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Feet-Beat: A Wearable device using FITS

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Abstract—The Human feet have long been thought to be closelyrelated to overall body health, from which a wealth of cardiovascular and skeleto-muscular data can be gleaned. With the help of this study, Feet-Beat is the first wearable foot-based device capable of detecting both pedal pulses and muscular activity. A five-unit sensing array has been built and characterized using the flexible iontronic sensing (FITS) technology in order to monitor both pedal pulse signals and muscle actions. It is built into the tongue of a running shoe to capture signals instantly.

The linear array also enables alignment-free pulse signal collection and offers a spatial reference for muscular activity. For individual units, an ultrahigh sensitivity of up to 1 nF/mmHghas been attained with a range of 1 to 200 mmHg. The heart rate (HR) and respiratory rate (RR) from the pedal pulse waveforms have been determined, and the pulse-derived HR is compared with the electrocardiogram (ECG). Additionally,distinct pedal movements have been analyzed using individual tendon responses, from which multichannel signals can be usedto separate various activities.

Index Terms—Muscular activity, Sensing array, Flexible ion- tronic sensing (FITS), Pulse signal collection

I. INTRODUCTION

Through the development of wearable interfaces, a number of physiological signals, in- including blood volume fluctuations, blood oxygen levels, electrocardiogram (ECG), elec- troencephalogram (EEG), and respiration, have been success- fully acquired and evaluated. The wearable gadget has a hurdlein locating the best bodily part to house a long-term attach- ment. Research on this issue has been ongoing for the pastfew years in both the industry and academia, focusing on the entire human body (such as the head, chest, upper arm, wrist, waist, fingers, and feet). Typically, indications such as blood volume fluctuations and accelerations have been recorded fromthe wrist. However, there are still drawbacks. Poor long- term wearability in particular is the main obstacle preventing wearable technology from becoming extensively used. It may be difficult to form a long-term bond because of the hard, constrictive, or painful design and materials employed in thosewearing gadgets. Despite being thought of as the best areafor wearable technology to be placed, human feet, pediatric pulse oximetry monitoring in clinical settings and activity tracking are all that are currently being addressed by available technologies. Accelerometers with embedded microchips have been incorporated into shoes or attached as shoe clips to recordsteps taken while exercising or to recognize kinematic changes in gait cycles [1]. In addition, to the body informationassessedby existing devices as previously stated, the human the foot contains an abundant amount of musculature, strong tendons and muscles, and distinctive bone structures from which valuable health information and muscular activities can becontinuously collected and precisely extracted. FeetBeat is foot-based wearable technology, which can track both muscle activity and pedal pulse impulses. The FeetBeat array, which has the highest documented pressure-to-capacitance sensitivity,was integrated with flexible iontronic sensing (FITS) sensors into the tongue of a sports shoe. Due to the extremely high interfacial capacitance and quick polarization of the iontronic materials, the FITS principle has demonstrated its advantages in pressure sensing with high sensitivity, great mechanicaltoughness, and consistent flexibility [2].

A solid-state flexible ionic coating in elastic contact with a conductive electrode array makes up the FeetBeat array, which has a detection range of 1 to 200 mmHg and a device sensitiv-ity of up to 1 nF/mmHg. With With such high sensitivity, we can easily track variations of blood pressure correspondence toeach cardiac cycle from a dorsal pedal artery, which isalso known as the pedal pulse waveform, with gentle con-tact around the baseline of20 mmHg. Critical cardiovascular metrics, including upstroke duration and augmentation index, as well as derived vital signs, including heart rate (HR) and respiration rate, have been looked into and studied after the pulse waveform has been acquired. Real-time comparisonsbetween the FeetBeat-derived HR and the conventional A 2- lead electrocardiogram (ECG) has been made. Additionally, the location of the pedal artery serves as a spatial anatomic reference for muscular activity, and the linear array with manysensing units spans the transverse plane on the dorsum, enabling the acquisition of pedal pulse signals without the need for any additional alignment steps[3]. Finally, a highly integrated method for classifying foot gestures, analyzing gait,and tracking body state is provided by recording individual tendon activities at a sufficient resolution to collect muscular re- responses.

