SODA – Soft Origami Dynamic Utensil for Assisted Feeding

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***Abstract*—The design of assistive feeding systems for individuals with limited mobility faces challenges in ensuring comfort, safety, and adaptability. Traditional utensils, such as forks and spoons, are rigid, often causing discomfort or fear when operated by autonomous robotic arms, and typically require frequent changes to handle different food types, leading to inefficiencies and increased caregiver involvement. Addressing these issues is crucial for enhancing the independence and quality of life for users of assistive feeding devices. This paper introduces SODA, a novel multi-purpose 3D printed utensil incorporating origami-inspired artificial muscles to provide a flexible, adaptive approach to food handling. The SODA utensil seamlessly transitions between gripping and scooping, accommodating various food textures. Through its unique design, SODA offers a safe, comfortable, and versatile alternative to conventional utensils, improving both user experience and functional efficiency. This demonstrates the possibility of origami-inspired designs to address the complex requirements of assistive feeding technologies.**

I. INTRODUCTION

Robot-assisted feeding systems hold significant promise for enhancing the independence and quality of life of individuals with motor impairments. These systems are designed to help users perform the essential task of eating without the continuous need for a caregiver. The development of such systems, such as Assistive Dextrous Arm (ADA) [1] and Obi [2] involves sophisticated technology, including computer vision, haptics, and advanced control algorithms, to ensure precise and safe food handling and transfer.

Modern systems must address the complex requirements of picking up food, positioning it correctly, and transferring it safely to the user's mouth [3, 4, 5, 6]. Researchers have focused on improving the interaction between the robot and the user, ensuring safety through compliant hardware and control mechanisms, and enhancing user control over the feeding process [7, 8]. These systems are equipped with multiple safety features, such as force thresholds and anomaly detection, to prevent accidents and ensure a comfortable feeding experience.

Traditionally, robot-assisted feeding systems use standard utensils like forks and spoons [9]. While these utensils are familiar and intuitive for human users, they present significant challenges for robotic manipulation [10]. The rigidity and lack of adaptability of traditional utensils can lead to difficulties in securely picking up and transferring food items, often resulting in spills and inefficient feeding [11].

Previous works like the Kiri-Spoon [12] have emerged to address these challenges. The Kiri-Spoon combines the familiar shape of a traditional spoon with a kirigami structure that can adjust its curvature, but it requires a fine fabrication process and cannot handle liquid food.

We introduce SODA (Fig. 1), a novel approach to robot-assisted feeding that integrates fluid-driven artificial muscles within an origami-inspired utensil design, achieving an effective combination of softness, adaptability, and cost-efficiency tailored to critical user needs. By harnessing the flexibility and simplicity of origami structures, SODA offers a safer, more adaptable tool for individuals with motor impairments, enhancing interaction quality between user and robot. Furthermore, the design streamlines manufacturing (Fig. 2), making it highly accessible and feasible for daily use. SODA also provides a comprehensive digital fabrication pipeline that includes 3D-printable origami models and an efficient workflow, facilitating ease of assembly and customization.

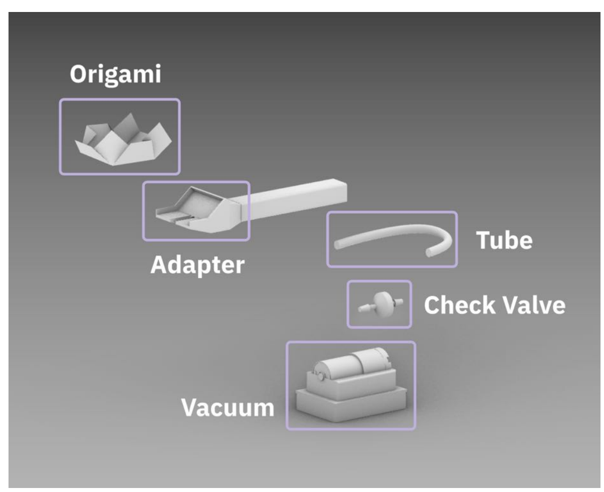


Fig. 1: The SODA acquisition system comprises 5 components: A 3D printed origami structure with membrane; An adapter to fix the tube and origami; An extension tube; A check value to maintain pressure in the membrane; and A vacuum motor as the actuator.

