Comparative Analysis of Soft Robotic Hands for Sign Language Communication with Deaf Individuals

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***Abstract* —This article examines the development and performance evaluation of a robotic hand that facilitates communication for the hearing impaired by mimicking hand signals for sign language communication. This study focused on comparing three different actuation technologies—shape memory alloy (SMA),pneumatic bending actuators and origami robots (cPEVA fibers)—to determine their suitability and effectiveness in altering human movements and to improve translation.**

The motivation behind this study is an effort to bridge the communication gap between the deaf and the hearing world and thus ensure that access is easy and inclusive. While traditional robotic hands often lack the ability to meet needs and desires, soft robotic hands show promise due to their flexibility and adaptability.

I. INTRODUCTION

Sign language is a form of communication with visuals and gestures used by hearing impaired people. It provides accessibility, inclusivity and connection across cultures. Learning a language can improve communication, cultural understanding and break down barriers. Language recognition is a step towards a more integrated society. Sign language is a unique and complex form of communication and is the primary form of communication for deaf people worldwide. Sign language is a beautiful, handcrafted and gestural language that allows millions of people to express their thoughts, feelings and ideas. However, the communication connection between hearing and deaf people is still an ongoing problem, highlighting the need for new solutions.

Manual robots are great tools for communication. It increases accessibility and supports language learning through consistent sign language. Although difficulties such as accuracy therefore they should complement human interpretation, not replace it. Traditional hand robots come with various drawbacks that soft robotics can eliminate

Soft robotics offers distinct advantages over conventional mechanical robot hands when it comes to sign language interpretation. Traditional mechanical systems often lack the dexterity, flexibility, and naturalness required to replicate the intricate hand movements and gestures of sign language accurately. Soft robotic hands, on the other hand, are designed to be highly compliant and adaptable, mimicking the soft and pliable characteristics of human hands. This compliance allows for more precise and expressive movements, enabling a soft robotic hand to convey the nuances of sign language with greater fidelity. Additionally, the inherent safety and gentle touch of soft robotics make them more suitable for human interaction, a crucial aspect when interpreting sign language.

This research paper delves into the actuation mechanisms employed by robotic systems, specifically focusing on Shape Memory Alloys (SMAs), pneumatic bending actuators, and origami robots. The study aims to comprehensively examine and compare these three distinct actuation methods to identify the most suitable and efficient option .This study considers the mechanical properties and components of each technology and evaluates their impact on the overall performance

Finally, this study demonstrates the problems and opportunities of developing a robotic hand for communication, with the aim of demonstrating the future success of technology use and promoting better communication and understanding for deaf and hard of hearing people.

II. PNEUMATIC BENDING ACTUATORS

Pneumatic bending actuators have emerged as a compelling technology in the realm of soft robotics, particularly in the development of hand robots and wearable hand grippers. These actuators harness the power of compressed air or gas to generate motion and mechanical work, providing a versatile and adaptive solution for mimicking the dexterity and compliance of the human hand. With a wide range of applications, including assistive devices, prosthetics, and human-robot interaction, pneumatic bending actuators have gained significant attention in recent years.

Pneumatic bending actuators function on the principle of controlled inflation and deflation of chambers within their structure. Typically composed of flexible materials such as elastomers, they consist of multiple chambers that, when inflated sequentially, create a bending motion. In hand robots, pneumatic bending actuators play a pivotal role in replicating the complex and dexterous movements of human hands. Their ability to achieve a wide range of joint angles and adapt to varying object shapes is invaluable in tasks such as grasping, manipulating objects, and performing delicate tasks. These actuators enable hand robots to perform tasks with a level of finesse and adaptability that is often challenging to achieve with rigid mechanical counterparts.

PneuNets are a soft actuators developed by the Whitesides Research Group at Harvard. These can be used to form the fingers and thumbs of the hand robot.They are actuated by inflating chambers using compressed gas or air. When they are pressurised expansion occurs in the least stiff regions.Therefore they can be programmed by selecting wall thickness according to the type of motion they require.In this case, they need to move like fingers and therefore the thinnest layer will be on the outside.[1]

A. Design of the PneuNet bending actuator

They contain a series of chambers arranged where the thinnest wall sections are between the chambers adjacent to each other .There is also a strain limiting layer embedded in the base .When the device is inflated the thin walls expand more compared to the others allowing it to achieve a bending motion while the strain limiting layer gives it stability. The elastomer which is the main body and the strain limiting layer are manufactured separately and then glued together. [1]

B. In relation to the hand robot

In the context of employing PneuNet bending actuators as the constituent components for the fingers of a hand robot intended for sign language communication, an intricate approach to finger design is essential. The design includes the integration of three discrete PneuNets for each finger, allowing for exceptional flexibility and precision in motion. Notably, this tripartite configuration permits the fingers to exhibit an extended range of movements, ultimately enhancing the accuracy and articulation of the sign language gestures. This design principle is consistently applied across all four fingers of the robotic hand.

