공학석사학위논문

상지 웨어러블의 압력 감소를 위한 힘 프로파일과 모멘트암 구조 개발

Reduction of Compression in Upper Body Wearable Robot using Passive Actuator and Moment Arm Structure

2019 년 2 월

서울대학교 대학원

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Reduction of Compression in Upper Body Wearable Robot using Passive Actuator and Moment Arm Structure

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As many occupations such as car mechanics, orchardists, and laparoscopic surgeons require prolonged and repetitive use of their upper body, the prevalence of musculoskeletal disorder in shoulder is particularly high among these professionals. However, a weight compensation of upper extremity can reduce the burden borne by the shoulder. There have been several researches on wearable solutions with rigid structures that reduce the upper limb fatigue, but a user can further benefit with minimal intrusion of workspace and safer interaction when the soft counterpart is applied. As tendon actuation is one of the popular choices among soft wearable robots, the intrinsic issue of axial compression due to the size of the moment arm needs to be addressed. In this paper, a method to reduce the tensioninduced compression in upper body soft wearable device is proposed. Unlike the constant moment arm modelling assumed in the previous upper limb wearable device, the added structure on the shoulder increases the moment arm, thus significantly decreasing the tension and compression on anchored region while generating the equal amount of torque. The proposed quasi-zero stiffness mechanism generates a steady tension force which produces resulting sinusoidal torque when coupled with the new moment arm structure.

Keywords: Weight Compensation, Passive Mechanism, Compression, Moment Arm, Quasi-Zero Stiffness

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Chapter 1. Introduction

The use of upper limb is indispensable in carrying out many activities of daily living. Simple tasks such as drinking and opening doors all require the mobility of upper extremity. However, some professionals use their arms more repeatedly and extensively because of their occupation-specific settings. Car mechanics, orchardists, and laparoscopic surgeons are few examples of people with tasks that require prolonged use of their upper body [1]-[3]. Assuming a fixed angle of the elbow, a gravity compensation of upper limb can be modelled as an inverted pendulum as shown in Figure 1.

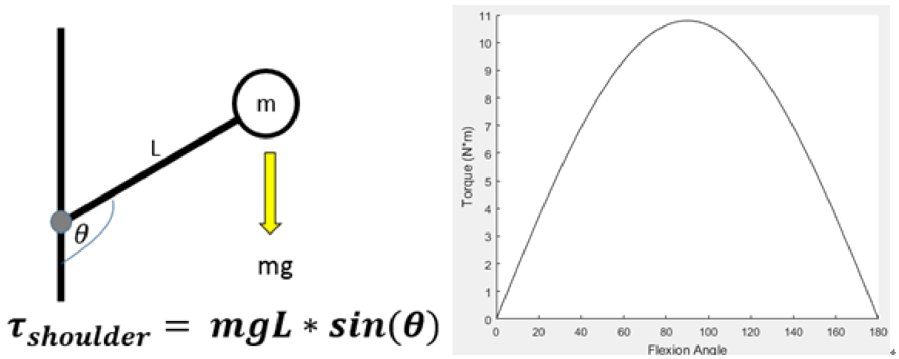

Figure 1. (Left) Human arm is modelled as an inverted pendulum. (Right) The required torque of upper limb weight compensation can be approximated as a flexion angle theta dependent function.

Because of fatigue inducing nature of these occupation related activities, it is important to protect such workers from overexertion of their muscles [4], [5]. Number of researches on wearable robots has been carried out to reduce the burden mainly on the shoulder joint. However, majority of these assistive devices use rigid structures to generate torque on the joint [6], [7]. While these devices generate the sufficient amount of force to fully compensate the arm weight, further improvement in reducing workspace intrusion and enhancing safer interaction with the device is achievable with soft counterpart.

