

Design of a Continuum Wearable Robot for Shoulder Rehabilitation

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Abstract. A wearable robot for rehabilitation therapy is often shared by a group of patients in a clinic. If the wearable robot only consists of rigid links, the link dimensions usually need to be adjusted from time to time to fit different patients. It is then difficult to make sure these on-site adjustments could introduce the desired kinematic compatibility between the robot and each individual patient. A previous investigation shows it is possible to construct a compliant wearable robot that can provide Anatomy Adaptive Assistances (AAA), which means the robot passively adapts to different patient anatomies while providing consistent motion assistances. However, the previous design also possesses drawbacks such as limited motion ranges and limited payload capabilities. This paper presents a kinematics-based type synthesis for the construction of a new continuum wearable shoulder robot, aiming at overcoming these drawbacks as well as maintaining the capabilities of providing AAA. Three structural concepts of such a continuum wearable shoulder robot are studied through kinematic modeling. One concept is eventually selected based on the comparison results. Preliminary experiments are also presented to demonstrate the feasibility of the selected design.

Keywords: Wearable robot, continuum mechanism, type synthesis, kinematics, AAA (Anatomy Adaptive Assistances).

1 Introduction

Research on wearable robots and exoskeletons has been quite active in the past a few decades. Many exoskeleton systems or wearable robots were developed for upper and/or lower limbs (e.g. [1, 2]). Some exoskeletons aim at augmenting a healthy wearer's physical performance with robotic actuation (e.g., the BLEEX system [3], the MIT load-carrying exoskeleton [4], etc.), whereas the others aim at delivering rehabilitation therapies to patients with neuromuscular defects after injury or stroke, such as the rehabilitation wearable robots for lower limbs [5-8], and the ones for upper limbs [9-18].

Most of the existing wearable robots and exoskeletons share one similar design approach: a rigid kinematic chain (serial or parallel) is actuated to mobilize an attached user. The use of rigid links in an exoskeleton system might be suitable for

strength-augmenting applications to shield the wearer so that excessive external loads can be undertaken by the rigid structure. But these rigid links introduce drawbacks such as system bulkiness, high inertia, and the difficulty of maintaining kinematic compatibility between the wearable robot and a wearer. In a clinic for rehabilitation therapy, one wearable robot is often shared by many patients. If the wearable robot has a rigid structure, a physician needs to adjust the dimensions of the wearable robot from time to time to match the robot to different patients. It is difficult to guarantee these on-site adjustments could introduce the desired kinematic compatibility. For this reason, some design alternatives that use compliant components have been investigated [14, 15, 19, 20]. Particularly, a continuum shoulder wearable robot was constructed to demonstrate the capability of providing Anatomy Adaptive Assistances (AAA) [16-18, 21]. Without requiring any hardware adjustments, the continuum wearable robot passively deforms and adapts to different wearer anatomies while providing consistent motion assistances. Such a feature avoids the challenging studies on how to maintain ergonomics as in [22-24].

Besides the identified characteristics of providing AAA, the wearable robot was also found to have some drawbacks, such as limited motion ranges, limited payload capabilities, and the difficulty to wear on an impaired subject. This paper hence presents the descriptions and selection of three structural concepts of a new continuum wearable robot for shoulder rehabilitation, aiming at overcoming the aforementioned drawbacks. The contribution of this paper mainly lies on the proposal and kinematic analysis of the three design variations. The model-based comparison suggests that the selected design is promising in terms of maintaining the capability of providing AAA, enabling big motion ranges, allowing large payload, as well as easing the process of wearing the robot.

The paper is organized as follows. Section 2 summarizes the drawbacks of the existing continuum wearable shoulder robot and presents three design concepts. Section 3 presents nomenclature and a basic kinematics model so that the kinematic analysis and simulation comparisons of the three design variations can be presented in Section 4. Preliminary designs and experiments are reported in Section 5 for the selected design concept. Conclusions and future work are summarized in Section 6.

2 Existing Drawbacks and New Design Concepts

The constructed continuum wearable shoulder robot as in [17, 18] is shown in Fig. 1. It consists of i) a rigid armguard, ii) an upper arm sleeve, iii) a flexible continuum shoulder brace, iv) a body vest, v) a set of guiding cannulae, and vi) an actuation unit. Actuation of the continuum shoulder brace orients a patient's arm accordingly.

