2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
July 15-19, 2024. Boston, MA, USA

On the Design of a Soft Robotic Neck for the Social Robot HARU

Georgios Andrikopoulos[1] *Member, IEEE*, Lars Hässler[1], and Randy Gomez[2] *Member, IEEE*

***Abstract*— This paper focuses on the application of soft robotics in the area of social interaction, and presents a modular approach on the design of a soft robotic neck for integration with the social robot HARU. The proposed design incorporates soft robotics and additive manufacturing principles, enhancing safety through compliance for absorbing contacts with users or objects, while modularity allows for easy replacement or upgrade to meet HARU's specific application requirements. The paper discusses the conceptual design specifics of the soft robotic neck and provides an overview of the prototype development stages and its main functionalities.**

I. INTRODUCTION

Social robots, designed to interact with humans in a personalized and engaging manner, have gained significant interest in recent years. These robots, often with human-like features, are used in various scenarios, including education [1], healthcare [2], and home assistance [3]. Among them, robots designed for children are of particular interest due to the potential for dynamic and safe interactions. For social robots, especially those designed for children, safety is a critical concern. In order to ensure safe human-robot interaction, safety must be taken into consideration even from the robot conceptualization and design stages.

A critical component for the interaction safety and functionality of social robots that follow head-based configuration is their neck, which plays a vital role in facilitating head movements and overall interaction with the user [4]. Traditionally, existing neck design approaches have relied heavily on rigid components [5], [6] which can pose a potential safety hazard, while replacing or upgrading these components can be time-consuming and expensive.

The advent of soft robotics and 3D printing technologies paved the way for the development of soft actuators [7] and unlocked their structural optimization for best fitting the requirements of their application targets. These soft actuators, made from materials such as silicone or flexible thermoplastics, bring inherent safety due to their compliance, absorbing impacts and reducing the risk of harm during interaction [8], [9]. Additionally, they can be customized to a high degree, allowing for tailored movement capabilities [10], [11]. In this context, continuum actuators stand out as a compelling solution for a robot neck mechanism due to their inherent compliance and ability to mimic organic movement [12], [13], [14].

The use of compliant components to improve flexibility in robot neck configurations has only been recently researched [15], [13], [14], [11], showcasing the potential of utilizing such joint technologies as a replacement to standard rigid counterparts. Although promising, these efforts have yet to address the integration challenge of incorporating a soft robotic neck into an existing social robot system, which poses application-specific requirements in terms of space availability, motion performance, durability, noise, and, ultimately, social expressiveness.

While the benefits of soft actuation for safety and interaction are well-understood [16], achieving durability during long-hour operation is not sufficiently addressed [17]. The current body of research lacks a comprehensive approach to the development of a soft, 3D printed continuum actuator designed specifically for a social robot's neck, which would be able to support the head payload during dynamic motions of its components (e.g. moving eyes [5]).

Moreover, the need for modularity in the design of these robots is an aspect that has received less attention. Modularity offers the potential for easy replacement of parts, which becomes particularly important considering the potential wear and tear in long-term use of social robots by children [18]. This lack of focus on modularity restricts the potential for easy maintenance and upgradability in response to different application requirements. In addition, it hampers the widespread application of soft actuation in social robots, especially those designed for children.

The present design study aims to fill this gap by proposing a novel soft robotic module utilized as a neck for the social robot HARU [5], while it acts as a step towards the re-conceptualization of HARU's original rigid joints and replacement with soft counterparts (Fig. 1). The proposed design promotes safety and enhanced expressiveness through the organic motion of a 2 Degree-of-Freedom (DoF) soft continuum component, while also supporting modularity for easy replacement or upgrade. Preliminary motion tests of the developed module prototype highlight its potential of facilitating more widespread adoption of soft actuation in social robotics, improving safety and user experience in human-robot interactions.

The rest of the article is structured as follows. Section II describes the design process from the initial conceptualization to the selection and mechanical design of the module parts. Section III presents the developed prototype with all its structural and electromechanical components. Section IV provides the preliminary evaluation results of the robot's capability for motion reproduction and durability during operation. Finally, conclusions are drawn in Section V.

