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A Wearable Auricular Laser Acupuncture Device with IoT Sensors for Personalized Wellness Enhancement

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***Abstract*— Laser acupuncture has long been regarded as an effective and minimally intrusive practice for regulating body dysfunctions. However, there are critical gaps, notably unwearable devices and difficulty in acupoint localization without professional guidance, that impede the ability to introduce laser acupuncture therapy pervasively into telemedicine scenarios. This paper proposed a prototype wearable cyber-physical system for auricular laser acupuncture therapy that enables real-time, quantitative evaluation of treatment effectiveness. This paper also presents background research on laser acupuncture and a literature review of the most commonly used laser parameters for laser acupuncture. IoT sensors are also utilized for the real-time monitoring of physiological signals and feedback control during the telemedicine process of laser acupuncture therapy. The objective data collected by sensors along with subjective survey data are critical to assess the treatment effectiveness and provide crucial insights for personalizing the most effective laser parameters. The proposed wearable system has the potential to overcome gaps in current laser acupuncture practice and improve the customization of effective therapy in telemedicine settings.**

***Index Terms*— wearable, laser acupuncture, IoT sensors, telemedicine, cyber-physical system, machine learning**

I. INTRODUCTION

Acupuncture is among the oldest healing practices in the world, and has been progressively gaining credibility as primary or adjuvant therapy in modern medical theory. Traditional acupuncture involves the insertion of metal filiform needles into the skin to stimulate specific points, known as acupuncture points or acupoints [1], while electroacupuncture involves passing electric currents between needles. More recently, acupuncture practitioners have begun to use non-thermal, low-intensity laser irradiation to stimulate the acupuncture points used in conventional acupuncture practice, known as laser acupuncture [2], illustrated in Fig 1. Evidence was found to support the use of laser acupuncture in the treatment of various medical conditions such as hypertension [3], musculoskeletal pain [4], obesity [5], dental anxiety [6], etc. Laser acupuncture is advantageous because it is non-invasive, painless, sterile, and also generally requires a short amount of time to conduct.

Comparing stimulating acupoints on the body area, auricular acupuncture refers to treatment based on the acupoints located on the external ear area or auricular area for normalizing the body's dysfunction including pain relief [7]. Gaining knowledge from the long history of experiences since ancient times, Chinese acupuncturists have long held that

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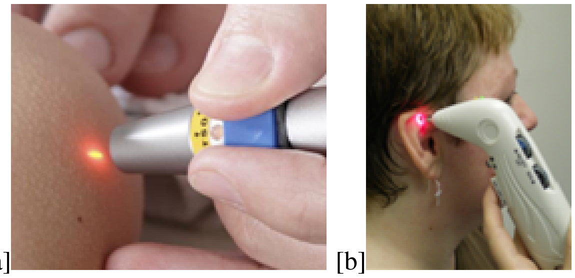
[a]  [b]

Fig. 1. a. Laser acupuncture on the body with a hand-held device [8]; b. Laser acupuncture on the auricular area with a hand-held device [9].

a functional relationship exists between auricular acupoints and corresponding body points. It was reported that when stimulating the auricle, a cascade of neural signals travels through sympathetic and parasympathetic nerve fibers from the ear to the brain and from the brain through the spinal cord to specific areas in the body [10]. This discovery highlights one of the fundamental mechanisms in the theory of auricular acupuncture. In short, it is believed in both Chinese and Western medicine that the microsystem of the ear is the projection of the whole body in its function and structure on certain parts of the body. Auricular laser acupuncture, illustrated in Fig 1.b., which refers to the stimulation of auricular acupoints with low-intensity, non-thermal laser irradiation, is consequently a promising approach to enhancing personal wellness.

Even though laser acupuncture has been regarded as an effective practice in regulating body dysfunction and appreciated for its noninvasive nature, gaps and questions are still far from being resolved, even recognized. Lack of agreement or established protocol regarding optimal acupuncture treatment is one of the most significant issues in studies of this field [11]. Although some common practices are well accepted in this field about what laser parameters or dosage should be used, most of them lack robust scientific evidence to prove the optimal operating conditions to be followed. From the research perspective, the customized nature of the acupuncture process also impedes the comparison between studies with all kinds of variables, including the acupuncture points selection, duration of treatment, and effectiveness interpretation. The variation in laser parameters used, coupled with disparity in outcome interpretation for optimal therapy, has led to contradictory conclusions and inconsistent reports of clinical effectiveness. Moreover, physicians need to be trained for years to precisely locate acupuncture points. For this reason, even with a laser acupuncture device, rendering laser acupuncture therapy outside of clinical settings is inaccessible to untrained individuals.