II. LITERATURE ANALYSIS

The study of wearable devices has become a popular re-search topic recently, where high-sensitivity, noise-proof sensing mechanisms with long-term wearability play critical roles in a real-world implementation, while the existing mechanical sensing technologies (i.e., resistive, capacitive, or piezoelec- tric) have yet to offer a satisfactory solution to address them all.[3] Here, we successfully introduced a flexible super capacitive sensing modality to all-fabric materials for wearablepressure and force sensing using an elastic ionic-electronic interface. Notably, an electrospun ionic fabric utilizing nanofi-brous structures offers an extraordinarily high pressure-to- capacitance sensitivity (114 nFkPa-1), which is at least 1,000 times higher than any existing capacitive sensors and one orderof magnitude higher than the previously reported ionic devices,with a pressure resolution of 2.4 Pa, achieving high levels of noise immunity and signal stability for wearable applications. In addition, its fabrication process is fully compatible with existing industrial manufacturing and can lead to cost-effectiveproduction for its utility in emerging wearable uses in the foreseeable future. [4]

III. FEETBEAT DEVICE

The human foot includes a dense network of blood vessels and unique bones and muscles. The posterior tibial artery and the dorsal pedis artery are the two principal arterial branches that travel to the foot. Both arteries' pulsations can be directly felt, and they have long served as a reliable gauge of peripheralvascular health in clinics. The dorsum region of the foot, wherethe dorsal pedis artery (ii) and a collection of parallel tendonsI iii, iv, v) are located between the skin and bones, is depicted anatomically in Fig 1. The muscles that give rise to the four primary tendons are specifically (i) tibialis anterior (TA), (iii) extensor hallucis longus (EHL), (iv) extensor digitorum longus(EDLS), and (v)Fibularis tertius (FT). It's important to note that the four tendon branches that join the EDLS are present having four distal toes that converge into one muscle near the heart. The tendons joining them the bones in the foot and the shank are all musculature significant responsibilities inregulating the pedal movements. One or more muscles contractto cause an intended motion. These tendon tissues are induced to contract and assist in pulling the bones with their flexible connections of substantial tensile tensions. This type of tensileforce could result in skin migration parallel to the tightening tendon creating noticeable pressure alterations over the skin.

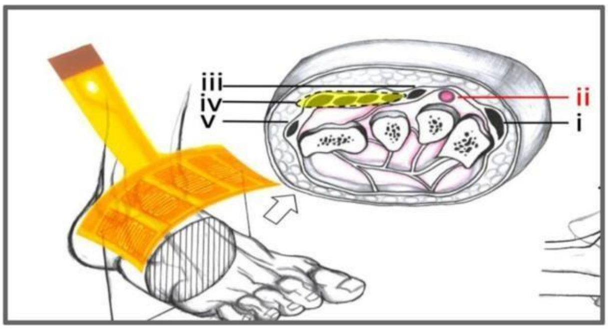

Fig. 1. Illustration of the anatomic structure of the dorsum region in the foot

IV. ARCHITECTURE OF FITS

The device architecture of FITS, which consists of a top sensing member with an ionic coating and a bottom flexible electrode, separated by a spacer layer, is shown in Fig 2 beforeand after a mechanical load is applied. In particular, theflexibleelectrode will deform and make contact with the ioniclayer whenever a mechanical loading (P) is applied. The mu- tual attraction of counter-ions accumulated in a nearby ionic environment and mobile electrons in a conductive solid phase results in the formation of an electric double layer (EDL) at thiscontact. As a result, the FITS device can provide extremelyhighinterfacial capacitance between the flexible electrode andioniclayer [5]. Interfacial capacitance and contact area both

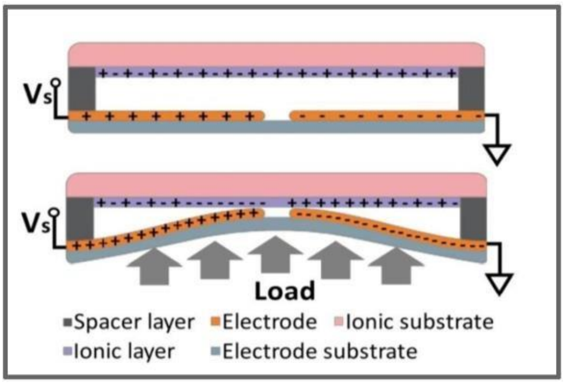

Fig. 2. Illustration of the anatomic structure of the dorsum region in the foot

increase when the external pressure rises, and this may be seenby the readout shown in Fig 3, where CEDEL1 and CEDEL2 are the equal-magnitude interfacial capacitances and Ri is the internal resistive value of the ionic film. The contact areabetween the ionic and electronic surfaces can be calculated using the traditional thin-plate theory and the touch-mode assumption that Ko’s group has validated. These interfacial capacitances are directly proportional to this contact area. Additionally, Cf stands for the fringe capacitance, which inour situation can be negligible and is considerably smallerthan CEDEL1 and CEDEL2, between the adjacent electrode surfaces. circuit.

