# Intelligent Robotic Grasping:
# Forging a Bond of Trust with Robotic Grippers That Can Feel

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# Introduction

The field of robotic grippers is one of the most extensive and cutting-edge areas of development in the discipline of engineering, with thousands of different users, applications, and constraints for every type of gripper, of which there are many. This research will focus on the development of a precise robotic gripper to work with current robotic systems for assistance with Activities of Daily Living (ADL).

For this specific application, there are a few important aspects and attributes this device must have. Most importantly, it needs to be extremely adaptive with regard to what objects are being picked up. There will be a variety of use cases and different shapes of objects being gripped, meaning that the gripper has to be able to hold on to objects that it has not been specifically designed for. For example, a user may need to pick up a banana, and then soon after pick up an iPhone or grasp a door handle to let themselves in, all three being very different shapes and materials. Additionally, nearly all tasks will involve the manipulation of objects around the user (feeding, interacting with electronic devices, etc), and in many of those situations, the gripper needs to be able to determine when an object has been successfully and safely grasped without damaging it. This awareness of the gripper's internal state and interaction with objects, also called proprioception, is critical for practical assistive robotics applications.

Beyond the technical challenges, the true goal of assistive robotics is to provide users with greater independence and empowerment in their daily lives. For many individuals with physical disabilities, relying on others for simple tasks can affect not only convenience, but also confidence, privacy, and quality of life. In order for an assistive robotic system to be genuinely useful, the user must be able to trust it. A robotic assistant that drops objects, crushes fragile items, or behaves unpredictably cannot realistically become integrated into someone's everyday life. Because of this, one of the most important requirements of assistive robotics is the creation of a reliable bond of trust between the user and the robotic system. The robot must consistently and safely interact with the world in a way that the user can depend on without hesitation.

Balancing the two aspects of adaptability and grasp-state awareness is a complex technical challenge, with one significant issue: the impact of underactuation on precision and controllability. There are two major types of adaptive grippers: fully-actuated and underactuated. Fully-actuated grippers are devices where all joints of motion are able to receive power independently of other joints. This requires a system where the number of actuators (power-outputting devices, e.g. motors) is equivalent to the number of degrees of freedom of the device. This results in an extreme amount of algorithmic and mechanical complexity, with each individual joint in a finger needing to know where it should be in order to grasp or curl around a specific object. While powerful in certain applications, this level of complexity means that it is rarely ever viable to use outside of a lab setting. The alternative to this is underactuation, where the number of actuators on a gripper is fewer than its degrees of freedom. This means that through various ways of power distribution (gear differentials, seesaw mechanisms, fluid differentials), actuator power can be split up into multiple joints, with some being passively controlled. This allows the gripper to be able to physically adapt to the gripped object, without any complex actuator power inputs or control systems. However, as the motion is passively controlled, underactuation is inherently imprecise, as we do not have finite control over all aspects of our system or direct awareness of the grasp state during operation.

This poses an odd conundrum, wherein the system that is precise is difficult to make adaptive, and the system that is easily adaptive is difficult to make precise and aware of its grasp state.

If solved, the field of assistive robotics would be revolutionized, allowing systems to be used in a large variety of differing situations and applications. With a gripper that is adaptive and capable of reliably detecting grasp state, the same gripper could be used to do nearly everything that your hand does on a daily basis, while safely interacting with delicate and unpredictable objects. More importantly, it would help create robotic systems that users can truly rely on in everyday life. That is the question which this paper serves to answer: "How can encoder-based proprioception be used to detect and classify grasp state in an underactuated adaptive robotic gripper for assistance with ADLs (Activities of Daily Life)?"