[1]Robot Design Lab, Mechatronics Unit, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden
[2]Honda Research Institute of Japan Co. Ltd., 351-0188, Wako, Japan.
Corresponding Author's Email: geoand@kth.se

979-8-3503-9154-1/24/$31.00 ©2024 IEEE

(a)

(b)

Fig. 1. (a) The social robot HARU as first presented in [5], and (b) renders of the re-conceptualized HARU version incorporating soft joints for enhanced expressiveness and safety.

II. Conceptual Design

In the context of designing a robotic neck for a social robot intended for interaction with children, the key requirements were: i) safety through compliance and reduced mechanical complexity, ii) expressiveness through organic motion, iii) 2 DoF motions with ranges dictated by the robot base and eye dimensions, iv) a neck structure robust enough to support the weight of the robot's eyes during operation and when powered off, v) a neck structure soft enough to enable motion within the permissible range without overloading the actuators, vi) durability for enabling long-hour operations, vii) cable routing capability for connecting the eye's electromechanical components to the base, and viii) modularity for easy integration and maintenance.

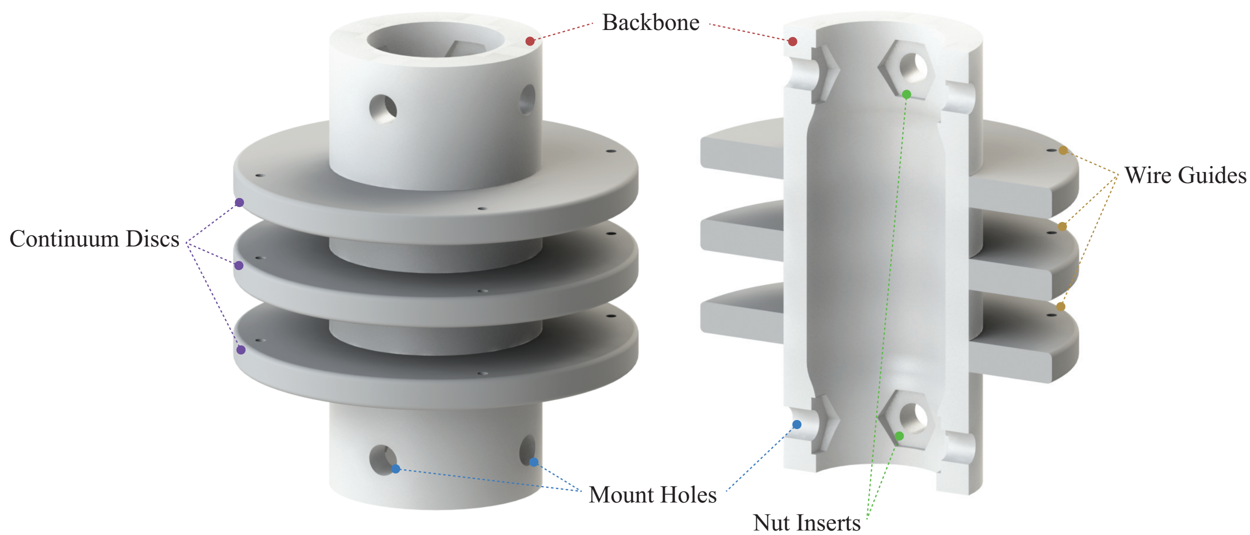
A. Design Specifications

1) Actuator Selection: Actuation selection plays a crucial role in the performance and safety of a soft robotic neck, while various actuation methods come with their unique sets of advantages and disadvantages. Hydraulic and pneumatic systems, despite their high force generation and lightweight nature, respectively, can pose safety risks due to the possibility of leaks. They also tend to be noisy, which can be disruptive in a social environment [7]. Other choices such as twisted coiled polymer actuators (TCPA) [19] and shape memory alloys (SMA) [20] are inherently soft and offer a high force-to-weight ratio, respectively, but their slow response times could limit the robot's expressiveness and overall motion performance. Furthermore, these actuators operate via heating, which can pose a safety risk and would require a customized cooling mechanism, thus increasing complexity and cost. Considering these factors, motor-based actuation was deemed as the most suitable for a soft robotic neck designed for social interaction, as motors offer precise control over position, velocity, and torque, thus enabling highly expressive movements with quieter operation profiles.