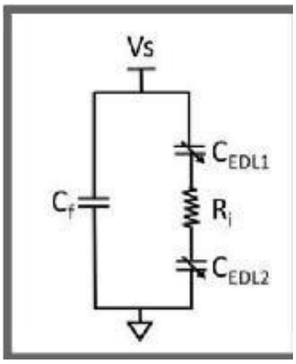

Fig. 3. Equivalent circuit model of the FITS device

The total capacitance (Ct) of FITS device can be expressed as in eqn (1)

$C(EDL1)C(EDL2)$ 1

$C = Cf + \_\_\_\_\_\_ = C(EDL1)$ (1) $-$

$C(EDL1) + C(EDL2)$ 2

$\Gamma\left(^{64D \times h}\right.$

$= \quad 4 \quad P \quad)1 + 0.488^{h^2})^2$ (2) display the signals. Fig 5(b) shows the block diagram of the

$\pi C0(r -$

t^2

V. IONIC SENSOR FABRICATION

The ionic coating plays a central role in determining the unit-area capacitance and the overall device performance. The polymeric matrix polyvinyl alcohol (PVA) and the ionic liquid (1-ethyl-3-methylimidazolium tricyanomethanide, [EMIM][TCM]) are combined to create the ionic layer, which is subsequently cured by a regular solvent evaporation process.In particular, 10 g of distilled water were used to dissolve 0.5g of PVA. This PVA solution was then combined with 0.25 g of [EMIM][TCM] and agitated for two hours at 50 °C. Using acommercial spinner, the solution was applied to the surface of a polyimide film and spun for 30 seconds at 600 rpm to create a homogenous thin-film ionic coating.

The resulting polyimidefilm with the ionic coating was baked on a hot plate at 120 °C for two hours in the open atmosphere. A UV laser wasthen used to trim the coated polyimide film according to the planned arrangement. Fig 4 depicts the sequential process of FITS fabrication [4].

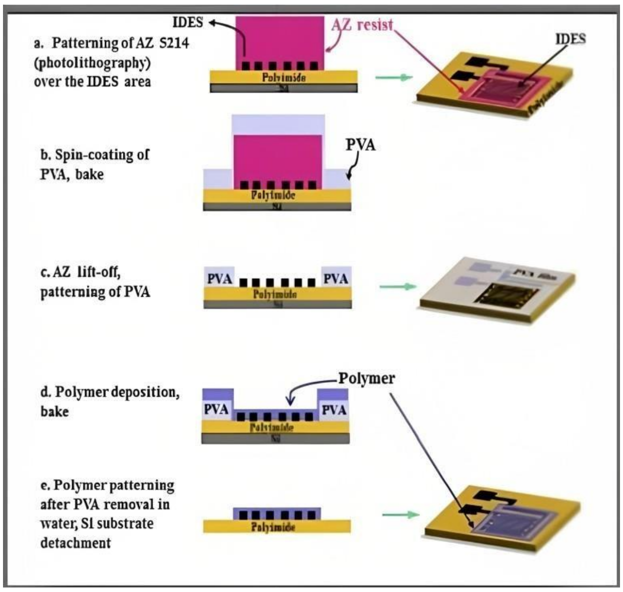

Fig. 4. Sequential process of FITS fabrication

To continuously collect and transmit the signal data fromthe optimized sensing array, a custom circuit was designed andbuilt on a printed circuit board to detect capacitive changes. Fig5(a) shows the FeetBeat sensing array and its customized circuit board. Specifically, the circuit, connecting to the five- unit iontronic pressure sensing array (1), is comprised of an analog front (3) with five low-voltage operational amplifiers (LMV324, Texas Instruments), an 8-bit MCU (4) with ADC component (EFM8, Silicon Labs), a Bluetooth low energymodule (5) (CC2541, Texas Instruments), and the power management module (2) with a standard rechargeable Lithium-ion battery [6]. Moreover, a custom graphic user interface(GUI) was programmed in MATLAB to receive, process, and circuitry and also shows the system integration of FeetBeat in a regular athlete shoe.