Structure of the continuum shoulder brace is also depicted in Fig. 3. The brace consists of an end ring, a base ring, a few spacer rings and several backbones. All the backbones are made from thin super-elastic nitinol (Nickel-Titanium alloy) rods. The backbones are only attached to the end ring and can slide in holes of the spacer rings and the base ring. Miniature springs are used to keep the spacer rings distributed evenly. Simultaneous pulling and pushing of these backbones are achieved by the

actuation unit as the backbones are routed through the set of guiding cannulae. Bending of the continuum brace orients a patient's upper arm.

Advantages of the continuum wearable robot include: i) safety and comfort introduced by the inherent compliance, ii) passive adaptation to different patient anatomies, iii) a redundant backbone arrangement for load redistribution and reduced buckling risks, and iv) design compactness achieved by dual roles of these backbones as both the motion output members and the structural components.

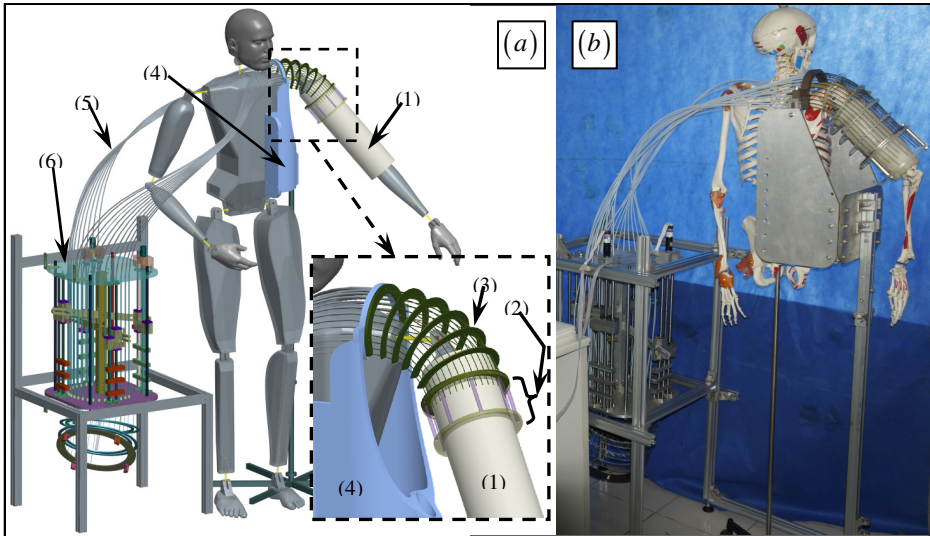


Fig. 1. The continuum wearable shoulder robot in [18]: (a.1) a rigid armguard, (a.2) an upper arm sleeve, (a.3) a flexible continuum shoulder brace, (a.4) a body vest, (a.5) a set of guiding cannulae, and (a.6) an actuation unit; (b) the constructed prototype

Although this wearable robot's characteristic of providing AAA (Anatomy Adaptive Assistances) is particularly advantageous in rehabilitation applications, some drawbacks were also identified. Firstly, it can be seen from Fig. 1 and Fig. 3 that the brace has a sparse structure and the payload capability is limited. Secondly, the brace has to be designed big enough to fit a group of patients. When the brace has a big diameter and a relative short length, the available motion range is limited. What's more, the shoulder brace can't be conveniently worn by an impaired subject. Design modifications are hence desired to overcome these drawbacks.

Three design concepts are considered in this paper, attempting to overcome the aforementioned drawbacks, as shown in Fig. 2. These design concepts are all proposed to modify the structure of the shoulder brace for possible improvements. The design concept in Fig. 2(a) has a non-uniform routing intended for an improved payload capability. The design concepts in Fig. 2(b and c) are proposed for enlarged motion ranges and the reduced obstruction of wearing. Nomenclature and basic kinematics are presented in Section 3 so that these three design concepts could be carefully studied in Section 4.