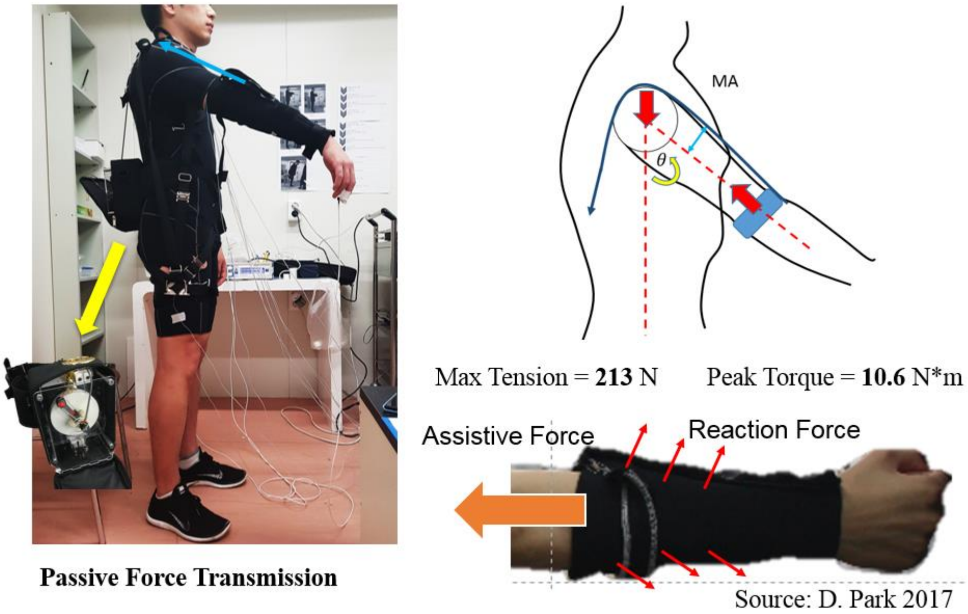

Figure 2. (Left) Existing upper limb assistive soft wearable robot with no additional moment arm structure [8]. (Right) Due to moment arm size, tension and compression is high at anchored locations such forearm and shoulder.

Despite the benefits offered by choosing soft materials over rigid materials, the intrinsic issue of soft wearable robot needs to be properly addressed. When the soft wearable robot is actuated using a tendon, one of the popular choices of force transmission in soft robotics, the size of moment arm is practically smaller compared to the rigid wearable robots as shown in Figure 2 [8]. As a result, greater amount of tension force is required to generate the equal amount of torque [9]. While completely eliminating the axial force due to tendon is very challenging, minimizing the harmful effect of compression can be achieved with proper moment arm design and the force generating mechanism.

In this paper, the Quasi-Zero Stiffness Mechanism is proposed as a force generating passive actuator. The passive mechanism has been selected as a source of restoring force because while active motor powered system can generate higher force, it is also drawbacks such as added weight, increased chance of malfunction, and increased complexity of motor control [10].

The proposed mechanism coupled with the new moment arm design generates a sinusoidal torque profile (Figure 1) at the main range of motion of workers, which is between 40 and 120 degrees in flexion of shoulder [11], [12]. Therefore, proposed mechanism and moment arm design achieve torque assist on the shoulder joint with decreased compression on anchored regions compared to the previously developed upper body soft wearable robot.

Chapter 2. Design of the Moment Arm Structure

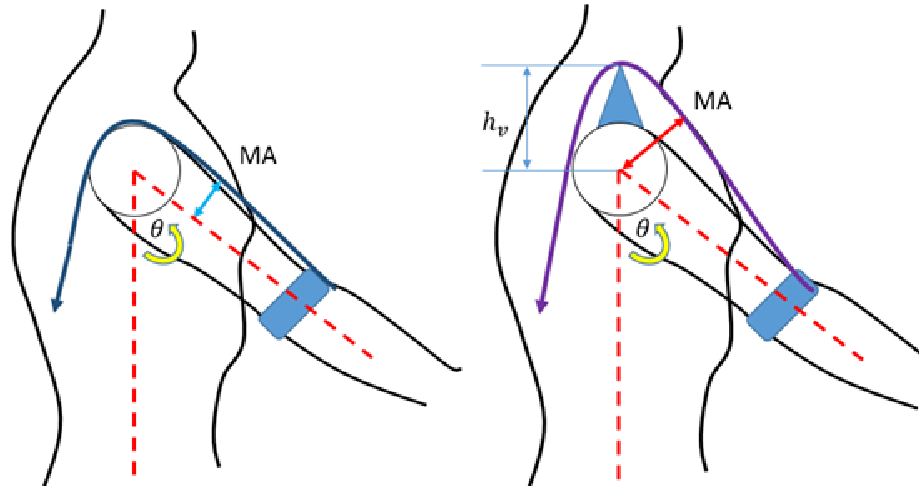

Figure 3. (Left) Moment arm of previous wearable robot is assumed as a constant value of human arm thickness. (Right) Proposed moment arm design has increased moment arm value due to added height of the shoulder mounted structure.

