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Soft Robotics for Human-Robot Interaction Applications

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Abstract: As the prevalence of robots in society rises, the necessity for interaction with them is becoming imperative. The domain of Human-Robot Interaction (HRI) has gained significance as robots increasingly undertake repetitive and laborious tasks. Recently, the domain of soft robotics has shown significant growth in both research and commercialization. Industry 5.0 emphasizes human-robot cooperation, hence advancing the domain of soft robotics. Nonetheless, the human-robot interaction for soft robotics remains in its embryonic phase. This paper reviews and discusses the implementation of human-robot interaction (HRI) in soft robots. We first examine the control, design, materials, and fabrication of soft robots. This will elucidate the nature of the interaction. Subsequently, we examine the many input and output modalities used in human-robot interaction (HRI). The literature provides a detailed discussion of the applications of Human-Robot Interaction (HRI) in soft robots. The constraints of human-robot interaction (HRI) for soft robots and the many research possibilities within this domain are examined comprehensively. It is concluded that there exists significant potential for the advancement of human-robot interaction in soft robotics.

Keywords: *Soft robots, Human-Robot Interaction, Input modalities, Output modalities, Polymer, Actuator, Gesture*

Introduction

The adjectives compliant, flexible, and soft are often ambiguous when used to describe machinery. Compliant mechanisms use the inherent flexibility of materials for motion, while flexible mechanisms include diverse flexible components, like cables and springs, for movement [1]. The soft mechanisms integrate compliant and flexible components to facilitate adaptable and gentle motion, frequently emulating natural movements and interactions. A soft robot is a robotic system constructed from compliant materials, allowing it to deform, bend, and adjust to its surroundings, hence providing flexibility and safety in human-robot interactions. Soft robots exhibit safety and compliance in contrast to rigid-bodied robots during human-robot interaction (HRI). It was regarded as a suitable choice for HRI because of its reduced unintentional impact forces and elevated power density ratio [3]. Soft robots, inspired by organic beings, may be used for safe human-robot interaction (HRI). Wearable electronics and soft robots prioritize tactile and skin-friendly interfaces. The transition from rigid-bodied robots to soft-bodied robots encompasses ethical and philosophical considerations, as explored in [5]. The advancements in human-robot cooperation up to 2018 are documented in [6]. A survey of human-robot interaction in soft robotics previous to 2019 may be found in [7].

It elaborates on bio-inspiration, modeling, actuation, control, and applications comprehensively. A survey of secure physical human-robot interaction before to 2008 is available in [8]. An atlas of physical human-robot interaction (pHRI) addresses safety, mechanics, control difficulties, reliability, and established performance criteria. It underscores that the safety and reliability concerns in pHRI still to be resolved [9]. These issues have been addressed in recent years [10]. The societal acceptability of machines and robots depends on the trust established in their interactions with humans. The trust was established on physical security, operational comprehension, and social education. Soft robots, characterized by their adaptability and use of pliable materials, improve safety and operational convenience [11].