## Review of Literature

This review of literature summarizes prior work in the field of robotic grippers to establish how different designs have handled adaptability, precision, and localization when gripping objects of diverse shapes. It covers four major areas in a thematic manner: the historical development of grippers, major categories of adaptive underactuated mechanisms, existing methods for sensing and state estimation, and considerations from assistive human robotics. Together, these topics and works provide context for understanding underactuated versus fully actuated gripper, and the approaches used for state estimation and precise grasp behavior in both. Despite extensive work on adaptive mechanisms and grasp stability, comparatively little attention has been given to how the internal state of underactuated grippers is consistently localized during operation. Current research, covered in this review, investigates methods of state estimation in the context of fully actuated grippers or uses models to predict the position, leaving the true state of the grasp insufficiently characterized. This review focuses not just on how existing grippers handle adaptability, but how many of them implicitly or explicitly address state estimation, and where limitations persist.

1. History of Robotic Grippers

The development of robotic grippers has evolved along two major trajectories, reflected across survey work (Hernandez et al., 2023). Early systems were fully actuated, stiff, and optimized for standardized objects and repeatable conditions, well-suited to structured industrial environments. However as robots moved into human-centered and assistive domains, adaptability, ease of control, and robustness in the context of object variability became central concerns to the functions of robotic grippers. This shift led to the widespread development of underactuated, mechanically adaptive grippers, which trade direct joint-by-joint control for passive behaviors shaped by the gripper's structure, compliance, transmission, and environment (Cairnes et al., 2023). These two trajectories and design ideologies of grippers emphasize the diversity of requirements for robotic grippers, with industrial environments where repeatability and strength are required using fully-actuated systems, and with human environments where underactuated grippers are used due to their adaptability and passive behaviors.

2. Existing Adaptive Underactuated Grippers

Underactuated grippers rely on mechanical intelligence rather than explicit per-joint control to allow them to adapt to the object being gripped. Across this field of study, three major families of underactuated mechanisms have emerged: compliant mechanisms, differential-based mechanisms, and linkage-spring mechanisms. Although technically very distinct, these three large bodies of work collectively summarize how mechanical intelligence can produce adaptable and simple-to-control grasping solutions, and how this same versatility can generate complex, environment-dependent behaviors during use.

a. Compliant Grippers

Compliant Mechanisms use flexible joints or materials to conform naturally to diverse object shapes. Studies such as Chang et al. (2019) outline multiple compliance strategies, including pre-shaped compliant fingers and geometry-conforming pads. Additionally, modeling-based work (Hussain et al., 2018; Huang et al., 2019) shows that the stiffness of compliant joints can determine grasp modes, fingertip trajectories, and the force distribution across a gripper, establishing compliance as a predictable design parameter. Angelella et al. (2025) also demonstrates compliant differential systems that can act as passive force regulators, illustrating how compliance can be used within other mechanisms to change the power flow of a system.

Across these works, compliance is consistently demonstrated to be an effective method for achieving safe and robust grasping in environments with uncertain object geometry. However, many of these sources offer limited information on how internal deformation states can be reliably sensed or reconstructed to estimate gripper state during real-world use.

b. Differential-Based Grippers

Differential mechanisms form a core category of underactuated design. These systems mechanically distribute a single actuator or input's motion across multiple outputs (fingers or joints), producing coordinated behavior without requiring specific joint-level control.

i. Transmission principles

Work by Birglen & Gosselin (2006) categorizes differential types, including pulley-based, seesaw-based, fluidic, and gear-based systems, and analyses how force and displacement can be split across multiple outputs. Their results show that grasp sequencing and joint engagement depend strongly on the differential topology and contact conditions.

ii. Floating and multi-stage differentials

Laliberté et al. (2010) extend these principles through floating seesaw mechanisms in prosthetic hands. These seesaws self-align according to tendon tension, reducing friction and enabling more predictable force redistribution. Their behavior changes dynamically as contact forces evolve, illustrating how differentials adapt during grasp formation.

iii. Differential-controlled multi-modal grasping

Ma et al. (2016) explore differential tendon systems that allow a gripper to operate in multiple grasping modes, such as underactuated grasping, fully actuated precision gripping, and in-hand manipulation. Their work demonstrates how mechanical couplings can produce natural multi-stage grasp sequences, such as a proximal closure followed by distal articulation.