There are different types of laser devices available in the market or clinic setting for laser acupuncture therapy. One type is the handheld "laserpen", as shown in Fig 2.a., which requires the therapy provider to steadily point the beam onto the specific acupoints one by one during the treatment [12]. Another type of instrument, called "laserneedle" depicted in Fig 2.b., is brought in contact with the skin and can be fixed in place using stickers [13]. The laser light is then delivered through a long fiber from the instrument to the skin. While the fixed "laserneedle" approach eliminates the need for hand-holding, it can make it difficult to discern the placebo effect in clinical practice.

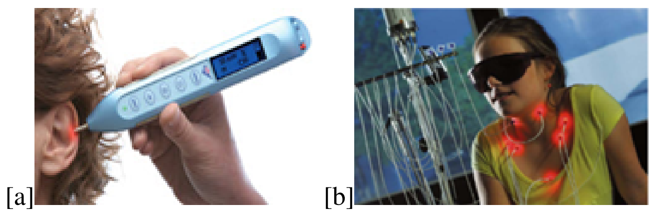


Fig. 2. a. Laserpen from 3B Scientific [12]; b. Laserneedle from 3B Scientific, Germany [13].

Unlike existing laser acupuncture devices, our proposed solution is innovatively designed to accommodate multiple laser beams irradiating simultaneously and directly onto the skin, which could improve treatment outcomes and contribute to investigating the placebo effect in clinical practice.

The objective of this paper is to introduce a novel wearable auricular laser acupuncture device that leverages IoT sensors and actuators. Additionally, our device incorporates real-time feedback control through physiological sensors throughout the treatment duration. Overall, our wearable device represents an exciting advancement in the field of laser acupuncture, offering a potentially more effective and personalized treatment option for patients.

This paper is organized in the following. Section Two will present a literature review on the laser parameters used in previous laser acupuncture studies, while Section Three will provide a detailed description of our prototype wearable device and how our device will incorporate real-time feedback control through IoT sensors. Future work to improve this wearable platform will be discussed in Section Four.

II. Literature Review on Laser Acupuncture Studies

With the variation of laser parameters in previous studies, a crucial question emerges: what constitutes the optimal laser parameters for therapeutic use? To address this research question, a systematic review of laser acupuncture literature was first conducted to discern the relationship between the therapy variables and the study's effectiveness. Such knowledge also benefits the design of our wearable device. In this regard, we examined 618 papers sourced from PubMed, Web Science, and Google Scholar databases. After screening titles and abstracts, we narrowed the pool of relevant papers down to 113. Of these targeted studies, only 67 employed a random controlled methodology, which is significant to eliminate the placebo effect of acupuncture therapy.

The majority of these studies evaluated their study reliability by reporting the statistical significance between the intervention and control groups. Even though not completely precise to simply evaluate the clinical effectiveness by statistical significance, it is found that most of these studies used pre-therapy and post-therapy assessment variation compared between groups as the main outcome of the study. The calculated p-value, derived from t-test or ANOVA, rejected the null hypothesis of no difference between the control and the laser acupuncture intervention group [14]. Consequently, smaller p-values imply greater reliability of the difference between the groups.

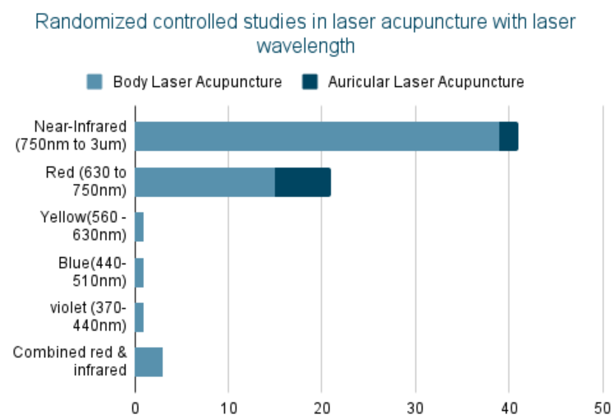


Fig. 3. The numbers of randomized controlled studies fill in each laser wavelength range.

