

Design of Wearable Orthopedic Devices for Treating Forward Head Postures using Pneumatic Artificial Muscles and Flex Sensors

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Abstract – Forward head posture is one of the most common symptoms that modern people experience as sedentary life with prolonged use of computers or smart devices becomes more common. In this research, we propose a rehabilitation device that actively corrects the neck posture for treating forward head posture. The device is composed of a flex sensor and a pneumatic artificial muscle and a flex sensor that help monitoring and correcting the neck angles, respectively. Although PAMs have been traditionally used for the linear contraction force, we take advantage of the radial expansion to apply mechanical pressures to the neck in our device. Also, by combining the two elements in one system, it is possible to construct a feedback control loop for treating forward head posture. The proposed system was experimentally characterized, and the performance was compared with existing devices.

Keywords – healthcare robots, rehabilitation robotics, soft robotics, pneumatic artificial muscles, flex sensors

1. Introduction

Forward head posture (FHP) refers to the symptoms caused by a head posture tilted forward as the lower neck is flexed and the upper neck is extended [1]. In a healthy state, the earhole lies on the same vertical line with the shoulder bone, and seven cervical vertebrae are aligned with a C-shaped curve when viewed from the left. With a FHP, however, the spinal configuration tends to be straight or sometimes even curved to be a reverse C-shape when the symptom becomes more severe. It may cause a systemic disease on other body parts ranging from the temporomandibular joint and spine to the pelvis by breaking the balance of the whole body. Due to these complications, people with FHPs have a higher risk of fracture 1.7 times higher than healthy people, and the mortality rate is 1.4 times higher than the average [2].

For diagnosing the symptom of the FHP, Cobb's angle and craniovertebral angle (CV angle) are commonly used as criteria [3, 4]. Cobb's angle is defined as the angle between the superior plane of the superior end vertebra and the inferior plane of the inferior end vertebra. Those whose Cobb's angles are less than 35° are diagnosed as FHP [5]. CV angle is the angle of the direction of the tragus when the seventh cervical vertebra is set to be the origin of the coordinate. If this angle does not exceed 50°, it is diagnosed as FHP [6, 7].

Previously, FHP has been treated with various methods including chiropractic and orthotic therapies. While chiropractic corrects misalignment of the cervical

vertebrae by massaging, many therapeutic devices, such as craniomandibular applications and correction collars have already been introduced [8, 9, 10]. Chiropractic is merited since it offers perfectly customized therapies with favorable results. However, it is limited in that the therapy do not fully address the physical diversity of various people and require routine commute to the clinic. Hence, a wearable device that not only does not seriously interfere daily life but also is applicable to people with physical variances will be beneficial.

The goal of this paper is to discuss the main design criteria of wearable devices for treating FHPs and to propose prototypes following the criteria. Two main design criteria were identified, and two different types of devices were developed using pneumatic artificial muscles (PAMs) for physical correction of the symptoms, as shown in Fig. 1. The device was then integrated with a monitoring system composed of a flex sensor, in order to check the degree of the symptom. Finally, the proposed devices were evaluated by comparing with commonly used commercial devices. The advantage of our design is the light weight and the capability of addressing the physical variances of the users while maintaining the critical functions.



Fig. 1. Overview of Prototype 1 and 2. Rear view of (a) Prototype 1 and (b) Prototype 2. Side view of (c) Prototype 1 and (d) Prototype 2.

2. Design

2.1. Key Functions

Before designing, two key functions for FHP treatment were identified. The first is upward traction of the occipital region to keep the cervical spine erect and to secure the distance between the cervical vertebrae (Fig. 2-a). Since the cervical vertebrae tend to bend forward making a straight line (or sometimes a reverse C-shape) as the FHP develops, the neck and the head should be properly supported for the mobility and the recovery of the neck posture.

