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A SOFT WEARABLE ELBOW SKELETON FOR SAFE MOTION ASSISTANCE BY VARIABLE STIFFNESS

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ABSTRACT

Wearable robots could provide external physical assist, contributing to the well-being of elderly or disabled users in accomplishing tasks or therapeutic procedures. However, closely integrating robot dynamics into human activity demands for safety, pleasance and effectiveness simultaneously, requiring both strength and compliance. Soft robotics is generally regarded as a suitable alternative to rigid motor-based actuators for their light weight and passive compliance. However, existing approaches either have predetermined and/or limited passive compliance, or have moderate payload or motion range. While proven very successful in hand actuation in terms of various robotic gloves, their fundamental limitations restrict further expansion to driving other human body parts with higher demands in payload and speed. Previously we have developed an origami soft robotic joint with high torque, customizable dimensions and motion range. In this paper, we report the most recent results on controller development and wearable system integration of the proposed soft actuator in achieving excellent variable-stiffness compliant performance with inherent safety. Using the newly proposed controller, we demonstrate that a higher stiffness leads to quicker passive recovery than human's normal reaction, suitable in stabilizing common object; while a more submissive configuration, represented by a lower stiffness, could delay the submissive interaction time allowing for a more delicate control of the dynamics of the interaction port with further involvement of human commands, suitable for objects requiring smoother dynamics like preventing a cup of coffee from sloshing. The proposed control strategy and framework has been implemented in a 3D-scanned, 3D-printed wearable robot with elbow actuation, to demonstrate the advantages and new features through experimental results.

Keywords: Wearable, Variable stiffness, Soft robots

1. INTRODUCTION

The rapidly growing need for safe, effective and comfortable physical assistance has stimulated vast research attentions on wearable robotic devices with global aging and rising number of stroke patients in recent years. A variety of wearable devices have been developed to provide motion assistance both in performing activities of daily living (ADLs) and in rehabilitation [1-2], such as wearable robotic gloves for hands [3-5], assisting robotic suits for upper limbs [6-10] and lower limbs [11-14]. Various efforts have been devoted to the safety of wearable robots. One focus is to provide the robots with passive compliance essential in performing ADLs by reducing the peak force [15] under interaction. For electric-motor-driven wearable robotic devices, passive compliant mechanism is often additionally added into the transmission line, like using cables and Serial-Elastic-Actuators, to increase the safety of the devices, as in the [16]. The introduced passive mechanism often has fixed compliance, meaning either a high one, excellent at position tasks but with poor compliance, or a low stiffness, unafraid of interaction but hard to control precisely. In fact, human would adjust the stiffness of his muscles according to different situations. For a fixed passive stiffness wearable robot, the contradiction of its stiffness with human who give commands in different scenarios, would potentially cause unpleasant wearing experience and even reduce the effectiveness of doing ADLs.

Variable stiffness is a desirable feature in wearable robotics, being safe and comfortable [17-19], providing alternations to passive reactions and human-like interaction port dynamics from the point of energy efficiency and safe interaction [20]. However, the complex structure poses a challenge to the mechanical design considering the weight and size constraint in wearable robots, and the control of variable stiffness is much more complex than a normal device, leading to limited numbers of such devises.

On the other hand, although some devices with variable stiffness have been designed, as in AVSER[21] by using two electric motors to control position and passive stiffness separately, or in [22] and [23] by using antagonistic configurations of PAMs to control position and passive stiffness simultaneously, these studies are mainly focusing on the mechanism design and safety common for traditional robotic manipulators, without emphasizing on other potential benefits of applying variable stiffness in wearable robots.

In this paper, we propose a light-weight soft motion assistive device with the following features for elbow to accomplish ADLs: (1) Large working range for the human joint. (2) Large torque to assist ADLs. (3) accurate position control with back-drivability ensuring safety. (4) Ability to adjust the passive compliance to provide more efficient and comfortable wearing experience. We also illustrate that the effectiveness of applying variable stiffness in a wearable robot in accomplishing daily tasks by showing that it could buy more time upon collision waiting for post-human involvement to achieve a smoother dynamic. This gives us further possibility on how to utilize passive stiffness in handling daily objects.