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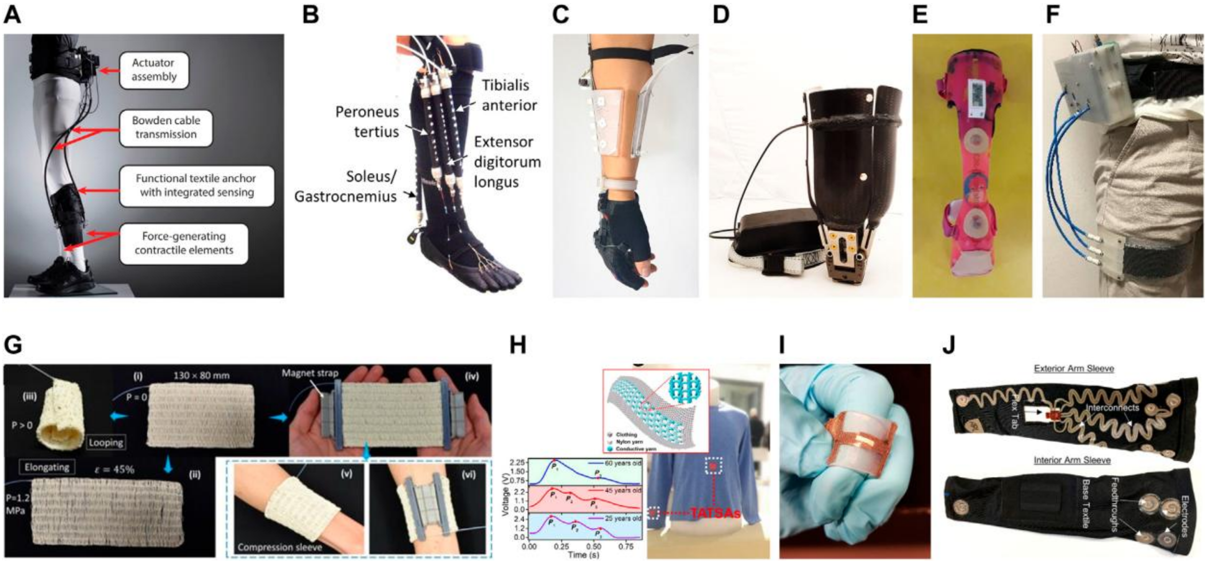

Figure 1: Soft robotic exosuit for assistive and rehabilitation applications in post-stroke patients

Various phases exist in the degrees of cooperation between robots and humans. The categories are: (1) Caged Robot, (2) Human-Robot Interaction, (3) Human-Robot Collaboration, (4) Physical Human-Robot Collaboration, and (5) Human-Robot Teaming. This is seen in Figure 1. In caged robots, there is no interaction between the human and the robotic being. The robot is situated inside a confined enclosure where it performs the designated duty. In human-robot interaction, the robot engages and communicates with people. This would involve utilizing input and output modalities. Human-robot cooperation occurs when robots aid people in attaining common objectives. In physical human-robot cooperation, activities are accomplished jointly via direct physical contact between people and robots. In human-robot collaboration, people and robots engage in a cooperative alliance to attain common objectives via synchronized activities. The degree of cooperation and inherent safety of robots escalates with the enhancement of their level.

Human Robot Interaction applied to Soft Robotics

The domain of HRI in soft robotics concentrates on the design of robots using pliable materials and mechanics to provide safe and intuitive human contact. Industry 5.0 emphasizes human-robot collaboration, making human-robot interaction (HRI) in soft robotics crucial for establishing a relationship between humans and robots. Multiple modalities contribute to this interaction. The control, design, and production of these soft robots are crucial from the user's standpoint due to their interaction with them. The benefit of human-robot interaction in soft robotics lies in the emphasis on safety during engagement. The robot's pliable design may reduce or eliminate injuries to people. In contrast to the HRI for rigid-bodied robots, a wider demographic of individuals, from babies to the elderly, may benefit from the HRI for soft robots. Consequently, this domain in robotics has extensive opportunities for investigation, and several contributions are anticipated in the next years.

Input and Output Modalities

In recent years, academics have been investigating control systems for soft robots. In a study by [25], the collaborative effort of humans and soft robots was shown to be successful. The study indicated that continuous haptic assistance will effectively benefit experienced users, but customized instruction is necessary for novice users.

Input Modalities

This section examines the various input modalities used in the domain of Human-Robot Interaction (HRI) for soft robots. These include compliance, gesture recognition, brain-computer interfaces, touch sensitivity, balloon sensors, robotic skin, triboelectric nanogenerators, and the human face. They were identified in the literature we selected for this survey.

Adherence

It is the capacity to deform a certain material. Mechanical compliance is crucial in physical human-robot interaction (pHRI). A research

conducted to analyze the behavior of compliant links and compliant joints in pHRI showed that compliant links surpass compliant joints, while underscoring safety in pHRI.
A compliant actuator using magneto rheological (MR) fluid was used for secure physical human-robot interaction (pHRI). A two-link planar robotic manipulator was constructed using the MR fluid-based compliant actuator, and safety analysis was conducted experimentally in both static and dynamic situations [24].