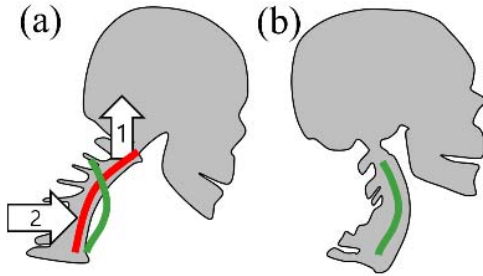


Fig. 2. (a) Forces in two directions needed in cervical vertebrae to correct FHP shown with red line. (b) Normal vertebral configuration after forces are properly applied.

The second is compression of the rear of the third and the fourth cervical vertebrae in order to directly recover the C-shaped curve of neck (Fig. 2-a). It should be noted that this procedure needs simultaneous performance with the first function (i.e. the upward traction of the occipital region) to prevent the neck and the head from being further bent forward, since it may cause aggravation of the symptom. The implementation of the second function is thus sometimes inhibited for those whose cervical alignment is already in reverse C-shaped curve. Due to this reason, we mainly focused on achieving the first function and regarded the second one as an additional requirement.

2.2. Actuator

In addition to the above key functions, the actuator should be flexible and stretchable and have many degrees of freedom to easily conform to the user's body. We excluded use of conventional electromagnetic actuators, such as motors, to reduce the weight of the system and vibration as much as possible.

Considering the above requirements, we selected a PAM as a main actuator [11]. Since PAMs could be made of lightweight and flexible materials and conform to 3D surfaces. Also, the flexibility of PAMs makes themselves adaptable to different body size of the users. Also, PAM can help reducing the number of actuators as it provides force in multiple directions by axially contracting and radially inflating simultaneously [12, 13].

One important property of PAMs to be considered in our design is that they are resistant to bending when activated. Since a PAM needs to apply forces to a curved

surface of the body (i.e. rear of the neck) in our application, it was segmented into multiple nodes to maintain the flexibility even with actuation. In this way, the entire body structure of the PAM can be bendable while each node can still contract axially and expand radially. However, the increased number of nodes will reduce the maximum contraction of the PAM although it will make the PAM more flexible. Hence the number of nodes needs to be optimized. To determine the number of nodes of the PAM whose length L is 310 mm, a couple of conditions were considered. First, the cross section of the human neck is circular, and the PAM only bends at the nodes, as shown with the black solid lines in Fig. 3. Since the device should embrace the entire neck to effectively apply forces, a chinrest will be placed at the front of the neck, and the two ends of the PAM will be anchored at the two ends of the chin rest.

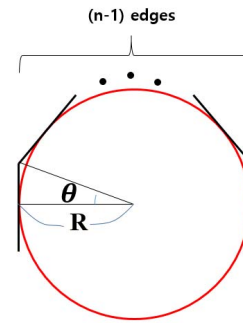


Fig. 3. Schematic of n -node PAM wrapping neck.

For the device to fully conform to the neck, the total length of the PAM should be larger than the minimum required length (i.e. the total length of the black solid lines in Fig. 3), which yields

$$L \geq 2R(n+1)\tan\theta \quad (1)$$

where R , n , and θ are the radius of the neck, the number of nodes, and the central angle of a tangent segment, respectively, as shown in Fig. 3. Equation (1) allows the device including the PAM and the chinrest to fully conform the neck. Following the statistics regarding average data of adults, we chose the neck circumference of male and female to be 380 mm and 330 mm, respectively, [14]. The cross-section of the human neck is assumed to be circular, and the neck radii for male and female are 60.5 mm and 52.5 mm, respectively. Numerically solving Equation (1) with each of the values, it turns out that n should be equal or larger than 3 for both male and female.

However, the contraction length of the PAM decreases as the number of nodes increases since the node locally inhibits contraction by preventing mesh from inflating (Table 1). It means that n should be kept as little as possible to preserve the contraction capability of the PAM. Therefore, considering both requirements, the optimal number of the node is 3, dividing the PAM into 4 segments.