iv. Differential geometry and precision behavior

Studies focusing on underactuated precision grasping also highlight the constraints of differential-based underactuation. Kragten et al. (2011) show that simple straight-finger designs are inherently very unstable in precision grasps, identifying geometric conditions required for stable contact. In contrast, Lu et al. (2021) demonstrate a three-arm “helical” gripper, using fingers rotated from axes orthogonal to one another with articulating fingertips and actuated with a three-way seesaw differential.

v. Summary of differential underactuation

Across these various contributions to the field of differential underactuated grippers, there are three major takeaways:

1. Differential systems can create coordinated but non-prescribed joint trajectories.
2. Grasp behavior depends on contact order, object shape, and internal force balance, rather than predefined joint angles.
3. Specific topologies can determine which grasp modes are naturally stable and transition between modes

This body of work defines differential underactuation as a structured but constant-driven mechanism that yields predictable grasp patterns while remaining highly adaptive. Nonetheless, the same characteristics of differentials that allow adaptive grasping make different-driven systems difficult to localize precisely, as identical actuator inputs can yield differing joint power outputs and multiple stable configurations depending on contact conditions and object geometry.

c. Linkage + Spring-Based Grippers

Linkage and spring architectures form another major type of underactuated systems. Designs such as Tlegenov et al. (2014) and Gao et al. (2016) exhibit two-stage grasping, with a rigid-body motion during approach and passive object wrapping from the distal joints once contact is initiated with the object. This idea of multi-stage adaptability shows up again in Tan Ai et al. (2023) and Wang et al. (2022), whose designs are able to transition between pinch, partial-encompassing, and full-encompassing grasps based on the object's dimensions.

Additionally, mechanisms like the aFinger (Kok, 2019) and Liu & Zhang (2023)'s Hoecken linkage-based systems show how linkage geometry and torsion springs can determine whether the finger acts as a parallel jaw gripper or an adaptive, curvature following mechanism. Rahman et al. (2024) evaluate similar designs in the context of ADLs, demonstrating effective performance on everyday objects, such as foods, bottles, magazines, and spherical items.

Together, these works describe linkage and spring-based adaptive grippers as systems with very deterministic, contact-triggered transitions defined by specific joint placement and the use of passive elements. Although these architectures provide far more deterministic transitions and movement than other underactuated mechanisms, their reliance on passive elements and contact-triggered motion still introduces uncertainty in joint configuration that is rarely addressed through explicit sensing or state estimation frameworks.

3. Localization and State Estimation of Grippers and Gripped Objects

As underactuated motion is governed by passive interactions rather than specific commanded trajectories, a largely parallel body of research focused on sensing and state estimation during grasping.

a. Tactile and Haptic Sensors

The application of tactile sensing in this context ranged from high-resolution optical methods (She et al., 2021) to deformation-based sensor modules (Yamamoto et al., 2025). Zhan et al. (2021)'s survey categorizes many of these modalities and highlights the recurring parameters and trends—focusing on resolution, durability, power, and complexity of integration into bigger systems. All of these works frame tactile sensing as a possible method of localization and grip state estimation in very specific environments, albeit with a high level of complexity, calibration requirements, and extremely limited scalability across different mechanical systems.

b. Model-Based State Estimation for Underactuated Hands

Numerous papers also focus on understanding the mechanics of a gripper and using models to determine how underactuated joints settle into equilibrium configurations based on contact constraints and deterministic compliance (Odhner & Dollar, 2025; Hussain et al., 2018; Tlegenov et al., 2014). Additionally, probabilistic and control-based approaches (Hang et al, 2020; Azulay et al., 2023) estimate object pose or internal hand-object states using particle filters or MPC (Model Predictive Control) driven by haptic inputs. These model-based methods together loosely portray state estimation in underactuated systems as an inference problem, shaped by deterministic mechanical couplings and limited direct observability. However this 'portrayal' of state estimation depends upon simplified contact models or known object properties, severely limiting their robustness in unstructured environments where object geometry and contact conditions are uncertain.