Gestures

The gesture refers to an individual's capacity to indicate and signify information for comprehension by a system or another person [75]. A soft module was constructed using slapping, squeezing, and tickling as input gestures for the modules [37]. The module was constructed from silicone, with two polyvinylidene fluoride (PVDF) sensors affixed to it. The operation of the system is as follows: (1) The user's input gesture is captured (2) The vibration is detected by the PVDF sensor (3) The data undergoes processing and filtering (4) Features are retrieved (5) Classification is performed via a machine learning algorithm (6) The identified gesture is given vocally. The input modality for the soft developing robot [57] consisted of the operator's gestures monitored by a motion capture device, which are correlated with the robot's kinematics for teleoperation.
This interface interprets signals from the human brain and designates specific actions for each signal [75]. A novel multimodal human-machine interface (mHMI) was created by integrating electrooculography (EOG), electroencephalography (EEG), and electromyography (EMG). The technology included a pneumatically actuated soft robotic hand. A combination of hand gestures and eye movements in the EOG, EEG, and EMG modalities was used to enhance the motor function of stroke survivors [27].

Control, Design, Materials and Manufacturing of Soft Robots

This section examines the several control strategies used in the domain of Human-Robot Interaction (HRI) for soft robots. Subsequently, we examine the design of several soft robots on which human-robot interaction has been conducted. This is followed by a concise overview of the material selection and production process for the soft robots, in which the HRI has been conducted.

Control

A survey of model-based control of soft robots is provided in [18]. The research in [24] illustrates the compliance control of a robotic manipulator for secure physical human-robot interaction (HRI). In [25], shared control for the teleoperation of a soft growing robotic manipulator was implemented. A master-slave position control was implemented for a 2 DoF exoskeleton robot. In [27], real-time control of a soft robotic hand

