

Extending Robot-Assisted Feeding to Spoon-Based Foods with the Articutool: A Modular Active End-Effector

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Abstract—Robot-assisted feeding is a physically intimate and technically demanding task that requires reliable acquisition, gravity-sensitive transport, and safe transfer near a user’s face. Prior work has focused primarily on fork-based feeding, where skewering simplifies transport by mechanically securing the food. In contrast, spoon-based feeding introduces gravity-constrained manipulation: scooping becomes contact-rich and transport requires continuous retention under orientation limits. Enforcing these constraints globally at the arm level collapses the feasible planning manifold and induces computational brittleness.

We introduce the Articutool, a modular, untethered 2-DOF active wrist that decouples fine-grained utensil regulation from gross arm transport. By relocating gravity-referenced orientation control to the end-effector and verifying trajectory compatibility prior to execution, the system expands planning feasibility while preserving strict retention guarantees.

In physical experiments and a large-scale transport benchmark, the Articutool improves acquisition mass across granular, viscous, and liquid foods, achieves a 96% constrained transport success rate with a median planning time of 4.0 seconds (compared to 75.7 seconds for a monolithic 8-DOF baseline), and delivers a 70.0% meaningful success rate in end-to-end feeding, substantially outperforming a rigid 6-DOF baseline. These results suggest that gravity-constrained assistive tasks benefit not from increasing manipulator complexity alone, but from architectural decoupling and localized active regulation.

I. INTRODUCTION

Robot-assisted feeding is one of the most technically demanding assistive tasks. Any feeding action requires three stages: acquisition, transport, and transfer. Together, these stages form a pipeline that must be repeated many times throughout a meal, as shown in Fig. 1: the robot must acquire food from a dish (Fig. 1(b)), transport it safely toward the user (Fig. 1(c)), and present it in a way that enables comfortable and dignified transfer at the mouth (Fig. 1(d)).

In recent years, substantial progress has been made in fork-based feeding systems. These systems rely on pre-cut, bite-sized pieces and acquisition via skewering. Although skewering is a contact-rich manipulation problem, it provides a structural simplification: once the food is mechanically secured to the fork, the transport stage becomes comparatively easy. The bite is securely attached to the utensil and orientation changes during motion generally do not compromise retention. As a result, skewering-based feeding naturally decouples acquisition from transport. Most of the technical load lies in reliably spearing bites, while transport can be executed under relatively looser orientation constraints.

However, many everyday foods such as cereal, yogurt, and soup are not amenable to skewering. We refer to feeding tasks involving such foods as scooping-based feeding. Unlike skewering, scooping does not mechanically secure the food. Retention is governed by gravity. Consequently, the spoon must be continuously stabilized during motion. Angular disturbances induced by the feeding arm can cause rolling, sloshing, or dripping. Orientation constraints that were secondary in fork feeding become central in scooping-based feeding.

Acquisition also changes in character. Scooping requires a dynamic trajectory that regulates entry angle, depth, and exit motion to control volume. The amount acquired depends sensitively on utensil orientation and shape, as well as local food geometry. At low fill levels, repeated scooping from the same region can create pits that do not refill, degrading performance over the course of a meal. In Section II, we formalize this shift and characterize spoon-based feeding as a gravity-constrained manipulation regime.

Simply replacing the fork with a spoon exposes these coupled challenges. Transport becomes brittle under strict leveling constraints, planning failures increase, and spillage during motion may undermine safety and trust for users. One possible response is to increase global arm dexterity, for example by using an 8-DOF manipulator to better satisfy simultaneous position and orientation constraints. However, this approach couples the solution to specific robot platforms and increases system complexity without directly addressing the gravity-referenced nature of spoon retention. In Section III, we derive a set of design requirements for scooping-based feeding that preserve compatibility with existing assistive arms.

We argue that scooping-based feeding demands a redistribution of control authority. The arm should provide gross positioning for acquisition and transfer, while the utensil’s local actuation maintains the orientation necessary for stable transport. To realize this, we introduce the Articutool, a modular active end-effector that provides two degrees of pitch and roll actuation, along with onboard sensing, computation, and power. By regulating spoon orientation relative to gravity at the tool level, the system restores a practical decomposition: acquisition and transfer remain arm-dominated tasks, while retention during transport is managed locally.