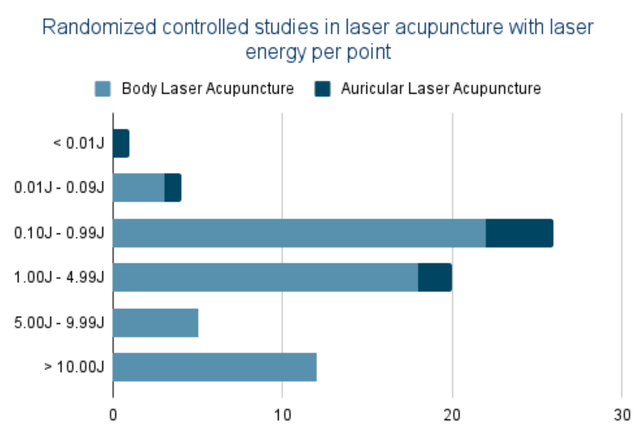


Fig. 4. The numbers of randomized controlled studies fill in each laser dosage range.

In this review, we focus on two key laser parameters: wavelength and dosage per acupoint, which is the energy delivered per acupoint. As shown in Fig 3, the wavelength of the majority of lasers falls within the near-infrared or red wavelength range. Fig 4 suggests that the most commonly used laser dosage should range from 0.1J to 4.99J in reviewed laser acupuncture studies. When comparing study effectiveness using p-value as a metric, we find that studies with laser dosages between 1J and 4.99J are more likely to be statistically significant than those with dosages between 0.1J and 0.99J as depicted in Fig. 5.

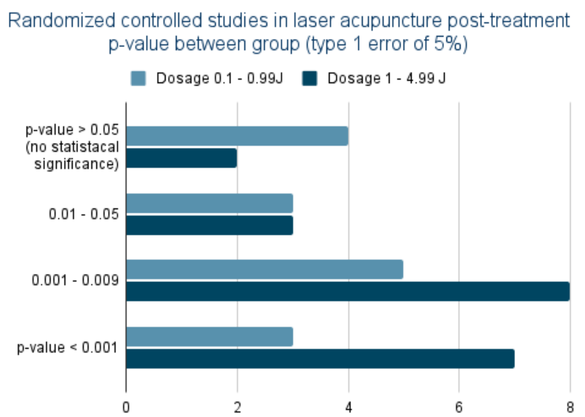


Fig. 5. The numbers of studies distributed in different statistical significance (p-value) compared between studies with laser dosage 0.1J - 0.99J and laser dosage 1J - 4.99J.

Based on these findings, our prototype device utilized lasers with near-infrared wavelength and dosage per point of 1J to 4.99J. By tuning these laser operating parameters and gathering data on the effectiveness of laser acupuncture, we can analyze the optimal laser treatment recipe to help customize the treatment plan for irradiating certain groups of acupoints.

III. PROPOSED DEVICE

As mentioned above, in this paper, we propose a wearable device designed for auricular laser acupuncture therapy, which accommodates multiple laser beams irradiating simultaneously and directly to the ears.

A. Auricular Laser Therapy Delivery Platform

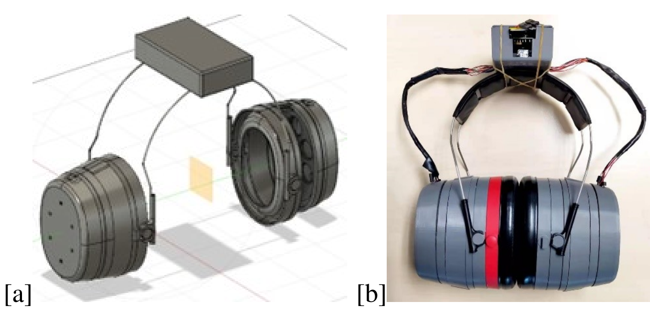


Fig. 6. a. The proposed device profile with the shape of a headset; b. photo of the prototype device developed.

The proposed wearable is designed to be like a headset instead of being held all over the body. This wearable form factor, shown in Fig 6., makes laser acupuncture therapy more convenient to conduct. While all the lasers and laser drivers are embedded in each side of earmuffs, circuitry and power supply are settled in the box at the top of the headset.