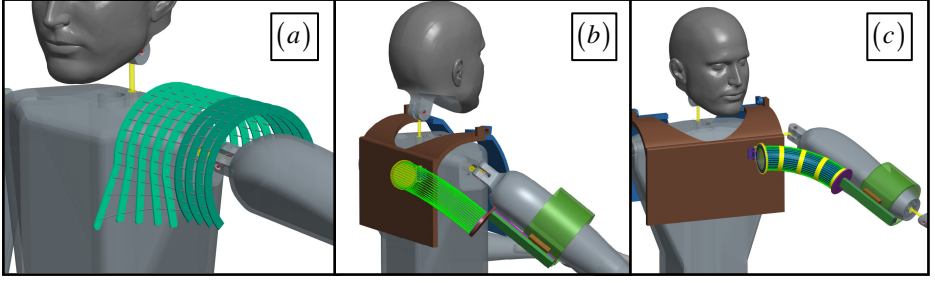


Fig. 2. Design concepts for improvements: (a) the non-uniform-routing brace, (b) the back-mounting brace, and (c) the front-mounting brace

3 Nomenclature and Kinematics

The nomenclature and the kinematics assume that the continuum brace bends into a planar shape within the bending plane as shown in Fig. 3. Shapes of the backbones are assumed by a sweeping motion of the structure's cross section along the imaginary primary backbone. This work doesn't assume the imaginary primary backbone's shape to be circular, which has been experimentally verified in [17, 18].

3.1 Nomenclature and Coordinate Systems

To describe the shoulder brace, nomenclatures are defined in Table I, while coordinate systems of the continuum brace are defined as below

- *Base Ring Coordinate System* (BRS) is designated as $\{b\} \equiv \{\hat{\mathbf{x}}_b, \hat{\mathbf{y}}_b, \hat{\mathbf{z}}_b\}$. It is attached to the base ring, whose XY plane coincides with the base ring and its origin is at the center of the base disk. $\hat{\mathbf{x}}_b$ points from the center of the base disk to the first backbone while $\hat{\mathbf{z}}_b$ is perpendicular to the base ring. The backbones are numbered according to the definition of δ_i .
- *Bending Plane Coordinate System 1* (BPS1) is designated as $\{1\} \equiv \{\hat{\mathbf{x}}_1, \hat{\mathbf{y}}_1, \hat{\mathbf{z}}_1\}$ which shares its origin with $\{b\}$ and has the brace bending in its XZ plane.
- *Bending Plane Coordinate System 2* (BPS2) is designated as $\{2\} \equiv \{\hat{\mathbf{x}}_2, \hat{\mathbf{y}}_2, \hat{\mathbf{z}}_2\}$ obtained from $\{1\}$ by a rotation about $\hat{\mathbf{y}}_1$ such that $\hat{\mathbf{z}}_1$ becomes backbone tangent at the end ring. Origin of $\{2\}$ is at center of the end ring.
- *End Ring Coordinate System* (ERS) $\{e\} \equiv \{\hat{\mathbf{x}}_e, \hat{\mathbf{y}}_e, \hat{\mathbf{z}}_e\}$ is fixed to the end ring. $\hat{\mathbf{x}}_e$ points from center of the end ring to the first secondary backbone and $\hat{\mathbf{z}}_e$ is normal to the end ring. $\{e\}$ is obtained from $\{2\}$ by a rotation about $\hat{\mathbf{z}}_2$.