To ensure reliability, we further introduce a trajectory compatibility verification step, described in Section IV, that evaluates whether a planned arm motion can be compensated within the kinematic and dynamic limits of the Articutool prior to execution. This proactive verification reduces

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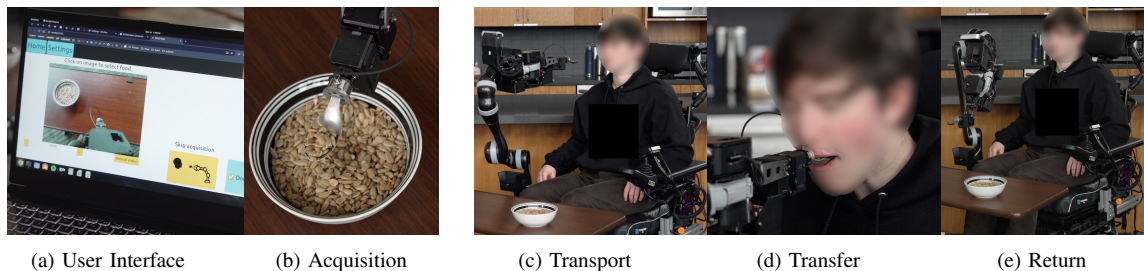


Fig. 1: Overview of the robot-assisted spoon feeding pipeline. A user selects a target through the interface (a). The robot performs contact-rich acquisition (b), transports the spoon under gravity constraints (c), presents the utensil for transfer (d), and returns to a safe staging configuration (e). Spoon-based feeding introduces gravity-sensitive constraints during both acquisition and transport, motivating the Articutool’s active regulation.

execution-time failures and improves transport robustness.

We evaluate the system across granular, viscous, and liquid foods using both physical experiments and a simulation benchmark that isolates constrained transport planning. The experimental design and results are presented in Section V and Section VI. Together, they demonstrate improved acquisition consistency, reduced spillage during transport, higher planning success rates under orientation constraints, and greater meaningful end-to-end feeding success compared to rigid baselines.

II. SPOON-BASED FEEDING IS GRAVITY-CONSTRAINED

To understand why spoon-based feeding cannot be addressed by simply replacing a fork with a spoon, we conducted controlled experiments with granular, viscous, and liquid foods. These studies revealed that scooping-based feeding requires fundamentally different manipulation.

In skewering-based feeding, acquisition and transport are naturally decoupled. Once a bite is mechanically secured to a fork, retention is effectively binary. The food is rigidly attached, and moderate orientation changes during motion do not compromise stability. As a result, most of the technical burden lies in reliable acquisition. Transport remains primarily a kinematic problem. In contrast, scooping-based feeding does not mechanically secure the food. Retention depends continuously on orientation relative to gravity. We observed that acquisition quality directly determines transport robustness. Entry angle, depth, and exit trajectory influence how the food settles in the spoon and how sensitive it is to motion. Larger scoops often reduce stability, while conservative scoops increase stability but prolong meals.

Transport is therefore no longer forgiving. During experiments with rigid spoons on a 6-DOF assistive arm, we observed increased planning timeouts, irregular arm motions, and spillage when strict leveling constraints were imposed globally. Enforcing narrow orientation bounds throughout the motion plan reduced the feasible set of trajectories and made planning brittle. Small changes in configuration produced disproportionately large changes in planning time and path structure. In practice, transport became a continuous stabilization problem rather than a purely geometric one.

These effects manifested differently across food classes but were consistent with the same underlying mechanism. Granular foods created pits that degraded acquisition quality

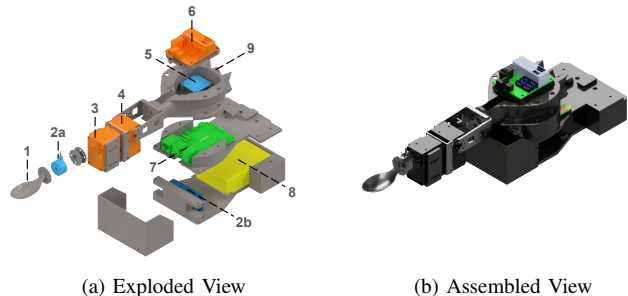


Fig. 2: The Articutool’s modular hardware assembly. **Left: Exploded view** showing Actuation (Orange), Computation (Green), Power (Yellow), and Sensing (Blue). Key components: (1) Utensil, (2a) F/T Sensor, (3-4) Pitch/Roll Motors, (5) IMU, (7) Raspberry Pi 5, (8) Battery, and (9) Mounting Interface. **Right: Assembled view** showing the interface for robotic attachment.

over time, increasing transport variability. Viscous foods adhered to the underside of the spoon and released during motion, causing delayed drips away from the bowl. Liquids exhibited the smallest tolerance to tilt, making transport particularly sensitive to angular disturbances. Across all cases, stabilizing the spoon solely through global arm constraints either reduced acquisition performance or compromised transport reliability.

