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Using Pain to Prevent Harmful Events when Controlling Robotic Devices with Limb Movements

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I. Introduction

Humans are increasingly interacting with and controlling robots, whether it be through teleoperation to perform surgical operations, or the increasing use of wearable devices such as robotic prostheses or supernumerary robotics limbs [1]. However, we still lack the ability to efficiently convey information regarding the state of these devices and their interactions with the environment, in particular to prevent potentially harmful events such as collisions.

Currently, such information is primarily conveyed through sets of vibration motors simulating the somatosensory system [2]. This method presents major limitations as the number of actuators increases rapidly with the complexity of the controlled robotic device and task, which makes the interpretation of, and reaction to, the conveyed information difficult for the brain. This is known as neural resource allocation problem [3]. The present paper investigates *pain* as a potential alternative, in order to convey critical information to the user that requires an immediate response, such as to avoid a collision.

Although it may appear counterintuitive, sensory feedback based on pain could possess all of the properties necessary for such situations. In particular, pain is fast because it interrupts ongoing brain processes with high-priority signals [4], such that cortical responses occur approximately $60\,\mathrm{ms}$ faster than that of concurrent tactile stimulation [5]. Fast responses to pain are also reflected in spinal nociceptive withdrawal reflexes (NWR), allowing limbs to rapidly retract from nociceptive stimuli [6]. Furthermore, expected pain signals are self-reinforcing in the brain [7], meaning that the brain increases its expectancy of receiving pain when performing an action that has been painful once, even in absence of pain in the current execution of the said action.

From a control perspective, these properties would be particularly interesting if they could be triggered in the presence of threats (that may not be directly visible to the human) to the robot. For instance, if one could trigger a NWR when a teleoperated robot is about to hit an obstacle, it could (i) prevent the collision with higher probability than with traditional vibrotactile stimulation, and (ii) durably modify the behavior and trajectories of the user, reducing the probability of a future collision. In what follows, we present the setup and experimental procedure that will be performed, the current stage of the implementation, and the perspectives of this ongoing work.

II. Methods

To assess whether the NWR can be triggered when controlling a robot, we have developed an experimental platform in which a robotic arm's end-effector follows the movements of a participant's hand. Pain is generated using a custom heating device worn by the participant. Below we detail the different components of the developed platform and the proposed experimental protocol that will be performed.

A. Material

The subsystems described below are synchronized using an electronic trigger to allow an accurate assessment of the human reaction to pain when controlling a robot. A data flow diagram is presented in Fig. 1A.

Robotic Limb: A six degree-of-freedom robotic arm (Unitree Z1, $1\,\mathrm{kHz}$) is used to mirror the motion of the user's hand.

Human kinematics: The kinematics of the human hand are recorded using a magnetic motion capture system (Polhemus Liberty, $240\,\mathrm{Hz}$); a sensor is placed on the tip of the participant's dominant index finger.

Muscle activity: electromyographic (EMG) sensors (MiniX, Cometa, $2\,\mathrm{kHz}$) are used to record muscle activity in the user's arm during the experiment to detect NWR events. Specifically, signals are recorded from the flexors brachioradialis, biceps brachii, and anterior deltoid, and the extensors triceps brachii (both long and short heads) and posterior deltoid.

Pain Feedback: A custom thermal stimulator is used to induce painful sensations (Fig. 1B). The stimulator is made from: (i) a Peltier thermode to create a temperature gradient, along with relevant drivers and filters; (ii) a thermistor to provide accurate temperature feedback; (iii) a custom interface used to contact the skin; and (iv) a servo motor that allows the device to create and break contact between the custom interface and the skin.

B. Experiment

The experiment tasks users with controlling the robotic arm so that it touches either the top or bottom surface of a midair target. Participants move their hand in a parasagittal plane using elbow and shoulder flexion/extension movements; the position of the hand is mirrored by the end-effector of the robotic arm. The thermal stimulator is placed on the ventral side of the participants forearm, such that the Peltier plate contacts the skin at the ventral side of

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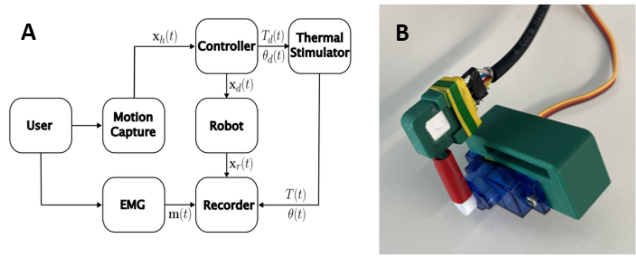

Fig. 1: Information flow chart and thermal stimulator. **A.** Information flow chart of the designed platform. The users hand position $x_h(t)$ is captured and transformed into a desired robot position $x_d(t)$, temperature $T_d(t)$, and stimulator angle $\theta_d(t)$. The current robot position $x_r(t)$, EMG data $m(t)$ and the temperature $T(t)$ and angle $\theta(t)$ of the stimulator is recorded. **B.** Picture of the developed thermal stimulator interface.