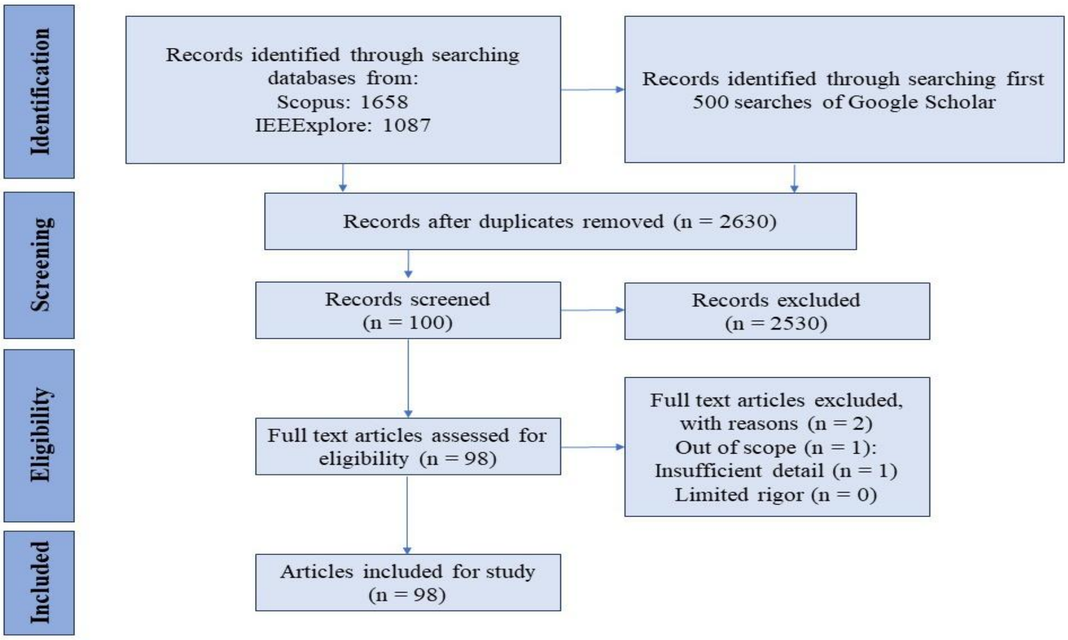

Figure 2: The PRISMA flow diagram that shows the search results and screening

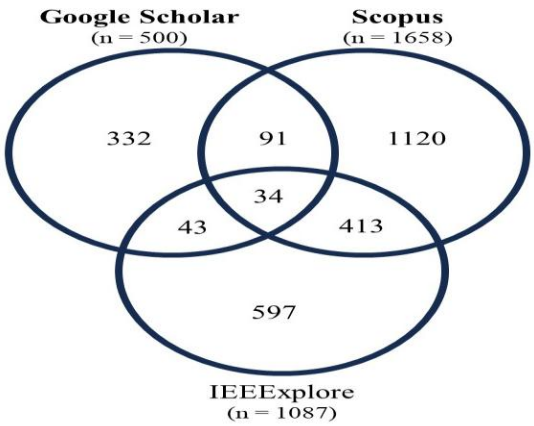

Figure 3: The Venn diagram showing the duplicates in the three databases

The action was executed. A model-based dynamic feedback control was executed for a planar soft robot in [28]. In the study referenced as [29], an active compliant control mode was used to engage with a pneumatic soft robot. In [30], model-based online learning and adaptive control for a human-wearable soft robot were conducted and presented. The impedance control of a hand-arm for human-robot interaction was conducted and documented in [31]. In [32], the active compliance control of soft fingers and force detection for human-robot interaction was shown. A model-based control system for the quasi-static regulation of motion and force in a soft robotic exoskeleton for hand aid and rehabilitation was created and reported in [33]. A cable-driven soft joint using torque-displacement modeling and a sliding mode controller shown resilience in low-level torque regulation [34]. An adaptive quasi-static model-based control system has been used to regulate a wearable device (a soft robotic exo-digit) [35].

In the study referenced as [36], a pressure feedback controller was used to detect touch and delicately hold the item. The soft robotic module described in [37] was regulated by machine learning algorithms for secure physical human-robot interaction (pHRI). The impedance control of the soft robot ALTER-EGO was addressed in the study referenced as [38]. The same impedance control was used to the soft robot in [9] for secure physical human-robot interaction (pHRI). The soft robot in [39] was controlled by a bespoke deep neural network (DNN) algorithm. A hybrid controller designed for stiffness modulation and interaction regulation to shape behaviors, ensuring safe interactions between the robot and its environment, has been introduced in [40]. In the study referenced as [41], low-gain feedback mechanisms were integrated with feed-forward actions to regulate the soft robot's interaction with its surroundings. In [42], the soft robotic hand was regulated using a closed-loop PID control methodology for the flexion and extension angles of the robotic hand.

Discussion

Distinguishing soft robotics from conventional robots. Contrary to traditional beliefs and assertions that soft robots exhibit more naturalness than stiff robots [6–8], no statistically significant difference in total perceived naturalness ratings was seen among the three robots. No statistically significant changes were seen in the ratings of the naturalness of appearance, movement, and tactile sensation. Consequently, we determined that the quantitative analysis fails to substantiate the notion that soft robots are seen as more natural than conventional stiff robots. This outcome contradicts dominant beliefs about individuals' perceptions of soft robots in contrast to traditional robots. Secondly, we noted a diverse array of responses when participants were prompted to define the term "natural". This discovery indicates that the language and discourse related to robotic embodiments require more meticulous consideration. Concerning the particular hypotheses, H1 posited that the soft robots would be seen as having a more natural look than the stiff robot, which was not substantiated. A plausible reason for this outcome may be that most participants saw the term "natural" as customary or habitual. The blue robot may have been seen as having a "unnatural" look, given that the hue is hardly found in natural species, while its softness concurrently deviates from conventional assumptions about robotics. Likewise, the rigid robot may have been regarded as moving naturally due to its adherence to the principles of its mechanical design, which are apparent from its appearance.

H2 posited that perceived naturalness and appeal would not be connected; yet, our findings reveal a strong connection between perceived overall naturalness and overall appeal for all three robots. This may suggest that "natural" functions both as a descriptive phrase and as a term of positive value, as previously emphasized in discourse analysis [51, 52].