2. MOTIVATION OF VARIABLE STIFFNESS IN WEARABLE ROBOTS

The variable stiffness in wearable robots have been more concerned to the safety and efficiency aspect because it allows for a safer interaction and could store energy. Many researchers are hesitated on the worthiness of introducing variable stiffness at the cost of more complexed structures, increased weight and complicated control, only for solving a safety matter that could otherwise be easily tackled. Therefore, we provide a variable stiffness wearable robot with simple structure and light weight. We also discuss its potential importance in effectiveness in accomplishing ADLs in the following.

2.1 Composition of the reaction source

The wearable robots are a semi-autonomous device that takes human's desire and generate corresponding motion. The human desire could be a specific active command like bending a joint. The robot itself have high level planning layer, acting as robot's brain, providing robot's active command. Thus, depending on who is in charge, the system could be regarded as human-dominant commanding system and machine dominant commanding system.

The robot's low-level layers like impedance control, pressure control, and even passive stiffness control layer, would act as internal loop. Together with the passive compliance of the mechanism, they react timely to the external disturbance and generate corresponding behavior.

Thus, the final control effect could be regarded as a combination of the human/robot's active command on intention, the robot's internal control effect owing to disturbance, and the robot's passive reaction.

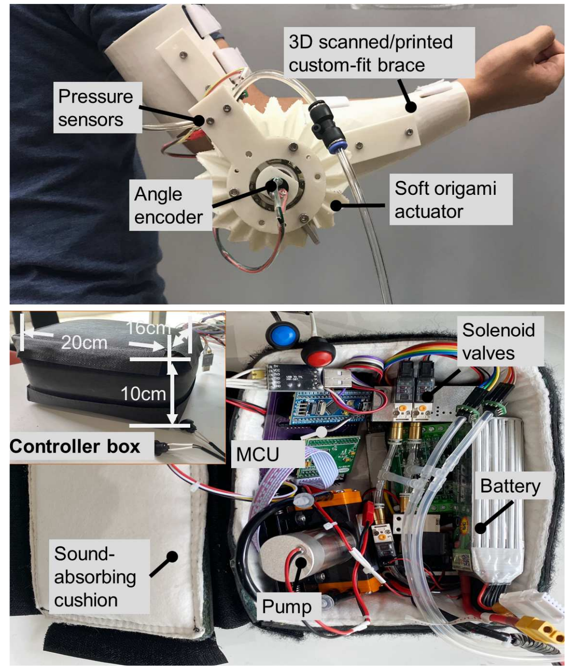

Fig. 1. The proposed soft wearable elbow skeleton. It consists of a 3D scanned/printed custom-fit brace, a soft origami actuation system, together with a portable controller box.

2.2 Necessity and limitation of human-dominant commanding system

Human-dominant commanding system is essential in situations where human inputs are preferred or encouraged. In robotic rehabilitation, accepted theory is that it is the patient's active attention and efforts along with external motion repetition that matters in achieving an effective therapy [4]. Indeed, too much autonomous assist from the robot may reduce the therapy result by making people slack. This guide us to encourage human's intention into the high-level control loop. In motion assist, humans being power-amplified through wearing the robot, it is also natural for the human to be the central commander for a more intuitive and comfortable experience.

However, this human-dominant commanding system, has a biological limitation which is the delay between gaining information input and generating reaction signals [24]. Studies have shown that the mean reaction time of human response is around 200ms [24].

This inevitable delay gives rise to the problem that human-dominant commanding system could not react to sudden disturbance timely on its own. Thus, it could only rely on the robot's internal control reaction and passive compliance to cope with the instant disturbance. Thus, in a human-dominant commanding system, the instant behavior is determined by the high-frequency robot's internal control loop and its intrinsic passive compliance.

2.3 Necessity of variable passive stiffness in human-dominant commanding system

The fact is that, in performing ADLs sometimes we want these "combined passive reaction" (CPR) to helps us gain faster and stronger response, like keeping steady holding an object. But sometimes we do not, preferring a total human-commanding behavior without the interference of the CPR. This is because CPR may generate unwanted high acceleration of the object, causing unpredictable side effect. In a common daily scenario in doing ADLs, under sudden collision, a cup of water would possibly slosh or spoil because of the high returning acceleration by CPR.

Human would act more submissively, relying on high-level command to cope with such situations. Same idea goes to the wearing robot. We wish to let the human command take care of the water-collision problem. This means, we need to shut off the internal control loop, and get a more submissive passive compliance trying to avoid strong reaction before human active commands.