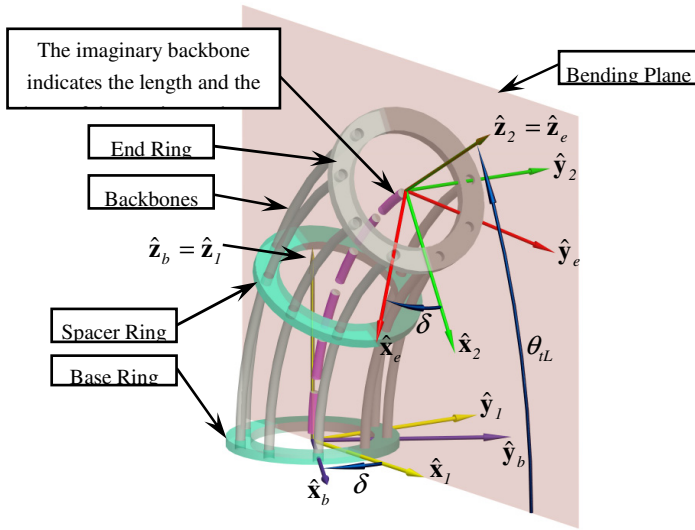


Fig. 3. Nomenclature and coordinates of the continuum brace

Table 1. Nomenclature used for kinematics modeling

m	Index of the backbones, $i = 1, 2, \dots, m$
r_i	The distance from the imaginary backbone to the i th backbone in the brace. r_i can be different for different i .
β_i	β_i characterizes the division angle from the i th backbone to the first backbone. $\beta_l \equiv 0$ and β_i remain constant once the braces are built.
L, L_i	Lengths of the imaginary backbone and the i th backbone measured from the base ring to the end ring.
$\rho(s), \rho_i(s_i)$	Radius of curvature of the imaginary backbone and the i th backbones.
$\mathbf{q}_i$	$\mathbf{q}_i = [q_1 \ q_2 \ \dots \ q_m]^T$ is the actuation lengths of the backbones and $q_i \equiv L_i - L$.
$\theta(s)$	Angle of the tangent to the imaginary backbone in the bending plane. $\theta(L)$ and $\theta(0)$ are denoted by θ_L and θ_0 , respectively. $\theta_0 = \pi/2$
δ_i	A right-handed rotation about $\hat{\mathbf{z}}_i$ from $\hat{\mathbf{x}}_i$ to a ray passing through the imaginary backbone and the i th backbone.
δ	$\delta \equiv \delta_l$ and $\delta_i = \delta + \beta_i$
Ψ	$\Psi \equiv [\theta_L \ \delta]^T$ defines the configuration of the shoulder brace.
${}^b\mathbf{p}(s)$	Position vector of a point along the imaginary backbone in $\{b\}$. ${}^b\mathbf{p}(L)$ is the tip position and is designated as ${}^b\mathbf{p}_L$.

3.2 Kinematics

Thorough kinematics analysis of such a continuum brace can be found in [25, 26]. The model was extended to the cases that the imaginary backbone has a non-circular shape and the backbones are arbitrarily arranged [17, 18]. Basic entities are summarized here so that the kinematic analysis of the three concepts can be elaborated in Section 4.

Configuration of the continuum brace is parameterized by $\Psi = [\theta_L \ \delta]^T$. The length of the imaginary backbone is related to the length of the i th backbone as in Eq. (1). The integral can be derived to give Eq. (2), as detailed in [18]. Referring to the definition of q_i in Table 1, Eq. (3) is obtained from Eq. (2).

$$L_{ii} = \int ds_{ii} = \int (ds_{ii} - ds_t + ds_t) = \int (ds_{ii} - ds_t) + L_t \quad . \quad (1)$$

$$L_{ii} = L_t - r_{ii} \cos \delta_{ii} (\theta_0 - \theta_{iL}) = L_t + r_{ii} \cos \delta_{ii} (\theta_{iL} - \theta_0) \quad . \quad (2)$$

$$q_{ii} = r_{ii} \cos \delta_{ii} (\theta_{iL} - \theta_0), \quad i = 1, 2, \dots, m \quad . \quad (3)$$

Equation (3) suggests that actuation of the continuum brace only concerns the values of θ_L and δ . The actuation doesn't depend on the actual shape of the shoulder brace. This feature provides a particular advantage for rehabilitation in a clinic: when the wearable robot is put on different patients, different anatomies form different shapes of the brace, but the actuation remains the same while orienting a patient's upper arm to the same direction that is characterized by θ_L and δ .

Rotation matrix ${}^b\mathbf{R}_e$ that associates $\{e\}$ and $\{b\}$ is as follows:

$${}^b\mathbf{R}_e = \mathbf{R}(\hat{\mathbf{z}}_b, -\delta) \mathbf{R}(\hat{\mathbf{y}}_1, \theta_0 - \theta_L) \mathbf{R}(\hat{\mathbf{z}}_2, \delta) \quad . \quad (4)$$

Where $\mathbf{R}(\hat{\mathbf{n}}, \gamma)$ is a rotation about $\hat{\mathbf{n}}$ by an angle γ .

Tip position of the continuum brace is governed by Eq. (5). When the imaginary backbone has a circular shape, the tip position is then given by Eq. (6).

$${}^b\mathbf{p}_L = {}^b\mathbf{R}_I \left[\int_0^L \cos(\theta(s)) ds \quad 0 \quad \int_0^L \sin(\theta(s)) ds \right]^T \quad . \quad (5)$$

Where ${}^b\mathbf{R}_l = \mathbf{R}(\hat{\mathbf{z}}_b, -\delta)$ and the integrals depend on the actual shape of the imaginary backbone.

$${}^b\mathbf{p}_L = \frac{L}{\theta_L - \theta_0} \begin{bmatrix} \cos \delta (\sin \theta_L - 1) & \sin \delta (1 - \sin \theta_L) & -\cos \theta_L \end{bmatrix}^T. \quad (6)$$

4 Kinematic Analysis and Simulation Verifications

Three design concepts are proposed to overcome the identified drawbacks of the previous design of the continuum wearable shoulder robot. Kinematic analysis and simulations were conducted to verify the feasibility of the designs. One design was eventually selected and finalized as shown in Section 5.1.