4. The Human Side of Assistive Robotics

   Literature in socially assistive and medical robotics (Clabaugh & Matarić, 2019; Weber & Matsiko, 2023; Salman et al., 2025) emphasizes design constraints common to assistive systems but not often covered, like reliability, physical simplicity, and predictability. However, above all, all of these works point to two major objectives and constraints: Long-term adaptability to user-specific behaviors, and the involvement of the customer (or beneficiary) in the development process.

This review of literature establishes two dominant approaches to adaptive grasping: fully actuated grippers that achieve precision through joint-specific control, and underactuated grippers that achieve adaptability through mechanical intelligence. Methods of mechanically adaptive grasping, such as compliance, differentials, and passive linkages, are shown to be extremely effective in grasping objects of diverse shapes, but also produce contact-dependent behavior that is harder to interpret, and therefore localize. Much of the existing work addresses this issue through sensing modeling and inference, though these approaches still remain fragmented and not viable for use in the real world. However, the literature lacks research on experimentally validated systems that enable precise reliable grasp-state estimation in mechanically adaptive, underactuated grippers without sacrificing the very mechanical intelligence that makes these systems effective. Overall, this body of research frames grasp-state localization in underactuated grippers as a central, unresolved challenge that emerges from the field's shift toward mechanically adaptive manipulation.

## Methods

This research investigated how encoder-based proprioception could be used to detect grasp completion and classify grasp state in an underactuated adaptive robotic gripper intended for assisting with Activities of Daily Living (ADL). The methodology combined qualitative and quantitative research through expert interviews, iterative prototyping, and physical experimentation, Qualitative methods were used to better understand the real-world limitations and needs of current assistive robotics systems, while quantitative experimentation evaluated the reliability of grasp detection and the system's ability to safely manipulate fragile objects.

This mixed-methods approach was selected because assistive robotics exists at the intersection of engineering and human interaction. A technically functional system is not inherently useful if users cannot rely on it consistently in daily life. As a result, this research focused not only on grasping performance, but also on the broader issue of reliability and trust in assistive robotic systems, as it relates to grasping.

1. Expert Interviews

    Two semi-structured interviews were conducted with professionals working in assistive robotics and human-robot interactions. The purpose of these interviews was to identify common limitations in current assistive robotic systems and better understand the practical challenges involved in implementing robotic systems outside of the controlled laboratory environments in which they are normally tested.

    The first interview was conducted with Dr. Amal Nanavati, a researcher specializing in Human-Robot interactions and physically assistive robotics, with his doctoral dissertation being on robot-assisted feeding. The questions asked to him focused on environmental variability, grasping reliability, robot compliance, and common oversights when designing assistive robotic systems.

    The second interview was with Vy Nguyen, an occupational therapist at Hello Robot who works directly with users of assistive robotic systems in home environments.

The questions for Vy focused on how users interact with robotic systems in daily life, the emotional and social impact of assistive robotics, and the importance of reliability during simple everyday tasks.

After both interviews, the responses and notes taken were compared and analyzed to highlight the key points and concepts to take away, related to adaptability, reliability, and user trust.

2. Iterative Prototyping and System Development

A three-jaw adaptive robotic gripper was designed and fabricated to investigate grasp-state detection in an underactuated system. The gripper used a triangular seesaw differential mechanism to distribute force from a single actuator across all three jaws, allowing the mechanism to physically adapt to different object geometries without requiring independent control of each joint.

The system was actuated using a single servo motor connected to the differential seesaw mechanism through a tendon-driven spool system. Each of the three corners of the seesaw were then connected to each of the jaws, and the jaws were also equipped with an absolute rotary encoder used to continuously track jaw position throughout the grasping process. An ATMega 2560 microcontroller processed encoder readings and controlled the movement of the servo. A computer-based visualization and control interface was also developed to interface with the ATMega 2560, and display jaw movement and allow users to control the system in real time.

