Robotic Self-Touch and Think-Gesture for Cognitive Offloading

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Abstract

Under appropriate sensorimotor conditions, robotic limbs can be integrated into the body schema, yet how such technological mediation reshapes the perceptual boundary between self and other remains underexplored. This study will systematically investigate whether a robotic arm that performs self-touch and thinking gestures can replicate the cognitive and affective benefits of biological limbs—such as stress relief and reduction of cognitive load, reduction—while identifying key factors that influence whether users perceive it as a self-extension or an external agent. The prototype will be evaluated through a multi-modal dataset comprising subjective measures (NASA-TLX, customized embodiment and trust questionnaires), behavioral metrics (task performance and interaction patterns), physiological and physical signals (self-touch force and robotic motion trajectories), and qualitative insights (semi-structured interviews and think-aloud transcripts). The findings are expected to provide theoretical and empirical support for the application of embodied robotic arms in assistive technologies, with potential to enhance cognitive-affective support for non-disabled users and expand interactive experiences for individuals with physical impairments.

Keywords

robot, human, touch,gesture

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1 Introduction

The boundaries of human bodily and mental capacities are not fixed but highly plastic. The Extended Mind thesis argues that cognitive processes can extend beyond the biological organism into external tools and environments, forming a coupled human–artifact–world system [6]. In virtual reality, synchronous visuospatial - tactile / kinesthetic feedback during first-person avatar control systematically induces embodied experience, capturing ownership, agency, and self-location which can be measured with standardized questionnaires [12]. External objects can be incorporated into bodily representation, yielding ownership sensations and proprioceptive drift [5]; tool-use research further demonstrates that short- or long-term practice reshapes peripersonal space and action representations [14]; and in virtual reality, synchronous visuospatial–tactile/kinesthetic feedback during first-person avatar control systematically induces embodied experience—capturing ownership, agency, and self-location which can be measured with standardized questionnaires [12]. Taken together, these findings reveal the mechanisms by which external entities (e.g., virtual limbs, tools, or robots) can be integrated into bodily experience under specific spatiotemporal and causal conditions.,Building on this plasticity, researchers have begun to explore its value for assistive and augmentative technologies. In robotics and prosthetics, evaluation frameworks for prosthetic embodiment emphasize the joint contribution of ownership and agency [18]. Representative cases include hand-augmentation devices (e.g., the "Third Thumb"), which can elicit adaptive changes at the neural and behavioral levels after short-term training [7]; wheelchair-mounted robotic arms and assistive manipulators, which not only improve everyday function, but can also support nonverbal communication [1, 2, 19]. Notably, prior work has focused primarily on functional augmentation, while the affective and cognitive regulation potential of embodied technologies remains comparatively underexplored.,This gap matters because human behavior routinely leverages bodily action to regulate cognitive state. Self-touch and certain postures can effectively reduce stress and modulate affect [15]; gestures externalize parts of cognition and facilitate problem solving [8, 13, 16]; and affective touch can buffer acute stress responses and mitigate social exclusion [9, 11, 17]. These works in the literature motivate a central question: Can external systems reproduce these embodied regulation mechanisms—thereby enabling "cognitive offload" through robotic self-touch—without interrupting primary tasks and with parameters that are precise, repeatable, and ethically controllable? To investigate this question, we design experiments in which a chair-side robotic arm delivers two representative regulatory actions during high-load cognitive work (continuous typing + planning): thinking gestures (e.g., chin-cradling) and self/ functional touch. We pose the following research questions:

(1) RQ1: How do robotic thinking gestures and self-touch affect task performance, stress levels, and subjective cognitive load? [8, 11, 15],

(2)RQ2: Under what conditions is the robotic arm experienced as a self-extension versus an other-agent? How do spatiotemporal predictability and morphological/spatial matching shape this boundary? [3, 5, 14]

(3)RQ3: When the arm is experienced as self, how do user preferences for interaction parameters (e.g., force, trajectory) differ from using the biological limb to perform the same actions? [18],Correspondingly we advance three hypotheses:

(1) H1: Relative to a no-touch control, robotic regulatory actions will improve task performance and recovery, and reduce stress indices and subjective load (lower NASA-TLX).

(2) H2: High trajectory similarity and low latency will promote self-attribution, whereas added delay/trajectory perturbations will bias toward other-attribution [3].