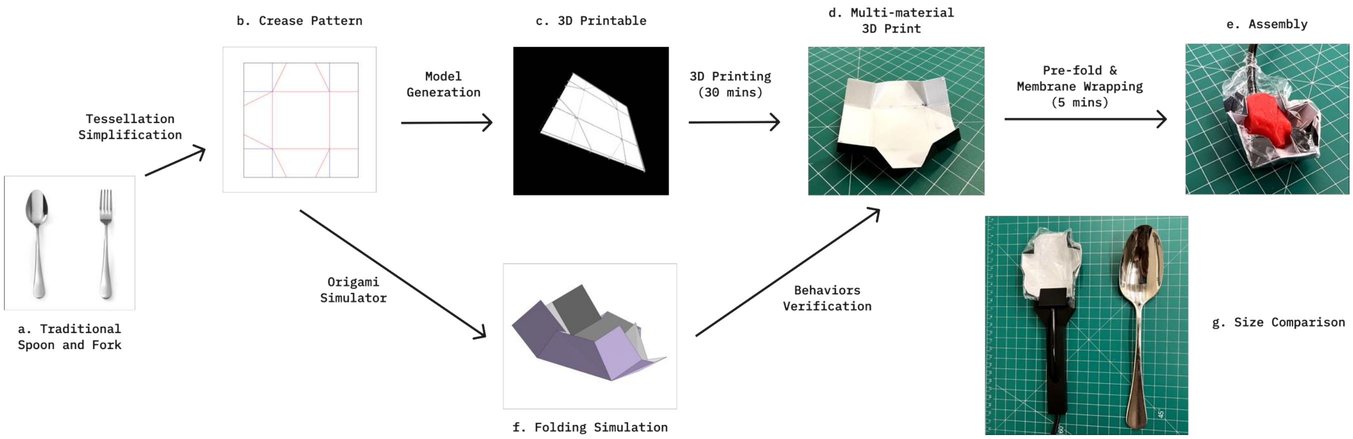


Fig. 2: The pipeline that how we design and fabricate SODA: b. Simplified crease pattern based on waterbomb design; c. 3D printable STL model generated using the web application Cadigami; d. Flexible PLA and regular PLA mixed 3D printing for origami structure; e. Assemble all parts in the acquisition system including membrane, adapter, tube, check valve, and vacuum motor; f. Verify simplified crease pattern in simulation; g. Size comparison between SODA and regular spoon.

II. Related Works

A. Origami-based Robots

Previous research has applied origami concepts to robot design in several innovative ways, focusing on the adaptability and functionality of origami structures [13, 14, 15, 16]. The magic ball origami structure wheel robot [17] is a notable example that utilizes the magic-ball origami pattern to transform from a long cylindrical tube to a flat circular one, enabling the wheel to adapt to various terrains and reduce mechanical complexity. Another exemplary application is the origami robot for patching stomach wounds [18, 19], designed to be swallowed and navigate to specific locations within the stomach to perform tasks such as patching wounds. It unfolds from a compact capsule once ingested, demonstrating crucial adaptability for operating in a complex environment. The use of origami in robotics offers increased flexibility, reduces complexity, and leads to lighter, more versatile components that are easier and more cost-effective to manufacture [20]. Additionally, the inherent compliance of origami structures enhances safety and interaction with humans by absorbing impacts and adapting to physical constraints more effectively than rigid components.

B. Accessibility

Accessibility in the physical environment remains a significant barrier for many individuals with disabilities. Our target users belong to this accessibility group and face considerable inconveniences during mealtimes, often relying on caregivers for assistance, which can impact their independence and dignity [21]. These users struggle with traditional utensils due to difficulties in gripping, maneuvering, and safely transferring food. These challenges are exacerbated when such utensils are operated by autonomous robotic arms, creating an intimidating and uncomfortable experience. Prior ADA robot systems used hard and sharp forks, which heightened users' fears and discomfort.

To address these issues, we conducted user research, focusing on the specific needs and preferences of our target audience. Through interviews, observations, and prototype testing with both able-bodied participants and individuals with disabilities, we gathered crucial insights into the physical and psychological requirements for an effective robot-assisted feeding system. The feedback emphasized the need for a softer, safer, and more intuitive utensil design, capable of handling different types of food without the need for frequent changes. These studies also highlighted the importance of cost-effectiveness and ease of replacement to ensure the system's practicality for everyday use.