These observations led us to three requirements. First, retention must be actively regulated during transport rather than enforced exclusively through global arm constraints. Second, acquisition and transport should be decoupled as much as possible to restore structural simplicity. Third, the solution should preserve compatibility with existing assistive arms rather than require increased global arm complexity.

III. THE ARTICUTOOL: MODULAR ACTIVE END-EFFECTOR DESIGN

The analysis in Section II suggests the need for active utensil orientation regulation during transport, while preserving compatibility with existing assistive arms. We thus designed the Articutool as a modular, gravity-referenced active end-effector that relocates stabilization authority from the global arm to the utensil itself. An overview of the design specifications and rationale can be found in Table I; the modular hardware assembly can be seen in Fig. 2.

A. Design Principles

Three principles guided the design.

TABLE I: Articutool Hardware Specifications and Design Rationale

Subsystem	Design Target	Implementation	Rationale
Degrees of Freedom	2 DOF (Pitch, Roll)	Serial pitch-roll wrist	Sufficient to regulate gravity-relative orientation and enable dynamic scooping without increasing arm planning dimensionality.
Peak Angular Velocity	~ 2 rad/s	Dynamixel XC430	Matches observed feeding dynamics from prior ADA deployments; provides margin for disturbance rejection.
Peak Forces	~ 35 N at tool tip	XC430 torque rating	Supports high-force skewering and scooping actions.
Orientation Sensing	Gravity-referenced tilt estimation	Onboard IMU (ICM-20948)	Yaw-invariant leveling; avoids magnetic disturbance sensitivity near assistive devices.
Onboard Compute	≥ 100 Hz local control	Raspberry Pi 5 (ROS 2)	Enables untethered operation and decoupled regulation loop.
Power	Untethered during meal duration	10,000 mAh battery	Supports full feeding session without external cabling; preserves modularity.
Mass	≤ 1.5 kg Jaco2 gripper payload	~ 838 g total mass	Maintains safe inertial profile near user; compatible with Jaco2 payload.
Communication	≥ 10 Hz. supervisory interface	Wireless ROS 2	Decouples tool control from arm planning; supports modular attachment.

Local Gravity-Referenced Regulation. Retention during transport depends on maintaining spoon orientation relative to gravity. The tool therefore provides two degrees of actuation in pitch and roll, which are sufficient to regulate the spoon orientation independently of the arm’s yaw. This minimal configuration allows dynamic scooping motions during acquisition and a level trajectory during transport without increasing global arm complexity.

Modularity and Platform Compatibility. Assistive arms in real deployments are constrained by cost, reliability, and regulatory requirements. The Articutool is designed to be grasped by a standard parallel-jaw gripper and operated as a temporary attachment. This preserves compatibility with existing platforms and enables a broader vision of tool-based manipulation in assistive settings.

Untethered Operation. Cables constrain motion, complicate docking, and introduce reliability risks. The Articutool integrates onboard power, sensing, and computation in a self-contained module. This enables independent regulation at the utensil without modifying the base arm hardware.

B. Mechanical and Actuation Architecture

The Articutool implements a compact two-axis pitch-roll mechanism. The joint ordering was selected to maximize reachable orientation envelopes while maintaining mechanical simplicity and avoiding singularities in typical feeding poses. Joint limits were chosen to exceed the empirically observed tilt tolerances required for granular, viscous, and liquid foods, while mechanical stops provide safety redundancy.

Utensils attach via a modular interface at the distal end of the tool. During development, we observed that collisions between the tool housing and bowl rims limited reachable scoop geometries, particularly for liquids. This motivated the design of elongated spoon geometries that extend the bowl further from the actuation stack, increasing usable scoop depth without enlarging the tool body.

Actuation is provided by compact high-torque motors selected to exceed the maximum angular disturbance induced by typical arm motion during feeding. Motors are current-

limited to ensure safe operation. The tool operates at a high local control frequency, enabling rapid rejection of small disturbances during transport.

C. Sensing, Control, and Onboard Computation

The Articutool integrates an inertial measurement unit to estimate utensil orientation relative to gravity. Because retention during spoon-based feeding is gravity-referenced, only pitch and roll are required for stabilization; yaw estimation is unnecessary. This reduces state complexity and improves robustness by eliminating dependence on magnetic heading estimation, which can be unreliable near assistive devices and powered mobility equipment.

Control is organized into two distinct loops that operate at different time scales. A high-frequency stabilization loop runs entirely onboard the Articutool. Using inertial measurements, this controller continuously regulates utensil orientation relative to gravity during transport. By compensating for angular disturbances induced by arm motion, it maintains the spoon within the allowable orientation envelope identified in Section II. Because this loop is executed locally on the embedded processor, it does not depend on wireless communication with the base arm, and stabilization performance is therefore unaffected by network latency. A separate supervisory loop coordinates higher-level behavior between the assistive arm and the Articutool via wireless ROS 2 communication. This loop operates at a lower rate and issues mode changes and action primitives such as acquisition, post-acquisition leveling, transport initiation, and transfer positioning. It does not participate in real-time stabilization.