Moreover, particular attention is directed towards the thumb's functionality. For the thumb, an even more specialized configuration is implemented, employing two distinct sets of PneuNet bending actuators. This dual arrangement for the thumb is purposefully structured to enable the robotic hand to mimic the complex and versatile movements of the human thumb, which are pivotal for executing many signs in sign language. The integration of two separate PneuNet bending actuator sets for the thumb underscores the commitment to achieving a high degree of anthropomorphism in the robotic hand's sign language communication capabilities.

These discrete PneuNet bending actuators, distributed across the fingers and thumb, are meticulously coordinated and actuated in precise sequences to emulate the desired sign language gestures. Such an approach to actuation ensures that the hand robot can closely replicate the intricate and nuanced movements essential for effective communication in sign language, marking a significant advancement in the field of human-robot interaction and assistive technology for the deaf and hard of hearing.

A significant drawback associated with employing PneuNet bending actuators as individual components for each finger in a hand robot designed for sign language communication is the inherent complexity of separately actuating each discrete PneuNet actuator to convey distinct symbols and gestures, leading to potential time delays in the signing process. The need for sequential actuation not only hampers the pace of signing but also poses challenges in achieving fluency and naturalness in sign language communication. While ongoing research seeks to optimize the actuation process, this remains a critical consideration in designing efficient and fluid hand robots for sign language applications.

III. SHAPE MEMORY ALLOYS

The pneumatic Shape memory alloy strips have already been the subject of numerous studies on how to create assistive devices, soft therapy, and prosthesis that improve the activities of daily living (ADL) for stroke victims and amputees' quality of life. These robotic hands when paired with an AI algorithm can be used to perform ASL (American Sign Language) Communication in place of humans.[2]

Even though motors such as direct motors , Servo motors and stepper motors are usually used to run the machine they fail to satisfy the demands required to perform the versatile movements required by the hand robot and are noisy, heavy and provide less energy per unit volume. Pneumatic systems can be versatile however they require supplementary elements such as pumps and valves making the arrangement bulky. Hence, Shape memory alloys might be a new option. They can also return to their original shape after heating and have very many advantages such as small size, elevated energy concentration, reduced mass, and increased strength, adaptability, silent operation,uncomplicated configuration, friction free, anticorrosive ,possess an elevated lifespan, strong damping, and increased resistance ,extremely condensed structure, and straightforward assimilation into novel arrangments. More precisely, SMAs function flawlessly as transducers.[2]

However they do have some disadvantages such as lesser power usage,reduced displacement, comparatively diminished strain resilience and they require longer cooling period post heating. They also are prone to non linear behaviour.

A. Literature review of papers that use SMA for hand robot

The plate based SMA actuator (by Engberg at al) uses strips, plates, or bending beams to move the hand.These plates are shaped to resemble flexed human fingers when heated. She et al. (2015) developed another robot hand with five fingers .The finger is composed of a nickel-chromium wire for the heat simulation, an actuator made of shape memory alloys, and a piezoelectric sensor. When the input current was 1A, the finger could carry up to 412 g and responded in about 11 s.[2][4][5]

The tube based actuator(by Ades et al.) contains an interior reservoir for a fluid control arrangment that provides cooling. The finger bends when heated and expands when cooled. The peak maximal force exerted by the finger reached 4.35 Newtons.[2][4][6][7]

The Spring based actuator (by Hironari et al.) uses spring coils that create restoring force instead of electric current. The system has fingers with 3 degrees of motion and a thumb with two degrees. The twisted shape memory alloy (SMA) filament comprised four linkages derived from a singular SMA wire, this decreases the dimensions and mass of the actuator. The gripping strength of the artificial hand measured 10 Newtons, aiming for an operation duration of one second.[2][8][9]

