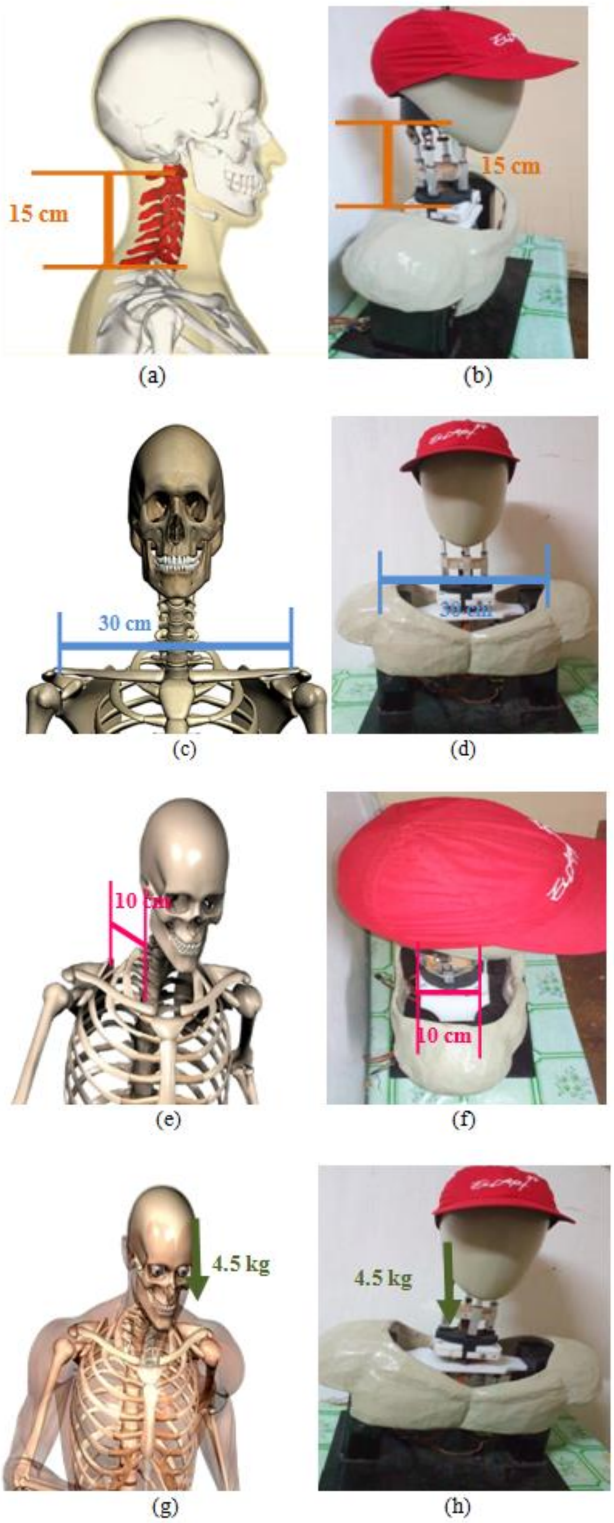

Figure 3. Dimensions of Human Parts and the Prototype (a) Human Neck Length (b) Robotic Neck Length (c) Human Shoulder Length (d) Prototype Shoulder Length (e) Human Shoulder Width (f) Prototype Shoulder Width (g) Human Head Weight (h) Prototype Head Weight

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2. Positioning of Actuators

Linear motor is applied to perform the hyper extension/flexion movement, lateral bending and atlanto-occipital flexion/extension movement. For the rotation, they use servo motor as the actuator of the movement. The position and orientation of the actuators were based on the human neck anatomy [6] as shown in Figure 4. To obtain human-like range of motion ([7],[8]) and structure in mimicking the movement of the human neck, proper positioning of actuators is applied.

Figure 4. Positioning of Actuators

3. Length of Stroke

To connect the linear actuator to the head, the proponents decided to apply a universal joint. For maintaining the neutral position, the proponents extended the motors at halfway lengths so that the connecting joints will be situated at parallel distances; the length of the joint used is measured 25 mm from the tip of the motor to the head.