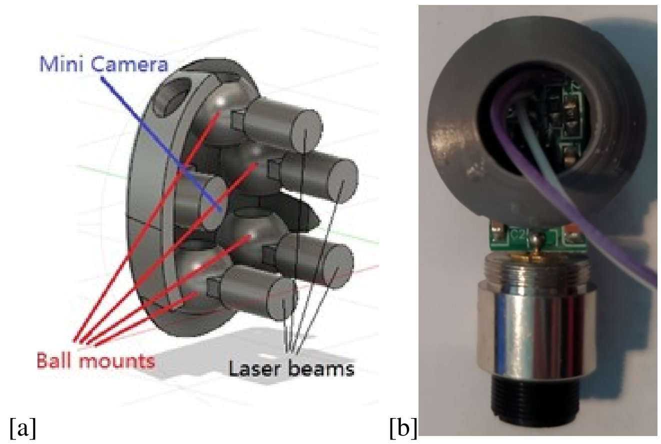


Fig. 7. a. The internal structure of the proposed device earmuff; b. A ball mount that can be steered for laser beam direction.

Each laser header can be individually directed onto one acupoint. In this prototype, we have incorporated six lasers in total (three beams on each side of the ears), whose output power can also be individually controlled via graphic user interface software. Each laser is installed in a ball mount that can be steered to position the laser beam onto the desired acupoints, as shown in Fig. 7.b.

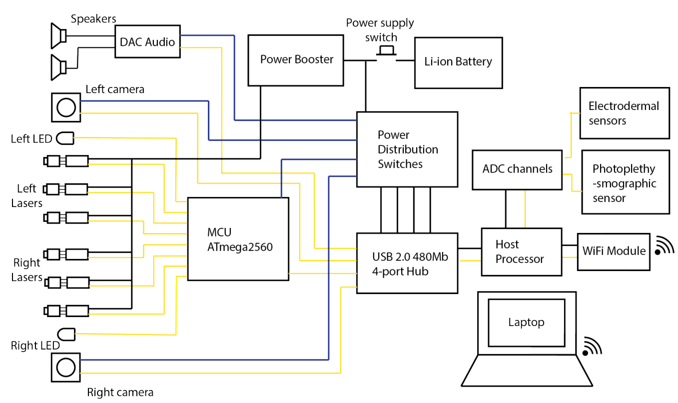


Fig. 8. System blocks of the proposed wearable device.

The system block diagram of the proposed device is illustrated in Fig 8. The main functional modules of the system include laser power control and data communication.

Laser power control is achieved by transmitting Pulse Width Modulation (PWM) signals to the laser driver. To implement this PWM control in a compact wearable space, Reduced Instruction Set Computer (RISC)-based Microcontroller Unit (MCU) and corresponding programming interface are integrated into a custom-designed Printed Circuit Board (PCB). Lightning LED and cameras are used to ease the practice of laser acupuncture.

For the purpose of remote administration, camera threads and control data are relayed through an onboard hub to a dedicated graphical user interface software. To minimize circuitry size, the communication hub, power switch, and overcurrent protection are all integrated into the custom-designed PCB. Speakers are included to provide an immersive and comprehensive experience to the user. An audio interface is also integrated into the PCB. As such, each earmuff houses laser headers, lightning LEDs, cameras, and speakers, all of which are controllable via the custom circuitry.

Additionally, to evaluate the treatment effectiveness in real-time, we facilitate the collection of physiological data through ADC channels and specific sensors, including photoplethysmographic and electrodermal sensors. The photoplethysmographic sensor is deployed to collect pulse wave data, as well as to do blood pressure monitoring, which will be discussed in the next section. The electrodermal sensor, on the other hand, is utilized to record sweating conditions, contributing to the comprehensive suite of collected physiological signals.

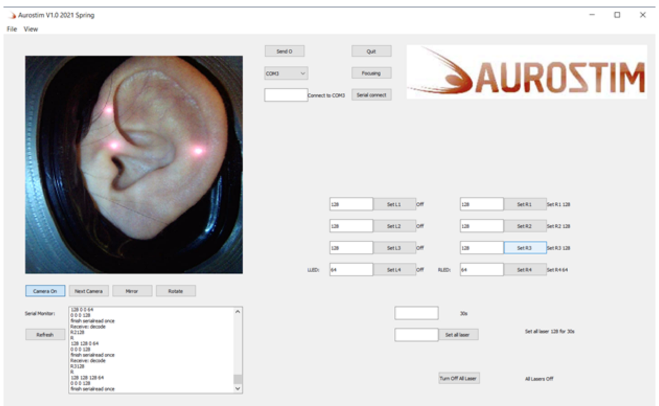


Fig. 9. Dedicated software for camera threads, lightning, and laser power output control.

