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Learning-Based Touch Detection and Force Estimation in Cutaneous Electrohydraulic Devices

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I. Introduction

Wearable haptic devices enable expressive and engaging communication by delivering rich tactile sensations to the skin, including new contacts, variable pressure, and broad-bandwidth vibrations [1]. Among these, the *start and end of contact* are particularly salient and emotionally engaging, yet this kind of haptic feedback has rarely been used in wearable systems [2]. Our cutaneous electrohydraulic (CUTE) devices (Fig. 1) offer an electrically driven platform capable of rendering a wide range of sensations including contact/no contact feedback, slowly changing pressure, and high-frequency vibrations up to 500 Hz [3]. This new soft actuation approach offers unprecedented control over the tactile sensations that can be presented, with users achieving almost perfect cue recognition and rating almost all sensations as pleasant [3].

While novel haptic actuation systems promise richer haptic feedback, the *consistent delivery of haptic cues* over time and across users remains a challenge in numerous applications ranging from virtual reality to wearable consumer devices. Actuator characterization is often performed in benchtop settings, which cannot account for user-specific variability. As a result, identical control signals often lead to differing perceptual outcomes on the final system worn by the user, diminishing the predictability and utility of haptic feedback. For example, vibrotactile stimuli change systematically with strap tightness, anatomical mounting site, and user body composition [4]. For contact feedback, the instant at which an actuator starts to touch the skin depends not only on the command but also on how it is presently mounted to the user's body.

To provide reliable haptic feedback, CUTE wearable devices would greatly benefit from incorporating real-time estimation of both actuator-skin contact and the force applied to the skin. Measuring contact would enable closed-loop control over actuation timing and intensity and would also allow for dynamic adaptation to individual users, detection of poor device fit, and adjustment of haptic feedback to maintain perceptual consistency. The capacitance of electrohydraulic actuators has been used to estimate actuator displacement [5]; however, capacitance measurements are not sufficient to directly predict forces in a broad-bandwidth wearable haptic device due to the multi-variable nature of the force-displacement behavior in soft devices, which can depend on the mounting conditions, skin mechanics, and the actuator's non-linear dynamics.

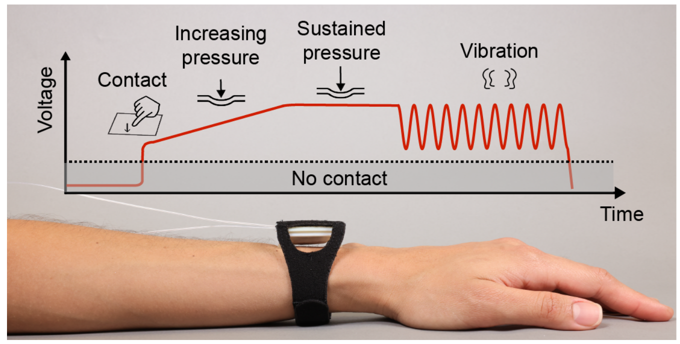

Fig. 1. Contact state in a CUTE device across different actuation voltages.

In this work, we present a learning-based framework for real-time contact detection and force estimation in soft cutaneous electrohydraulic actuators. Two neural networks were trained to predict either binary contact states or continuous force values using input voltage and historical actuator capacitance under different actuator mounting conditions. Our results demonstrate reliable contact detection and promising force estimation, supporting the feasibility of this approach for future real-time implementation in wearable haptics.

II. Materials and Methods

A. Data Collection and Processing

To develop and evaluate our learning-based framework for contact detection and force estimation, we collected a dataset comprising input voltage, actuator capacitance, and corresponding normal force measurements against a rigid surface. As shown in Fig. 2, a rigid plate was mounted on an ATI Nano17 force sensor, positioned at a variable height d above the actuator. We recorded six custom haptic cues (Fig. 3) lasting 5 s each, under four different mounting distances d (9.7–12.7 mm) to simulate a range of contact conditions. This process yielded a dataset of 24 unique trials representing diverse actuating signals and mounting configurations.

The time-varying actuator capacitance was computed across each recording by analyzing the magnitude change and phase shift between an imperceptible 1000 Hz sinusoidal AC voltage signal (50 V peak-to-peak) superimposed on the 6 kV actuating signal and the current measured across a shunt resistor, following the method described by Acome et al. [5].