In order to produce the movements of the robotic neck, the proponents considered the length of stroke that the motors must extend or retract in order to perform the necessary movements by using trigonometric equations and functions [10].

4. Force Requirement

The proponents considered the needed force required in the linear motor to support the weight of the head. In computing it, the proponents applied the concept of summation of forces given the load which is 4.5 kg and the dimensions of the prototype reaching the maximum of its range of motion.

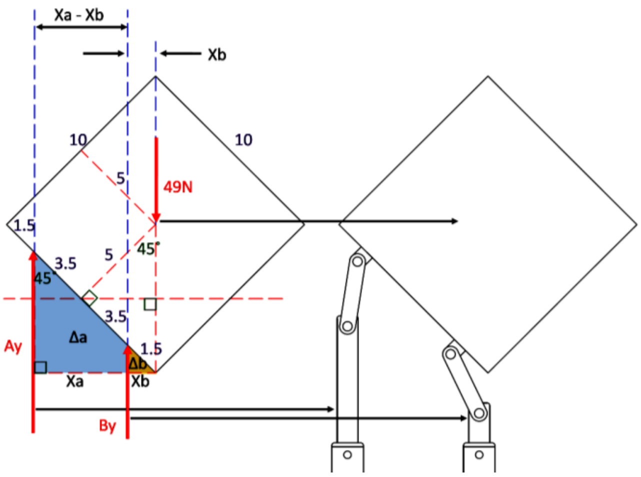

Figure 5. Representation of the Head for Force Requirement Computation

In the normal position of the head, its force 49N (5kg) is equally distributed to the four linear motors. However, when two parallel linear motors that correspond to a DOF of the neck moves, the force requirement for each motor changes. The other two linear motors in the middle are neglected since it served only as a bearing.

A_y and B_y represent the two linear motors holding the position of the head, and the head is represented by a parallelogram having a mass of 5 kg as shown in Figure 5. To solve the summation of forces, the proponents get first the distance between A_y, B_y and the center of gravity of the head using the trigonometric functions. Summing up all the pre-information gathered based on computation of materials, measurement and position of parts, the proponents determined the human neck anatomy and the position on each muscle that is responsible for each degree of freedom, acquiring knowledge on how to present muscles and bones in the neck. Solidworks aids the proponents in designing, visualizing and simulating the project before it is built and dynamic simulation in Solidworks shows how the project will function in the real-world scenario.

B. Evaluation of the System

1. Calculating the Percent Difference to know if there is an Improvement with respect to the Previous Study

For the evaluation, the proponents would want to know if there is an improvement for lateral bending and hyper-flexion/extension movement using linear motor for force requirement to support the head through the relationship between the robotic neck's position and the human neck controller's neck position given the different neck movement. To achieve the objective, the proponents compared the result of the previous study and the current study. The proponents monitor first the data using LabVIEW interface. The collected signal will be sent through a serial communication into the computer for the LabVIEW processing. The data are then converted into angular values in which these values will be evaluated through waveform chart. When the angle needed is displayed in the monitor, the percent difference is calculated to determine how close the human neck movement and the robotic neck movement are. Through this, they will know if the system has improved. If the percent difference between the two movements is less than 10%, then the actuator gives enough force to support the weight of the head. The proponents used this range of percent difference since they are improving the response of the previous study [3].

$$\%\ Difference = \frac{|E_1 - E_2|}{\frac{1}{2}(E_1 + E_2)} \bullet 100 \qquad (1)$$

where:

E_1 = angle produced by the controller

E_2 = angle produced by the prototype

2. Evaluating the Significant Difference between the Human Neck Movement and the Robotic Neck Movement

To determine if there is a significant difference between the human and robotic neck movement, angle produced by the human and the robot were used as data.