Therefore, variable stiffness is essential in helping achieve a better performance in performing certain daily tasks. This ability to change the passive stiffness gives the possibility of switching between robot's timely SPR and human's delayed full control. A lower passive stiffness would elongate the submissive reaction time (SRT), buying time for the active response from human as tested in the experiment part. The SRT is defined as the maximum non-return time after collision, which we will verify in the following.

3. SYSTEM DESCRIPTION

Goals for the design and fabrication are set as follows:

1. Motion range. Motion of the device is required to follow the range of human elbow joint [25, 26], full range of an elbow was found with $[0^\circ, 145^\circ]$ from the extension state to the flexion state.

2. Torque output. Desired torque is calculated to fulfill the requirements of ADLs [27]. In a simplified situation where a ball weighing 1kg, most of the daily objects fall into this category, is held with wrist and fingers in rigid, taking the weight of forearm into consideration, desired torque T_d is calculated as

$$T_d = G_1 l + G_2 L, \tag{1}$$

where G_1, G_2 are respectively the gravity of forearm and object, l, L are their arms of force. Hence, around 5Nm joint torque are desired to fulfill the requirements of ADLs.

3. Elbow angle servo. The ability of angle servo could offer conditions for various assistive tasks. Considering the application of soft robots in human-robot interaction, average response speed and accuracy are desired from the robotic system.

4. Variable stiffness tuning. To ensure the safety of both robotic system and users, variable compliance tuning is desired, which will make the robot capable of handling the unexpected situations. It is worth to be noted that both angle servo and variable compliance tuning heavily rely on the entire robotic system integration.

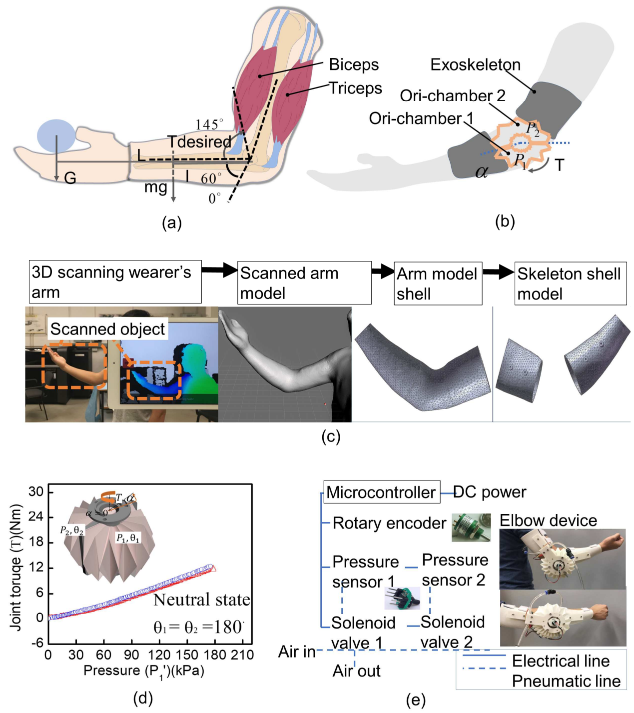

Fig. 2. System description. (a) Illustration of human arm with biceps-triceps muscles. (b) Human arm with robotic device. (c) Design and fabrication process of custom-fit brace. (d) Actuator pressure-torque relations. actuator, with P_1 and P_2 the pressures, and θ_1, θ_2 the angles of each antagonistic chamber. (e) System configuration of soft elbow robotic device with control hardware.

3.1 System description

The entire robotic system is mimicking the mechanism of human biceps-triceps muscle system to maximumly achieve smooth and natural flexion-extension assistance. Key features of this system are noted as the integration of antagonistic robotic system under the actuation of soft actuator and transmission of custom brace. Inspired by the human biceps-triceps muscle system, pioneering efforts on the antagonistic design powered by pneumatic artificial muscles in pairs showed the promising humanoid variable-stiffness behaviors for safer interaction and impact avoidance [28, 29]. In the human biceps-triceps muscle system, as in Fig. 2(a), the biceps and triceps are antagonistic muscles controlling the flexion and extension of elbow joint. Under the modulation of human nerve system, various tasks could be handled by the human arm. Similar to the human biceps-triceps muscle system, the proposed device (Fig. 2(b)) could also achieve the superior performance.