III. Design Process

A. Design Objectives

The primary objectives for the design of our multi-purpose utensil for robot-assisted feeding are:

1) Ensuring softness and safety: our design aims to eliminate hard and sharp edges, making the utensil safe and comfortable for users.
2) Maximizing efficiency and versatility: we integrate the functionalities of both a fork and a spoon into a single utensil, ensuring versatility and efficiency in handling various food types.
3) Maintaining cost-effectiveness: we fabricate SODA through 3D printing and simple assembly processes, reducing production costs while maintaining functionality.
4) Facilitating easy replacement: we make the only component that needs to be replaced is the membrane which could be easily switched enabling a high usability.

B. Iterative Design

Based on existing origami-inspired robotic designs, an intuitive solution was to use a half-magic ball structure to achieve our design objectives. Our initial attempt involved creating an origami waterbomb tessellation, as this design

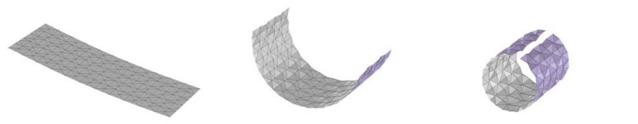


Fig. 3: The basic waterbomb crease pattern folding simulation 0%, 30%, 50%

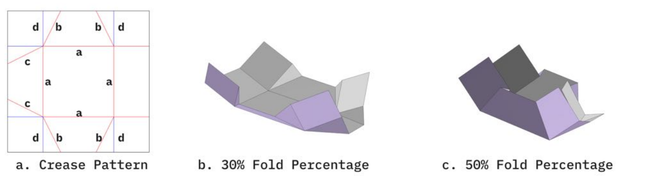


Fig. 4: SODA crease pattern. Boundary edges are in black, mountain creases are in red, valley creases are in blue.

inherently provides the desired behaviors: at 10% folding, it serves as a spoon, while at 20% folding, it functions as a gripper. However, constructing the tessellation could take 2-3 hours for individuals without complex origami folding experience. For instance, the design shown in Figure 1, consisting of a 22×5 grid, requires at least 219 folds. Therefore, we explored alternative structures that could meet our design goals more efficiently.

1) Tessellation Simplification: To ensure the origami maintains the desired utensil shape while retaining the functionality of the magic ball tessellation [22] (Fig. 3), we simplified the magic ball creases and aligned the overall shape with that of a regular spoon. To maintain a central area for containing food, we preserved four mountain creases (a in Fig. 4a) to form a rectangular section as the main container. For gripping functionality, we aimed for the lateral facets to contract toward the central area, mimicking the triangular units of the tessellation to facilitate inward movement (formed by b,d in Fig. 4a). Additionally, we added two extra triangular units at the front tip to enhance the scooping ability of the utensil (c in Fig. 4a). This design only requires 10 folds compared to waterbomb's 219 folds.

2) Simulation: To validate the reverse-engineered design, we used Origami Simulator[23] to simulate the folding process and the resulting structure, as shown in Fig. 4b,c.

IV. Fabrication

To ensure that the fabrication process is as accessible as possible, we propose a fabrication pipeline that requires only commercially available materials and tools, which can be easily purchased online or at a local store. A comprehensive list of required materials is provided on the project website. The pipeline consists of four main steps:

A. Printable Design Generation

We developed a web application called "Cadigami" which assists in generating 3D-printable origami crease models (Fig. 5a). Users can specify parameters such as hinge thickness, angles, and width to easily generate the desired output.

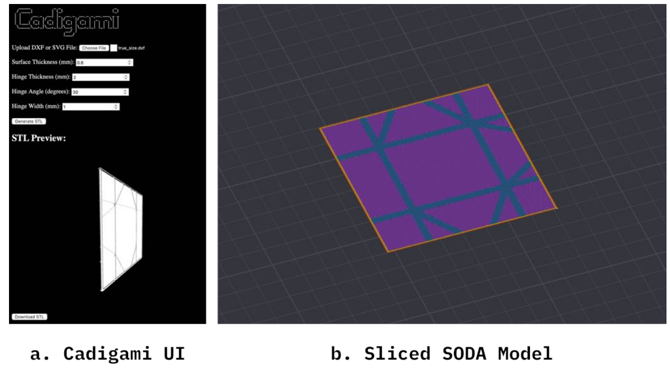


Fig. 5: a. Cadigami - A model generation tool for origami crease pattern; b. Sliced SODA model exported from Cadigami

The process of converting a CAD design into a 2D crease pattern for a printable 3D model requires manual effort to design hinges based on the origami crease pattern. Each hinge must be specified with a V-shaped slot to guide the crease to fold as either a valley or mountain fold. Cadigami is designed to address this complexity.