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The proponents set the significance level to the standard value of 5%. Knowing the area, they used the z-test table and found the critical value 1.96. The computed z value was the basis of the proponents if they will accept or reject the hypothesis.

$$z = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{(\sigma_1)^2}{n_1} + \frac{(\sigma_2)^2}{n_2}}} \qquad (2)$$

where:

z = z-test result
$\bar{x}_1$ = mean of the first group
$\bar{x}_2$ = mean of the second group
n_1 = no. of samples in the first group
n_2 = no. of samples in the second group
σ_1 = standard deviation of the first group
σ_2 = standard deviation of the second group

III. RESULTS AND DISCUSSION

A. Design of the Prototype and the Controller

1. Robotic Neck Design

To be able to construct a design of the robotic neck, the proponents acquired all the necessary dimensions. The proponents based the dimensions of the robotic neck to the average size of a human neck. The muscles and bones were represented by the actuators.

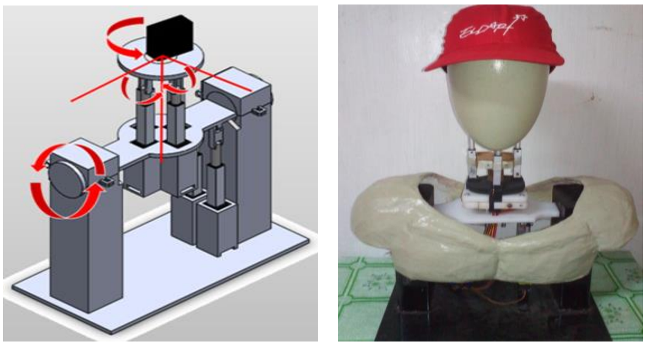
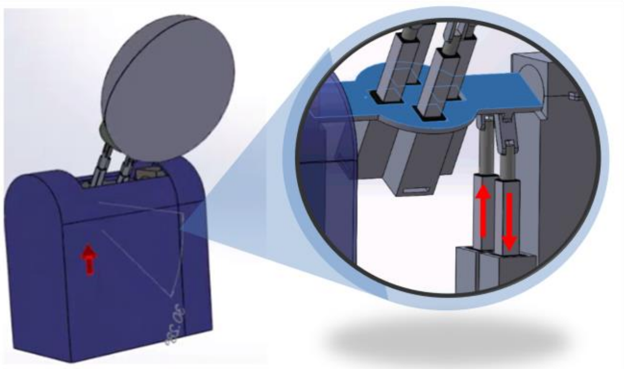
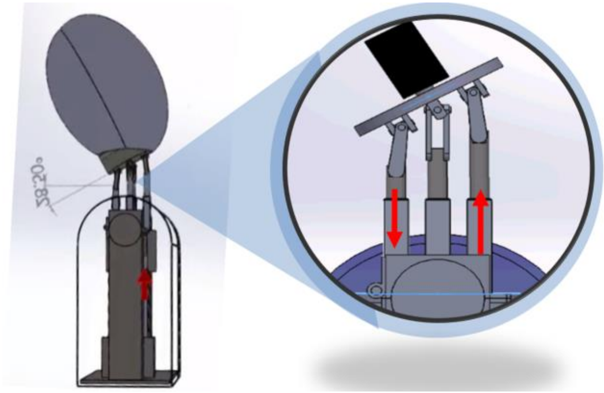


Figure 6. Final Design of the Robotic Neck

The over-all mechanical structure of the robotic neck after the proponents met the required specifications is shown in Figure 6. This design mechanism can do all the necessary neck movements considering the right placement of the actuators which is shown in Figure 7. The dimension of the design is not bulky making it close to the dimension of human neck.



(a)



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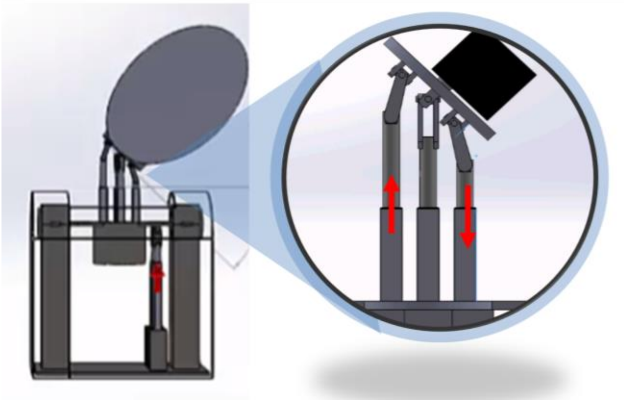