3.2 Custom-fit brace

The brace is also the key component facilitating the device, since it directly contacts the human arm and used as a torque transmitting medium. Hence, main consideration of brace design is to maximally align it to the shape of human arm for the enhanced ergonomics, which will further result in efficient torque transmission from the actuator to human arm.

3D scanning technology combining 3D printing technology are adopted to design the custom-fit brace achieving maximum comfort of wearers, low production cost and high resolution. Preliminary case study was conducted in a healthy person. The initial arm model was 3D scanned by a portable 3D scanner (Structure sensor). Modification on the arm model to obtain the custom-fit brace model was conducted in an open-source model-editing software (Meshmixer). Finally, it could be fabricated using PLA materials (Polylactic acid) with a 3D printer (Delta-bot). The brace design and fabrication process were illustrated in Fig. 2(c).

3.3 Bio-inspired actuation system

The actuation system design includes two antagonistic origami chambers (ori-chamber 1 and ori-chamber 2) act as the biceps and triceps respectively completing the elbow flexion and extension. The origami chamber could be deployed in radial direction completing the joint rotation under the actuation of compressed air. Customization of motion range and torque for the elbow robot could be provided by the proposed actuator with customizable ori-chambers design required to offer the desired torque for the ADLs and rotation range for the elbow flexion-extension movement.

Analyzing the mechanism of proposed device, torque is generated from these two antagonistic origami chambers T, which are described as

$$T = a(P_1 - P_2) + b\alpha\,, \tag{2}$$

where a, b are constants for the specific origami chamber design. α is the defined elbow joint angle. P_1, P_2 are chamber pressures. Its static characteristics were shown in Fig. 2(d). A linear torque-pressure and torque-angle relations could be achieved by utilizing the origami chambers, as the origami structure reduces the nonlinear inflation of hyper-elastic chamber with structure deployment. Maximum motion range could be achieved when T=0Nm. $a = 6.9\mathrm{e}-5m^3$, $b = -0.1\,Nm/\deg$ were chosen regarding the desired torque and motion range.

The passive stiffness range of the devices ranges from 5Nm/rad to more than 20 Nm/rad under the pressure source of 200kPa. This provides an adjustable back-drivability of the device, ensuring a safe interaction. The bandwidth of the system is 2Hz. An increased source pressure would increase the bandwidth of the device. The ori-chambers were 3D-printed with TPU materials (Thermoplastic polyurethane) by a consumer-grade 3D printer (Delta-bot). The total mass of the device is around 700g, without the actuation system.

3.4 System assembling

Assembly of robotic device was shown in Fig. 2(e), with control hardware. In this device, two pressure sensors (0-200kPa, accuracy: 0.5%) and one rotary encoder (0-360 degrees, accuracy: 0.5%) were utilized providing real-time pressure and angle signals feedback. In the pneumatic system, two proportional valves (Festo MPYE 5/3-way) were used for pressure processing. A micro-controller (Arduino mega R2560) dealing with signals processing, actuation and control. The entire system loop runs in 60Hz for data acquisition, filtering and calculation

3.5 Comparison with other variable stiffness wearable robots.

For electric-motor actuated wearable robots, the position and stiffness are commonly individually controlled by two separate motors, as in AVSER. Both meeting the daily requirement of torque and motion range, the design and structure of AVSER is very complex while our device is quite simple and straight forward. The second is that the wearing weight of AVSER is approximately 1.6Kg, while our proposed devices is half the weight of that, being a good advantage in daily usage. Also needs to mention is that, the passive stiffness part in AVSER is serialized into the transmission chain, giving the upper limit of the overall stiffness of the system, which means it becomes harder to stabilize an object through active control in the situation of small passive stiffness. Our device is a parallel configuration of active control and passive stiffness, which gives active control more independent of the passive stiffness. Finally, the electrical motors need to be sustainably actuated, while our pneumatic solution could be shut down maintaining the necessary passive characteristic.