B. Multi-material Crease Pattern Printing

We used dual polylactic acid (PLA) material to print the SODA origami model (Fig. 5b). Based on our experiments (Fig. 6), a thickness of 0.6mm (0.2mm for hinges and 0.4mm for facets) was found to be optimal, as it best replicates the behaviors observed in the simulation. The thickness significantly impacts flexibility and safety. If the material is too thick, the vacuum actuator cannot effectively move the facets, and the hinges are prone to breaking. Conversely, if the material is too thin, the origami structure becomes too soft to function effectively as a spoon.

While PLA is a rigid material, the SODA utensil is printed with a maximum thickness of 1mm. This ensures the structure remains compliant upon contact with users, reducing the risk of discomfort or injury during feeding interactions. The thin-walled design allows controlled bending upon touch, ensuring safety when interacting with the user's mouth or face.

Hinges made from a single material tend to break over time, prompting us to explore a multi-material solution combining flexible and rigid materials. To ensure seamless fusion between facets and hinges, we used flexible PLA, which performed similarly to thermoplastic polyurethane (TPU). This solution worked well with a single-nozzle printer, allowing the facets and hinges to bond effectively while maintaining structural integrity and compliance.

C. Pre-fold and Membrane

This step ensures that the origami maintains its intended shape and functionality during use. The pre-folding process involves manually folding the origami structure along the designated creases to prepare it for membrane attachment. If we don't perform pre-fold, the origami would be actuated as a flat sheet (Fig. 7b) middle.

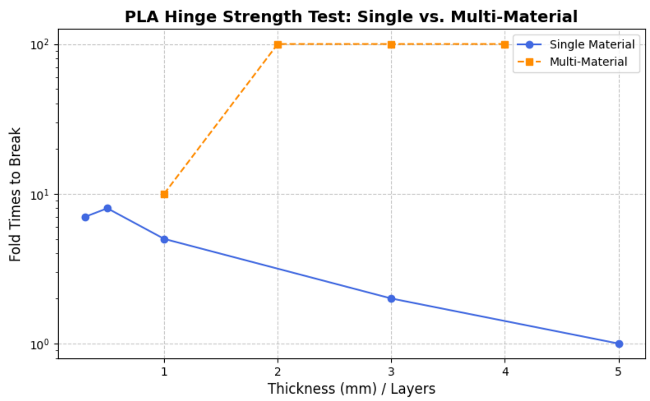


Fig. 6: Materials comparison between single PLA and multi-PLA. Hinges printed in flexible PLA perform strong durability.

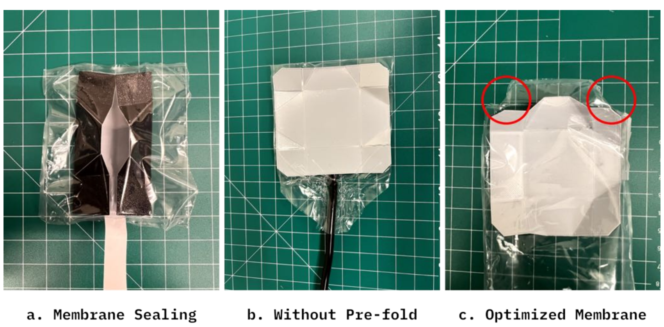


Fig. 7: a. We used a hot sealer to seal the membrane, and left an entrance for tube insertion; b. Origami doesn't contract without pre-folding; c. Cutting two edges to optimize the membrane design helping the contraction.

The membrane, made of an elastomeric material, is then attached to the structure to provide additional flexibility and the vacuum space to actuate the origami. And the shape and size of the membrane matter. If we have the membrane as the same size as the origami, origami wouldn't contract much. But if we reduce the width of the membrane and cut two corners in the front, it would guide the lateral facets to move even towards the center (Fig. 7c).

V. Experiments and Results

To evaluate the performance of the SODA utensil for food acquisition tasks, we designed a series of experiments to characterize the key aspects that directly impact the robot's ability to handle and acquire food. The following tests were conducted:

A. Actuation Speed

The actuation speed test aim to evaluate the responsiveness of the SODA utensil during both folding actuation and releasing actions. This is an essential step to understand whether the utensil can quickly and accurately adapt to different scenarios, such as handling different food types with varying levels of complexity.

