

Bridging the Embodiment Gap: Hand Morphology and Control Method in Dexterous Teleoperation

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Abstract—Dexterous robotic manipulation requires simultaneous consideration of hardware and control algorithms, but these are often developed in isolation. To address the embodiment gap in teleoperation, we present an evaluation framework that integrates three morphologically diverse robotic hands (ORCA, Inspire, LEAP) and two control modalities (direct joint angle and inverse kinematics) on a single robotic arm. Preliminary system integration reveals significant friction between human biomechanics and robot kinematics, such as biologically unnatural IK solutions and limitations of coupled joints. We additionally propose an evaluation methodology using standardized clinical dexterity tests with quantitative metrics.

Index Terms—dexterous manipulation, teleoperation, embodiment gap, robotic hands

I. INTRODUCTION

Robotic hands are increasingly being viewed as the way to achieve fine manipulation tasks. While grippers or suction-based end-effectors may suffice for most pick-and-place tasks, human hands currently still hold the advantage in precision grasping as defined by the Cutkosky grasp framework [1]. Despite the development of robotic hands with human-like dexterity, the embodiment gap between a robotic hand and a human hand remains a challenge.

Robotic hands vary widely in actuation methods, kinematic structures, size, proportions, etc. Human teleoperation has shown the potential to bridge this divide by providing a wealth of information [2]. The need for hardware-aware teleoperation systems has been identified [3], yet most works are still evaluated on a single robotic hand platform. This makes it difficult to determine whether the performance of a control method stems from the algorithm itself or from a favorable match between that specific hand’s morphology and the desired task. Different approaches to teleoperation make different assumptions about the correspondence between human and robot hands, but the relative influence of hardware morphology versus control method has not been deeply studied.

This work presents a unified evaluation framework that integrates three morphologically diverse robotic hands (ORCA, Inspire, and LEAP) with two control modalities (direct joint angle control and fingertip-based inverse kinematics), all interchangeably mounted on the same robotic arm. This shared platform allows us to isolate the effects of hand morphology or control method under identical teleoperation conditions. Initial findings show clashes between human biomechanics and robot kinematics, and we further propose an evaluation methodology using standardized clinical dexterity tests to enable quantitative comparison across hand-control combinations.



Fig. 1. Comparison of joints in the human hand to the ORCA, Inspire, and LEAP hands. The MCP Abd/Add for the thumb is also the CMC joint.

II. METHODOLOGY

A. Hardware Selection

We selected three robotic hands to represent a range of morphologies, namely the ORCA, Inspire, and LEAP hands. The ORCA hand is cable-driven with 17 fully independent degrees of freedom (DoF). The Inspire hand is also cable-driven but only has 6 DoF. The LEAP hand is direct-driven with 16-DoF across four fingers. For reference, the human hand has 21 DoF (excluding the wrist) with three joints per finger. The index, middle, ring, and pinky fingers have the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints. The thumb has the interphalangeal (IP), MCP, and carpometacarpal (CMC) joints. Of the three platforms, the ORCA and LEAP hands most closely approximate human joint count and structure (Fig. 1).

Teleoperation input is captured via a Rokoko Smartglove, which streams real-time finger pose data using built-in IMU (inertial measurement unit) and EMF (electro-magnetic field) sensing, eliminating the need for external cameras. The robotic hands can be interchangeably mounted on a 6-DoF Kinova Gen3 arm, whose end-effector pose is driven by a Vive Ultimate Tracker worn on the operator’s wrist.

B. Joint Mapping and Control Methods

We implement and compare two control methods, direct joint angle control (forward kinematics) and inverse kinematics, for each hand. Joint and fingertip data are extracted from the Rokoko Smartglove’s streaming output and mapped to the corresponding joints in each robotic hand.

Under joint angle control, captured human joint angles are applied directly to the corresponding robot joint. Scaling factors are introduced as necessary to account for differences in hand size. Under IK control, target joint angles are calculated from captured fingertip positions using PyBullet’s `calculateInverseKinematics` function, which implements a Damped Least Squares (DLS) solver. This method was selected for its built-in DLS solver and ease of integration with our system.