Individuals exhibited more audacity in manipulating and physically engaging with the soft robots compared to the stiff robot. Participants manipulated the entire surface area of the soft robots, inadvertently causing damage to one of them. The tactile interaction with the stiff robot was mostly (81% of participants) confined to the soft end effector. We assert that these interaction patterns are crucial for robot designers, since they directly pertain to safety and dependability. Our findings indicate that soft silicone material encourages tactile interaction in a manner that rigid materials do not. From a design standpoint, we recommend that just the tactile components of a robot should be constructed from soft silicone; if the whole morphology consists of soft materials, as shown in the red and blue robots, individuals may feel secure (or even compelled) to touch all aspects of it. The exposure of soft robots to more vigorous handling indicates that durability is essential for robots designed for intimate physical contact with people. Users lack familiarity with soft robotics technology compared to mechatronics and traditional robots, and we discovered that some individuals erroneously believe that a soft morphology can endure almost any condition. The apprehension or restraint shown by individuals towards conventional robots does not seem to extend to robots constructed from soft materials. In instances involving intimate physical contact, this may provide challenges for both the robot and the human.

Conclusions

This study examined human-robot interaction (HRI) in soft robots, emphasizing control, design, materials, manufacturing, modalities, and applications comprehensively. We examined the constraints and research prospects for this domain based on these information. The domain of control in soft robots is complex and presents ongoing problems. The design field must guarantee that the human-robot interaction (HRI) is secure for both humans and the soft robot. The materials used in the fabrication of soft robots must be wear-resistant to provide prolonged durability. The manufacturing technique should facilitate the efficient manufacture of the interface device and soft robot, both in batch and mass quantities. The selected modes for engagement must account for individuals from diverse backgrounds. Consequently, the domain of human-robot interaction concerning soft robotics is an emerging discipline with significant potential for expansion in the next decade. The essay underscores the considerable potential for advancement in Human-Robot Interaction (HRI) concerning soft robotics, noting substantial research chances for multimodal interaction during user situational impairments.

Limitations and further work

This research has challenged the idea that soft robots are inherently more "natural" than conventional robots and has discerned potential variations in human interactions with soft and regular robots. Nevertheless, the study possesses certain limitations. A limitation is that participants were only requested to evaluate the robots in an open-ended, ambiguous setting. For the ratings to be applicable to certain applications or use cases, the research should preferably consider that certain embodiments and aesthetics may be favored for various objectives. A robot characterized by safety and accuracy may be favored in healthcare settings; however, this criterion may not be relevant for educational robots (cf. 3.3.1). Furthermore, the absence of a defined task or objective in the interaction may have influenced the perception of the robots as more subject-like. A further disadvantage is that the data represents first perceptions and engagement behaviors that may evolve or diminish over time as individuals acclimate to the robots. The results indicate how people perceive and interact with silicone-based soft robots during early encounters, which is crucial for the eventual acceptance and adoption of innovative technologies [60].

The context is a factor to consider about the recruiting process and the implementation of the two trials. Participants were recruited at public events on a university campus specializing in information technology, perhaps introducing bias into the outcomes. Given the age range of participants (19-70 years) and the significant percentage of individuals inexperienced in human-robot interaction (54%), it is plausible to conclude that many participants were neither students nor faculty members. The two experiments occurred over two days: the trial using soft robots was held in the evening at a citywide event, whilst the trial with the stiff robot took place during the day at a matchmaking event for college and university students.

A further limitation of the study is the questionnaire we developed to answer the unique research issues that prompted this investigation. Additional efforts are required to ascertain the validity and reliability of this subjective self-reporting instrument.

Statistical analysis indicated that our results did not substantiate the assertion that soft robots are seen as more natural than stiff robots. We observed lower mean scores, suggesting a greater degree of agreement, for the overall naturalness evaluation of the soft robots in comparison to the rigid robot. Consequently, the data' failure to substantiate this hypothesis may stem from the study's statistical underpowering, rendering it unable of identifying minor differences.

This work constitutes a singular case analysis using a particular kind of soft robot. Further investigations are required to ascertain the distinctions in individuals' perceptions and intuitive interactions with soft robots compared to standard robots. Furthermore, the observed differences should be validated in studies with a larger sample size to enhance generalizability.

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