Supplementary Information

Supplementary Note. S1: Microchannel processing and material selection

To avoid a large amount of energy being absorbed by the PDMS in the propagation path of the acoustic wave, as shown in Fig.2(b), a 20 μm thick rigid PDMS film was used as the bottom structure of the channel in this experiment. The microchannels and bottom film were bonded using a plasma bonding apparatus, and subsequently placed on a heating plate at 130°C to enhance the bond strength. The microchannels and the SAW device are processed independently. The microchannel was positioned directly on the lithium niobate substrate, ensuring that the neck structure was aligned with the focal point of the F-IDT. This configuration allows an effective combination of surface acoustic waves and the fluid within the microchannel, thereby enhancing the reusability of the piezoelectric substrate.

Supplementary Note. S2: Experimental equipment and data processing

A sinusoidal electrical signal generated by a signal generator (N9310A, USA) was amplified by a power amplifier (BSA0125-25, Germany) and transmitted to F-IDT to form surface acoustic wave. A high-speed video camera (VW-9000, Denmark) was employed in this experiment to observe the interfacial evolution behaviour. The length of the microdroplets was measured during the data analysis using the ImageJ software. The length of the droplets was measured across a range that included the central bright zone and the liquid film region. The average length of the droplets was determined by measuring at least 20 droplets for each condition.

Supplementary Note. S3: Hydrogel material selection and preparation

Gelation of PVA solutions was achieved using borax solutions and a freeze cycle process. Prepare a 20wt% PVA aqueous solution by boiling 2g PVA powder with 8mL deionized water at high temperature. Subsequently, use a vacuum chamber (-0.8 bar) to further remove bubbles from the solution. As show in Fig.3, Borax solution was prepared by mixing borax powder with deionised water in mass ratios of 1:100, 1:50 and 3:100. Before depositing the liquid metal droplet-PVA mixture solution into the mold, to prevent the liquid metal droplets from leaking by gravity, a 100 μm-thick layer of PVA solution is deposited into the mold and sprayed with 0.1 ml of 2 wt% borax

solution, and after the thin layer of PVA is gelatinised, the prepared liquid metal droplets encapsulated with PVA are deposited onto it. In this study, a plastic catheter is used to connect the channel outlet to deposit the PVA-coated liquid metal droplets into the mold. The catheter sweeps all areas in the mold in an S-shaped trajectory during the deposition process. The alignment density of the liquid metal droplets was continuously increased by the multilayer deposition method until the microdroplets were uniformly arranged by spontaneous assembly, place the mold in a vacuum chamber (-0.8Bar) for 30 minutes to remove any bubbles from the solution. And then 0.1 ml of a 2 wt% borax solution was sprayed into the mold. To enhance the mechanical characteristics of the hydrogel, the deposited hydrogel solution transferred to a -40°C environment for 12 hours. It was then returned to a room temperature environment for 12 hours to thaw. This process resulted in the formation of a double crosslinked network in the PVA material after two rounds of freeze-thaw cycles.

Supplementary Note. S4: Conductive Hydrogel Performance Testing

Tensile testing of the hydrogels was conducted at room temperature using a universal testing machine (HLD-1-SF-50, China) and a 50 N transducer. The hydrogel molds were shaped into a bone-like structure, with a width of 4 mm in the central section. The dimensions of the specimen were 4 mm in width, 25.0 mm in length, and 2 mm in thickness. The hydrogels were secured in the central position of the testing apparatus, and the hydrogels were subjected to tensile strain at a rate of 10 mm/min. The hydrogels were thawed and soaked in deionized water for 24 hours before testing. The tensile strain ε was calculated using the following formula: $\varepsilon = (l - l_0)/l_0$. Where l is the tensile length of the hydrogel and l_0 is the initial length of the hydrogel. The tensile stress was calculated as follows: $\sigma = F/A_0$. where F is the loading force and A_0 is the original cross-sectional area of the sample.