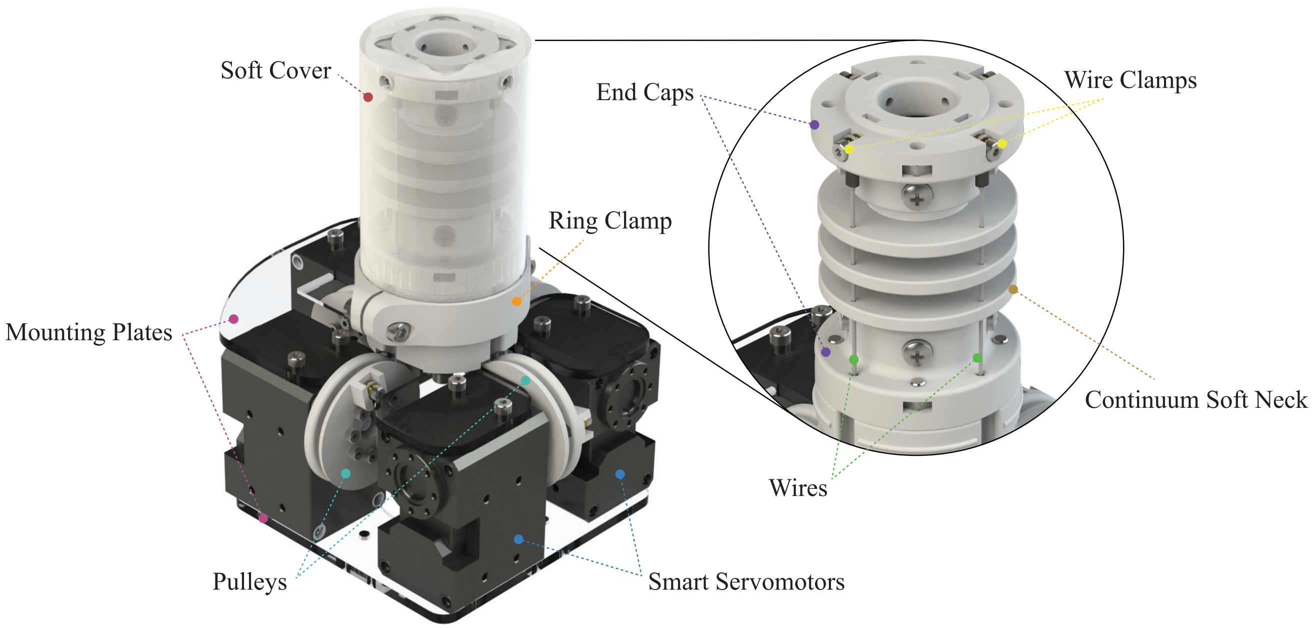
2) Motor Selection: Motor selection plays a pivotal role in designing a soft robotic neck for child-centric applications, with safety, expressiveness, noise reduction, low weight, and fast movements as crucial factors [21]. Direct Current (DC) motors and Brushless DC motors, although simple, cost-effective, and quiet, lack the required control precision and necessitate supplementary components for feedback, thus increasing system complexity [22]. Stepper motors, while offering high precision and ease of control, suffer from efficiency issues, particularly at high speeds, and can introduce undesirable vibration and noise due to resonance [23].

In contrast, servomotors and smart servomotors provide precise control and compact design. Despite their cost, smart servomotors stand out as they incorporate integrated sensing capabilities, allowing for proactive damage detection and management, thereby enhancing safety. Their high torque-to-weight ratio and simple control commands further reduce system complexity [24]. Given these advantages, smart servomotors were selected as the most fitting choice for the intended application.

3) Motor Configuration: The choice of the number of motors in a soft robotic neck significantly affects the system's performance characteristics, which can range from safety and expressiveness to control complexity and the ability to detect and manage damages. Opting for a two-motor configuration could simplify the system and reduce weight, but could also limit expressiveness and accuracy when controlling each DoF bi–directionally. The integration of springs or wire tensioners for bi–directional motion would improve safety by adding passive compliance, but would also introduce motion control challenges and operational risks, as overlapping wires escalate the risk of cables connecting the head to the base getting tangled and cut during operation. These issues could affect the system's performance and potentially necessitate



(a)



(b)

Fig. 2. Graphical representations of the (a) continuum soft neck component in isometric and section view, and (b) soft robotic neck module with annotated main properties.

frequent maintenance.