This separation restores a practical decomposition of the feeding task. The arm planner focuses on positioning and collision avoidance, while the Articutool locally enforces gravity-referenced orientation constraints. As a result, the arm no longer needs to maintain strict leveling constraints throughout the entire motion plan, reducing planning brittleness and improving transport reliability.

D. System Integration

The Articutool is operated as part of a task sequence consisting of acquisition, post-acquisition stabilization, transport,

and transfer. The base arm provides gross positioning for acquisition and presentation at the mouth, while the Articutool maintains orientation stability during transport. Communication between the arm and the Articutool occurs via wireless ROS 2 messaging. By relocating gravity-constrained stabilization to the utensil, the Articutool restores a practical decomposition: the arm solves positioning, collision avoidance, and transfer, while the tool solves retention. This architectural separation addresses the brittleness observed with rigid spoons on 6-DOF arms and enables reliable spoon-based feeding without increasing global arm complexity.

IV. CONTROL AND TRAJECTORY COMPATIBILITY VERIFICATION

The Articutool enables gravity-referenced stabilization during spoon-based feeding. To realize this capability reliably, we combine a high-rate local orientation controller with a proactive trajectory compatibility verification procedure. The former compensates for disturbances during execution, while the latter ensures that the planned arm motion does not exceed the physical limits of the tool.

A. Active Orientation Regulation

The objective of the local controller is to regulate the spoon’s “up” direction relative to gravity. Because retention is gravity-constrained and yaw-invariant, only pitch and roll components of orientation are controlled. The inertial measurement unit provides acceleration and angular velocity measurements, which are fused using a complementary filter to estimate tilt relative to gravity. The magnetometer is not used, maintaining robustness to magnetic disturbances commonly present near powered assistive devices.

The control law regulates the deviation between the desired gravity-aligned direction and the measured utensil orientation. Joint velocities are commanded to reduce this error while respecting actuator limits. A velocity-based formulation allows smooth compensation for arm-induced angular disturbances. Near joint limits and kinematic singularities, the controller applies damping to avoid aggressive corrections and to preserve stability. This local loop operates independently of the global planner and runs entirely onboard the Articutool. As a result, stabilization performance does not depend on wireless communication latency.

B. Kinematic Model of the Articutool

To relate joint motion to utensil orientation, we model the pitch-roll mechanism analytically. The controlled quantity is the direction of the spoon bowl normal, expressed in the Articutool base frame. Closed-form forward kinematics provide this direction as a function of the two joint angles. The corresponding analytical Jacobian maps joint velocities to changes in the controlled direction vector.

This model enables computation of the joint configuration required to achieve a desired spoon orientation, such as gravity alignment during transport or a commanded tilt angle during scooping. It also allows prediction of how joint velocities translate into changes in utensil orientation, which is critical for evaluating dynamic feasibility.



Fig. 3: The Articutool performing dynamic twirling of spaghetti during acquisition and delivering the bite for transfer.

C. Arm-Induced Disturbance

During transport, motion of the assistive arm induces angular velocity at the Articutool base. Given a time-parameterized arm trajectory, we compute the end-effector angular velocity using the arm Jacobian. This disturbance is transformed into the Articutool base frame, yielding the angular motion that must be counteracted to maintain gravity alignment. The local controller can compensate for this disturbance only within actuator velocity and torque limits. When arm motion induces angular velocities that exceed the corrective capability of the tool, retention cannot be guaranteed through feedback alone.

D. Trajectory Compatibility Verification

To address this limitation, we introduce a plan-then-verify procedure. Given a candidate arm trajectory, we evaluate its compatibility with the Articutool before execution. For each time step along the planned trajectory, we check three conditions. First, kinematic feasibility: the joint angles required to achieve the desired spoon orientation must lie within joint limits. Second, dynamic feasibility: the joint velocities required to counteract the predicted arm-induced disturbance must lie within actuator limits, with a safety margin. Third, singularity margin: the Jacobian of the pitch-roll mechanism must remain well-conditioned to avoid amplification of small disturbances. If any condition fails, the trajectory is rejected. The planner then replans with modified constraints, reduced timing, or an alternate path. Instead of relying solely on reactive stabilization during execution, the system uses proactive verification to ensure the planned motion lies within the stabilizable region of the tool.

This combination of local regulation and proactive verification restores robustness to spoon-based transport. The arm is free to plan without globally enforcing strict leveling constraints, while the Articutool guarantees that gravity-constrained retention remains physically achievable along the chosen trajectory.