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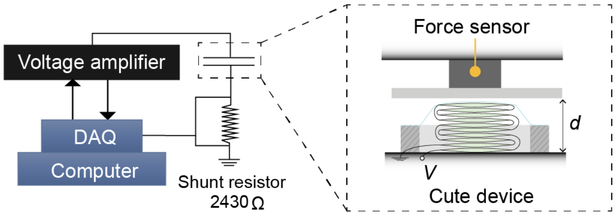

Fig. 2. Experimental setup for data collection.

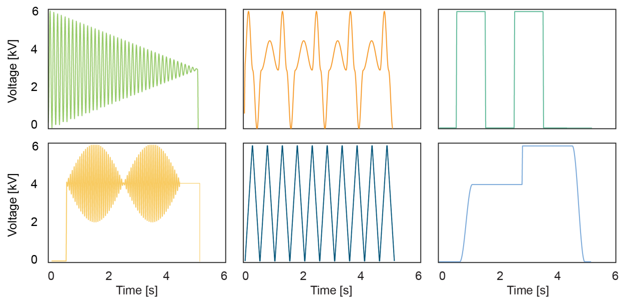

Fig. 3. Voltage signals for the six haptic cues in the dataset.

B. Model Architecture and Training

Two lightweight feedforward neural networks were implemented to perform either binary contact classification or continuous force regression, respectively, at a sampling rate of 10 Hz. Each neural network receives a five-dimensional input vector consisting of the present input voltage and four historical capacitance measurements to capture temporal actuator dynamics based on the most recent 400 ms time window. The classification model comprises a fully connected hidden layer with three neurons and a $\tanh$ activation function, followed by a two-neuron softmax output for binary prediction of the contact/no contact state. Similarly, the regression network includes a single fully connected hidden layer with three neurons and a $\tanh$ activation function, followed by a single-neuron output layer to produce a continuous estimate of the contact force. We intentionally used minimal network complexity to reduce the risk of overfitting on our relatively small dataset and to support future deployment in real time on resource-constrained hardware.

The dataset was split into training (75%), validation (12.5%), and test (12.5%) sets, ensuring no overlap of trials across splits. For contact labeling, we used a threshold of 0.02 N to define ground-truth contact events. A decision threshold of 0.45 was selected for the classifier based on the peak F1-score on the validation set.

III. Results

As shown in Fig. 4, the binary classifier achieved 95.6% accuracy in identifying ground-truth contact events and 99.0% accuracy in detecting non-contact states. These results demonstrate the capacity of our approach to provide good generalization across variations in mounting height and haptic signals that emulate inter-user variability in wearable settings.

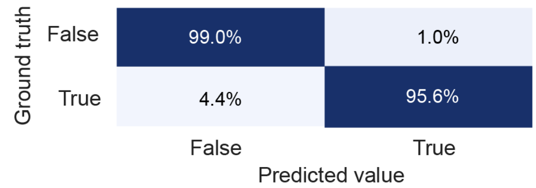

Fig. 4. Confusion matrix for contact classification.

For contact force estimation, the regression model achieved a root mean squared error (RMSE) of 0.26 N across contact events. This RMSE corresponds to approximately 13% of the maximum measured forces in the dataset, demonstrating the potential of this method for real-time force estimation in wearable soft electrohydraulic devices and highlighting its ability to generalize effectively to unseen data. The supplementary video shows force prediction during application of successively larger voltage pulses to a device on a human wrist; the model correctly estimates non-zero contact force at the time where skin contact is visibly apparent.

IV. Conclusions and Future Work

This work demonstrates that the skin contact and normal force rendered by a soft wearable haptic devices can be estimated using input voltage and a time window of actuator capacitance measurements. The framework achieves robust contact detection performance despite the inherent nonlinear behavior of CUTE devices and the variability in actuator mounting conditions and haptic cues. Reliable classification of contact events marks an important step toward personalized, adaptive haptic feedback and supports further exploration of generalized contact/no-contact feedback across users.

Future work will extend the proposed framework to interactions with deformable, skin-like substrates that replicate the diverse mechanical properties of human tissue. We also plan to significantly expand the dataset in both scale and variability, enable real-time inference, investigate alternative machine-learning architectures, improve the accuracy of force estimation, and quantitatively validate the predicted contact forces across multiple users.

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