The use of three motors, arranged in a triangular formation, leads to coupled kinematics as the control of each DoF is not anymore independent. Moreover, the dynamics of the system could become more complicated due to the interaction between the motors, which could potentially limit the system's ability to dampen vibrations and achieve stable motion. A four-motor system, where each motor is responsible for one direction of each motion plane, provides useful redundancy and enhancing control capabilities, thus allowing for more expressive and accurate movements. Using smart servomotors, each acting as a sensing point, the system gains an increased ability to detect and manage damages, providing an added layer of safety. While this setup adds to the cost of the system, and potentially increases complexity and heat generation, these issues can be managed effectively with the right motor selection and design. Given these considerations, a four-motor system was deemed to be the most suitable choice, as it offers the best balance between expressive movements, safer operation, manageable complexity, and performance requirements.

4) Joint Selection: In the context of designing the neck joint, the key requirements are primarily driven by factors such as design complexity, fabrication, assembly, and motion behavior. In addition, the need for safety through compliance and reduced mechanical complexity, as well as expressiveness through organic motion, eliminate classical joint designs such as ball, universal, or even more advanced types such as quaternion joints [25]. A multi-segment compliant structure, despite offering high precision and complex motions, can pose assembly challenges and potential safety risks during human-robot interactions due to its rigid segments [26]. Moreover, such a design introduces increased mechanical failure points, requiring regular maintenance [27].

In contract, a single piece soft structure presents several benefits, making it the most suitable choice for this application. This design simplifies the assembly process, reduces fabrication effort, and produces smooth, natural movements resembling biological neck motions, thus enhancing the robot's expressiveness. The inherent compliance of the soft structure increases safety by absorbing unintentional contacts, reducing the risk of harm. The absence of joints minimizes mechanical failure chances, and the wide design customization allows for efficient cable routing, mitigating tangling / snapping risks and possible user injuries. Overall, the single piece soft structure was deemed as a suitable choice for HARU's neck.

B. Soft Neck Module Design

Graphical representations of the proposed soft robotic neck component and resulting module design are displayed in Fig. 2. Central to the design of the continuum core component is a cylindrical backbone, around which three spacer discs are evenly distributed along its longitudinal axis (Fig. 2 (top)). These discs come equipped with four holes each, serving as guides for wires. Additionally, the backbone is designed with four mounting holes intended for securing the core to the module's end cap components using screws, which are fastened into nuts housed within insert cuts inside the backbone. This soft continuum structure is instrumental in enabling the module to move in two distinct motion planes, hereafter referred to as neck pitch and roll.

The module (Fig. 2 (bottom)) is designed around this core component, which is held at both ends by rigid end caps that attach it to the eyes and the rest of the module. Actuation is achieved through four wires that pass radially through the continuum disks. These wires are attached to their respective motors, and their linear motion, when activated by the motors, is translated into the curved motion of the flexible component. To mitigate the risk of injury from the moving wires and enhance the neck's organic appearance, a soft cover was designed to encase the flexible component. The cover affixed at the top by being pressed between the upper fixture and the head sub-assembly, and at the bottom by a ring clamp to prevent it from tearing during operation.

The four motors that drive the wires are mounted beneath the flexible component. They are positioned between two plates to ensure stability and to align them with the wire paths on the flexible component. A cone-shaped piece is installed in the heart of the motor assembly, serving the critical role of guiding the cables from the base of the robot to the eyes, reducing the risk of cables getting snagged between the wires and motor pulleys during operation.