We named our first prototype "Aurostim" with dedicated graphical user interface software to give full control of the device, as shown in Fig. 9. Threads from each camera can be present under this software to monitor the status of the lasers. Additionally, it features an integrated timer to regulate treatment duration, facilitating an automated control of the treatment process. For added safety, we have incorporated a phototransistor module designed to detect surrounding light and automatically switch off all lasers in the event of device removal by the user.

For a preliminary test, we configured each continuous-wave laser to output at 5 mW, irradiating auricular acupuncture points for 5 minutes at a wavelength of 780 nm. For the sake of simplicity, we overlooked the Gaussian property of the laser beam, the lens, and optical geometry, and assumed to have a 100% reflection percentage with no scatter. The energy irradiated per point was calculated as 5 milliWatts × 300sec equating to 1.5 Joules, which falls in the preferred range of 1J - 4.99J. The status of the lasers irradiating each ear was monitored via embedded cameras throughout the laser acupuncture therapy, with captured images displayed in Fig. 10. It should be noted that the bright spots in Fig.

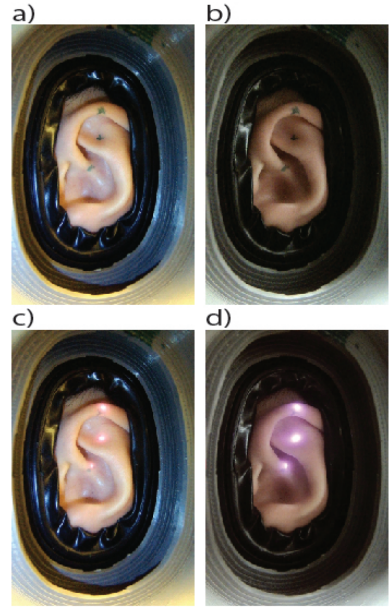


Fig. 10. Ear images captured through the embedded cameras during the therapy: a) with LED on and lasers off; b) with LED and lasers off; c) with LED and lasers on; d) with LED off and lasers on.

10, induced by light reflection from laser irradiation, can be moved by clinic practitioners to adjust laser positions for mapping into acupoints. Since the device is equipped with WiFi connectivity feature, remote administration of the treatment by an expert using our device can be easily achievable, thereby lowering the deployment barriers typically associated with conventional laser acupuncture solutions.

B. Physiological Signals Processing

While acupuncturists still need to prescribe acupoint selection and customization of laser dosage based on various medical conditions at this stage, the subsequent incremental accumulation of effectiveness data and physiological signals will facilitate the determination of optimal treatment variables. This can be achieved with the assistance of machine learning applied to the data collected through this system. To enable real-time monitoring and quantitative assessment of the device's effectiveness, the integration of machine learning algorithms and proper sensor solutions are needed.

Existing studies have demonstrated the potential of auricular acupuncture in mitigating anxiety levels among a population of healthy volunteers [15] and within preoperative settings [16]. Postoperative pain, which has been observed to have a strong correlation with preoperative anxiety [17], is also a condition that can be regulated with laser acupuncture. Since these medical conditions exhibit bi-directional interactions with the autonomic nervous system (ANS) [18], objective physiologic signals, such as Heart Rate (HR), Heart Rate Variability (HRV), Arterial Blood Pressure (ABP), can be served as indicators of therapy effectiveness [19].

Photoplethysmography (PPG), as one of the most affordable optical sensors, is often employed in health monitoring [20]. This non-invasive technology utilizes a light source and a photodetector at the surface of the skin to measure

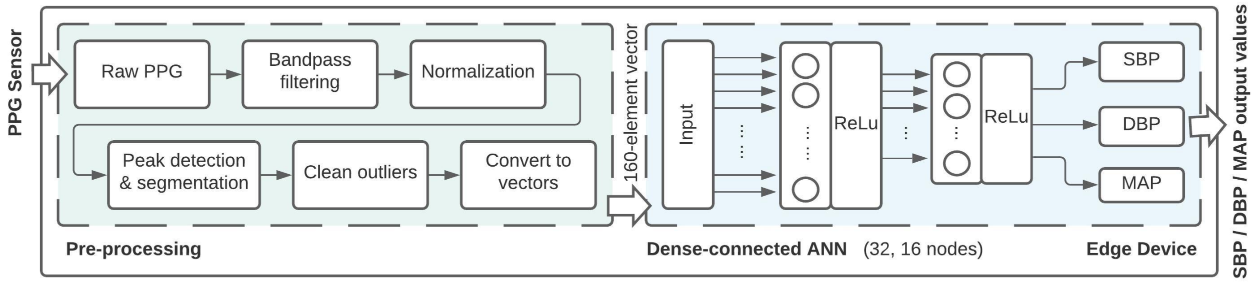


Fig. 11. Previously proposed energy-efficient blood pressure monitoring solution on edge device by authors [21].