The moment arm of the previous soft wearable robot for upper body weight compensation developed by the BioRobotics Lab at Seoul National University assumes a constant moment arm of the actuating tendon of 50 mm (Figure 3, left). When the tendon is closely positioned on the arm regardless of the flexion angle of the shoulder, it is reasonable to assume that the moment arm value does not vary significantly to affect the resulting torque. This approach yields a convenience in designing a tension generating mechanism as both required torque and the corresponding tension are sinusoidal shape based on the proposed weight compensating objective.

However, because the moment arm is equal to the arm thickness in the aforementioned wearable device, the tension required to generate a given amount of torque is inevitably high. As a result, greater tension leads to greater compression at the anchor points such as arm sleeves and shoulder. Because the wearability and comfort of the wearable robot are important requisites, this issue needs to be addressed. To achieve lower compression applied on the body, the structure that increases the moment arm and the force generating mechanism have been developed in this research.

The greater the moment arm, the lesser required tension becomes. However, there is a limitation on increasing the height of the moment arm due to practical reason. Ideally, the force applied perpendicular to the axis of the arm will generate the most torque when the equal amount of force is exerted. Yet, such device will require bulky structure which defeats the purpose of a soft wearable approach. Thus, a selection of moment arm height has been conducted with the criteria that meets both practicality and performance.

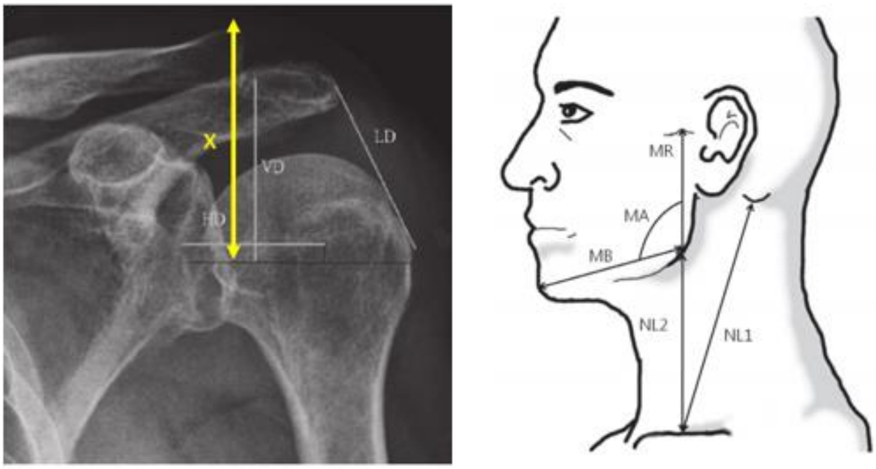

Figure 4. (Left) Distance from the shoulder joint to the surface of the shoulder is calculated based on the radiograph of upper limb [13]. (Right) Neck Length is considered based on the average distance NL2 measured among the patients [14].

As mentioned, greater moment arm is desirable in theory, but compactness and usability should not be neglected. For such reason, the proposed moment arm structure is designed based on the anatomy and the concept of minimal workspace intrusion. The vertical distance from the clavicle to the chin is 92 mm as shown in Figure 4 [14]. Because the real working condition is dynamic and unpredictable, the moment arm structure on the shoulder should not intrude the performance of tasks. Thus, a conservative value of 55 mm has been used to ensure the effect of tension and compression reduction by approximately 50%.

Figure 5. (Left) The side view of the overall wearable component of the device. (Right) Rear view of wearable component and actuator. A bearing is embedded so that horizontal movement of upper body will not cause derailment of the force transmitting tendon.

Adding the 55 mm of moment arm height and the vertical distance from the Glenohumeral joint to the shoulder adds up to total of 110 mm, which is twice the value of the previous wearable device. The addition of height with a structure on the shoulder is intuitive, but analyzing its moment arm based on the flexion and extension of shoulder is more challenging. As the tension is torque divided by the moment arm, the tension model changes depending on the moment arm model assuming the torque profile is fixed. Therefore, a behavior of the proposed moment arm structure is analyzed so that the required tension can be built based on the modeling.