Table 1. Total length of contraction and contraction loss with regard to the number of nodes.

n	Contraction length (mm)	Contraction loss (mm)
0	55	-
1	49	6
2	45	10
3	42	13
4	39	16
5	35	20

2.3. Sensors

In addition to simple physical correction, a real-time monitoring system that could warn the user of a bad posture was implemented by incorporating a flex sensor in the device. The CV angle was used as a criterion to determine FHP in the system, and the angle of the user's neck was measured to detect the correctness of the posture. A piezoresistive flex sensor (SEN-08606, Spectra Symbol) was used for measuring the angle and was characterized first, as shown in Fig. 4. The flex sensor was assumed to deform symmetrically in this case.

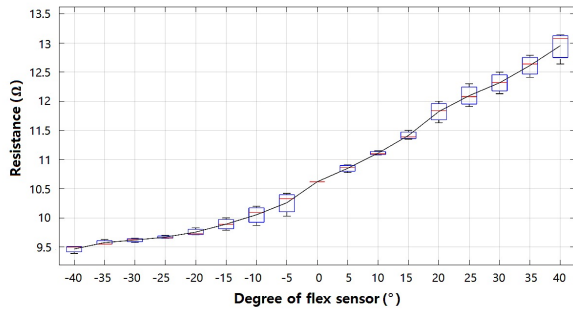


Fig. 4. Calibration result of flex sensor.

Fig. 5 and Eq. (2) show how flex sensor was applied to human body. When assuming the shape of flex sensor to be an arc of a circle, the triangle AOB is isosceles because line OA and OB are two tangential lines from same point, O. Then, $\angle BOC$ can be expressed by α , the angle measured by flex sensor, as shown in Eq. (2). Once more assuming that CV angle approximates to $\angle BOC$ since point C and O lie close to each other, CV angle is derived from angle measured by flex sensor.

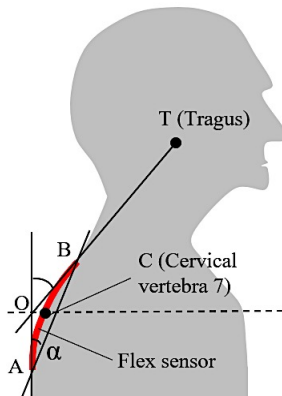


Fig. 5. Schematics of the flex sensor attached to the neck.

$$90 - 2\alpha = \angle BOC \quad (2)$$

α : Angle perceived by flex sensor

2.4. System Integration

The actuator and the sensor need to be integrated to consistently notify the patient of current posture and determine whether to activate the correction procedure. The operation algorithm of the system is shown in Fig. 6. After setting a default posture, the system detects the deviation of the current posture from the default posture. If the deviation exceeds a threshold level, it alarms the user and the posture correction procedure is initiated. There will be a slight intended time delay before the correction begins to eliminate the false alarm from accidental minor movements.

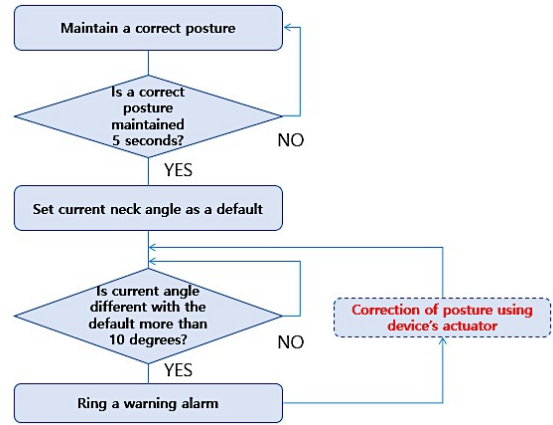


Fig. 6. Operation algorithm of the appliance.

3. Fabrication

Based on the functions and the requirements identified, two prototypes were proposed in this study. The main feature of Prototype 1 is that it delivers force in two directions only with one PAM. Using a linkage system attached to the nodes of the PAM, the contraction of the PAM pushes up the occipital region. On the other hand, the Prototype 2 generates only upward pushing force (function 1).