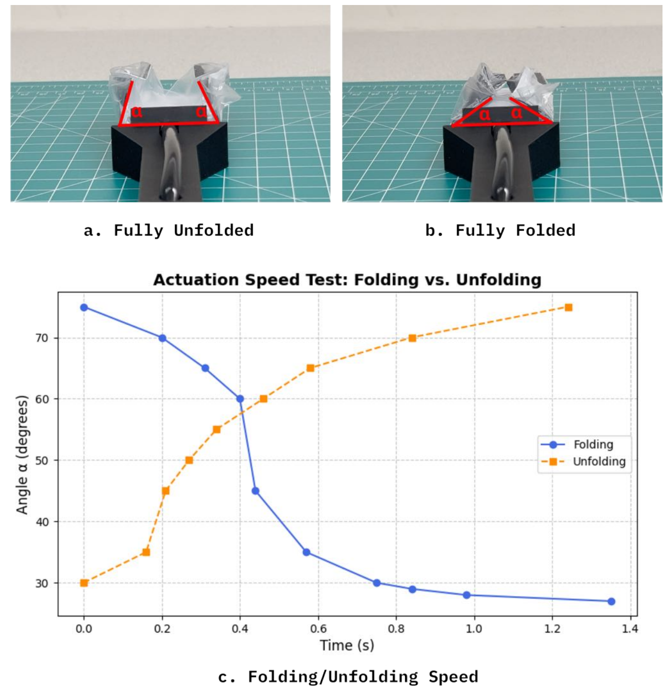


Fig. 8: Actuation speed test by measuring the angle α using a protractor during folding and unfolding phase.

The actuation was applied using a DC 6V vacuum motor, constructed from aluminum and plastic, featuring a 4mm diameter air outlet port connected via a tube to the SODA structure. The motor operates with a rated current of 400mA and an airflow rate of 2 to 3.2LPM (liters per minute) without load, providing sufficient vacuum pressure for actuation. The maximum achievable vacuum is 56kPa, ensuring reliable folding and unfolding of the origami structure. The actuation angle (α) is measured during the folding and releasing processes. The initial angle (α) was approximately 75°, and the actuation was initiated to achieve either a fully folded or fully released state.

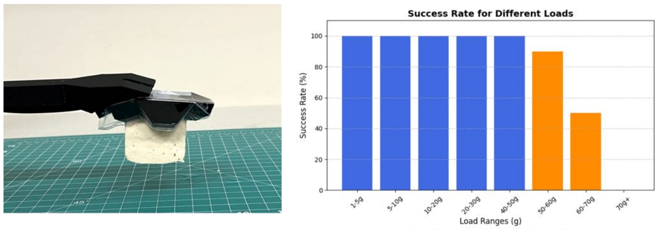
The two phases of the test included:

1) Folding Actuation: The origami structure was compressed, causing the angle to decrease.
2) Releasing: The origami structure was expanded, resulting in an increasing angle.

Overall, the results demonstrate that the SODA utensil can achieve rapid folding and unfolding, which is crucial for effectively handling different food textures. The smooth transitions seen in both folding and unfolding phases indicate a well-balanced design that can be used in real-world applications requiring quick adaptation and precise control.

B. Load Capacity

The load capacity test was designed to assess the maximum weight that the SODA utensil could lift and handle without structural deformation or failure. The test utilized tofu as the test material due to its delicate nature and varying weight distribution, which presents a realistic scenario for food handling.



a. Firm Tofu for Load Test b. Load Test Result

Fig. 9: Load capacity test using incremental tofu weights.

The experiment incrementally increased tofu weight from 1–70 grams to evaluate the SODA utensil's gripping capacity. The maximum tested weight was 50 grams, based on usability study data from five participants, where the average maximum bite size was 30 grams. To account for variations in user preferences and food densities, we set 50 grams as the upper limit to ensure real-world applicability.

SODA successfully grasped and lifted weights up to 50 grams (Fig. 9a) with a 100% success rate below this threshold. Failures beyond 50 grams were due to slippage, not structural deformation, highlighting that the origami design remained intact but lacked sufficient friction due to the smooth plastic membrane.

For large food items like tofu, only the two lateral sides of SODA make contact, limiting grip stability. However, in real-world scenarios, food bites are smaller than SODA's volume, allowing the utensil to fully fold around the object, improving grip stability even for slippery foods.