If the shoulder joint is assumed as a sphere and arm as a cylinder, the moment arm can be calculated as a function of flexion angle theta. As the thickness of the arm, the distance from the joint to the anchor point, and vertical distance from the joint to the structure are constant, the elongation of the force transmitting wire and the size of the moment arm can be derived. Plotting the moment arm as a function of flexion angle theta, it is evident that the moment arm is approximately sinusoidal shape. From this profile, a derivation of required tension is possible with a sinusoidal required torque.

Because the value of moment arm is no longer assumed as a constant, the shoulder flexion angle dependent moment arm value is calculated based on the model (Figure 6, 7).

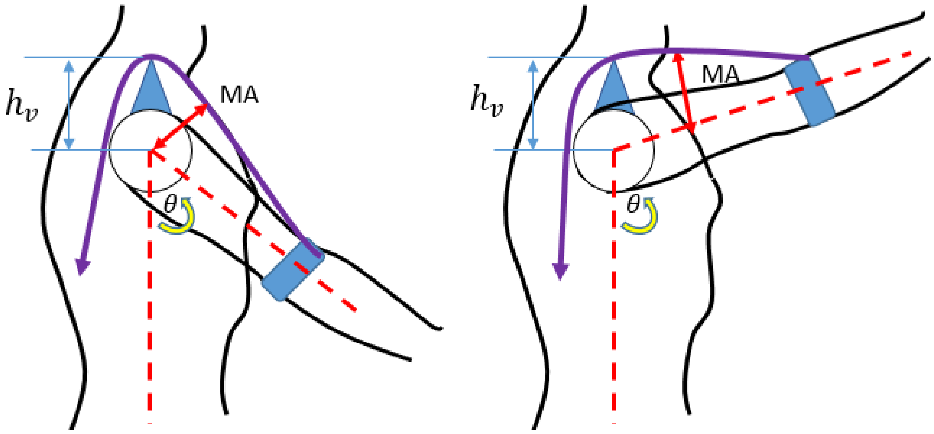

Figure 6. Because the moment arm value changes as flexion angle changes, the angle dependent moment arm value is calculated based on the simple model shown in the following figure.

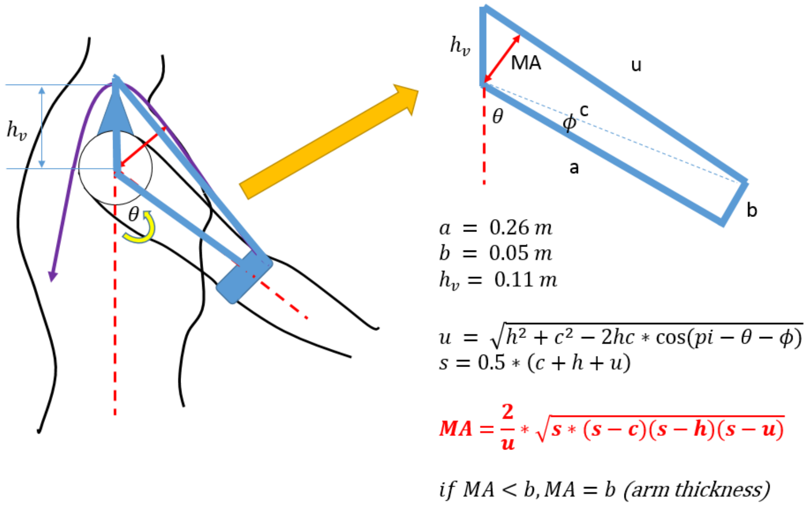

Figure 7. The moment arm value is calculated based on the simplified model of the human upper body. The minimum value of the moment arm is the arm thickness itself.

The value of moment arm is calculated based on the parameters of human body measurements. a is the distance from the shoulder joint to the anchored point on the arm while b is the radius of the arm at the anchor point when the arm is assumed as a cylinder. h_v is the distance between the shoulder joint and the top of the moment arm structure. u is the current length of the tendon. With these given values, the moment arm is calculated as a function of theta (Figure 7).