Comparing with other antagonistic devices using PAMs, as in [29], the advantage of our device is that we have a large working range and a more consistent output capability throughout the whole working range, which is easier to design and fabricating. PAMs-based device would suffer from the limitation of PAMs, that is the small contraction ratio and dramatically decreasing output force, which makes the design and setup more complex. Secondly, we have predictable fixed size at joint, while PAMs-based devices would be axially expanded, enlarging the actual device volume. The pressure source we use is also comparatively low(200kPa) compared with PAMs-based one(300~400kPa) because little friction is introduced in the actuation process, more suitable in daily use. Also, the model and control of our device is easier than the complex model and highly nonlinear behavior of PAMs.

Compared with cable driven robotics, the direct drive through pneumatic power avoids the pulley system which would complex the system design, or the friction induced by tendon-sheath mechanism. Also, this avoids the problem of cables' minimum bending angle, fatigue and elastic elongation effect. This comes at a price of wearing the robot on the arm.

Considering the light weight (700g) of the device, we think this won't be a big problem.

4. MODELING AND CONTROL

Significant features of the proposed device are marked as highly linear and easy-to-model performance, which could be further used to guide the elbow angle control and variable stiffness tuning. The modeling and control work of entire robotic system are presented in this section.

The modeling work starts from the elbow torque output which correlates to the performance of actuator. To complete the full range motion of elbow joint, the initial position of device, $\alpha_e = 0^\circ$, was set in actuated state of actuator where $\alpha = -72.5^\circ$. Developed from Eq. (2), model on torque, elbow angle and pressure are presented as

$$T_e = a(P_1 - P_2) + b\alpha_e + c\,, \tag{3}$$

where T_e, α_e are respectively the generated torque and arm angle by the device. *a, b, c* in the equation are constants for the specified actuator design, $c = -72.5^\circ \cdot b = 7.25\text{Nm}$.

Referring to the joint rotational stiffness, stiffness describes the ability of origami chambers to generate deformation in response to external load, which is defined as

$$K = -\partial T_e / \partial \alpha_e\,. \tag{4}$$

Substituting (3) into (4),

$$K = -b - a\left(\frac{\partial P_1}{\partial \alpha_e} - \frac{\partial P_2}{\partial \alpha_e}\right). \tag{5}$$

From model (5), we could conclude that the variable stiffness of device is related to the change of pressure and elbow angle. Therefore, this variable could be achieved with different pressure and angle sets. This conclusion will be validated in the next section.

To better describe the dynamic behavior of the proposed system to guide angle control, based on (3) and derived from the Lagrange's equations, the dynamic model is presented as

$$M\ddot{\alpha}_e + F_f + G + \Gamma = T_e\,, \tag{6}$$

which takes forearm inertia *M*, friction force F_f, the net output torque of the device Γ, the actuator inherent structure stiffness and potential energy $G = G_1 h \cos\alpha_e$ of forearm in position α_e into consideration. Benefitting from the adoption of a direct actuation method (actuator directly attached to the elbow joint) with low friction loss, friction could be ignored in the system.

Based on the static and dynamic models of robot motion and stiffness and system configuration, to implement the elbow angle control, combining the derived dynamic model (6) with PID feedback processing, a PID-based cascaded controller is proposed in the robotic system. Schematic diagram of the controller is shown in Fig. 3. In this control framework, low-

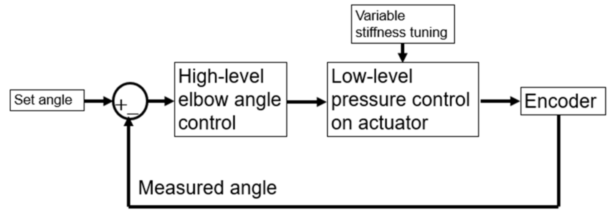

Fig.3. Control block diagram of elbow robotic device.