The hydrogel was fixed on a uniaxial stretching fixture and the hydrogel was connected to the wire using liquid metal microdroplets. A digital multimeter (DT-9205A+, China) was used to measure the resistance of the hydrogel and output electrical data. The tested hydrogels had the same dimensions as in the mechanical tests. Conductivity was calculated according to the formula $L/(RA_0)$, where L is the distance between electrodes, and R and A_0 are the resistance and cross-sectional area of the hydrogel, respectively.

The ECG monitoring module used for ECG testing, ADS1292R module collected the bioelectrical signals, which were amplified and filtered to the STM32F103C8T6 core board, and subsequently transferred to the computer side via the USB to TTL HW-597 module. The prepared conductive hydrogel was attached to the right wrist (positive electrode), the left wrist (negative electrode) and the right abdomen (reference electrode) using medical tape, and the test signals were processed and visualised by the serialplot-0.12.0-win32 software. The EMG detection module utilised the dual-channel EMG signal collector (INA128), the USB to TTL HW-597 module and the STM32F103C8T6 core board. Conductive hydrogel was attached to three locations on the inner forearm (positive and negative) and wrist (reference electrode) of the left hand using medical tape. The collected data were visualised on the computer side by serialplot-0.12.0-win32 software. The volunteer for the human experiment was first author Siyu Zhao.

Supplementary Note. S5: Numerical simulation of grids and reliability verification

（1）Grid Independence Verification

The channel structure was subdivided into four grid models, each comprising a different quantity of grids, to verify the independence of the computational grids. A flow ratio of $Q_d/Q_c = 0.5$ was selected for the calculation, with the corresponding flow rates of the continuous phase set at 20 μl/min and 10 μl/min. The grid convergence relationships of the microdroplet length size (l_d) with the number of grid cells for the four grid quantities are presented in Table S1. The maximum errors of the simulation results under different grid volumes are presented, with the horizontal cross-section microdroplet length used as a benchmark for comparison. Upon reaching a grid volume of 12.9 thousand, the error accuracy meets the requisite standards. Therefore, the grid volume selected in this chapter is 12.9 thousand grids.

Tab. S1 Grid independence verification

Maximum error	Experiment	28.3 thousand	12.9 thousand	7.2 thousand
Droplet length (μm)	200.01	203.5	195.7	185.5
Error	/	1.74%	2.15%	7.25%

（2）Model Reliability Verification

In this section, the reliability of the simulation results is verified by comparing the experimental and numerical simulation results under the same flow conditions. We selected two groups of working conditions with flow ratio α = 0.5 and α = 0.75 for experimental analysis, as shown in Table S2. The microdroplet length errors of the experiment and simulation under the two groups of working conditions are within 5%, which meet the error requirements.

Tab. S2 Simulation and experimental results of droplet length under different flow rates

Q_d/Q_c	Experimental length	Simulation length	error
0.5	200.01	195.7	2.15%
0.25	144.82	140.8	2.78%

Supplementary Fig. S1: Verification of droplet size fitting formula
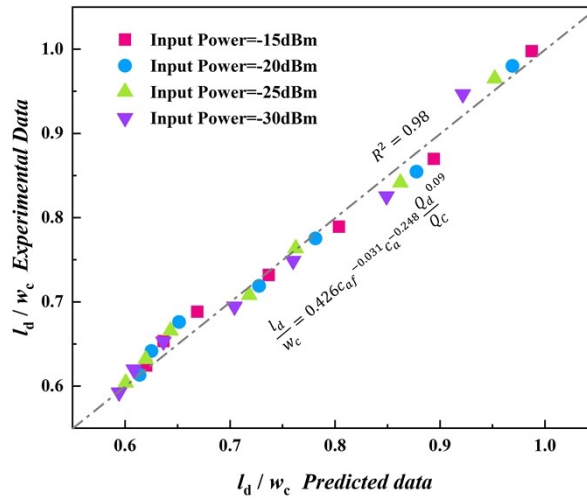

Fig. S1 Comparison between experiment and prediction data of liquid metal droplet size