The primary focus of the iterative design process was the development of a grasp-detection algorithm capable of determining when an object had been securely grasped without applying excessive force. The algorithm compared expected jaw motion to actual encoder-derived jaw movement, and when jaw movement stopped despite continued servo input, the system classified the grasp as complete and stopped applying additional force.

3. Experimentation and Analysis

Experimental testing was conducted using several objects with varying shapes and fragility ratings, including a very ripe banana, a plush toy, a peeled and boiled egg, a peeled clementine, and a tennis ball. These objects were selected to represent a range, semi-soft, and fragile real-world objects commonly encountered in daily life.

The gripper was tested under two conditions: grasp detection enabled and grasp detection disabled. During each trial, the gripper attempted to grasp each object, and the entire gripper was lifted up and held upside down to ensure sufficient grasp stability. After each grasp, the object was closely inspected for deformation, visible damage, or structural failure.

Quantitative measurements included grasp success rate and object damage ratings. Damage was evaluated on a 0-5 scale, with 0 representing no observable damage and 5 representing complete structural failure of the object. The experimental findings were then compared against some of the themes identified in both of the interviews and review of literature to evaluate the effectiveness of encoder-based grasp detection and how it addressed current limitations in adaptive assistive robotic grasping systems.

## Results

1. Interview Findings

Both interviews emphasized that assistive robotic systems frequently struggle when operating outside controlled laboratory environments. Dr. Amal Nanavati identified the diversity of different environments, variability in object characteristics, and inconsistent grasping conditions as major limitations in current assistive robotics systems. The interview also emphasized the importance of compliance and adaptability, prioritizing the idea of designing for the unpredictable.

Similarly, Vy Nguyen emphasized that successful assistive robotics systems must prioritize the needs and routines of the user rather than requiring users to adapt their environments around the robot, and from a social perspective, the importance of creating a bond of trust between a user and the assistive robotic system. The interview highlighted that many important Activities of Daily Living involve manipulating small, delicate, or irregularly shaped objects that require both precision and consistency.

A major commonality between both of the interviews was the importance of reliability. Both interviews emphasized that assistive robotics systems **must** behave **consistently** and **predictably** in order for users to trust them in daily life.

2. Iterative Prototyping Results

The final prototype successfully demonstrated adaptive grasping using a three-jaw underactuated differential mechanism. The differential system was able to redistribute force across all three jaws and physically adapted to objects with varying shapes and sizes without requiring independent control of each joint.

The encoder-based grasp-detection algorithm was able to reliably identify when an object had been securely grasped by monitoring for changes in jaw movement during grasping. Once the jaw movement stopped despite continued servo input, the system classified the grasp as complete and stopped applying additional force.

The system also continuously tracked jaw positions throughout the grasping process, allowing the approximate location and geometry of the object to be inferred using only internal measurements from the gripper.

3. Experimental Results

Experimental testing demonstrated that grasp detection significantly improved the system's ability to safely manipulate fragile objects while maintaining stable grasps. With grasp detection enabled, the system successfully grasped and held all tested objects, achieving a grasp success rate of 100%. All five objects, including the ripe banana, boiled egg, and peeled clementine were all successfully lifted and held without visible structural damage.

<u>Testing Data</u>

| Object | Fragility Rating | Damage Rating w/o Grasp Detection | Damage Description w/o Grasp Detection | Damage Rating w/ Grasp Detection |
|---|---|---|---|---|
| Banana | 3/5 | 3/5 | Noticeable Crushing but not fully destroyed | 0/5 |
| Plushie | 2/5 | 1/5 | Slight compression but recovers | 0/5 |
| Egg | 4/5 | 5/5 | Structural failure and egg white broken | 0/5 |
| Peeled Clementine | 5/5 | 5/5 | Complete rupture, spilled juice | 0/5 |
| Tennis Ball | 0/5 | 0/5 | No damage | 0/5 |

When grasp detection was disabled, the gripper consistently overapplied force to soft objects. The banana experienced noticeable crushing, the boiled egg fractured during compression, and the peeled clementine ruptured completely. Across all tested objects, the average damage rating without grasp detection was 2.6/5, compared to 0/5 when grasp detection was enabled.