V. EXPERIMENTAL DESIGN

We designed a three-part evaluation to validate our core claims regarding enhanced acquisition under contact-rich scooping, reduced gravity-induced spillage during transport, and improved end-to-end feeding performance. The evaluation combines physical experiments that measure real-world feeding behavior with a large-scale simulation benchmark that isolates geometric planning complexity under gravity-referenced constraints.

To reflect the practical demands of a user-facing assistive system, all physical experiments were conducted using a Kinova Jaco2 6-DOF robotic arm – often used for assistive tasks – and the RRT* optimizing planner [1] with a strict 15-second planning timeout. This timeout was empirically derived from our simulation results as a realistic upper bound on acceptable planning latency during a meal. For the simulation benchmark, we used the RRT-Connect non-optimizing planner [2] to provide a clear measure of planning feasibility and time-to-first-solution independent of optimization effects.

We define several key task configurations in the workspace. *Home* represents the default arm configuration. *AbovePlate* positions the wrist-mounted camera to view the food. *Resting* serves as an intermediary pose after acquisition. *Staging* places the utensil a safe distance from the user’s mouth prior to final presentation.

A. Experiment 1: Physical Acquisition Performance

This experiment evaluates whether the Articutool’s decoupled pitch–roll control improves acquisition performance relative to a rigid 6-DOF baseline. We conducted 20 trials for each system and food type combination (120 total). Before each trial, we placed a constant, pre-measured mass of food in a source bowl (125 g of noodles, 250 g of water, or 125 g of pecans). The robot started from *AbovePlate*, executed its acquisition strategy, and then transported the utensil under leveling constraints to a fixed *Resting* configuration. After stabilization, an experimenter measured the mass of food remaining on the utensil.

We compared the mass acquired by the Articutool’s decoupled actions against the baseline’s synchronous 6-DOF scooping motion. The primary metric was acquired mass per trial. We additionally recorded failure modes including empty scoops, collisions, and spills during acquisition.

For granular foods, we quantified mass degradation across repeated scoops without human redistribution to characterize pit formation. A significant higher mass acquired by the Articutool validated improved contact-rich acquisition capability.

B. Experiment 2: Transport Reliability

To isolate gravity-constrained transport performance, we used both simulation and physical evaluation.

a) Simulation Benchmark. We generated a candidate set of 100 start–goal transport tasks with level orientation constraints. To construct a fair common benchmark, we filtered this set to include only tasks confirmed kinematically reachable by all systems via inverse kinematics. Identical

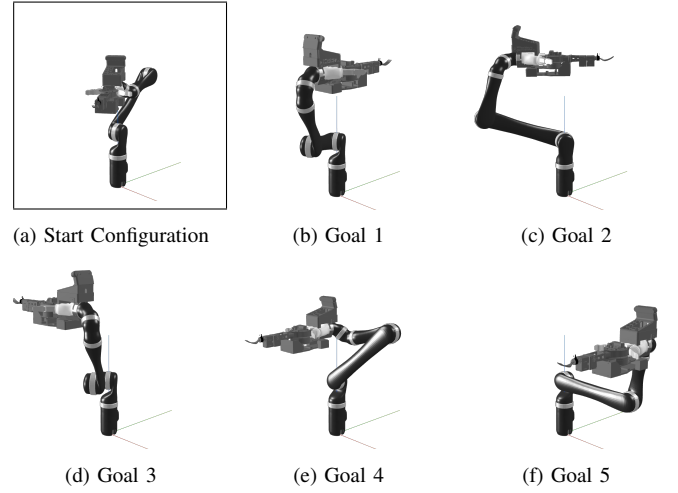


Fig. 4: The common start configuration (a) and five diverse *Staging* goal configurations (b-f) used for the physical transport reliability experiment.

planning parameters were enforced across all conditions, including RRT connection range and collision checking resolution, isolating constraint manifold volume as the primary independent variable affecting planning complexity. The monolithic baselines enforced a strict, continuous orientation constraint of $\pm 10^\circ$ in pitch and roll throughout the trajectory. The Articutool condition relaxed arm-level orientation constraints and relied on local regulation with trajectory compatibility verification.