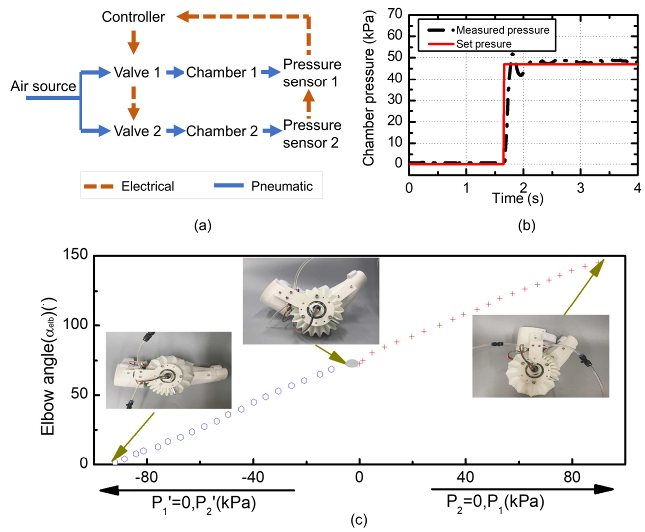

Fig. 4. (a) Pressure control loop with electrical circuits and pneumatic circuits illustrated. (b) Experimental results of pressure control. (c) Elbow motion in the full range. Motion demonstration of soft elbow robotic device with photos in: fully flexed state, neutral state, fully extended state.

level pressure control is set in the internal system guaranteeing the precise pressure regulation and safe pressure for the system, while higher-level angle control could be set from external users for the desired performance. With the implementation of this controller, balance of faster trajectory-following capability, safety against over-pressurization, and compliant robot-environment interactions could be achieved when compared to other soft robotic controllers.

5. EXPERIMENTS

In order to evaluate the preset goals in device performance, a series of experiments are conducted and presented in this section which are structured as follows. At first, the ability of pressure control was tested. The proposed controller could ensure the requirements for the proposed robotic system. After that, the device was proven to achieve full motion range of human elbow joint. Within this range, multiple step response was conducted to verify the ability of robotic system in angle servo. Static torque generated by the device was also tested, which could fully satisfy the requirements for the ADLs. Finally, variable stiffness tuning was tested. It was proven that the stiffness could be tuned by different pressure sets to handle the unexpected disturbance from environments/users. All these

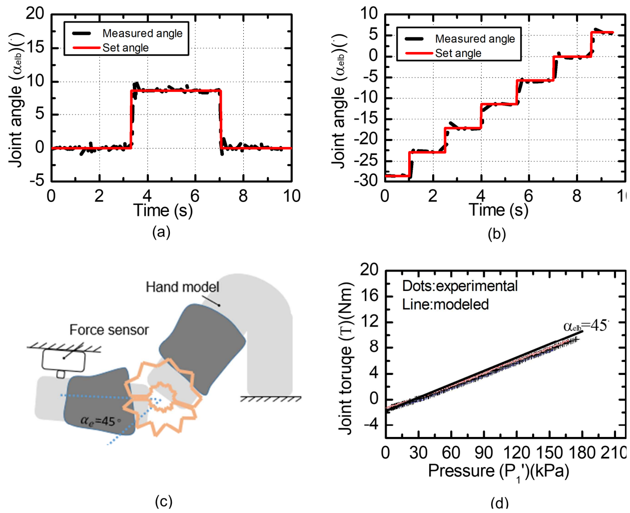

Fig.5. (a) Single step response. (b) Multiple steps' response. (c) Illustration of torque test setup. (d) Static torque test results of elbow joint.

features were evaluated by a hand model to eliminate the influence from users.

5.1 Pressure control

The control work starts from the air pressures of two chambers. The closed-loop pressure diagram (Fig. 4(a)) consists of two servo valves controlling the air inlet and outlet flow, and two pressure sensors monitoring the chambers pressure. In this loop, pressure could be regulated by controlling the flow rate through the Festo proportional valves, referring to the well-documented study on air flow dynamics [30].

In the robotic system, absolute pressure of air source was maintained in 200kPa. Proportional control on pressures of ori-chamber 1 and ori-chamber 2 was implemented.

Fig. 4(b) shows the experimental results, where target pressure was randomly set in an absolute pressure 47kPa. Under the regulation of proposed controller, measured pressure reached at the maximum pressure after 0.15s with 4kPa overshoot. Chamber pressure took around 0.5s to the set pressure, which proved that pressure regulation capability of the proposed controller could be used in the robotic system.