Rigid objects such as the tennis ball were unaffected in both testing conditions, while software objects produced clearer feedback and data to analyze the effectiveness of grasp-state detection.

Overall, the results demonstrated that encoder-based proprioception could reliably detect grasp completion and present excessive gripping force without requiring complex external sensing systems such as cameras or tactile sensor arrays.

## Discussions and Limitations

1. Encoder-Based Proprioception as a Method for Grasp Detection

The most significant finding of this research was that encoder-based proprioception could reliably detect grasp completion without requiring complex external sensing systems. During experimentation, the gripper consistently identified when an object had been securely grasped by monitoring the relationship between commanded motion and actual jaw movement. Once jaw motion stabilized despite continued servo input, the system classified the grasp as complete and stopped further actuation.

This fundamentally changed how the system interacted with fragile objects. Without grasp detection enabled, the gripper behaved similarly to many conventional robotic systems that apply a fixed motion or force profile regardless of object geometry or material properties. In these conditions, soft objects were consistently damaged. The banana was visibly crushed, the egg fractured under compression, and the peeled clementine ruptured completely.

Once grasp detection was introduced, the interaction became far more controlled. Instead of continuing to squeeze after contact, the system stopped once the object had been securely grasped. Across all experimental trials, fragile objects could be lifted and held without visible structural damage.

This finding aligns with existing literature surrounding tactile sensing and grasp estimation. Zhan et al. describe how many modern robotic grasping systems rely on high-resolution tactile sensors and complex sensing architectures to estimate contact and grasp state. Similarly, Azulay et al. demonstrate grasp-state estimation through advanced haptic sensing and Model Predictive Control frameworks. While these approaches can achieve high levels of precision, they often require complicated hardware integration, calibration, and computational overhead.

In contrast, this research demonstrates that meaningful grasp-state awareness can emerge directly from the adaptive behavior of the mechanism itself. The gripper was not explicitly measuring force through dedicated tactile arrays. Instead, it interpreted changes in motion and mechanical response during interaction with the object.

2. <u>Underactuated Systems Require Measurement Rather Than Assumption</u>

A second major finding of this research was that underactuated systems cannot reliably determine their own state from actuator input alone. Throughout testing, identical servo inputs frequently produced different jaw configurations depending on the shape, stiffness, and contact conditions of the object being grasped.

This behavior is a direct consequence of differential underactuation. Unlike fully actuated systems, where each joint follows a prescribed trajectory, the jaws of the gripper redistribute motion dynamically according to contact conditions and force balance within the mechanism.

This observation strongly supports the work of Birglen and Gosselin, whose research showed that differential mechanisms distribute forces and motion based on interaction conditions rather than predefined trajectories. Similar behavior was also described by Laliberté et al., who demonstrated that underactuated systems continuously shift configuration in response to changing contact forces.

Because of this, the system needed to directly measure its own interaction with the environment rather than assume the result of commanded motion. Encoder-based tracking allowed the gripper to continuously observe how the mechanism responded during grasping, making it possible to identify contact, detect stabilized grasps, and infer grasp state.

3. Internal Tracking and Practical Grasp Awareness

Beyond grasp detection itself, the encoder system also enabled continuous tracking of jaw movement throughout the grasping process. Using only internal measurements from the three jaws, the system could approximate the location and geometry of the object being held.

This finding contrasts with much of the current literature on object localization in underactuated hands. Hang et al. use particle filters and external sensing systems to estimate object pose during manipulation, while other model-based approaches rely heavily on simplified assumptions regarding object geometry and contact conditions.