We measured planning success rate and time-to-first-solution distributions under an extended 1000-second timeout. This extended horizon allows us to distinguish true kinematic infeasibility from computational difficulty. A significantly higher success rate and lower median planning time validated improved constrained transport feasibility.

b) Physical Transport Reliability. We evaluated physical transport performance using five diverse *Staging* goal configurations shown in Fig. 4. The diversity of the goals tests the planner’s ability to find reliable, spill-free paths across different regions of the workspace. For each system and food type, we conducted 20 trials (80 total), evenly distributed across the five goal configurations. Before each trial, we placed a pre-defined mass of food on the utensil (2.5 g of pecans and 8.0 g of water). These payloads were chosen to exceed the average masses observed in Exp. 1, creating a challenging stress test for gravity-constrained transport. For each trial, we measured the mass of the spill, the number of spill events and the location of the spill. A statistically significant lower average spillage for the Articutool validated improved gravity-referenced retention during transport.

C. Experiment 3: End-to-End Feeding Performance

To evaluate the complete architectural approach, we conducted full feeding trials consisting of acquisition and transport to *Staging*. We selected noodles for this evaluation because they require both effective contact-rich acquisition and stable gravity-constrained transport, depicted in Figure 3.

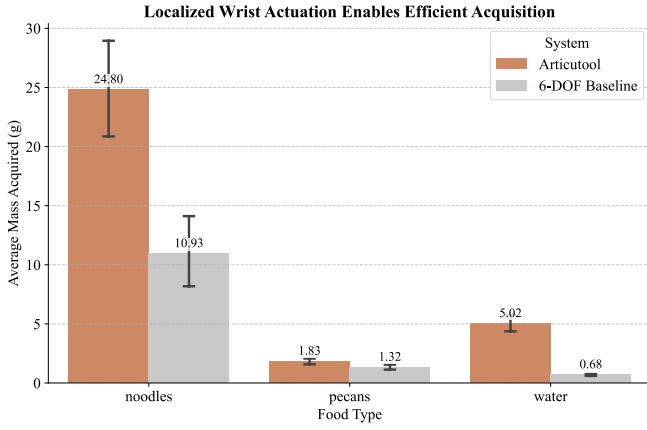


Fig. 5: The Articutool acquires significantly more mass across all food types. Improvements are most pronounced for challenging foods such as noodles and water. Error bars show 95% CI.

We ran 20 trials for each system (40 total). Each trial was categorized into one of four mutually exclusive outcomes:

- **Meaningful Success:** Spill-free delivery exceeding 3.0 g.
- **Trivial Success:** Spill-free delivery at or below 3.0 g.
- **Non-Critical Failure (Table Spill):** Any spill confined to the table.
- **Critical Failure (User Spill):** Any spill on the user, wheelchair, or floor.

The 3.0 g threshold was empirically derived from bimodal acquisition data separating failed captures from successful bites. Deliveries below this threshold are considered functionally insufficient in an assistive context due to robotic feeding latency. Meaningful success rate serves as the primary metric for evaluating end-to-end system performance.

VI. RESULTS

Our experiments validate the architectural claim that decoupling gravity-referenced regulation from global arm planning improves acquisition dexterity, constrained transport feasibility, and meaningful end-to-end feeding performance.

A. Localized Wrist Actuation Improves Acquisition

The Articutool’s localized pitch–roll actuation demonstrated a clear advantage in acquiring challenging foods (Exp. 1). For granular foods, the Articutool acquired 1.83 ± 0.61 g, a significant improvement ($p = 0.0062$) over the baseline’s 1.32 ± 0.48 g. The benefit was greater for contact-sensitive foods. For noodles, the Articutool acquired 24.80 ± 9.56 g, compared to the baseline’s 10.93 ± 7.01 g ($p = 0.0$). For water, the Articutool acquired 5.02 ± 1.62 g, significantly exceeding the baseline’s 0.68 ± 0.18 g ($p = 0.0$). These results, shown in Fig. 5, demonstrate that separating utensil orientation control from global arm motion materially improves acquisition in gravity-sensitive regimes, validating the claim that spoon-based acquisition is inherently contact-rich and benefits from localized actuation.

Computational Cost of Redundancy: 8-DOF Baseline Requires Orders of Magnitude More Planning Time

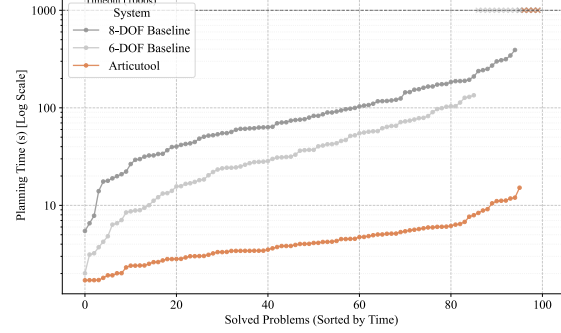


Fig. 6: Planning time profiles (Cactus Plot) for constrained transport tasks. The Articutool achieves high success rates with median planning times suitable for real-time interaction, significantly lower than monolithic baselines.