(3) H3: Under self-attribution with higher trust/ownership, preferred parameters will approximate those of one's biological self-touch; under other-attribution or low trust, users will prefer more conservative interaction (smaller forces and greater deviation from personal self-touch trajectories) [18].

2 Related Works

2.1 Embodiment, Extended Cognition, and the "Self-Other" Boundary Conditions

Clark's research shows cognition and bodily experience are flexible. The extended mind theory includes artifacts in the cognitive system [6]. The illusion of a rubber hand shows that visual-tactile pairings induce ownership and proprioceptive drift [5]. Tool use expands personal space and updates body schema [14]. VR uses questionnaires to assess ownership, agency, and self-location [12]. Predictive coding models explain the "self vs. other" boundary: predictable, self-generated touches are less intense than unpredictable, external ones. Adjusting temporal delays or trajectory mismatches can modulate this effect, involving cerebellar-somatosensory circuits. Non-zero delays can recalibrate the system, using "predictability" to manage agency and ownership in robotic touch [3]. In prosthetics, embodiment is seen as ownership and agency combined, with recommendations for measurement, warning against viewing embodiment as the sole acceptance factor [18]. These perspectives guide the study's design for self/other manipulation and measurement.

2.2 Self-touching, emotional touching, and thinking gestures under high load

Behavioral and neural findings indicate gestures and self-touch act as cognitive aids and emotional regulators. Co-speech gestures can decrease working memory load during explanations and problem-solving, with reviews confirming significant benefits across tasks [8, 16]. Spontaneous facial self-touch (sFST) increases with cognitive/emotional load, linked to transient neural state changes in EEG studies [15]. Self-soothing touch and hugs lower cortisol levels in trials; meta-analyses show significant benefits of touch in managing stress and anxiety; interpersonal touch, like hand-holding, reduces threat-related brain responses, underscoring its stress-reducing role [11]. If users perceive the robotic arm as an extension of their own body, it may also trigger the similar response.

2.3 Wearable/Auxiliary Robotic Arms and Emotional Touch in Robotics

Supernumerary robotic limbs (SRLs) and chair-/shoulder-mounted assistant arms demonstrate that extra limbs can share workloads,

Figure 1: Force Sensor 3D, modeled hand and robot arm

stabilize posture, and free biological hands; their control architectures (e.g., compliance/impedance, shared control) prioritize safety and comfort. The Third Thumb study reveals rapid learnability among the general population and significant neural reorganization after short-term training, highlighting the feasibility of embodied augmentation in daily tasks [7]. In assistive contexts, wheelchair-mounted robotic arms (e.g., JACO) significantly enhance independence in daily activities and yield measurable social impact; recent reviews systematically outline applications of eye-tracking/shared control in accessibility [1, 2]. In addition to operational tasks, emotionally-driven touch initiated by robots, as demonstrated by the HuggieBot series, shows that softness, warmth, and timing/pressure responsiveness significantly enhance the experience; design guidelines for autonomous hugs have been validated in user studies [4].

However, research on user-initiated interactions, where robotic arms are perceived as extensions of the body for self-touch, remains relatively scarce.

3 Method

3.1 Robot and Equipment

The experimental platform consisted of an integrated robotic system with sensing and control capabilities. The key components are as follows:

Robotic Manipulator: A 6-degree-of-freedom Piper robotic arm (Agilex Robotics) was employed. An open-source 3D-printed prosthetic hand was attached as the end-effector, capable of accurately replicating and holding any user-specified hand posture.Force Sensing Unit: Several high-precision pressure sensors (resolution: 0.01 N) were integrated. This unit operated in two modes: (1) Measuring interaction forces during self-touch performed by the user with their biological hand. (2)Measuring interaction forces between the user and the 3D-printed hand when mounted on the robotic arm.

Control and Data Acquisition: A central PC running the Ubuntu 22.04 operating system was responsible for overall system control and data logging.

Trajectory Recording and Playback System: A custom system application was developed using the Agilex Piper SDK. This software featured a "teaching" mode, allowing the experimenter to manually guide the robotic arm to record motion trajectories. These trajectories could then be accurately replayed with a single command, ensuring consistent experimental conditions across trials.

Safety Mechanism: An independent physical emergency stop button was installed, enabling the immediate deactivation of the robotic arm at any moment to guarantee participant safety.