4.1 Design Concept #1

The first concept shown in Fig. 2(a) has the backbones with a non-uniform routing. This design was intended for enhanced payload capabilities. The existing design with a uniform routing of the backbones cannot well resist an external twist about $\hat{\mathbf{z}}_e$. The experimental results in [27] showed that a weak torsional rigidity affects the payload capabilities greatly. With a non-uniform routing of the backbones, external twists might be resisted by the helically arranged backbones. Thus the payload capabilities might also be enhanced.

For the non-uniform routing of the backbones, r_i and β_i vary along the imaginary backbone. The length of the i th backbone shall be calculated as in Eq. (7).

$$L_i = L - \int_0^{\theta_0 - \theta_L} r_i \cos(\delta + \beta_i) d\theta, \quad i = 1, 2, \dots, m. \quad (7)$$

A Matlab simulation of this concept is shown in Fig. 4. After several backbone routing patterns were attempted, it was concluded that the length change of the backbones cannot be realized by the existing actuation unit. This design concept was then abandoned.

4.2 Design Concepts #2 and #3

From Section 4.1 it was concluded that the continuum brace shall have a uniform routing for its backbones in order to realize the actuation. When the backbones are arranged around a patient's upper arm, the brace's base ring has to be located around a wearer's chest. Then the brace will have a large diameter and a stumpy appearance.

Motion ranges are hence limited when the brace's length is not long enough compared with the brace's diameter. What's more, it is also not very convenient for an impaired subject to wear this brace.

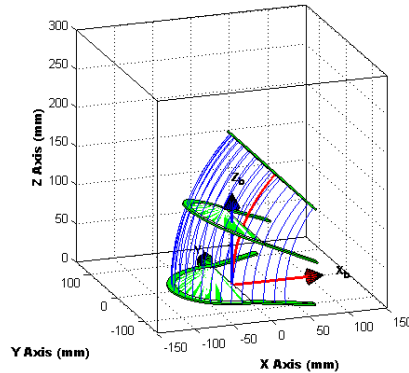


Fig. 4. Kinematic simulation of the design concept #1

The design concepts #2 and #3 were then conceived to allow a bigger motion range and ease the difficulty of wearing. A continuum structure was mounted on the back of a wearer and was connected an upper-arm sleeve in the design concept #2. Bending of this continuum structure orients the wearer's upper arm. The continuum structure was moved to the front of the wearer in the design concept #3. The reason will be elaborated below.

Exact shape of the continuum structure in the design concepts #2 and #3 depends on a minimal of the sum of the elastic potential energy of the continuum structure and the gravitational potential energy of the arm and the robot. The exact shape would also be altered by different anatomical parameters (e.g. shoulder widths) of the wearers.

Demonstrated experimentally as in [17], the shape of such a continuum structure differed from a circular arc. In fact the actual shape of the continuum structure would keep changing during the assisted motions for a patient. In order to verify the design concept #2, the simulations were conducted with an approximation that the shape of the continuum structure could be characterized as one circular arc plus a straight line.

The shoulder joint is represented by a spherical joint and the upper arm is represented by a cylinder in Fig. 5. The axis of the upper arm is parallel to $\hat{z}_e$ so that bending of the continuum structure orients the upper arm.

Main design parameters of the continuum structure in the design concept #2 include i) the length, and ii) the offset of the structure with respect to the shoulder joint. Possible combinations of these parameters were numerated. And it was found the tip of the continuum structure (namely, the origin of $\{e\}$) would translate along the upper arm for a relatively large distance. What's more, the length of the structure also needs to be quite long to allow the desired motion range (the flexion has a wider motion range than the extension in the sagittal plane). Such a prolonged length could reduce the payload capability of the continuum structure.