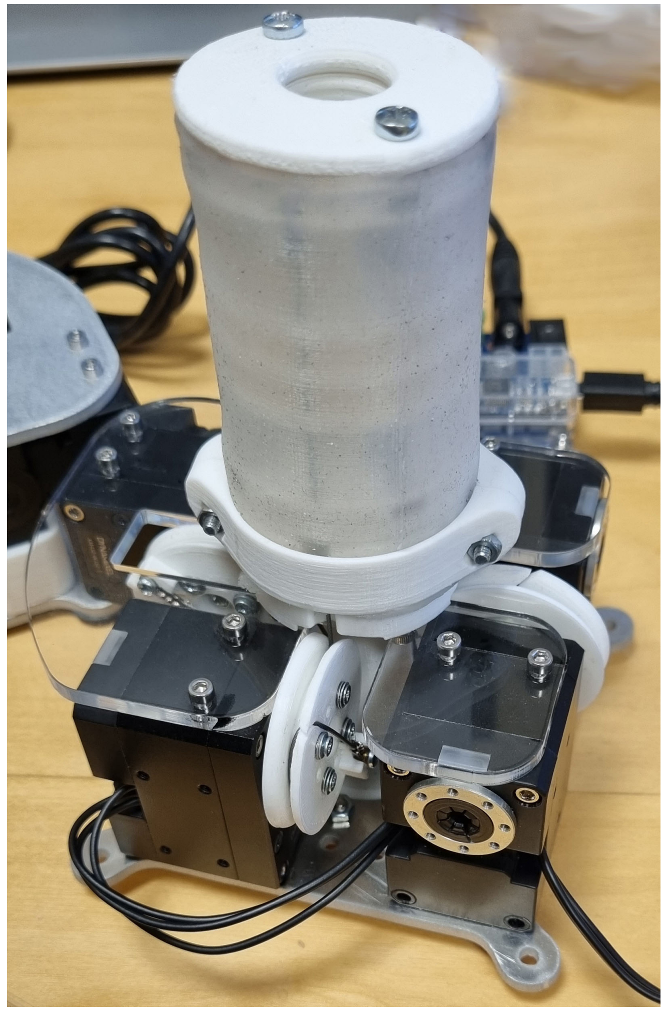


Fig. 3. The assembled robotic neck module prototype.

III. Prototype Development

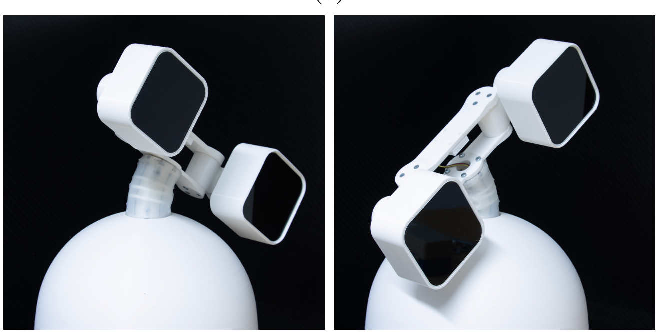
The developed soft neck prototype is shown in Fig. 3. Safety was a key consideration in the implementation of the neck module, particularly in relation to human-robot interaction. The presented elements were carefully selected and iteratively modified to provide the desired functionality, safety, and reliability during long-hour operation.

The selected continuum component for the soft robotic neck module was 3D printed via Fused Deposition Modeling (FDM) using Ninjaflex material, which was chosen through iterative testing of different soft materials. The geometrical properties of the structure were also determined in an iterative manner to meet the design requirements for support and softness. Finite Element Modeling (FEM) simulations were employed to evaluate the performance of the developed designs before fabrication and experimental testing.

To ensure stability and structural integrity, two rigid fixtures were incorporated into the module. These fixtures, which served as connection points to both the rest of the module and the robot's head, were 3D printed using nylon material. The neck module's motion was achieved through four Dynamixel XM430-W350-T smart servomotors, which

(a)

(b)



(c)

Fig. 4. Photographic stills displaying the robotic neck prototype integrated with a base and eye mock-up for testing the neck's motion performance under variable head loads and for different motion scenarios: (a) idle state, (b) neck pitch and (c) neck roll. The stills present the neck motion while under a 0.9 kg load.

provide feedback signals such as current, position, velocity, and temperature, thereby facilitating control and simplifying cable routing due to their daisy chain connection.

To achieve durable motion while handling the generated forces for actuating the robot neck, the four wires connected to the motors were multi-strand and coated for reducing friction, as these wires were routed radially across the continuum structure and passed through the disks. Connectors were used to securely clamp the wires at both ends, thus ensuring their reliable operation and absence of slippages.