C. Evaluation Metrics

We conduct an initial qualitative comparison of grasping performance and thumb-to-finger pinch accuracy across all hand-control pairings. As a more rigorous evaluation method, we propose adapting standardized clinical dexterity tests developed for human patients. The Box and Block Test (BBT) evaluates gross manual dexterity by measuring blocks moved from one side of a partitioned box to the other within a fixed time. The 9-Hole Peg Test (9-HPT) targets finer finger dexterity, requiring placement and removal of pegs from a pegboard. Because these tests are already validated benchmarks for human dexterity, they enable direct, standardized comparison between robot and human performance. We additionally propose supplementing these tests with manipulation tasks requiring sustained dexterity, such as lid-screwing and in-hand finger gaiting. Across all tasks, we propose pairing objective task metrics (e.g., completion time, success rate) with subjective teleoperator-reported metrics (e.g., cognitive load, perceived mapping intuitiveness).

III. RESULTS

Across hands, fingertip IK control achieved higher accuracy than direct joint angle control on high dexterity manipulation tasks. For the ORCA hand, IK produced substantially lower error than direct control during a lid-screwing task (error is evaluated across all fingers) (Table I).

Preliminary evaluation across all three hands indicates that direct control is better suited to coarse, large motions, where grasp success does not depend on precise and stable finger movements. The ORCA hand consistently outperformed the other two platforms in accuracy and showed the greatest promise for fine manipulation tasks. We attribute this to its close kinematic correspondence to the human hand and resulting ability to correctly reproduce teleoperated motion.

TABLE I
ERROR STATISTICS OF ORCA HAND FOR SINGLE LID SCREWING TASK

Retargeting Method	RMSE (mm)	MAE (mm)	Total Sum Error (mm)
Direct Joint Angle	306.147	295.609	21579.5
IK with DLS	144.549	129.949	9616.2

IV. DISCUSSION

Because direct joint angle control applies raw human joint angles without correction, its accuracy is constrained by the kinematic similarity between the operator’s hand and the target robot hand. IK control avoids this constraint by targeting

only fingertip position and relying on the solver to calculate required joint angles. However, without sufficiently tight joint limits, the solver sometimes converges on finger configurations that are biomechanically unnatural for a human operator.

The LEAP hand is roughly 30% bigger than the human hand and employs a universal abduction-adduction mechanism at the thumb MCP joint, which expands its range of motion and shifts its axis to always remain perpendicular to the index finger [4]. This structural difference likely contributed to the difficulty we observed in achieving a curved index-to-thumb fingertip pinch under direct joint angle control, which often required teleoperators to unnaturally rotate their thumb outward and back. To accommodate the LEAP hand’s larger palm, we applied an additional scaling factor to each thumb joint. Because the hand’s direct-driven joints have a 360-degree range of motion, IK control occasionally drove the index, middle, and ring fingers into backward bends at the DIP and PIP joints. Though kinematically valid, this can be a significant failure mode when performing tasks in a constrained workspace.

The Inspire hand’s thumb, in contrast to both ORCA and LEAP, only has 2 DoF, corresponding to CMC abduction/adduction and MCP flexion/extension. An index-to-thumb fingertip pinch is only achievable when the CMC joint is fully adducted to its inner 90-degree hardware limit, a configuration the human thumb cannot comfortably reach, as apparent during direct joint angle teleoperation. Additionally, the Inspire hand’s cable-driven PIP joint is mechanically coupled to its MCP joint. In contrast, the fully independent joints of the LEAP and ORCA hands enable finer decoupled finger movements needed for constrained manipulation.

V. CONCLUSION

Achieving stable and accurate dexterous manipulation requires designing control algorithms and hardware morphology in tandem. This work presents a teleoperation framework that jointly evaluates three robotic hands and two control modalities under matched teleoperation conditions. Our preliminary results reveal significant friction between human biomechanics and robot kinematics. To quantify this embodiment gap more rigorously, we propose adapting standardized clinical metrics, such as BBT and 9-HPT, alongside subjective human-centric measures. Future work should execute this proposed evaluation and extend the framework to additional control methods.

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