3.2 Participants

Participants were recruited using university channels and academic social media groups through a mixed-method strategy and convenience sampling based on criteria. Eligible participants were aged 18 or older without proprioceptive or tactile disorders. Exclusion criteria covered neurological or psychiatric disorders, skin issues affecting tactile perception, and recent substance use affecting the CNS or attention. A total of 24 participants, with no gender restrictions, were recruited. They signed written informed consent and received 50 RMB for completing the 60-minute session, which included preparation, the experiment, and a post-experiment inquiry. Partial compensation was given if they withdrew early.

3.3 Procedure

Participants provided written consent upon arrival. The experiment proceeded as follows:

Participants first completed the Montreal Imaging Stress Test (MIST) [10] without knowledge of subsequent tasks to establish behavioral baselines. Researchers instructed users to perform a common thinking gesture with a robotic arm and with their own hands, as shown in Figure 1's model hand; as a control, participants were reminded to keep both hands on the keyboard during testing without thinking gestures. The experiment involves a task that combines computation and word memory to simulate cognitive load. After completion, participants filled out the NASA-TLX scale and Avatar Emblem Questionnaire to assess cognitive load and memory performance.

Execution phase of experimental conditions: Participants underwent four experimental conditions. To counterbalance order effects, the sequence of conditions was arranged using a Latin Square design.

Biological Self-Touch Condition: Participants performed the MIST task using only their bare hand to touch their own body. It served as the baseline for natural self-touch.

No Self-Touch Condition: Participants performed the MIST task without using their hand to touch their body. They were explicitly instructed to keep their hands still and refrain from any self-touch during the task.

Robotic Arm Intervention Condition: A robotic hand delivered touch to the participant's body while they performed the MIST task. Participants could actively control when the robotic hand was operating: they started and stopped the robotic hand using a button, thereby deciding when touch was applied.

Clothed Robotic Hand Condition: This condition was identical to the Robotic Hand Condition, except that the robotic hand was covered with a piece of clothing. The added garment altered the visual and tactile appearance of the robotic hand while participants still controlled its activation via the same on/off interface.

Post-Experiment Interview and Data Collection: A semi-structured interview was conducted to explore participants' perceptions, attributions of robotic arm actions, and emotional state changes. Data collected included NASA-TLX scores, word memorization performance, force data from gloves and robotic arm, and qualitative interview data.

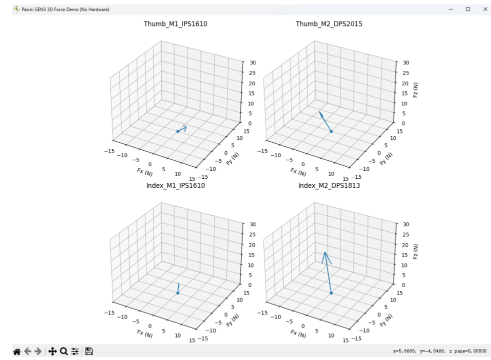

Figure 2: Force Sensor Data Visualization

3.4 Data Collection and Analysis

This study uses a multi-modal data collection: subjective (NASA-TLX scores, questionnaires on embodiment and trust[12]), behavioral (word memorization accuracy), physiological (self-touch forces, robotic arm trajectories, etc.), and qualitative (transcriptions from interviews and think-alouds). Analysis quantitative data, employing Repeated-Measures ANOVA for performance and load effects (RQ1/H1), logistic regression for robotic arm attribution (RQ2/H2), and t-tests and correlations for interaction parameters and trust-preferences (RQ3/H3). Thematic analysis of qualitative data offers deeper user experience insights, contextualizing quantitative results.

4 Summary & Timeline

We have currently confirmed the use of a 3D model hand to secure the sensors, avoiding errors caused by the flexible joints of the 3D model. We utilize Paxini's pressure sensors and can analyze the combined force and direction of each sensor through code. For the robotic arm, we employ Agilex's Piper SDK to achieve manual teaching and reproduction of movements, as well as file management for motion trajectories, including emergency stop functions. Next, we will combine pressure task experiments. From 11/17 to 11/21, we will implement the Minimum Viable Product (MVP) and conduct a pilot study with around 3 participants (possibly collecting eye-tracking data to confirm user gaze points). From 11/24 to 11/28, we will recruit approximately 14 users for user experiments. On 12/1, we will analyze the results and, based on the findings and the content of this report, prepare the HRI LBR content, aiming to submit by the AOE deadline on 12/8.

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