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REVIEW ARTICLE

Application prospects for wearable body surface microfluidic system in sports

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ABSTRACT

The wearable body surface microfluidic system has great application potential in the field of sports. The use of the wearable body surface microfluidic system to monitor the physiological state of athletes can solve problems faced such as long inspection cycle in sports monitoring, difficulties in continuous monitoring, dependence on laboratory platforms, athlete resistance and other problems faced in technological integration to promote the development of the sports field. In recent years, the development of key technologies such as microfluidic chips and microneedle delivery provides an ideal solution for real-time monitoring and even immediate intervention of physiological states during exercise. This paper summarizes the latest research progress of wearable body surface microfluidic systems and focuses on eight wearable body surface microfluidic systems that may be applied in the field of sports, with their application prospects in sports analyzed and discussed. Finally, the application direction of the wearable body surface microfluidic system that may achieve breakthroughs is illustrated with the prospect demonstration of the future research and development direction of wearable sports equipment. This paper aims to focus on technical problems in the development of the sports field, provide multi-disciplinary solutions and advocate technology integration as well as provide scientific and technological assistance for the development of the sports field.

Keywords: wearable technology; microfluidics; microneedles; biochemical analysis; motion monitoring

1. Introduction

The use of wearable equipment for sports performance and physiological state monitoring plays a very good role in promoting the scientific training of athletes and the improvement of competition performance. Wearable equipment refers to a monitoring device that can be directly worn or attached to the body. Traditionally, wearable equipment is generally used for monitoring physical indicators such as heart rate and the number of steps. Smart bracelets and electronic timing vests are typical wearable equipment. With the gradual development of wearable devices, the monitoring of some physiological and biochemical indicators has also gradually developed into wearable devices. Today, a new generation of wearable devices is used to non-invasively monitor inorganic salts, metabolites, pH and other indicators in human sweat, and to analyze important

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information such as athletes' exercise energy consumption, exercise fatigue and sports nutrition supplement needs. The use of wearable equipment to monitor the kinematics[1], physiological[2] and biochemical[3] indicators of athletes has become the most commonly used method to evaluate their sports performance and motor function. However, existing devices are worn in limited positions[4] and as such, often limits the physical activity of the athlete due to volume[2], shape[5], weight[6], and wired data transmission[1,2]. Furthermore, even some tests can only be performed in laboratories[7]. As a result, this brings a lot of inconvenience to the assessment of sports performance testing, sports injuries and sports rehabilitation progress of athletes.

Wearable equipment developed in recent years combined with microfluidic chip technology[7,11] can achieve rapid, minimally invasive or non-invasive monitoring of body indicators. For example, the sweat analysis microfluidic system can non-invasively detect glucose in sweat[12], lactate[7,11,12], sodium ion[11,13], potassium ion[11], chloride[7,12,14], creatinine[10], urea concentration [10], sweat pH value[7,12], total sweat volume and sweat rate[7,12,13] while other indicators are monitored, with physiological and biochemical analyses carried out without collecting blood samples, thereby providing convenience to sports practitioners to obtain high-quality data, while facilitating their timely adjustment of athletes' exercise programs, and promote the implementation of scientific training. In addition, the development of microneedle delivery in recent years[15,18] has enabled us to attain real-time intervention of physiological states during exercise in the near future[16], that is, through microfluidics, micro-sensors, or solid-state micro-monitoring of the concentration of various substances in athletes' sweat or inter-tissue fluid, and through a closed-loop feedback mechanism, the use of soluble microneedles or hollow microneedles percutaneous injection of the required nutrients or therapeutic drugs. The development of this new sports medicine system will trigger a new round of technological revolution in the field of sports, and promote the development of sports with the help of technological integration.

The development of wearable body surface microfluidic systems can solve multiple challenges in traditional motion monitoring: (1) Long inspection cycle: Most of the traditional motion monitoring adopts the method of sampling and sending it to the laboratory for analysis during which the results in the long time intervals can easily cause data inaccuracy, such as evaporation of water from sweat during the sending process, causing the concentration of electrolytes in it to rise. On the contrary, wearable body surface microfluidic systems can complete the monitoring on the body surface[7,10,14] and can transmit the data through wireless means[7,13] to achieve real-time monitoring of data. (2) Continuous monitoring is difficult: Various physiological and biochemical indicators of the human body are often changing rapidly during exercise. However, traditional blood sample analysis is obtained in point-like discrete data with usually very long intervals between data points, so it is difficult to reflect the real state changes of athletes in real-time. The wearable surface microfluidic system can achieve continuous monitoring, such as the use of microfluidic chips[12] to monitor the concentration of lactate and glucose in sweat in real-time. (3) Dependence on laboratory platform: traditional analytical methods are concentrated in the laboratory[7], which usually requires expensive equipment and professional personnel to operate. With the use of body surface microfluidic system, not only that data acquisition can be performed in situ, but also the test results can be directly displayed on the mobile phone[7,12], thereby avoiding the dependence on the laboratory and do not require the user to master professional skills. (4) Athlete resistance: Traditional test methods often have problems such as discomfort, trauma, and restriction of physical activity, such as the lactate threshold test[19] which requires blood retrieval through fingertips. The use of wearable surface microfluidic devices[7,11,12] can analyze sweat in a non-invasive, comfortable, and unrestricted physical activity method, and achieve the required physiological state monitoring and analysis through the correspondence of its results to the concentration of lactate in the blood[12].