Chapter 3. Force Generating Mechanism

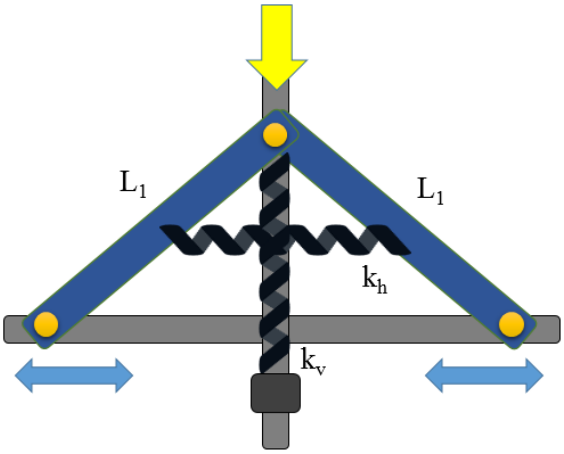

Figure 8. Quasi-zero stiffness structure schematics. Horizontal spring and vertical spring each generates negative and positive stiffness of the structure. Combining these two, a quasi-zero stiffness can be tuned based on the required force profile.

Since a tension force is a required torque divided by a moment arm, it is possible to calculate the required tension of the actuating system knowing the torque and the moment arm. The sine torque divided by the approximately sine moment arm leads to nearly constant required tension force.

A constant force can be generated with a constant force spring. However, there is a critical issue using such spring. The required force specification of full gravity compensation in the proposed device is between 110 N and 220 N while most compact constant load springs generate force below this requirement. It is more suitable to design a Quasi-Zero Stiffness Mechanism using a structural design as it allows more freedom to change parameters and tune the behavior of the output force.

Also, because the required tension is not perfectly constant, it is useful to have a design that can change the slope of the stiffness easily. To meet this need, a combined structure of negative stiffness and positive stiffness has been developed. The positive stiffness refers to a traditional linear spring under either compression or tension. The parameter that can be changed is the spring stiffness itself. Though no additional structure is used on the positive stiffness part, it is a necessary component that generates desired tension force when coupled with the negative stiffness structure.

The negative stiffness also utilizes the linear spring as a component, but its key traits come from the geometry of rods that are connected by a spring [15]. As shown in the Figure 8, a rod of length L1 is symmetrically placed. As displacement is made in downward direction, the reaction force of the structure linearly decreases. The "negative" stiffness does not mean that the direction of the reaction force opposite to a linear spring, instead, the size of the force decreases as the displacement increases. Such behavior is realized due to the structural design of the negative stiffness mechanism. As the horizontal spring attached on rods elongate, lesser force is converted to the vertical force because of the angle of two rods approaches parallel position.

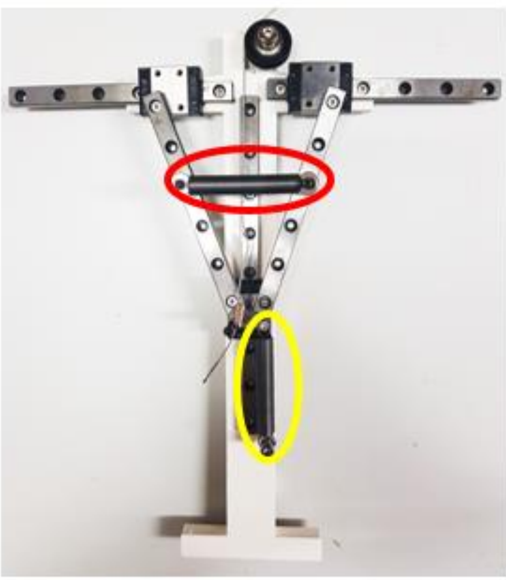

Figure 9. Quasi−zero stiffness structure top view. The horizontal spring marked with red ellipse contributes to negative stiffness while the vertical spring marked with yellow ellipse act as normal spring with positive stiffness.

Combining these two independent spring configurations, the quasi−zero stiffness can be achieved. The resulting generated force has a flat structural stiffness and can be tuned with increasing or decreasing the stiffness of springs in one or both parts. As required tension is nearly flat, but not perfectly constant, it is important to be able to adapt to different designs of the moment arm structure.

Chapter 4. Evaluation – Part 1

The evaluation of force generating mechanism combined with the increased moment arm height model has been evaluated using MATLAB plots.

First, the accurate matching of sinusoidal torque generation by the proposed Quasi−zero stiffness mechanism has been verified (Figure 10). The maximum error between the proposed mechanism and the target profile in main range of motion of workers is about 10.7%. As the error decreases near the region of flexion angle 90 degrees, it is noticeable that torque generation accuracy is acceptable and performs especially well at the range where torque support is needed. This verifies that the Quasi−zero stiffness mechanism coupled with the added height of the moment arm satisfies the objective.