5.2 Motion trajectory

In order to demonstrate the full motion range of elbow device, the device was put in free space and given with system pressures inputs. Initial position of the elbow joint was set in $\alpha_e = 72.5^\circ$, where both ori-chamber 1 and ori-chamber 2 were in standards air pressure, i.e., $P_1 = P_2 = 0\text{kPa}$. At this stage, elbow joint further flexed under the increase of ori-chamber 1 pressure and reached to the maximum elbow angle $\alpha_e = 145^\circ$ in $P_1 = 90\text{kPa}, P_2 = 0\text{kPa}$. Following the similar procedure in the opposite direction, elbow extension was generated when increasing the pressure of ori-chamber 2. Here $\alpha_e = 0^\circ$ in $P_1 = 0\text{kPa}, P_2 = 92\text{kPa}$. This process was

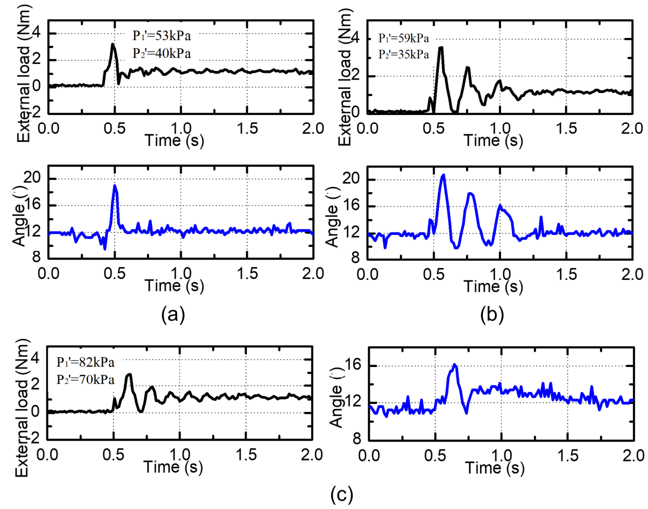

Fig.6. (a) Single step response. (b) Multiple steps' response. (c) Illustration of torque test setup. (d) Static torque test results of elbow joint.

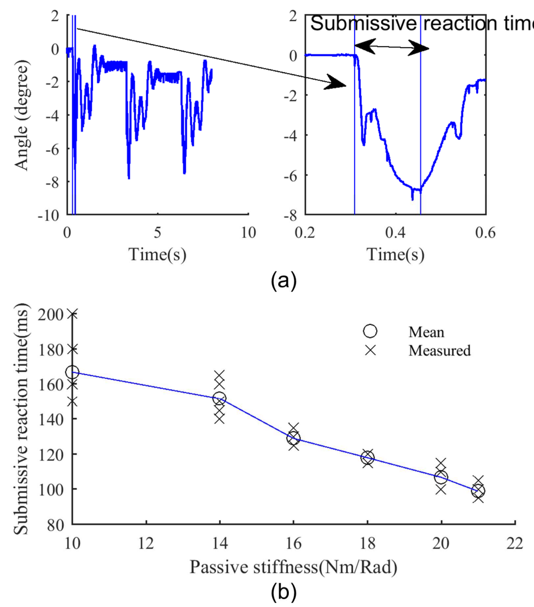

Fig.7. (a) Demonstration of submissive reaction time (SRT). It refers to the time of the maximum non-return time upon collision. (b) A lower passive stiffness would generate a larger submissive reaction time, which gains time for the involvement of human commands.

plotted in Fig. 4(c) with photo demonstration. Analyzing from the experimental results, we could see a linear relation between pressure and angle. Full angle range could be completed by the proposed device. In addition, the device could be actuated in low pressure, which is meaningful for the facilitation of lighter and lower cost wearable robotic systems.

5.3 Elbow angle control: step response

The proposed controller was implemented to the robotic system. Step response tests were conducted to evaluate the accuracy and response speed. Two step response tests were conducted with experimental results shown in Fig. 5(a) and Fig. 5(b).

Fig. 5(a) indicates that the device took around 0.32s to the desired position with overshoot of 1.1° and took around 0.25s back to the initial position with same overshoot. Fast and accurate response was shown in the robotic system.

Fig. 5(b) shows the system following with a given series target angles with every step 5.7°. It indicates that the robotic system could follow multiple steps with high repeatability and high accuracy.

5.4 Elbow joint static torque

The static torque output of device was tested in a fixed angle $\alpha_e = 45^{\circ}$ (Fig. 5(c)). Here only ori-chamber pressure was increased. Relations between torque and pressure are shown in Fig. 5(d), where modeled results of Eq. (3) and experimental results are respectively presented with line and dots. Agreements between the modeled results and experimental results could be observed, both indicated a linear proportional relation of pressure and torque. Maximum torque 11Nm in $\alpha_e = 45^{\circ}$ under $180kPa$ air pressure could be obtained enough for the daily tasks.