The design concept #3 is hence obtained as the continuum structure is mounted in front of the wearer. Under this configuration, the wearable robot could be easily put on a user and it entirely allows the desired assistive motion ranges. A structure feature was incorporated into the design to enhance the payload capability, which is presented in Section 5.2.

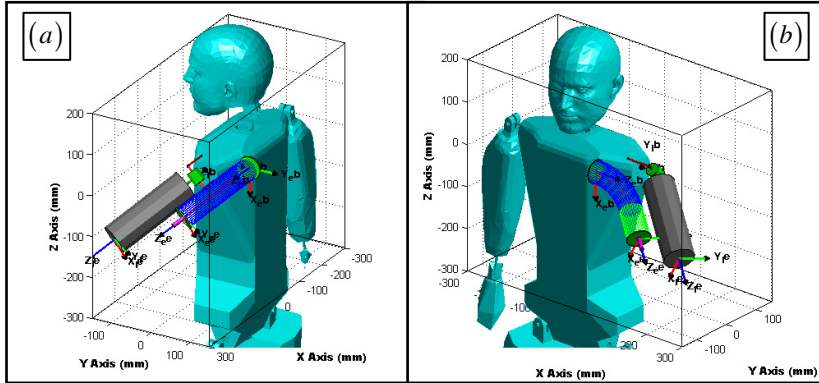


Fig. 5. Kinematic simulation of the design concept (a) #2 and (b) #3

5 Preliminary System Design and Experimentation

Following the design concept #3, a tentative design of the continuum wearable shoulder robot is reported in Section 5.1. Then a mockup system is constructed as in Section 5.2 for preliminary experimentations.

5.1 Tentative System Design

The tentative design shares some similarity to the existing design. The system in Fig. 6 also consists of i) a rigid armguard, ii) an armguard guide, iii) a flexible continuum brace, iv) a body vest, v) a set of guiding cannulae, and vi) an actuation unit.

The armguard can slide on the armguard guide. This will accommodate the translation of the guide with respect to the wearer's upper arm during assisted motions. The actuation unit pushes and pulls the backbones in the shoulder brace to bend the brace so as to orient a wearer's arm. Braided stainless steel overtube as shown in Fig. 6 is attached to the brace's surface to enhance the torsional rigidity.

5.2 Preliminary Experimentations

A mockup system is constructed as in Fig. 7 for preliminary experimentations to verify the intended characteristics of the wearable shoulder robot.

The shoulder brace was easily bent for 90° in arbitrary directions. Motion range of the brace is big enough for many intended rehabilitation exercises.

A loading experiment was also carried out as in Fig. 7. Weights of 3 kg and 5 kg were hung to the tip of the flexible brace. Deflections of the brace were acceptable. The brace is hence strong enough for the future use in such a wearable shoulder robot.

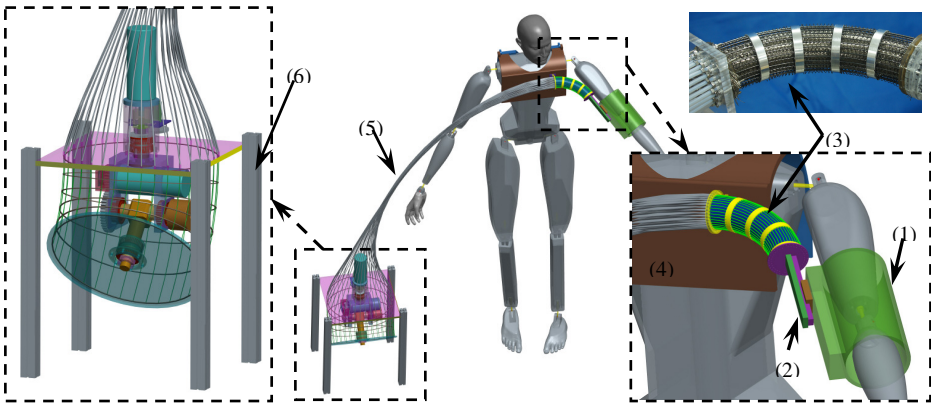


Fig. 6. Tentative system design of the new wearable shoulder robot: (1) a rigid armguard, (2) an armguard guide, (3) a flexible continuum brace, (4) a body vest, (5) a set of guiding cannulae, and (6) an actuation unit