Wire based SMA actuator are preferred because they increase the cooling speed which is very important when it comes to SMA actuators but this increases the overall weight. They also posses better thermomechanical properties compared to the above models. Lai et al. used SMA wires parallel enclosed inside tubes made up of silica gel. The fingers consisted of six sections of these tubes. Ali et al. (2021) Created an innovative design for a robotic digit employing curved shape memory alloy (SMA) wires for rotational functionality. The activating mechanism consisted of a series of 10 arc-shaped SMA wires. The empirical findings validated the effective control of the desired angles by the SMAs.[2][10][11][12][13][14]

IV. ORIGAMI HAND USING CPEVA FIBERS

Even though Shape memory alloys have many advantages they also pose some drawbacks. They Possess a constrained deformation, hysteresis, and elevated expenses, thereby confining their utilization.. However soft polymeric material-based actuators have effortless malleability and the ability to conform to alterations in the surroundings allowing for better design. They have high flexibility and high anisotropic properties. They deform with twisting, stretching, or bending when a specific thermomechanical treatment is administered. Compared to SMAs which have a large hysteresis for small actuation, these soft polymeric materials can have larger actuation with low or negligible hysteresis.[15][16][17][18]

In the context of actuation, an agonist-antagonist pair is employed, the motion of a fiber that acts as an agonist can be counteracted by the compression of another fiber that acts as an antagonist. Notably,

crosslinked arrangements founded on semi-crystalline polymer materials exhibit the remarkable capability of achieving self supporting reversible movement, rendering them particularly appropriate for scenarios requiring a reversible motion as seen in muscles compared to a solitary actuator.
The initiation of this movement is facilitated by crosslinked poly[ethylene-co-(vinyl acetate)] (PEVA)-based fibers operating within chambers with heating. Consequently, a singular actuator orchestrates the attainment of reversible movement, with the PEVA-based fibers contracting and expanding responsively to high temperatures. Above dynamic movement is subsequently relayed to the fingers through directing filaments.[3][23][24] [16]

Fibers were fabricated using a blend of granulates (PEVA+TAIC), followed by irradiation with varying doses of gamma beams. The origami hand model, mimicking the natural joints of a human hand, was intricately cut from printed paper, with its fingers folded accordingly. Each joint section was equipped with a polypropylene tube to serve as a conduit for guiding the fibers. Subsequently, the fibers were affixed to the tips of the fingers, navigated through the tubes that guide them inside the heating chambers.

The fingers exhibit closure through contraction induced by heating, and a reversible opening occurs upon cooling. This opening is attributed to the elastic rebound of the origami configuration and the extension of the filamentary activators during cooling, facilitating the reverse motion.[3][19][20]

The manipulation and regulation of movement are achieved through temperature driven fibers made of polymer positioned within the chambers where the heating takes place. Serving as a singular reversible actuator, a specific fiber contracts upon heating, resulting in the fingers being able to bend. Conversely, the fingers open and this is ascribed to a dual mechanism involving fiber elongation during cooling and the inherent elasticity of the hand. Notably, the cPEVA28 fibers exhibit a substantial recovery force of 0.2 N, a twofold increase in relation to the resilient force exerted by the fingers. Observably, an elevation in network density and a reduction in extension at break correlate to augmented irradiation dose. It is worth noting, however, that the influence of irradiation dose on the effectiveness of the backward motion of the fibers appears relatively moderate.[3][25][26]

V. RESULTS AND DISCUSSION

Integrating AI and computer vision methods into the creation of a sign language hand robot, particularly when paired with the aforementioned soft robotics techniques like pneumatic and shape memory alloy (SMA) actuators, offers a transformative approach to bridging communication gaps for individuals who use sign language. AI algorithms can be employed to interpret sign language gestures, enabling the robot to understand and respond to a user's signing in real-time. Computer vision, an essential component of this system, allows the robot to capture and analyze visual information, tracking the intricate hand movements and gestures associated with sign language. By leveraging deep learning models, the AI can recognize specific signs and their meanings, facilitating accurate communication between the user and the robot.
The incorporation of soft robotics, such as pneumatic and SMA actuators, further enhances the robot's ability to mimic the nuanced and dynamic hand motions inherent in sign language. These soft and flexible actuators enable a more human-like range of motion and dexterity, allowing the robot to replicate sign language gestures with greater precision and subtlety. The synergy between AI, computer vision, and soft robotics in this context holds the potential to not only create a technologically advanced sign language hand robot but also to foster more natural and intuitive interactions, promoting inclusivity and accessibility for individuals with hearing impairments.