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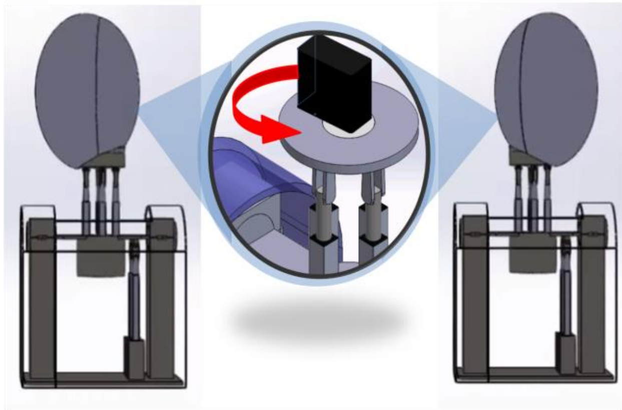

(d)

Figure 7. Placement of the Actuators (a) Parallel Linear Motor for Hyper-Flexion/extension (b) Parallel Linear Motor for Atlanto-Occipital flexion/extension (c) Parallel Linear Motor for Lateral Bending (d) Servo Motor for Rotation Movement

2. Control System

The proponents designed a control system which is capable to produce a required force to make angular movement while considering the weight of the object it supports. The proponents can control the length of extension and retraction of the rod of the linear motor to any desired position and the angle of the servo motor for the rotation of the head.

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The Motor Shield is a driver module for motors that was interfaced to Arduino to control the direction of the motor [9]. By simply addressing Arduino pins, it makes it very simple to incorporate a motor into the prototype. It also allows the controller to be able to power a motor with a separate power supply of up to 12V. When the resistance of the potentiometer of the controller reaches the resistance of the potentiometer of the linear motor, the motor shield will drive the motor thus; the proponents can maintain the desired position of the linear motor actuator to achieve the desired angle of the prototype.

If the value of potentiometer for the controller is greater than the value of feedback potentiometer for the prototype, the digital write pin for the switch of the motor turned high, thus making the two motors to switch on. The direction pin of the motors became high also causing the motor 1 to retract and the motor 2 to extend. Moreover, both motors are connected to supply and ground. One is in forward biased and the other is reversed.

But, if the potentiometer of the controller is less than the feedback potentiometer of the prototype, the motor is on and the direction pin is low causing the motor 1 to extend and the motor 2 to retract. Meanwhile, if the potentiometer of the controller is equal to the feedback potentiometer of the prototype, the motors will be off thus making no movement at all, regardless of the status of the direction pin.

3. Controller Design

Potentiometers were used as sensors for the controller to be worn. These are located and placed at the controller in their designated position based on the location of joints in accordance to human anatomy of neck movements.

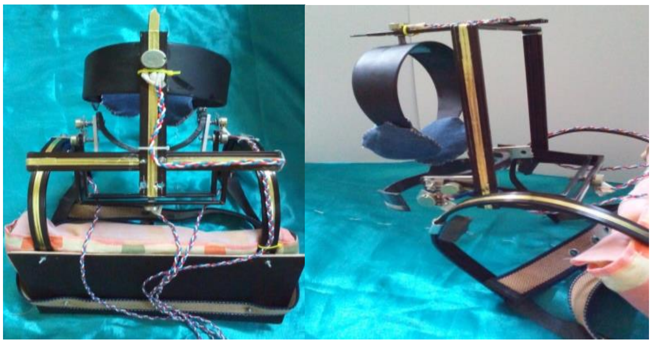

Figure 7. Wearable Controller

The proponents constructed the design of the wearable controller (as shown in Figure 7) that will satisfy the motion and also to locate the exact points as to where the position sensor must be placed on the controller which is illustrated in Figure 8.