5.5 Safe human-robot interaction

Being compliant allows soft wearable robots to safely cope with unexpected situations when interacting with users. For the proposed robotic device, a unique feature is its variable stiffness could be obtained with pressure variations of antagonistic pneumatic system, as mentioned in Section III.

With the implementation of proposed controller, ability to handle the unstructured disturbance was demonstrated. As in (5), variable stiffness could be achieved with different sets of constant ori-chambers pressures, which will further result in different robot performance. Fig. 6 (a-c) show the robotic system's abilities to handle the disturbance under three pressures sets ($P_1 = 53\text{kPa},\ P_2 = 40\text{kPa}$), ($P_1 = 59\text{kPa},\ P_2 = 35\text{kPa}$), ($P_1 = 82\text{kPa},\ P_2 = 70\text{kPa}$), where the device was held in the same position. Disturbance was randomly given by dropping a block at the forearm and recorded by a torque sensor (-20Nm to 20Nm, accuracy: 1%). At the initial stage, the elbow joint was kept in the same angle 11.5°, even with different pressures sets. Under the effect of disturbance, angle variations could be observed in these three groups. After that, the robotic system went into the steady state with the assistance of controller, demonstrating its ability in restoring to the initial position after disturbance. Performance differences could be compared by calculating the stiffness. According to the definition of stiffness in Eq. (4), stiffness regrading to these three groups is separately 0.46Nm/degree, 0.41Nm/degree and 0.68Nm/degree. The third group shows obvious increasing stiffness comparing to the previous two groups with the increase of pressures.

5.6 Variable stiffness on submissive reaction time

The effectiveness of variable stiffness in accomplish ADLs is tested as below. One arm of the devices is fixed on to the wall, and the other is free. The device is controlled at the zero position, with different passive stiffness setup. The two origami chambers were shut down for a complete closed state. This is to shut off the effect of robot's internal control. Then a constant weight is dropped from a constant height on to the free arm, generating an impulse response (Fig. 7(a)). Each stiffness setup was tested for 5 times, and the results are shown in Fig. 7(b).

Fig. 7(b) indicates that, a larger stiffness would result in a quicker response, i.e., a small SRT less than the common reaction time of humans. The reduction of passive stiffness could elongate the time of SRT to matching that of human reaction, giving possibility of waiting for human to fully control the successive dynamics without causing strong reaction behavior.

This experiment shows that variable stiffness could make a difference in specific task requirement where full human controlled dynamics is preferred in human-dominant commanding system. It gains time for the post involvement of human commands by tuning the SRT without causing strong response. This is especially useful in daily situations where human is required to keep a cup of water from sloshing. This effectiveness of variable stiffness in helping accomplishing ADLs, give us some insights about how to use the variable stiffness in real application in wearable robotics.

6. CONCLUSION

This work presented the design and control of a soft wearable robot for motion assistance, demonstrating the excellent potentials of applying variable stiffness in ADL tasks. Since the robotic device exhibit similar properties to the human muscles both in mechanical structures and performance, high compatibility and integrity between the soft wearable devices and humans could be obtained. These features largely ensure the natural performance of robots and comfort of users, together with the users' safety, therefore enabling the motion assistance and rehabilitation of soft wearable devices in human joints. Comparing to state of the art, the proposed device has simple structures, easier models, and suitable output capacity through the large working range, which greatly lower the effort of building a variable stiffness wearable robot.

On the other hand, the variable stiffness in wearable robots is detailed illustrated, and experimentally tested from the point of accomplishing daily tasks in a human-dominant command system. The variable stiffness could change the submissive reaction time upon sudden collision, enabling the switching between an enhanced combined passive reaction effect which is beyond human's reaction time, or a pure human-controlled behavior for smoother dynamics by slowing the submissive reaction process without causing strong reaction effect. This gives us a new angle to look at the functionality of variable stiffness in wearable robotics.

In future studies, the human's post involvement for a smoother dynamic will be studied to testify the different effects that human could achieve on the basis that the variable stiffness provides long enough submissive reaction time.

With this new device for easier design and control, and a new aspect of understanding the variable stiffness, we hope it could help further improve the development of a safer, pleasant and effective wearable robot.

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