B. Decoupling Regulation Expands Constrained Transport Feasibility

We next evaluate transport under strict gravity-referenced constraints (Exp. 2).

a) *Simulation Benchmark.*: The simulation benchmark isolates geometric planning complexity. As shown in Fig. 6, the Articutool solves 96.0% of constrained transport tasks with a median planning time of 4.02 seconds.

The 8-DOF baseline achieves a similar success rate (95.0%) under the extended 1000-second timeout, confirming that valid paths exist in the higher-dimensional space. However, the median planning time is 75.7 seconds. Despite additional kinematic redundancy, strict orientation constraints collapse the feasible configuration space into a narrow manifold, forcing extensive sample rejection.

The 6-DOF baseline requires a median of 31.0 seconds and fails in 14.0% of cases even with extended timeout. These results demonstrate that adding DOFs without decoupling regulation does not meaningfully reduce planning complexity. The Articutool’s architecture expands the effective feasible set by removing global tilt constraints from the arm planner.

b) *Physical Transport Performance.*: Physical trials confirm that architectural decoupling translates to real retention improvements. When transporting 8.0 g of water, the Articutool spilled an average of 0.00 g, a statistically significant reduction ($p = 0.0030$) from the baseline’s 1.31 g. Across pecans and water, the Articutool’s active leveling virtually eliminated gravity-induced spillage, as shown in Fig. 7. These results validate that local regulation is not merely computationally efficient but physically effective in reducing retention failures.

C. Decoupled Architecture Achieves Meaningful End-to-End Success

Finally, we evaluate complete feeding sequences (Exp. 3). Under the strict zero-spill metric, the Articutool achieved a success rate of 70.0% (14/20), compared to 35.0% (7/20) for the baseline ($p < 0.00012$). Furthermore, inspection of the baseline’s non-spill successes reveals that 5 of 7 (71%) delivered trivial mass (≤ 2.1 g). These outcomes

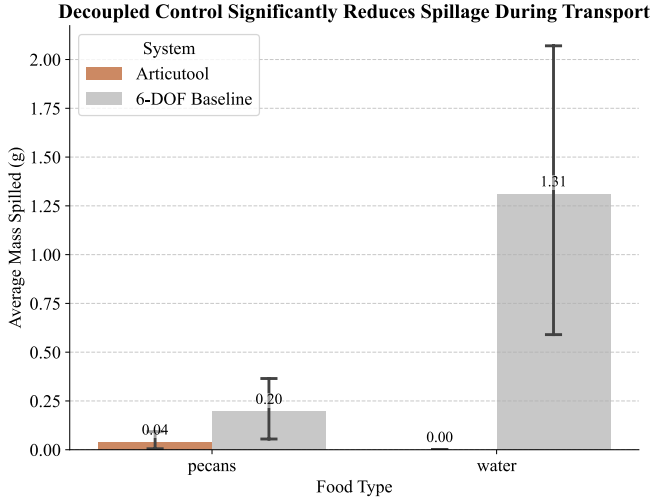


Fig. 7: Physical transport results confirming significantly reduced spillage under decoupled control. Active gravity-referenced regulation materially improves retention during transport.

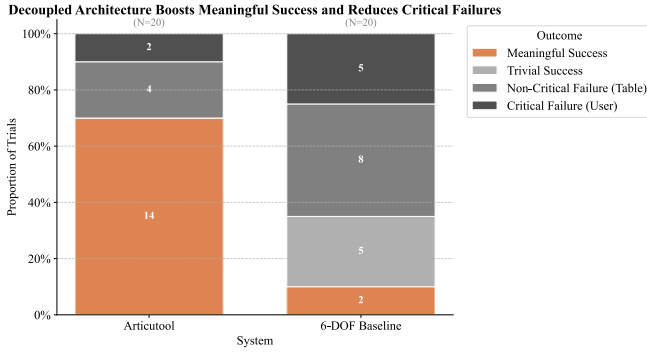


Fig. 8: End-to-end feeding outcomes. The Articutool achieves a high meaningful success rate while substantially reducing critical failures over the baseline.

are functionally indistinguishable from acquisition failures. Using the empirically derived meaningful mass threshold of 3.0 g, the Articutool maintains a meaningful success rate of 70.0% (14/20), while the baseline collapses to 10.0% (2/20). Failure severity also differs substantially. The Articutool caused a critical spill in only 10.0% of trials (2/20), whereas the baseline was 2.5 times more likely to spill on the user (25.0%, 5/20).

These results, summarized in Fig. 8, demonstrate that decoupling acquisition and transport regulation yields not only higher success rates but materially safer outcomes.