the volumetric variations of blood circulation. State-of-art algorithms have been emerging for ABP [21] and HR/HRV [22] estimated based on PPG signal. Electrodermal activity (EDA), also known as Galvanic Skin Response, is a measure of change in skin conductance resulting from sweat gland activity, thereby providing reliable and valid assessment of anxiety or pain [23]. The recording of EDA is facilitated by using two leads connected to the circuitry, typically applied on the index and middle finger of the non-dominant hand.

With these considerations in mind, our aim was to continuously collect and process HR/HRV, BP and EDA signals using our device. Although the previous study on auricular acupuncture for anxiety found no significant differences in intermitter HR, BP, and EDA values between the sham group and the intervention group [24], the lack of correlation between psychological and physiologic responses in that study may be attributed to the method of obtaining the physiological data (single measurement per point vs. continuous monitoring throughout the study period).

Collecting all these signals would consume a significant amount of energy if all of them were transmitted to the server through the wireless module. Therefore, with the advent of powerful cyber-physical systems, data processing can be done closer to where the data originates, known as edge computing, which has become an increasingly viable option [25].

We previously proposed an energy-efficient solution for continuous and non-invasive Blood Pressure Monitoring (BPM) based on single-site PPG signal with edge computing. This real-time solution implements an artificial neural network with edge computation, and the general algorithm dataflow is depicted in Fig. 11 [26]. Intra-patient experiments were conducted on a platform equipped with an ARM Cortex-M3. The resulting performance satisfies the AAMI criteria and is competitive compared to other studies. Evaluation experiments show that this solution takes an average of 42.2 ms, 18.2 KB, and 2.1 mJ energy per reading. It is clear that this data processing strategy is faster, energy efficient, and can be applied to data processing for other sensors.

IV. FUTURE WORK

Currently, a clinical feasibility study of the proposed device is ongoing in collaboration with physicians from Orange County Children's Hospital to evaluate its effectiveness in alleviating anxiety. The study involves pre- and post-treatment anxiety surveys as well as monitoring of physiological conditions throughout the course of treatment. Future efforts will aim to assess the effectiveness of laser acupuncture by employing quantifiable biomarkers, thereby establishing a direct correlation between these biomarkers and the treatment effectiveness.

With real-time communication, telemedicine enables physicians to remotely provide prescriptions and monitor treatments. Our proposed wearable platform takes advantage of wireless communication to make laser acupuncture accessible for day-to-day use. That's to say, with the prescribed laser dosage and acupoints from an acupuncturist, solutions associated with this wearable system would provide quantitative control on the auricular laser acupuncture therapy. To transition the proposed device from its current state into a practical, widely-adopted wellness tool, future developments for this system will be threefold:

1) The development of machine learning algorithms to assist in the localization of acupuncture points, complemented by the creation of cloud-to-edge computing resources to facilitate this process.
2) Large-scale data analysis to tailor the most effective laser parameters for individual cases, utilizing objective data collected by sensors, subjective feedback data, and users' medical histories.
3) The hardware development for electronic-controlled laser steering mechanisms that ease the alignment of lasers with acupoints. A closed-loop laser-focusing approach with feedback control on acupoints will facilitate hands-free alignment, making the proposed device a practical, wearable wellness tool for widespread use.

V. CONCLUSIONS

This paper proposes a prototype wearable cyber-physical system for auricular laser acupuncture therapy that allows for a quantitative assessment of its real-time effectiveness.

The major contributions of this paper:

- The paper provides a literature review of the most commonly used laser parameters for laser acupuncture practice.

- We introduce a proposed wearable platform that incorporates dedicated hardware and software that deliver controlled laser content to the user's ear, with edge computing of IoT sensor signals to collect real-time physiological feedback.
- The paper outlines future research aimed to utilize the proposed wearable infrastructure to automate and customize auricular laser acupuncture therapy for widespread usage.

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