Table 1 : Comparative Analysis

	Pneumatic bending actuator	SMA actuators	cPEVA Fibres
Citations	B. Mosadegh, et al., "Pneumatic Networks for Soft Robotics that Actuate Rapidly," Advanced Functional Materials, 2013. P. Polygerinos, et al., "Towards a soft pneumatic glove for hand rehabilitation," in Intelligent Robots and Systems 2013	Q.Y. Hamid, et al., Shape memory alloys actuated upper limb devices: A review 2023	Farhan, M., Behl, M., Kratz, K. et al. Origami hand for soft robotics driven by thermally controlled polymeric fiber actuators. MRS Communications 11, 476–482 (2021).
Properties	Three parameters that affect the actuator's behaviour: • Material stiffness: It affects the relationship between pressure and bend. Ecoflex, Elastosil M4601 deform more than PDMS silicone, Fabrics (e.g. fibreglass), Paper. For Eco Flex 30 and PDMS, the energy analysis is as follows: Input 38.1 mJ Recovered 34.1 mJ Lost 4.1 mJ. For Elastosil and paper. Energy analysis is as follows: Input 155.9 mJ Recovered 143.6 mJ Lost 12.3 mJ. • Morphology: by adjusting its shape. A thicker wall will deform less compared to a thinner wall. For an actuator of fixed length, it was observed that increasing the number of chambers decreased the pressure required for bending while increasing the wall thickness increased the pressure. For chamber height, up to a certain point, increasing chamber height decreased the pressure but this was only seen up to a certain limit after which pressure remained constant up to a certain plateau, increasing chamber height lowered the required pressure. Increasing the number of chambers also decreased the required pressure. Increasing chamber wall thickness increased the required pressure. • Geometry: The behaviour of the actuator changes drastically in relation to geometry.	• Tube based: Weight: 30g for one finger, DOF: 1, Number of actuators: 2, Dimensions: D* tube = 4.00 T* tube = 0.35 L* tube = 76.20 T* Plate =1.19 W* Plate = 9.53 L* Plate =63.50, Cooling technique: water pump, Control technique: PWM, Limitation: difficulty in installation • Spring-based: Weight: 656g, DOF: 12, Number of actuators: 10, Dimensions: SMA-wire = 0.2, coiling 0.64mm diameter, Cooling technique: None, Control technique: PWM, Limitation: due to no cooling technique operates only up to 0.125Hz. • Wire based: DOF: 3, Number of actuators: 6, Dimensions: (0.254) An array of 10 wire arcs, Cooling technique: None, Control technique: PD, Limitation: due to no cooling technique and complexity in wire connections.	• Reversible actuation: cPEVA28-165, ε′ rev= 10 ± 1% and cPEVA18-165 ε′. rev = 2 ± 0.5%. • Maximum force: 0.1±0.01 N at 20 mm extension. cPEVA28-165 fibers were seen to be most suitable due to their reversible performance. The degree of crosslinking was a major factor that affected the recovery force and work capacity. • Melting enthalpy: cPEVA28 ΔHm = 75 ± 4 J -g−1 and cPEVA28 ΔHm = 49 ± 2 J -g−1
Limitation	A significant drawback associated with employing PneuNet bending actuators as individual components for each finger in a hand robot designed for sign language communication is the inherent complexity of separately actuating each discrete PneuNet actuator to convey distinct symbols and gestures, leading to potential time delays in the signing process.	However, they do have some disadvantages such as low energy consumption, low stroke, relatively lower strain resistance and they require a longer cooling period post-heating. They also are prone to non-linear behaviour.	The reversible actuation observed in cPEVA fibers may have a limited range, both in terms of displacement and force. The actuation of cPEVA fibers is dependent on temperature changes. This may pose challenges in real-world applications where ambient temperatures can fluctuate.
Results	weight < 0.5 Kg Degrees of curvature 270 degrees 3 DOF Variable speed and force	SMA-PLATE ACTUATOR: lift up to 412 g of weight and the response time was approximately 11 s SMA-TUBE ACTUATOR: The maximum fingertip force of the robotic finger was 4.35 N SMA-SPRING ACTUATOR:10 N with goal operation time of one second, SMA-WIRE ACTUATOR: maximal force of 22 N.	Recovery/contracting force of 0.2 N with a work capacity of 0.175 kJ kg−1 w

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