Based on the above advantages, there are many research works[6,11] demonstrating the great potential of wearable surface microfluidic systems (**Figure 1**). However, most microsystems were seen to be still in the small-scale testing stage with still many urgent problems remaining to be solved for commercial promotion. For example, some microfluidic systems are expensive to manufacture[7] and unable to be used repeatedly[7,10,20]. At the same time, there is also the need to collect a large amount of first-hand data, standardize evaluation standards and establish cloud databases. This paper summarizes the latest research progress in the field of body surface microfluidic systems in recent years, focuses on eight wearable surface microsystems that have been applied or may be applied in the sports field in the future, and are classified according to their main technical categories, covering the cutting-edge research results of microfluidic systems[10,11,20], hybrid microsystems[12] and microneedle delivery[15,18]. Finally, the direction of the most likely breakthrough progress of the microfluidic system in the sports field is illustrated along with the analysis of the application prospect and possibility of the microfluidic system in the sports monitoring and the prospect of the research direction of wearable sports equipment.

Figure 1. Recent featured research on wearable skin-interfaced microfluidic systems[6,11].

2. Wearable microfluidic system

The application of wearable body surface microfluidic systems in sports mainly focuses on sweat analysis[21]. Sweat is a body fluid secreted by the skin that is rich in electrolytes[22], small molecules[23], and proteins[7]. It does not only come from a wide range of sources and is convenient for collection and analysis, but sweat may also reflect the levels of various components in body fluids. Quantitative analysis of sweat on the body surface has a wide range of applications in the monitoring of physiological status (such as hydration status[7]) and the diagnosis of diseases (such as bladder fibrosis[7,14,24,25]). Sweat analysis based on microfluidics mainly uses the pressure generated by sweat glands[11] to push sweat into a series of pre-designed micro-channels and micro-chambers on the microfluidic chip and then through some color reactions[7,10,12,14,26] followed by image analysis [7,26] to measure the concentration of each substance in sweat.

In the field of sports, sweat analysis can be applied to monitor the physiological state of athletes[21]. During the training process, the measurement of lactate concentration in sweat can provide a basis for evaluating the training intensity of athletes[27] to formulate a more scientific training plan. In addition, the measurement of glucose concentration in sweat is helpful for us to accurately judge the energy consumption of athletes[28], which is also of great significance for guiding nutritional supplementation after training. The measurement and analysis of total sweat volume can be used to assess the physiological status of athletes, such as hydration status[7] and thermal regulation status[7], which is expected to provide data support for the formulation of individualized precise hydration strategies in sports. Therefore, through sweat analysis, sports training can be optimized, and ultimately the sports performance of the athlete can be improved.

To collect and analyze sweat during exercise, Choi et al.[11] developed a microfluidic system that can collect sweat on the body surface in time sequences (**Figure 2A. a**). Sweat first enters the microchannel from the sweat inlet in the center of the chip, follows through a serpentine channel connecting to 12 sweat reservoirs and is further injected into 12 sweat reservoirs in chronological order under the control of a series of valve structures (**Figure 2A. b**). The circular design of the chip is to be able to extract the sweat collected in the sweat reservoir by centrifugation (**Figure 2A. c**). Choi et al.[11] used this system to complete the time-sequence-based sweat collection and the concentration determination of lactic acid, sodium ions and potassium ions in sweat. Its test results can be used to assess exercise intensity and electrolyte balance in athletes. In addition, Reeder et al.[20] developed a microfluidic system for water movement monitoring (**Figure 2B. a**), which can collect human sweat in a water immersion environment for biochemical analysis and can also measure body surface temperature.

The wireframe illustration in **Figure 2B. a** shows the sweat inlet and outlet design: The sweat outlet is extremely small that can prevent water from entering during use to ensure accuracy of the test results; the dye or reactant is stored adjacent to the sweat inlet in the chamber comprising of red and blue dyes with different dissolution rates. Due to the dissolution of the blue dye, a clearly visible color gradient can be formed in the micro-channels, which cleverly visualizes the total sweat volume (**Figure 2B. b**). Total sweat loss can be quantified by observing the number of cells filled with sweat (1.5 μL volume per paperclip). Similarly, if the dye is replaced with a suspension of silver chloranilate, a corresponding color reaction will occur in the microchannel, and the sweat color of each unit is compared with the standard colorimetric card in the central sector of the chip, where then the concentration of chloride in sweat in the cell can be obtained (**Figure 2B. c**). This microfluidic system expands the scope of application of traditional wearable equipment and opens up a precedent for monitoring and analyzing the physiological state of sports in water or water sports.