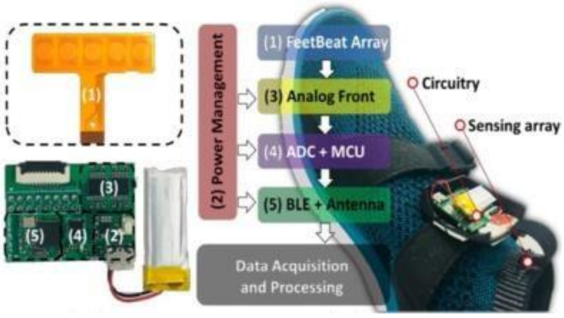

Fig. 5. (a) FeetBeat sensing array and its wireless-enabled circuit board (b) Block diagram of the circuitry and the system integration of FeetBeat in an athletic shoe

The position of the dorsal pedis artery has been located during the process of identifying pedal pulses, and as a result, it can serve as a natural spatial reference to determine the relevant tendon locations, as the anatomic structures among them are relatively fixed for a human subject. Utilizing the measurement unit of the strongest pedal pulses as the spatial reference, several different foot gestures can be identified fromthe rest of the sensing units by differentiating individual tendonmovement patterns, that is, big toe dorsiflexion, bigtoe plantarflexion, foot eversion, and foot inversion. Figure 4.3. represents different tendon activities. These gestures are mainly triggered by the tendons as they intended to measure by the FeetBeat array. As can be seen, for each gesture, there are two phases recorded in the plot, active phase and recovery phase. When the tendons are activated from the initial rest status, FeetBeat can measure the changes of pressure thatpassesthrough skin from five sensing channels. In big toe dorsiflexion, the contraction of EHL tendon causes the big toe to bend up. This contraction also lifts the position of EHL towards the shoe tongue and thus increases pressure received by the specific sensing channel. Moreover, based on pressure values that each channel receives during the active phase, a rule based fuzzy logic table is summarized in Table I. Using this table, each of the four foot gestures can be distinguished. Therefore, the FeetBeat has the potential to be utilized to detect individual tendon responses aspedal gestures. Furthermore, because these tendon movementsand pedal gestures play important roles in determining the bodyactivities, the fuzzy logic can be expanded in future, from which everyday activity tracking can be potentially obtainedin a natural and unnoticeable fashion.

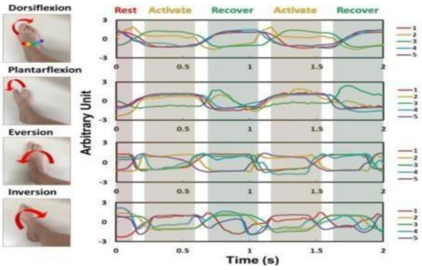

Fig. 6. Tendon activities: pinpoint individual tendons during foot gestures

TABLE I RULE BASE OF FUZZY LOGIC TO DISTINGUISH GESTURE

Foot gesture	1	2	3	4	5
Big toe dorsiflexion	Low	High	High	Low	Low
Big toe plantarflexion	High	High	Low	High	High
Eversion	Low	High	Low	Low	High
Inversion	High	Low	Low	Low	High

Based on the identified muscular movements, they havecurrently divided the pedal status into two states:

(1) The stationary condition, during which vital signs are tracked and analyzed using blood pressure waveforms.

(2) The motion state, during which foot gestures can be retrieved.

To achieve the crucial signal recognition during the motion state, need to incorporate more noise-canceling techniques andalgorithms in the upcoming development.

VI. CONCLUSION

In order to simultaneously collect body vital signals and track pedal skeletomuscular motions, a highly sensitive and flexible pressure-sensing array known as FeetBeat has been created. It has been seamlessly integrated into a shoe format. The FeetBeat device shows how a foot wearable can firstcapture high-definition peripheral artery pulse waveforms, from which both heart rates and respiration patterns may be derived with a level of accuracy comparable to that usedin medicine. Additionally, the sensing array's excellent spatialresolution enables the alignment-free collection of pulse signals and serves as a spatial reference for the pedal structures.Additionally, it allows for the tracking of specific pedal tendonmotions, from which the bulk of foot gestures can beevaluated in real-time.

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