3.1. Prototype 1

The first prototype consists of a chin rest, a PAM, and a scissor linkage as shown in Fig. 7. The chin rest was designed to fix the position of the jaw on collarbones. The chin rest was made of rigid material to resist deformation from the force generated by the PAM. When a force is applied to the back of the neck, the chinrest will be the mechanical ground in this case. Also, it prevents the structure from compressing the front of the neck. The PAM was placed around the neck to perform two main functions (upward and forward forces) simultaneously. The upward force was generated using a scissor linkage connected to the central segment of the

PAM. When the PAM contracts, two spherical end-effectors pushes the occipital area up. At the same time, the reduction of the entire length of the PAM pushes the back of the neck forward by compressing the third and fourth cervical vertebrae.

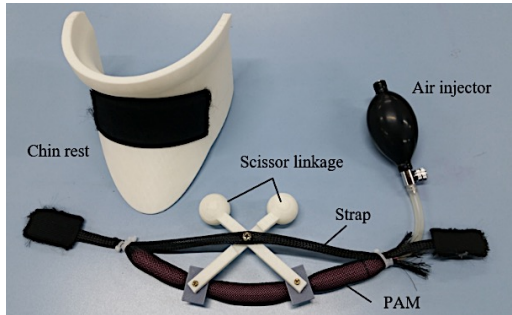


Fig. 7. Components of Prototype 1.

3.2. Prototype 2

Upon trying the first prototype, it turned out that the forward pushing force (Force 2 in Fig. 2-a) was more effective than the upward pushing force (Force 1 in Fig. 2-b). This is because that the forward force was realized only by the contraction of the entire PAM while upward force was generated by the contraction of the small middle section of the PAM. However, this is undesirable because the main posture correction is possible by the upward traction of the occipital region. Also, the lack of a vertical support for the linkage system made the entire device move downward instead of pushing the position of the head upward when the PAM was actuated.

For these reasons, a new prototype (Prototype 2) was devised with more emphasis on the upward force. In this prototype, a folding bellow type pneumatic actuator that conforms around the neck was employed, as shown in Fig. 8. In this prototype, the upward force was set to be the main target to achieve, and the back of the neck (the third and the fourth cervical vertebrae) was slightly pushed forward by a PAM located at the middle of the bellow actuator.

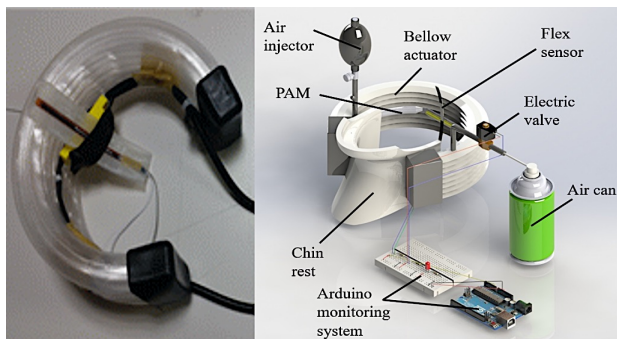


Fig. 8. Prototype 2 (left) and components (right).

4. Experiments

Experiments were conducted to evaluate the

performance of the proposed devices. Six measurement locations were selected to compare the performance of the prototypes with commercial products, as shown in Fig. 9. Pressures measured at locations 1 to 3 show how effectively the device applies upward forces, and pressures measured at locations 4 to 6 are related with forward forces. To process the data in real time, a microcontroller (Arduino) connected with piezoresistive pressure sensors (FSR 400, Interlink electronics) was used. The performances of the two prototypes and two commercial products (NTD-500 and NTD-1000, Jiangsu Medical Co., Ltd.) were experimentally compared based on the capability of delivery of forces to the six measurement locations.