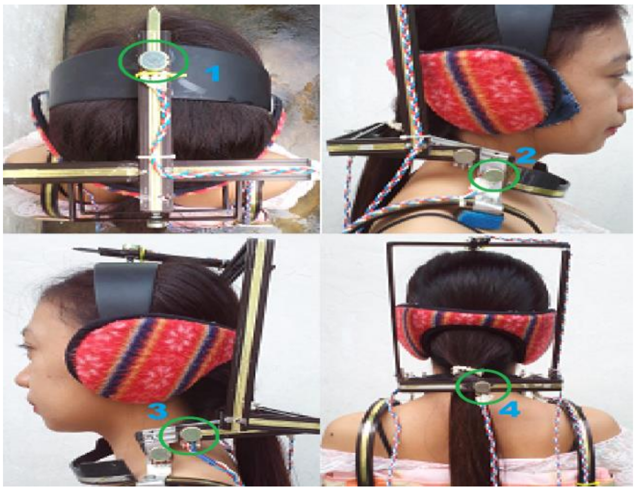

Figure 8. Position of Sensors at (1) Rotation (2) Lower-Flexion/Extension (3) Atlanto-occipital (4) Lateral Bending

B. Evaluation of the System

1. Comparison of the Previous Study and the Current Study

Robot that performs mimicking needs to compliment the movement of the user. Since the proponents improved the evaluation result of the previous study [3], they compare the results with the same method they used. After gathering the data, with the same number of trials of the previous study, the proponents calculated the percent difference of the average angle of each degree of freedom.

As shown in Table 1, the movement of the robotic neck compliment accurately in movement created by the human. Each movement gained an outstanding remark. In the previous study [3] shown in Table 1, they acquire 53.10% error for the lateral bending moving to the right and 46.36% error for the lateral bending moving to the left. Both have a fairly satisfying remark. They also gained 29.49% error for hyper-flexion with a satisfying remark. This section of their research is the part that the proponents of this study need to improve. The summary result on the lateral bending and hyper-flexion/extension movement of the current study is better than the previous study as shown in Table 1. It implies that the mimicking capability of the current study is better than the previous study. Moreover, it also shows that the actuators used by the system were able to produce the needed force to support the weight of the actual head while mimicking the movement of the human neck. Hence, there is small time delay in mimicking because of the force-speed inverse proportion issue of linear motors.

Meanwhile, lateral bending has the highest percent error in the current study with 3.60% and 2.99% moving to the right and left, respectively. Since this DOF produce the largest angle in all the degrees of freedom of the neck, the variation of center of gravity affect the stability of the head being carried. It implies that an object is in stable state if its center of gravity is at lowest possible position [11]. Overall, the percent difference shows that the system of this study has good mimicking capability in different degree of freedom provided by the neck.

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Table 1. Comparison of the Result of the Previous and Current Study

Movement	Percent Error the Previous Study (%)	Percent Error of the Current Study (%)
Lateral Bending (to the right)	53.10	3.60
Lateral Bending (to the left)	46.36	2.99
Atlanto-Occipital (Flexion)	2.08	2.45
Atlanto-Occipital (Extension)	5.66	2.81
Rotation (to the right)	7.58	0.61
Rotation (to the left)	5.07	-0.08
Hyper-flexion	29.49	2.34
Hyper-extension	4.26	1.51

2. Response of the System

Below are the data gathered coming from the tests and analysis made for the evaluation of the robotic neck with respect to the wearable controller with the mass of the head equivalent to 4.5 kg at different angular displacement. The proponents used LabVIEW interface to monitor the real-time response of the system. The response of the system is shown below.

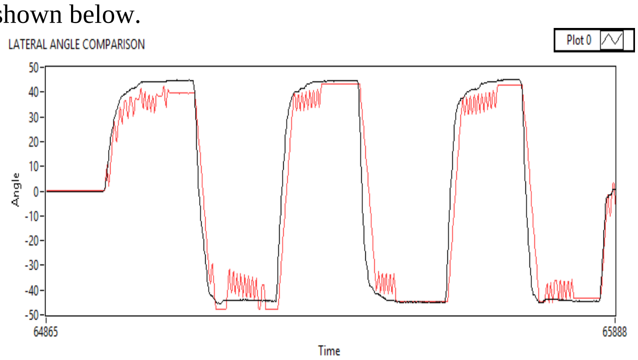

Figure 9. System Response with Lateral Bending at -45° (right) and +45° (left)