Those approaches can be extremely powerful, but they also introduce significant complexity. Cameras may struggle with lighting variability and occlusion, while probabilistic models often depend on assumptions that do not consistently hold in real-world environments.

The system developed in this research approached the problem differently. Rather than attempting to fully reconstruct the environment, the gripper focused on understanding its own internal state during interaction with an object. This simpler proprioceptive approach may be more practical in assistive robotics applications where reliability and robustness are often more valuable than perfect environmental reconstruction.

The broader implication is that adaptive robotic systems may not always require increasingly complicated external sensing in order to behave intelligently. In some cases, meaningful awareness can emerge from carefully interpreting the internal behavior of the mechanism itself.

## Limitations

Although the system successfully demonstrated reliable grasp detection across all tested objects, several limitations remain:

First, the set of objects tested was relatively small and focused primarily on common fragile items. While the selected objects represented a range of stiffnesses and geometries, five items cannot fully represent the enormous variability present in real-world environments.

Additionally, all testing was performed under relatively controlled conditions. Objects were stationary, clearly accessible, and grasped from predictable orientations. Real assistive environments introduce significantly more variability, including moving objects, cluttered surroundings, partial occlusions, and accidental collisions.

Another limitation was the lack of long-term user testing. The project evaluated technical system behavior, but did not involve deployment with users in real assistive scenarios. As emphasized during the interviews, successful assistive robotics depends heavily on human-centered factors such as comfort, trust, and adaptability to individual routines.

### Future Research

Future research could expand this work in several directions. One important next step would be testing the system in more dynamic and realistic environments, particularly during motion of a robotic arm or while interacting with cluttered surroundings.

Additional work could also explore slip detection and dynamic force adjustment during manipulation. While the current system successfully identified grasp completion, it did not actively respond to object movement after grasping.

Testing with a wider variety of objects and real users would also provide a better understanding of how the system performs in practical assistive settings. Since assistive robotics is ultimately centered around people rather than purely technical metrics, understanding how users perceive reliability and trust will remain critically important.

Overall, this work suggests that reliable grasp awareness in adaptive robotic systems may not always require increasingly complicated sensing architectures. Instead, future systems may benefit from better understanding and interpreting the mechanical behavior already present within the mechanism itself.

## Conclusion

Humans interact with fragile objects constantly without consciously thinking about it. Picking up a paper cup, holding a piece of fruit, or carrying a container all require subtle adjustments in force and motion that happen instinctively for most people. However, for many people living with physical disabilities, even these simple interactions can become frustrating, difficult, or impossible without assistance.

That broader human challenge became one of the main motivations behind this research. Early in the project, I was mostly interested in the mechanics of adaptive grippers and underactuated systems. However, as the research progressed, I started thinking much more about the people who would actually depend on these systems in everyday life, from an emotional and human perspective. If an assistive robotic system cannot reliably pick up common objects without dropping them, crushing them, or behaving unpredictably, it becomes difficult for users to comfortably trust the system in their daily routines.

Ultimately, the biggest takeaway from this project is that the true goal of assistive robotics is not simply just automation. The larger purpose is to create systems that can supply independence and a sense of normalcy that empowers people to live their fullest lives. If assistive robotics is going to become truly integrated into homes and daily routines, users need to feel that the system is dependable, safe, and consistent.

The most fundamental part of that is trust. A robotic assistant only becomes truly empowering when the user no longer worries that it will fail or require constant supervision. Without that bond of trust between the user and the robot, even the most advanced of systems will feel unreliable and impractical in everyday life.

I wanted this research to contribute toward that broader goal in a practical way. By improving grasp awareness through a cheap, simple, and unobtrusive proprioceptive approach, this work contributes toward creating robotic systems that users can more confidently depend on in daily activities. Looking back on the project, I think the most important thing I personally learned is that the best assistive robotics technology must balance technical capability with human trust, because ultimately, that trust is what allows the technology to empower people to take their lives into their own hands.

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