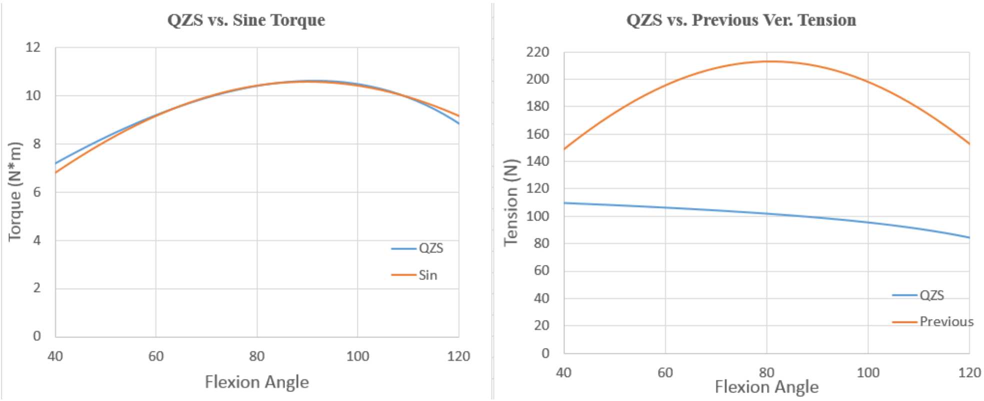

Figure 10. (Left) Quasi Zero Stiffness Comparison with Sine Torque

(Right) Tension Comparison with the Previous Passive Actuator

Another important evaluation is comparing the tension of the passively actuating system with the previous force generating mechanism. The Figure 10 shows the difference in required tension when the same peak torque is generated. The decrease in tension is up to 47% at the current tension generating mechanism compared to the previous passive actuator. The peak tension of quasi−zero stiffness is around 113 N, while the previous version requires 213 N in the shown range of motion. At 80 degrees flexion of shoulder, the tension of new mechanism is less than half of the previous mechanism. Considering that the workers mainly work within these range of motion, the effect of tension reduction is especially important.

The reduction of tension by nearly half the original value can be attributed to the increased moment arm of the system. However, a selection of tension generating mechanism that generates sinusoidal torque when coupled with the new moment arm structure has also been a challenge. As shown in Figures 10, the new device both satisfies accurate generation of sine torque and significant decrease in tension that leads to axial compression force on the anchor point on the sleeve.

Chapter 4. Evaluation – Part 2

Figure 11. (Left) The experiment setup with no MA structure. The compression is measured with Novel pressure pad placed on top of the shoulder of the mannequin. (Right) The experiment setup with the proposed MA structure. Same setup is applied except for the addition of moment arm structure on top of the shoulder.

To validate the change in compression on the anchored region when the moment arm structure is used, the experiment has been conducted using a Novel Pressure Pad (Figure 11). As expected, the distribution of the pressure became more even when the moment arm structure was mounted on top of the shoulder. Without the moment arm structure, the concentrated compression on the shoulder due to the passing tendon is observed as shown in the Figure 12 (left). On the contrary, the Figure 12 (right) shows that when moment arm structure is applied, the average pressure drastically decreased by the 75% (Table 1) because of both design of the flat surface and the increased height of the moment arm.

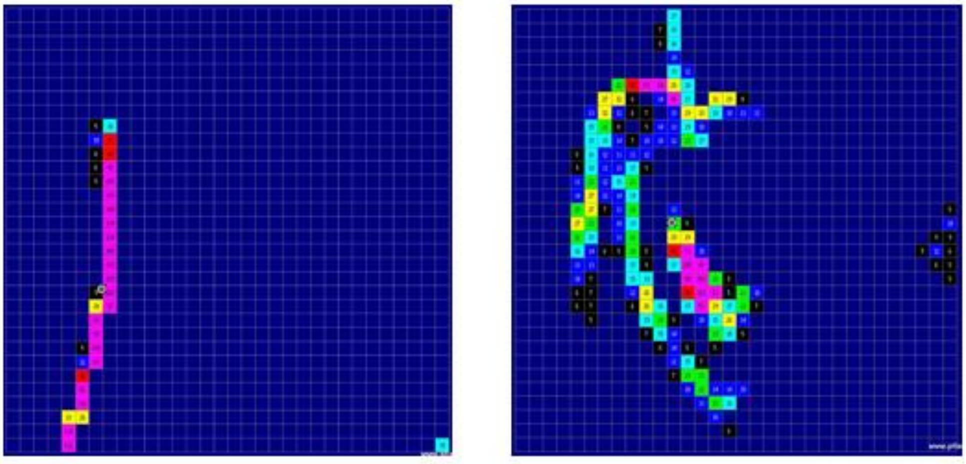

Figure 12. (Left) Pressure distribution on shoulder with no MA structure. The pressure is concentrated along the tendon path with higher average pressure. (Right) pressure on shoulder with the MA structure. The pressure is more distributed and peak value has decreased as well.