C. Cycle Fatigue

To determine the durability of the SODA utensil, we conducted a cycle fatigue test to evaluate its performance over repeated use. The utensil was subjected to repetitive folding and unfolding cycles, we fabricated a standalone test hinge and mounted it onto two servo motors, which repeatedly folded and unfolded the hinge to simulate real-world actuation stress. The results demonstrate that the SODA maintains its structural integrity even under repetitive use, with no observable deformation or decline in hinge flexibility across 500 cycles. This performance indicates a high level of durability, suggesting that the utensil is suitable for long-term usage in real-world feeding applications. The absence of deformation under continuous actuation aligns with the initial material selection and design objectives, validating the use of flexible PLA hinges and origami-inspired structural configurations in ensuring resilience. Future testing could extend the number of cycles to further confirm longevity and assess any potential long-term effects on flexibility and structural stability.

D. Food Acquisition

To evaluate the effectiveness of the SODA utensil in real-world food acquisition tasks, we conducted experiments using various solid and liquid food items to test the utensil's versatility in gripping and scooping. For solid foods, the utensil was tested with items of differing textures (soft, firm, and mixed) to assess its ability to grip securely without dropping. Each food type was tested over 50 attempts to ensure reliable data on the utensil's success rate in handling different consistencies.

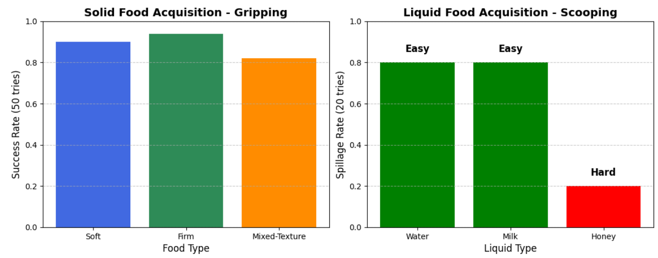


Fig. 10: Solid and Liquid Food Acquisition Results

The results (Fig. 10b) demonstrate that the SODA utensil is highly effective in gripping firm and soft food items, with a success rate of 0.94 and 0.90, respectively. Mixed-texture items presented a greater challenge, reflected by a slightly lower success rate of 0.82, suggesting that while the utensil maintains versatility, irregular textures may influence stability during transport. These findings highlight the utensil's overall adaptability, as it performs consistently well with common food textures encountered in assistive feeding contexts.

Additionally, the SODA exhibits remarkable flexibility, as it can grip food from different angles and adapt its origami-inspired shape to match the orientation of the food. This unique capability allows it to perform tasks that traditional utensils struggle with, such as securely gripping both rice and lettuce with the same design. Fig. 11 illustrates the utensil's effectiveness in handling diverse food types, showcasing its potential to improve user experience in a variety of real-world scenarios.

For liquid food acquisition, we evaluated three liquids of varying viscosities: water (low), milk (medium), and honey (high), assessing release efficiency and spillage rate. Release efficiency was rated qualitatively: Easy (flows smoothly with minimal residue), Medium (some resistance, minor residue), and Hard (requires external assistance, e.g., shaking or tilting). For the spillage rate test, the utensil was fully submerged to maximize liquid volume, then lifted and transferred 50 cm to a bowl. A trial was considered successful if no liquid spilled during transfer. Each liquid was tested 20 times, and the spillage rate was calculated as the proportion of failed transfers.

Results showed water and milk had a spillage rate of 0.8, indicating moderate containment stability, while honey had a significantly lower rate of 0.2 due to its high viscosity preventing unintended leakage. While SODA effectively retains low- and medium-viscosity liquids, future improvements may refine the utensil's edge geometry to enhance containment and controlled release for high-viscosity foods.

The results indicate that water and milk exhibited a spillage rate of 0.8, suggesting moderate containment stability, while honey had a significantly lower spillage rate of 0.2, primarily due to its high viscosity preventing unintended leakage.