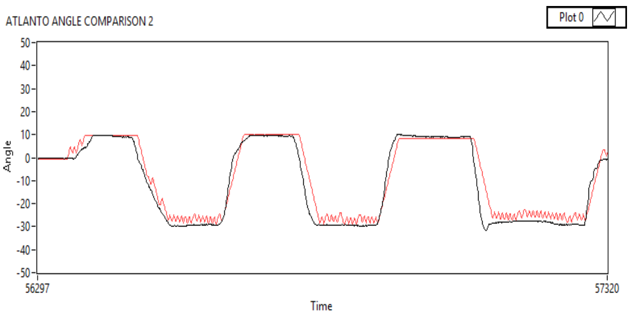

Figure 10. System Response with Atlanto-occipital at -30° (extension) and +10° (flexion)

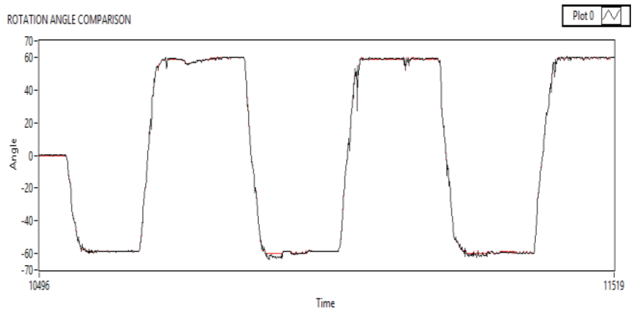

Figure 11. System Response with Rotation at -60° (right) and +60° (left)

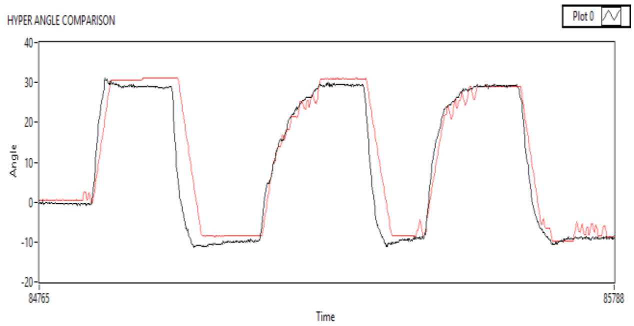

Figure 12. System Response with Hyperflexion/extension at +30° (flexion) and -10° (extension)

The figures show the relationship between the responses of the robotic neck with respect to the wearable controller relative to time in different degrees of freedom. The x-axis denotes the time in seconds, while the y-axis denotes the angle in degrees. The controller angle represents the controlled value of the test and the feedback angle represents the variable value of the test.

The graph shows the angle measured from the wearable controller (black line) and the robotic neck angle (red line). Some value of the human and robotic neck angle is almost equal or it coincides in the graph, when the user performed transition until it reaches the maximum desired angle, with lateral bending, atlanto-occipital flexion/extension, rotation and hyper-flexion/extension. However, in Figure 9 when the user steadies his neck at zero degrees angle or at rest and almost reaching the maximum angle, there is a small discrepancy between the two angles. It implies that the mimicking capability of the system is better when the user is performing dynamic motion and when it finally reached its maximum, than performing at rest or no movement. In Figure 10, it shows that the value of the robotic neck angle is slightly unstable compared with the human neck angle when the user is trying to reach the maximum angle. This is due to the unstable reading of the potentiometer in the controller that affects the signal to be fed in the feedback potentiometer of the prototype. Very small discrepancy can also be shown in Figure 11 which is the rotation. The prototype mimics the controller smoothly and with no time delay. Meanwhile, in Figure 12, the prototype mimics the movement of the controller but there is a time delay when moving a greater angle since the linear motor moves slow due to its inverse proportion with respect to force. Overall, the graph shows that the system has good response in different degrees of freedom.