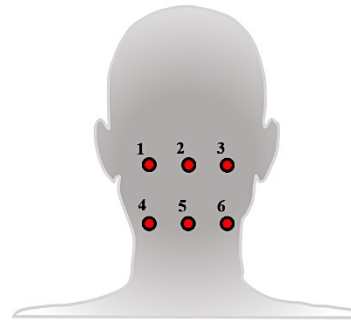


Fig. 9. Reference points of measurement marked on rear view of head.

The effect of the upward traction and the anterior compression of the cervical vertebrae was mainly of interests in the experiments. The force exerted on the back of the neck and the neck angle were measured at the same time under the following three conditions: i) only the bellow actuator was activated, ii) only the PAM was activated, and iii) both actuators were activated. The resulting data were analyzed using regression by setting the neck angle as a dependent variable and the forces applied to the cervical vertebrae and the occipital region as independent variables. The reliability of the regression model was also verified with a statistical significance test.

5. Results

In the first experiment, pressures at the measurement locations were recorded measured for the two commercial products and the two prototypes. Both commercial products showed capability of compressing the upper region (locations 1~3) and almost no pressure at the lower region (spot 4~6), meaning that forward pushing is not assisted at all, as shown in Fig. 10. On the other hand, Prototype 1 showed higher pressures on the lower region than on the upper region. Location 2 showed no pressure since the pressures were applied by the two end-effectors of the scissor linkage. Prototype 2 showed the best result showing high pressures on the upper region and well balanced force distribution within the same region. Since Prototype 2 had two different actuators for upward force and forward force, it also showed relatively high pressure delivery to the lower region.

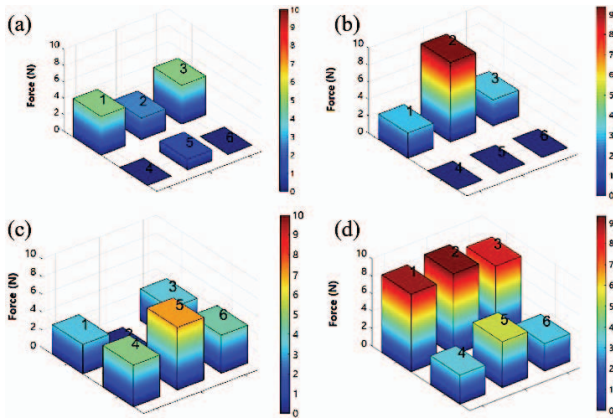


Fig. 10. Pressure distribution at measurement locations of the two existing devices and the two prototypes. (a) NTD-500, (b) NTD-1000, (c) Prototype 1, and (d) Prototype 2.

In the second experiment, CV angles and applied forces from the pneumatic actuators were measured and plotted for Prototype 1, as shown in Fig. 11. Only Prototype 2 was tested in this experiment since it showed much better performance than Prototype 1. Starting from a resting posture, the CV angle and forces applied to the occiput and to the cervical vertebrae were measured while air pressure was gradually increased. Fig. 11 shows that CV angle and forces at each region have a positive correlation with correlation coefficient 0.912 and 0.907, respectively. Though the strength of the neck muscles and the hardness of cervical spine depend on physical features of the user, at least the two key forces can be experimentally evaluated in this experiment.

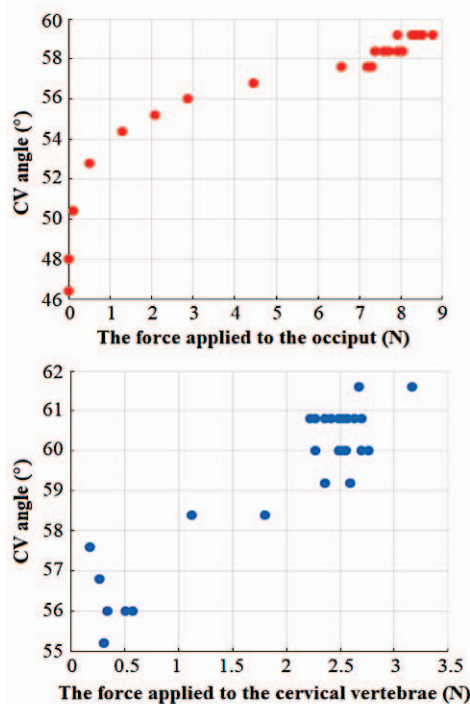


Fig. 11. Measured CV angle with varied upward forces (top) and forward forces (bottom).