To mitigate the risk of injury resulting from intentional or unintentional contact between the user and the moving wires, a soft cover, made of Ecoflex 00-50 silicon, encapsulated the continuum component of the neck module. 3D printed clamps were employed at the bottom of the cover to prevent tearing during operation. For improved cable routing, a conical piece was integrated into the middle of the motor assembly. This conical piece, serving as a cable guide, was 3D printed via FDM using standard PLA material.

IV. Results

To experimentally validate the soft robotic neck, preliminary integration with HARU's 3D printed base and eye mockups was performed. The objective of performed tests was to evaluate the functionality of the soft component and the motor antagonistic operation under varying loads placed within the two eye compartments. Fig. 4 (top) illustrates the configuration of the setup, while photographic stills showcasing the neck's pitch and roll motions are presented in Fig. 4 (middle) and Fig. 4 (bottom), respectively.

Data collected during the experiments included feedback signals such as motor position, velocity, current, temperature, as well as the roll and pitch angles of the neck, which were measured using an integrated Inertial Measurement Unit (IMU) within the eye mockup. The results consistently demonstrated that the two degrees of freedom (DOFs) of the neck were kinematically decoupled, allowing independent and unaffected operation of each DOF.

In addition, the neck exhibited accurate and smooth performance of roll and pitch motions, surpassing the initial requirement of 45 degrees, while subjected to head loads ranging from 0.1 to 0.9 kg. Importantly, the motor currents remained below 40 % of their maximum allowable values, and the internal motor temperatures remained below 40 ^{o}C for all tested scenarios.

Furthermore, experimental validation of the soft robotic neck included multiple durability tests, all of which exceeded target ranges of motion and normal operation. Indicatively, the module demonstrated the ability to withstand longitudinal extensions at approximately 450 N, while proving resilient against compressive forces, withstanding approximately 260 N without failure.

Finally, during constrained rotation tests, the neck exhibited no signs of major structural deterioration when repeatedly subjected to torques reaching a maximum of 4 Nm, which approximately caused a full rotation of the head. All these preliminary results validated the module's durability, thus confirming its suitability as the robot's neck component.

V. Conclusions

This article explored the design process of a soft robotic neck intended for use on the social robot HARU. The selection of a single piece, soft structure over a multi-segment one for the continuum actuator served to simplify the design and assembly process while still providing robustness and the desired motion profile. The use of four smart servomotors to actuate the soft neck provided advantages including enhanced expressiveness, independent control of the degrees of freedom, and redundancy that provides a fail-safe mechanism, thus improving safety. Finally, the modular design of the actuator allowed for easy replacement or upgrading, further extending the potential applications and lifespan of HARU.

The preliminary evaluation of the produced soft neck prototype involved its integration and testing with HARU's base and eyes. In all performed motion tests, the neck prototype exhibited accurate and smooth roll and pitch motions, surpassing the range requirement and remaining consistent when subjected to variable loading. Furthermore, the durability tests conducted on the soft robotic neck revealed its ability to withstand longitudinal extensions, exhibiting resilience against large compressive forces without evidence of structural failure. Finally, the constrained rotation tests showed no significant structural deterioration even when subjected to a full rotation of the head.

ACKNOWLEDGEMENT

The authors would like to acknowledge Seshagopalan Thorapalli Muralidharan, Haswanth Yalamanchili and Andreas Bekas of the Mechatronics Unit at KTH for their support during the prototype evaluation.

REFERENCES

[1] G. A. Zachiotis, G. Andrikopoulos, R. Gornez, K. Nakamura, and G. Nikolakopoulos, "A survey on the application trends of home service robotics," in *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2018, pp. 1999–2006.

[2] C. Breazeal, "Social robots for health applications," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2011, pp. 5368–5371.

[3] R. Gomez, A. Páez, Y. Fang, S. Thill, L. Merino, E. Nichols, K. Nakamura, and H. Brock, "Developing the bottom-up attentional system of a social robot," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 7402–7408.

[4] D. St-Onge, K. Gourgoulias, A. Bovo, R. Thandiackal, K. Melo, T. Horvat, K. Karakasiliotis, J.-M. Cabelguen, and A. Ijspeert, "A biomimetic robotic platform to study flight specializations of bats," *Science Robotics*, vol. 2, no. 3, 2017.