VII. DISCUSSION

Supporting independent eating for people with motor impairments has been an active research area for several decades [3]–[6]. Early systems such as the Winsford Feeder [7] mechanically positioned food relative to the user, while later devices including Handy 1 [8], Bestic [9], Obi [10], Neater Eater [11], and My Spoon [12] provided table-mounted robotic arms executing largely fixed trajectories. Long-term adoption has remained limited. Reported shortcomings include difficulty acquiring desired foods [13],

dropping food during transfer, and requiring precise user positioning that can cause discomfort [14]. Many of these limitations stem from fixed motion primitives and limited adaptation to food properties and transport constraints.

Research addresses some of these limitations by using sensors to increase robot autonomy [15]–[18]. Recent work has explored personalization and adjustable autonomy [19], [20], as well as multimodal perception and force-aware control for fork-based acquisition and in-mouth transfer [21], [22]. In fork-based feeding, transport is relatively unconstrained with respect to gravity. Acquisition and transport can therefore be treated as partially separable subproblems. Spoon-based feeding does not share this structural advantage, transforming feeding from a trajectory execution problem into a gravity-constrained manipulation problem.

The limitations of standard manipulators have led many researchers to develop specialized tools for feeding, including utensils with integrated sensors. Some systems incorporate force sensors to detect contact with the mouth or plate [23], [24], or cameras for visual servoing during the final approach to the mouth [25]. While effective for specific tasks, these tools are often passive in their mechanical structure or require a tether for power and data. This tethering can restrict continuous wrist rotation (essential for tasks like twirling spaghetti) and introduces the risk of snagging.

Actuated utensils also exist, such as Liftware [26], a self-leveling spoon for individuals with hand tremors. However, these utensils are typically handheld devices, lacking the communication interface to be commanded to specific non-level angles for scooping, and not designed to handle potentially large accelerations. Advancements in actuated utensils include the hardware used in the FLAIR system [25] features a 2-DOF motorized utensil with similar kinematics to the Articutool, used for executing dynamic skills like twirling and scooping with a fork. In their approach, the utensil’s orientation is managed by the robot’s central computer.

The central contribution of this work is not simply a new utensil but a reframing of spoon feeding as a regime shift. When gravity-sensitive retention is enforced globally at the arm level, the feasible configuration space collapses into a narrow manifold. Our simulation results demonstrate that although a monolithic 8-DOF system is kinematically capable of solving constrained transport tasks, it remains computationally inefficient under strict orientation limits, requiring a median of 75.7 seconds to find solutions. In contrast, the decoupled Articutool architecture achieves a 96% success rate with a median planning time of 4.0 seconds. This gap illustrates that additional degrees of freedom alone do not resolve narrow-manifold planning problems. The key is structural decoupling of regulation and planning. By relocating gravity-referenced orientation control to a localized wrist and verifying trajectory compatibility prior to execution, the effective feasible set is expanded without relaxing safety-critical constraints.

Physical experiments confirm that this architectural shift translates to real retention improvements and meaningful task outcomes. The Articutool achieved a 70.0% meaningful

success rate in end-to-end feeding, compared to 10.0% for the rigid baseline. The reduction in critical spills highlights that architectural decisions directly affect safety in physically intimate assistive tasks.

A. Limitations and Future Directions

Several limitations remain. The current prototype is graspable by a standard assistive robot gripper but does not yet support autonomous docking or tool exchange. A mature assistive tool ecosystem will require reliable self-equipping and disengagement mechanisms. While the system is untethered from the environment, internal cabling for the distal force/torque sensor currently limits continuous roll motion during certain primitives. This limitation may affect the transfer phase as well. While the current pipeline holds the spoon steady, relying on users to remove food from the spoon, motions to pour spoon contents may need to be integrated in later work. Future hardware iterations will integrate improved cable management or slip-ring mechanisms to enable unrestricted rotation.

This evaluation focuses on technical validation through simulation and controlled physical trials. Although the meaningful success metric captures functional bite delivery, aspects such as user trust, perceived safety, comfort, and long-term usability are critical dimensions in assistive robotics. Future studies will focus on feedback from users with upper-extremity mobility impairments on videos and interactions with the Articutool.

B. Toward Modular Assistive Tool Ecosystems

More broadly, this work suggests a shift in assistive robot design philosophy. Rather than increasing global manipulator complexity to accommodate every task-specific constraint, standard arms can be augmented with intelligent, task-specific tools that locally regulate critical task dimensions, whether that is leveling relative to gravity as shown here, or another regulation primitive. By reframing spoon feeding as a gravity-constrained manipulation problem and demonstrating that architectural decoupling improves both computational feasibility and physical reliability, this work lays the foundation for modular, regulation-aware end-effectors that combine global reach with localized intelligence.

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