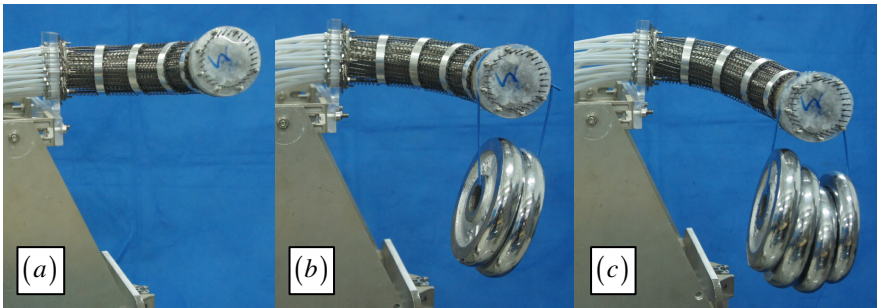


Fig. 7. Preliminary payload test of a mockup system: (a) no load, (b) 3 kg, and (c) 5 kg

6 Conclusions and Future Work

This paper presents the motivation, kinematics, design concept comparison, preliminary system design and experimentation of a continuum wearable robot for shoulder rehabilitation, aiming at improving the performance of an existing continuum wearable shoulder robot.

The existing continuum wearable shoulder robot could passively adapt to different anatomies while providing assistances. This feature is hence referred to as AAA (Anatomy Adaptive Assistances). However several drawbacks were also identified and three design concepts were hence proposed to overcome these drawbacks.

Based on kinematic analysis, the three concepts are compared and one is selected. The selected design concept is expected to possess a large payload capability, allow desired motion ranges and ease the difficulty for wearing.

Detailed system design of the selected concept was pursued and some preliminary experiments suggested the promising potential of the selected design concept.

Future work mainly includes the finalization and fabrication of the tentative design. Then experimental studies could be carried out for the new continuum wearable robot for shoulder rehabilitation.

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References

1. Brewer, B.R., McDowell, S.K., Worthen-Chaudhari, L.C.: Poststroke Upper Extremity Rehabilitation: A Review of Robotic Systems and Clinical Results. *Topics in Stroke Rehabilitation* 14(6), 22–44 (2007)
2. Dollar, A.M., Herr, H.: Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art. *IEEE Transactions on Robotics* 24(1), 144–158 (2008)
3. Zoss, A.B., Kazerooni, H., Chu, A.: Biomechanical Design of the Berkeley Extremity Exoskeleton (BLEEX). *IEEE/ASME Transaction on Mechatronics* 11(2), 128–138 (2006)
4. Walsh, C.J., Paluska, D., Pasch, K., Grand, W., Valiente, A., Herr, H.: Development of a Lightweight, Underactuated Exoskeleton for Load-Carrying Augmentation. In: *IEEE International Conference on Robotics and Automation (ICRA)*, Orlando, Florida, USA, pp. 3485–3491 (2006)
5. Durfee, W.K., Rivard, A.: Preliminary Design and Simulation of a Pneumatic, Stored-Energy, Hybrid Orthosis for Gait Restoration. In: *ASME International Mechanical Engineering Congress*, Anaheim, California, USA, pp. 1–7 (2004)
6. Banala, S.K., Agrawal, S.K., Fattah, A., Krishnamoorthy, V., Hsu, W.-L., Scholz, J., Rudolph, K.: Gravity-Balancing Leg Orthosis and Its Performance Evaluation. *IEEE Transactions on Robotics* 22(6), 1228–1239 (2006)
7. Saglia, J.A., Tsagarakis, N.G., Dai, J.S., Caldwell, D.G.: A High Performance 2-dof Over-Actuated Parallel Mechanism for Ankle Rehabilitation. In: *IEEE International Conference on Robotics and Automation (ICRA)*, Kobe, Japan, pp. 2180–2186 (2009)
8. Farris, R.J., Quintero, H.A., Goldfarb, M.: Preliminary Evaluation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 19(6), 652–659 (2011)
9. Tsagarakis, N.G., Caldwell, D.G.: Development and Control of a ‘Soft-Actuated’ Exoskeleton for Use in Physiotherapy and Training. *Autonomous Robots* 15(1), 21–33 (2003)
10. Perry, J.C., Rosen, J., Burns, S.: Upper-Limb Powered Exoskeleton Design. *IEEE/ASME Transaction on Mechatronics* 12(4), 408–417 (2007)
11. Gupta, A., O’Malley, M.K., Patoglu, V., Burgar, C.: Design, Control and Performance of RiceWrist: A Force Feedback Wrist Exoskeleton for Rehabilitation and Training. *International Journal of Robotics Research* 27(2), 233–251 (2008)
12. Stienen, A.H.A., Hekman, E.E.G., Prange, G.B., Jannink, M.J.A., Aalsma, A.M.M., van der Helm, F.C.T., van der Kooij, H.: Dampace: Design of an Exoskeleton for Force-