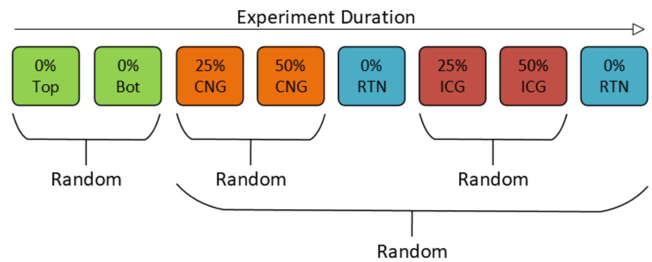

Fig. 2: Successive blocks of the experiment. CNG denotes congruent blocks, ICG incongruent, and RTN retention effect blocks.

the wrist. Importantly, when the robot reaches the target, a painful event, generated by the thermal stimulator, occurs with a predefined probability. An individual calibration of the threshold temperature to generate pain is performed by detecting the lowest temperature triggering a NWR.

Through a block-wise design, three probabilities of pain appearance are tested: $p \in \{0\%, 25\%, 50\%\}$. We also test the effect of the pain sensation occurring from the same direction as the robot's contact with the target. Information is considered congruent when the robot touches the top of the target (i.e. contact is below); incongruent is the converse. Congruent and incongruent test blocks are followed by a washout block to test for retention effects. In each block, $N = 100$ reaching trials will be performed, resulting in a total of 800 trials in the experiment. The blocks will be organized as detailed in Fig. 2.

III. Results

The developed system exhibits good performance in key metrics necessary for testing the NWR. The Robot Controller uses inverse kinematics to compute the necessary motion profile per program loop such that the mirroring of the user's hand is accurate to under $1\,\mathrm{cm}$. The scale of the robot's movements can also be changed to fit smaller or larger task spaces. The latency from motion sensing to robotic arm movement is under $5\,\mathrm{ms}$, with the majority of latency occurring in the communication between the central controller and the robot controller in the Lab Streaming Layer (approx. $3\,\mathrm{ms}$). Finally, the thermal stimulator uses closed-loop proportional control to achieve surface temperature stability of $\pm 0.5\,^{\circ}\mathrm{C}$ within the $40\,^{\circ}\mathrm{C}$ to $60\,^{\circ}\mathrm{C}$ range used for the experiment. This allows us to modulate the temperature of the stimulator to the heat-pain tolerance of the participant.

IV. Discussion

A system was built to explore the feasibility of triggering nociceptive withdrawal reflexes (NWR) to prevent harmful events during robotic limb control. The system is designed to allow the testing of five key hypotheses: (i) whether NWR can be used by participants in congruent conditions when controlling a robotic limb, as detected via muscle activation onset time under $150\,\mathrm{ms}$; (ii) whether participants can develop a new NWR in incongruent conditions, thereby decoupling the NWR from the direction of stimulation; (iii) whether NWR events occur less often as the probability of thermal stimulator activation increases due to the expectation of pain; (iv) whether approach kinematics and NWR parameters (EMG activity, robot retraction velocity) are impacted through trials due to adaptation and habituation effects; and finally (v) whether these effects persist in the retention blocks, e.g. with participants moving more cautiously despite a zero probability of pain. The verification of these hypotheses will provide notable results for utilizing pain and the NWR for robotic limb control. Importantly if (ii) and (iv) are verified - i.e. participants can develop a novel NWR pathway in incongruent situations during the duration of the experiment, and that the NWR persists after repeated occurrences although possibly with reduced parameters - these would suggest that pain reflex pathways are a robust neural mechanism to use in robotic limb control systems. Specifically, the location of the induced pain can be modified to suit the particular robot and task, and that pain feedback reduces the probability of future interactions that should be avoided. In summary, the developed system and experiment serve as a platform for evaluating the use of pain as a sensory feedback mechanism for the control of robotic devices.

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