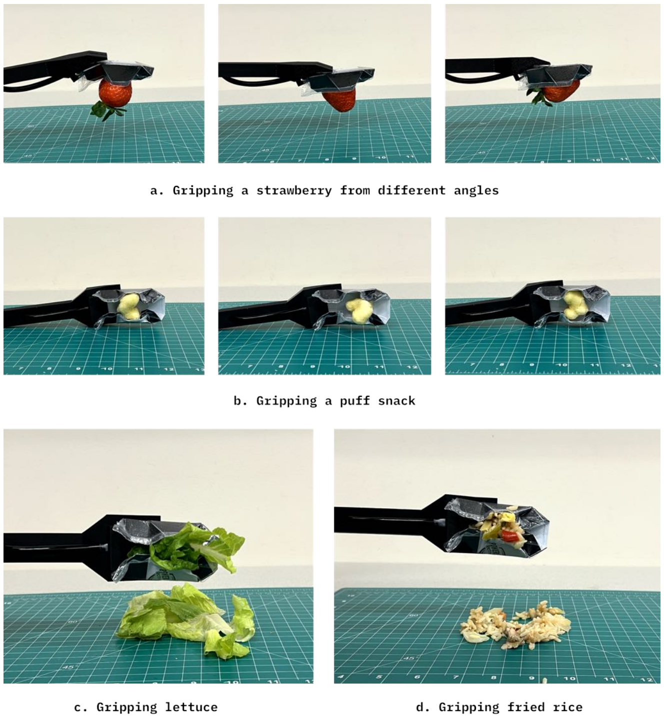


Fig. 11: Food Test Examples: a. SODA successfully grasps a strawberry; b. SODA shape can adapt to the shape of a puff snack; c,d. SODA is capable of grasping loose food items.

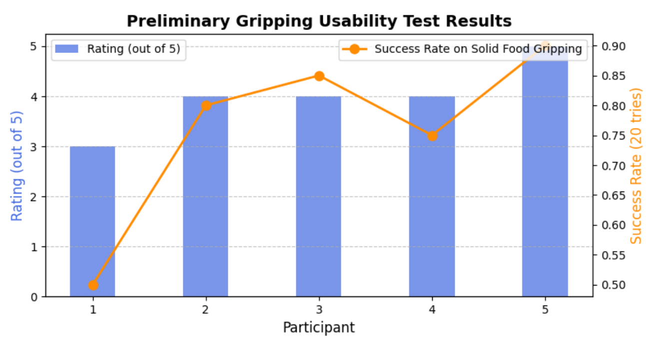


Fig. 12: Gripping Usability Test

These findings confirm that the SODA utensil performs well in retaining low- and medium-viscosity liquids but faces challenges with high-viscosity substances in terms of controlled release. Future iterations may focus on refining the utensil's edge geometry to enhance containment efficiency while improving liquid release for highly viscous foods.

Overall, these results underscore the SODA utensil's effectiveness in both gripping solid food items and containing liquids across a range of viscosity, supporting its practical application in assistive feeding. Future work may include optimizing the utensil's surface properties or structural adjustments to further improve handling and cleaning ease for high-viscosity substances.

E. User Interaction and Usability

1) Gripping Test: We conducted user gripping tests where participants manually used SODA to acquire various solid foods. Each participant attempted 20 grips, and the success rate along with subjective ratings (ease of use, comfort, efficiency, 1–5 scale) was recorded. This provided insights into user experience and areas for improvement.

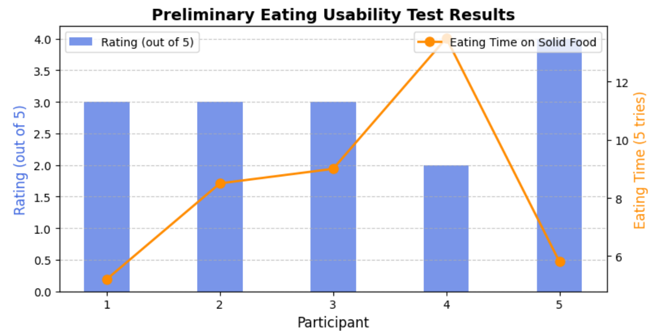


Fig. 13: Eating Usability Test

The results (Fig. 12) show generally positive responses, with ratings ranging from 3 to 5. Higher ratings correlated with greater gripping success, as Users 3, 4, and 5 achieved success rates above 0.80. User 1, who rated the utensil 3, had the lowest success rate (0.50), indicating potential usability challenges.

These findings suggest that while SODA performs well for most users, further ergonomic refinements may improve consistency in gripping performance across a broader range of participants.

2) Eating Test: We conducted an eating test to assess how effectively SODA facilitates food transfer. After successfully grasping 5 consecutive bites of the same food type, participants were asked to consume the food directly from the utensil.

Once grasped, the vacuum motor was turned off, allowing the origami structure to unfold and make the food accessible. Participants primarily used two methods: most tilted the utensil to let the food slide into their mouth, while some attempted to use it like a traditional spoon, requiring adjustment to SODA's unique shape.