- Coordination Training in Upper-Extremity Rehabilitation. *Journal of Medical Devices* 3(031003), 1–10 (2009)
13. Klein, J., Spencer, S., Allington, J., Bobrow, J.E., Reinkensmeyer, D.J.: Optimization of a Parallel Shoulder Mechanism to Achieve a High-Force, Low-Mass, Robotic-Arm Exoskeleton. *IEEE Transactions on Robotics* 26(4), 710–715 (2010)
 14. Mao, Y., Agrawal, S.K.: Design of a Cable-Driven Arm Exoskeleton (CAREX) for Neural Rehabilitation. *IEEE Transactions on Robotics* 28(4), 922–931 (2012)
 15. Galiana, I., Hammond, F.L., Howe, R.D., Popovic, M.B.: Wearable Soft Robotic Device for Post-Stroke Shoulder Rehabilitation: Identifying Misalignments. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Vilamoura, Portugal, pp. 317–322 (2012)
 16. Xu, K., Qiu, D., Simaan, N.: A Pilot Investigation of Continuum Robots as a Design Alternative for Upper Extremity Exoskeletons. In: *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, Phuket, Thailand, pp. 656–662 (2011)
 17. Xu, K., Qiu, D.: Experimental Design Verification of a Compliant Shoulder Exoskeleton. In: *IEEE International Conference on Robotics and Automation (ICRA)*, Karlsruhe, Germany, pp. 3894–3901 (2013)
 18. Xu, K., Zhao, J., Qiu, D., Wang, Y.: A Pilot Study of a Continuum Shoulder Exoskeleton for Anatomy Adaptive Assistancess. *ASME Journal of Mechanisms and Robotics* 6(4), 041011 (2014)
 19. Kobayashi, H., Hiramatsu, K.: Development of Muscle Suit for Upper Limb. In: *IEEE International Conference on Robotics and Automation (ICRA)*, New Orleans, LA, USA, pp. 2480–2485 (2004)
 20. Agrawal, S.K., Dubey, V.N., Gangloff, J.J., Brackbill, E., Mao, Y., Sangwan, V.: Design and Optimization of a Cable Driven Upper Arm Exoskeleton. *Journal of Medical Devices* 3(031004), 1–8 (2009)
 21. Xu, K., Wang, Y., Qiu, D.: Design Simulations of the SJTU Continuum Arm Exoskeleton (SCAX). In: *International Conference on Intelligent Robotics and Applications (ICIRA)*, Busan, Korea, pp. 351–362 (2013)
 22. Schiele, A., van der Helm, F.C.T.: Kinematic Design to Improve Ergonomics in Human Machine Interaction. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 14(4), 456–469 (2006)
 23. Kim, H., Miller, L.M., Byl, N., Abrams, G.M., Rosen, J.: Redundancy Resolution of the Human Arm and an Upper Limb Exoskeleton. *IEEE Transactions on Biomedical Engineering* 59(6), 1770–1779 (2012)
 24. Jarrassé, N., Morel, G.: Connecting a Human Limb to an Exoskeleton. *IEEE Transactions on Robotics* 28(3), 697–709 (2012)
 25. Xu, K., Simaan, N.: An Investigation of the Intrinsic Force Sensing Capabilities of Continuum Robots. *IEEE Transactions on Robotics* 24(3), 576–587 (2008)
 26. Xu, K., Simaan, N.: Analytic Formulation for the Kinematics, Statics and Shape Restoration of Multibackbone Continuum Robots via Elliptic Integrals. *Journal of Mechanisms and Robotics* 2(011006), 1–13 (2010)
 27. Xu, K., Fu, M., Zhao, J.: An Experimental Kinesthetic Comparison between Continuum Manipulators with Structural Variations. In: *IEEE International Conference on Robotics and Automation (ICRA)*, Hong Kong, China (2014) (accepted for presentation)