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Table 2. Z-test Result for Varying Angle in each Degree of Freedom

Degree of Freedom	Human Neck Angle			Robotic Neck Angle			Result of Z-test	Comment
	n_1	$\bar{x}_1$	σ_1	n_2	$\bar{x}_2$	σ_2		
Lateral Bending-Left	100	35.2931	15.0104	100	31.7809	15.8996	1.6063	Null Hypothesis is Accepted
Lateral Bending-Right	100	39.0404	11.4937	100	35.6918	14.0506	1.8447	
Atlanto-Occipital Flexion	100	8.3454	2.3116	100	8.1692	4.2673	0.3631	
Atlanto-Occipital Extension	100	26.0144	7.5854	100	24.8123	10.4890	0.9287	
Rotation-Left	100	51.4025	15.6652	100	51.3900	15.6933	0.0056	
Rotation-Right	100	41.8583	23.9026	100	41.8300	23.8920	0.0084	
Hyper-flexion	100	23.7427	7.1973	100	21.9913	8.7202	1.5490	
Hyper-extension	100	2.3361	11.4027	100	0.4053	12.9817	1.1175	

Table 2 shows the number of samples (n_1 and n_2), the mean of the samples ($\overline{x_1}$ and $\overline{x_2}$), the standard deviation of the samples (σ_1 and σ_2) and the z-test result. All of the z-test result shows that z value is within the range of $-1.96 \leq z \leq +1.96$. Therefore, there is no significant difference between the robotic neck angle and human neck angle.

Gathering z-test results, the proponents observed that the rotation movement has the lowest value which is equal to 0.0056 and 0.0084 for moving left and right, respectively. This is because the center of gravity of the head is in neutral equilibrium, thus making the prototype mimic the human movement smoothly. It implies that this DOF is the best movement in mimicking robotic neck. Meanwhile, the largest value of z-test result is computed from lateral bending right which is 1.8447. It is primarily due to the variation of the center of gravity of the head carried by the neck. Since lateral bending makes the largest angle, the center of gravity became higher as it moves. This resulted to unstable equilibrium of the object and affects the mimicking using linear motor. In addition, potentiometer reading in the controller greatly affects the portion of the signal going to the feedback potentiometer in the linear motor.

IV. CONCLUSION

With the completion of necessary procedures, the proponents concluded that the design and implementation of the controller's critical parts were achieved through the use of the simulation and programming. The orientation and proper positioning of linear motors were thoroughly observed in creating a mechanism that resembles the human neck. The proponents achieved to place also the potentiometer at the right positions to execute right movements. Upon finishing the design of the controller, the proponents concluded that there is a limitation for angle produced by the rotation movement. It is observed that the controller affects that capability of the user to move on a certain angle. The controller is also limited to only one person. For the prototype, it can mimic the four degrees of freedom and can support the weight of the head in mimicking the neck movements.

The evaluation results in different DOF of the current study are all outstanding as indicated in the rating scale. The current study performed better mimicking capability as compared with the previous study. The previous study indicated that torque of servo motors they used greatly affects the movements due to weight requirement and it caused a high percentage error. With this study, the system created percent error less than 10%. It implies that linear motor is better to be used since produced a force that is able to support the weight of the head while performing its mimicry. Meanwhile, there is small time delay in mimicking because of the force-speed inverse proportion issue of linear motors. Overall, the mimicking capability of the system is good in all the DOF of the human neck.

The results of z-test in different degrees of freedom are all accepted. Thus, there is no significant difference between the user and the controller. It implies that the mimicking capability of the system is effective in different DOF. Lateral bending shows the largest value of the z-test result. It indicates that the system experienced difficulty in mimicking the movement of the human neck. It is primarily due to the variation of the center of gravity of the head carried by the neck. An object is in stable equilibrium if its center of gravity is at the lowest possible position. In addition, potentiometer reading in the controller greatly affects the portion of the signal going to the feedback potentiometer in the linear motor.

RECOMMENDATION

For the future work, since lateral bending produced higher error as compared with other degrees of freedom, the proponents recommended using larger area of the base since it also affects the stability of the head.

A design of parallel mechanism with less number of linear motors that can mimic all the degrees of freedom of the neck is also recommended.

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