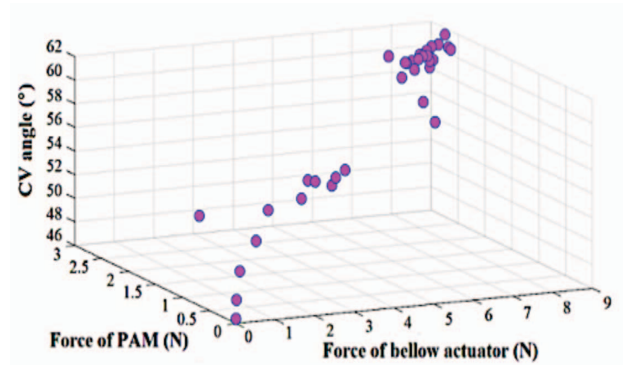


Fig. 12. Combined effect of forces exerted by the two actuators on CV angle.

Finally, we examined the interdependence of the forces exerted by the two actuators of Prototype 2. A first-order multi-variable regression analysis was performed, taking the CV angle as a dependent variable and using the forces from the two actuators as independent variables. Setting the forces exerted by the bellow actuator and the PAM were set as x_1 and x_2 respectively, and the CV angle as y , the regression model is as the following:

$$y = 51.7 + 0.00975x_1 + 0.00274x_2 \quad (3)$$

Since the coefficients of x_1 and x_2 are both positive, the device has a positive effect with force in both directions. Table 2 shows the result of R^2 test, F test and T test.

Table 2. Statistical significance test regarding the performance of the prototype

R^2 test ($0.9 < R_{adj}^2 < 1$)	$R_{adj}^2 = 0.910$	pass
F test ($F_{0.05,2,19} = 3.5$)	$F_0 = 43.1$	pass
T test ($t_{0.025,23} = 2.0$)	(for b_0) $t_0 = 77.8$	pass
	(for b_1) $t_0 = 2.50$	pass
	(for b_2) $t_0 = 0.240$	fail

In Table 2, the adjusted reliability value (R_{adj}) shows that the error for the model is sufficiently small, which supports the reliability of the model. F test also advocates the reliability of the regression model since F_0 well exceeds the reference value $F_{0.05,2,19}$. For the T test, cases for b_0 and b_1 passes the test while b_2 does not. It means that the upward traction of the occiput by the bellow actuator contributes to the entire correction more than the pressure to the cervical anterior by the PAM. However, it can be concluded that the symptom-based customization is proved to be possible because the effectiveness of the device varies independently with each of the forces when both actuators are working together.

6. Conclusion

In this study, we propose designs of orthopedic devices using PAMs to correct and monitor FHP symptoms. Unlike conventional treatments of FHPs, our orthopedic systems have integrated monitoring systems. With the proposed devices, one would be able to correct the disoriented posture in a daily life while monitoring the change of the posture at the same time.

Specifically, by regarding seven cervical vertebrae as one combined deformable body, two target motions for posture correction could be generated: the upward traction of the occiput and the forward traction of the third and fourth cervical vertebrae. Two different designs were tested in our study. One is based on a PAM and a linkage system, and the other is made of two different pneumatic actuators. While the first prototype was able to deliver forces in multi-directions, the force in the primary direction was not strong enough. To improve the efficiency of force delivery, the second prototype was designed using a bellow type pneumatic actuator and a PAM, which was able to apply a strong force in the primary direction. It was experimentally compared with commercial products and showed better performance.

Although this study showed useful result for addressing FHP symptoms, the design needs to go through multiple iterations and also subject testing to be more practical. Also, development of an automated system that can determine the severity of the symptom and the level of actuation will be another area of future work.

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