The peak pressure also decreased when the moment arm structure has been used. From 150 kPa of peak value in the previous version of soft wearable robot, the peak pressure of 121 kPa has been observed, which is 20% decrease in peak pressure value.

Version	Tension	Avg. Pressure
Previous Model	40.2 N	73 kPa
New MA Model	24.7 N	18 kPa

Table 1. Tension and Average Pressure Comparison

As shown in the table 1 in the previous page, a required tension to fully compensate the weight of the mannequin arm at flexion 90 degrees has decreased by 39% while the average pressure has decreased by 75% compared to the previous model without the moment arm structure. The force has been measured with push−pull gauge at static condition for both setup.

Chapter 5. Conclusion

A soft wearable robot has both advantages and disadvantages compared to rigid exoskeletons. To fully exploit its advantages, drawbacks need to be resolved. Weight compensation of upper extremity via tendon actuation has had generally higher axial compression due to the usage of pulling tendon. To improve the issue of discomfort on the anchored region where the force is applied, an increase in moment arm and the corresponding force generating mechanism have been introduced in this paper.

The proposed moment arm is made to be minimally intrusive to the workspace. Further increasing the structure height may reduce the required tension at the cost of bulkiness. The average neck height has been used as a guideline to choose the height of the moment arm structure. The passive force generating actuator has two components acting as one. The negative stiffness and positive stiffness structures interact as a tunable quasi-zero stiffness mechanism. It is preferred to a constant force spring as the force specification require larger force to fully compensate the weight of the human arm.

A reduction of tension by 47% when generating an equal amount of torque is a notable improvement, however, further benefit can be studied by analyzing the pressure distribution on anchored body parts. In the future, an evaluation of difference in discomfort level at different body regions will also be valuable in improving the design of the wearable component of the device.

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국문 초록

상지 웨어러블의 압력 감소를 위한 힘 프로파일과 모멘트암 구조 개발

상체는 거의 모든 작업에 쓰이며 특히 많은 직업군에서 더욱 활발히 또는 반복적으로 사용된다. 자동차 정비공, 과수원 농부, 그리고 복강경 수술의 같이 상지의 다양한 움직임을 장시간 사용하는 직업군에서는 특히 작업으로 인한 어깨의 부상이 잦다. 해당 문제를 해결하기 위해 팔의 무게를 보상해주는 메커니즘을 적용 할 수 있다. 입는 형태의 로봇을 통해 팔의 무게로 인한 관절의 부하를 줄이려는 시도가 여럿 있어 왔으나 해당 목적의 대다수 로봇들이 단단한 소재를 사용하기 때문에 무게나 부피로 인해 착용감이 좋지 않거나 소형화의 필요성이 제기되고 있다. 이러한 문제들을 해소하기 위해 최근에는 유연한 소재의 착용형 로봇들이 개발되고 있으나 다른 소재를 사용함으로써 발생하는 이슈들이 존재한다. 소프트 웨어러블 로봇에서 자주 사용되는 와이어 방식의 구동은 구조적 특성상 비교적 작은 모멘트암을 갖게 되어 신체에 압박을 주는 문제가 발생한다. 이에 대한 해결책으로 해당 연구에서는 모멘트암의 크기를 증가시키고 그에 상응하는 수동형 힘 발생 메커니즘을 개발하였다. 모멘트암을 작은 상수값으로 가정하던 기존 소프트 웨어러블과 비교하여 39%의 장력 감소와 75%의 평균 압력 감소를 실험을 통해 검증하였다. 결과적으로 동일한 토크 보조를 어깨에 전달하는 동시에 인체에 가해지는 압박을 줄이는 방식을 제시하였다.

주요어: 중력 보상, 수동형 메커니즘, 압박, 모멘트암, 준 제로 강성