Participants rated ease of eating, comfort, and usability (1–5 scale), and eating time was recorded. As shown in Fig. 13, ratings ranged from 2 to 4, with eating times between 5.2 and 13.5 seconds. Lower usability ratings correlated with longer eating times, suggesting challenges in food release and maneuverability. Future refinements may improve grip angles and utensil shape for a smoother eating experience.

These preliminary results suggest that while SODA effectively grips food, further optimizations are needed to improve the eating process, particularly in ensuring smooth food transfer from the utensil to the user's mouth. Future refinements may focus on enhancing the utensil's shape for easier retrieval, optimizing grip angles for better positioning, and evaluating the interaction between utensil flexibility and user motion to improve overall ease of use in real-world feeding applications.

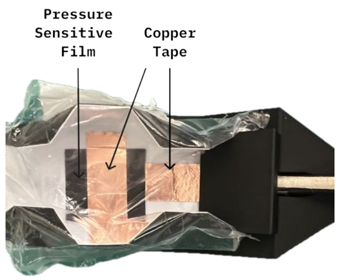


Fig. 14: Tactile sensor with three layers: two copper tape layers and one pressure-sensitive film.

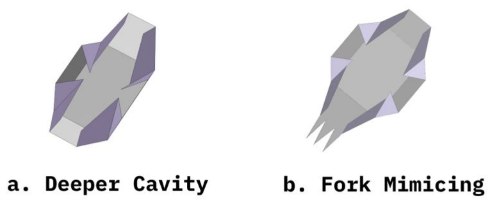


Fig. 15: a. A deeper cavity enhances liquid transfer; b. A fork-like tip enables piercing food.

VI. Discussion

A. Accessibility and Sustainability

To enhance accessibility, we have open-sourced all CAD files and the Cadigami tool for generating 3D-printable origami structures. The fabrication process uses readily available materials and a streamlined workflow, allowing even inexperienced users to assemble the utensil in under five minutes. Sustainability is a key consideration, with all 3D-printed components made from compostable PLA, and the membrane, the only frequently replaced part, crafted from compostable sandwich bags. All other components are reusable, minimizing waste and aligning with environmentally responsible design.

B. Tactile Sensing

Usability tests revealed that users apply extra force to confirm food contact, sometimes disrupting the insertion connector. To address this, we plan to integrate a tactile sensor at the center of the origami's bottom surface (Fig. 14) to provide a contact cue. Preliminary testing suggests this feedback improves actuation timing, though further studies are needed to evaluate its impact on success rates.

C. Design Variation

While SODA adapts well to solid foods, its shallow structure limits liquid containment, necessitating new designs. We explored alternative origami patterns and hinge configurations to expand its adaptability. As shown in Fig. 15, (a) features a deeper cavity for improved liquid handling, while (b) mimics a fork for piercing food, increasing stability. These variations enhance the SODA system's versatility for diverse food types and user needs.

D. Acquisition Automation

Currently, the SODA utensil has not been fully integrated into an automated robotic system and operates independently in preliminary testing scenarios. As a future goal, we plan to implement SODA within an existing assistive feeding system to enable fully automated food acquisition. Integrating SODA with an assistive robotic arm will require developing a control system that coordinates the utensil's movements with robotic actuation, allowing seamless food handling without manual intervention. Additionally, this integration could be enhanced with adaptive control features, enabling real-time adjustments in grip strength and orientation based on food texture and user feedback.

This step towards automation is expected to improve user experience by increasing the accuracy and reliability of food acquisition while reducing the need for caregiver assistance. Future work will focus on establishing a robust communication protocol between SODA's actuation mechanism and the assistive robot, enabling cohesive operation within a fully automated feeding system.

VII. Conclusion

We present a novel approach to robot-assisted feeding by integrating fluid-driven artificial muscles into a novel utensil design, achieving an optimal balance of softness, adaptability, and cost-effectiveness to address critical user needs and preferences. By leveraging the flexibility and simplicity of origami-inspired structures, SODA provides a safer and more efficient tool for individuals with motor impairments. This design not only enhances the interaction between the user and the robot but also streamlines the manufacturing process, making the system more accessible and practical for daily use. Additionally, SODA introduces a comprehensive pipeline that enables the generation of 3D-printable origami models and a corresponding fabrication workflow. This work highlights the potential of origami principles to revolutionize assistive devices, offering a promising foundation for future advancements in human-robot interaction.

To promote accessibility and encourage further development, we have open-sourced all design files, fabrication instructions, and assembly videos on our project website: https://rayxsong.github.io/soda/.

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