[5] R. Gomez, D. Szapiro, K. Galindo, and K. Nakamura, "Haru : Hardware design of an experimental tabletop robot assistant," in *Human Robot Interaction (HRI)*, vol. 8, Chicago, IL, USA, 2018, Conference Proceedings, pp. 233–240.

[6] M. Jeung, G. Lee, and Y. Oh, "Realization of human neck motion with novel robotic mechanism," in *2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, 2016, pp. 482–486.

[7] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.

[8] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Robotics and Autonomous Systems*, vol. 73, pp. 135–143, 2015.

[9] A. Lindestam, S. Thorapalli Muralidharan, G. Andrikopoulos, and R. Gomez, "Model identification of a soft robotic eye actuator for safe social interactions," in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 2024.

[10] H. Liu, W. Yu, X. Liang, and E. Torres-Jara, "Soft actuators for soft robotic applications: A review," *Advanced Materials Technologies*, vol. 4, no. 9, 2019.

[11] A. Niikura, H. Nabae, G. Endo, M. Gunji, K. Mori, R. Niiyama, and K. Suzumori, "Giraffe neck robot: First step toward a powerful and flexible robot prototyping based on giraffe anatomy," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 3539–3546, 2022.

[12] D. Trivedi, C. Rahn, W. Kier, and I. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Applied Bionics and Biomechanics*, vol. 5, no. 3, pp. 99–117, 2008.

[13] L. Nagua, C. Monje, J. Muñoz Yañez-Barnuevo, and C. Balaguer, "Design and performance validation of a cable-driven soft robotic neck," in *Jornadas Nacionales de Robotica (Spanish Robotics Conference)*, 06 2018.

[14] D. Copaci, J. Muñoz, I. González, C. A. Monje, and L. Moreno, "Sma-driven soft robotic neck: Design, control and validation," *IEEE Access*, vol. 8, pp. 199 492–199 502, 2020.

[15] Y. Zhou, H. Cheng, H. Jiang, and L. Hao, "Design of a pma-driven bionic neck robot with a spring spine," in *2017 IEEE International Conference on Cyborg and Bionic Systems (CBS)*, 2017, pp. 35–40.

[16] G. Andrikopoulos and G. Nikolakopoulos, "Humanoid robotic leg via pneumatic muscle actuators: implementation and control," *Meccanica*, vol. 53, no. 3, pp. 465–480, 2018.

[17] T. G. Thuruthel, E. Falotico, F. Renda, and C. Laschi, "Control strategies for soft robotic manipulators: A survey," *Soft Robotics*, vol. 5, no. 2, pp. 149–163, 2018.

[18] G. Hoffman and W. Ju, "Designing robots with movement in mind," *Journal of Human-Robot Interaction*, vol. 3, no. 1, pp. 89–122, 2014.

[19] S. M. Mirvakili and I. W. Hunter, "Artificial muscles: mechanisms, applications, and challenges," *Advanced Materials*, vol. 30, no. 6, p. 1704407, 2018.

[20] M. H. Elahinia, *Shape Memory Alloy Actuators: Design, Fabrication, and Experimental Evaluation*. John Wiley & Sons, 2016.

[21] C. Majidi, "Soft robotics: A perspective—current trends and prospects for the future," *Soft Robotics*, vol. 1, no. 1, pp. 5–11, 2014.

[22] G. Andrikopoulos, A. Papadimitriou, A. Brusell, and G. Nikolakopoulos, "On model-based adhesion control of a vortex climbing robot," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2019, pp. 1460–1465.

[23] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*. Springer, 2016.

[24] H. Asada and J.-J. Slotine, *Robot Analysis and Control*. John Wiley & Sons, 2014.

[25] Y.-J. Kim, J.-I. Kim, and W. Jang, "Quaternion joint: Dexterous 3-dof joint representing quaternion motion for high-speed safe interaction," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 935–942.

[26] S. Haddadin, A. Albu-Schaffer, A. De Luca, and G. Hirzinger, "Requirements for safe robots: Measurements, analysis and new insights," *The International Journal of Robotics Research*, vol. 30, no. 11, pp. 1337–1354, 2011.

[27] D. Pavlichenko and P. Manoonpong, "Bioinspired spring-loaded biomechanics applied to the robotic leg," *IEEE Transactions on Robotics*, vol. 33, no. 6, pp. 1289–1301, 2017.