The wearable body surface microfluidic system can not only be used for the determination of chloride concentration in sweat but also can integrate multiple chromogenic reactions on one chip to realize the simultaneous determination of multiple indicators.

Zhang et al.[10] developed a body surface microfluidic system that integrates water-repellent sweat collection and color reaction (**Figure 2C. a**). The system contains a serpentine channel for total sweat volume and perspiration control. Quantitative analysis was carried out through the micro-channel and the aforementioned micro-valve[11], where the sweat was also introduced into 3 consecutive chambers (3 chambers each for pH, creatinine and urea concentration measurement, 9 chambers in total) in chronological order. Thanks to the excellent waterproof function of the device, it can be used not only for sports athletes but also for infants, the elderly or sick people who cannot exercise vigorously.

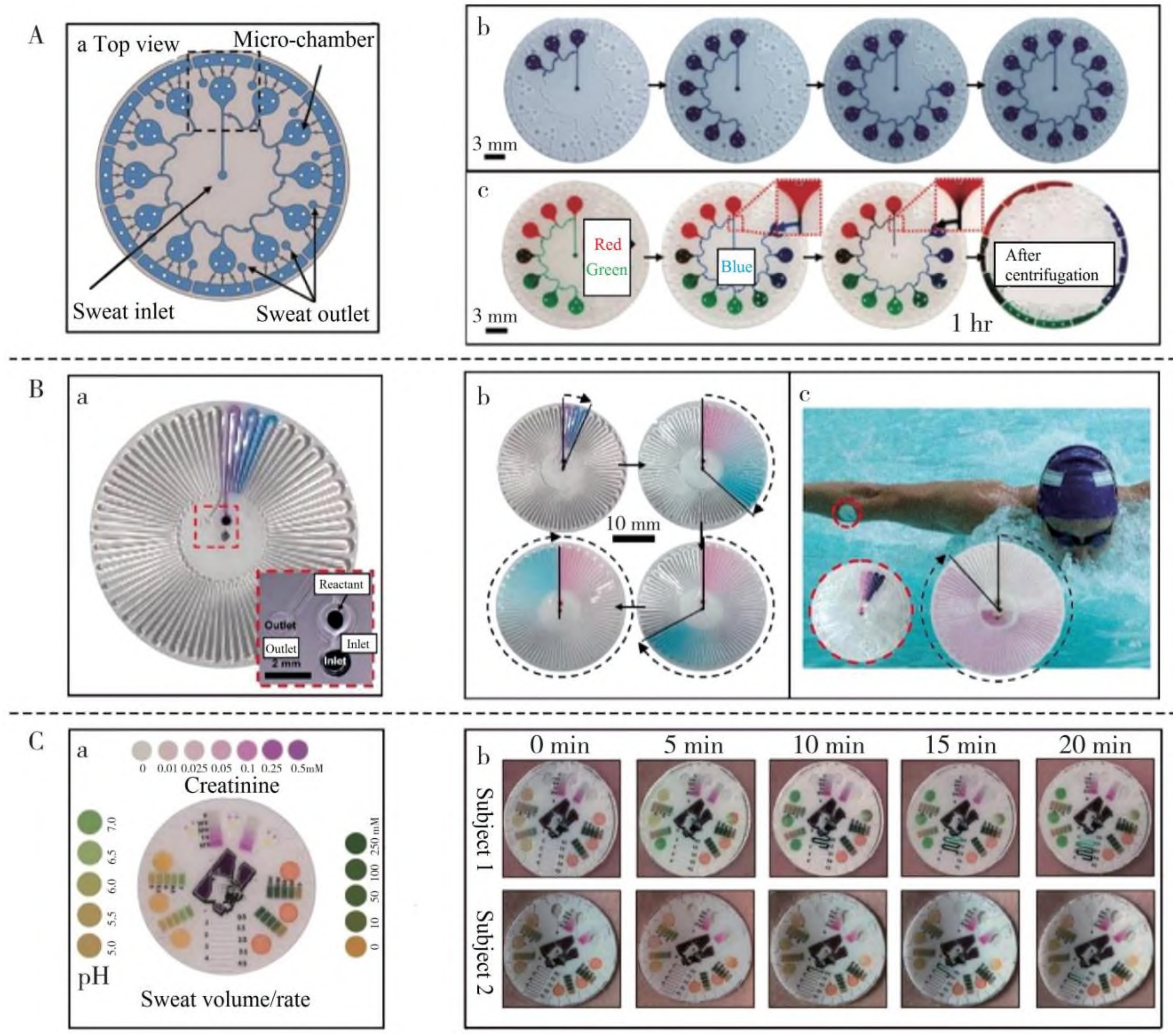

Figure 2. Wearable skin-interfaced microfluidic systems: **(A) a**. skin-mounted microfluidic systems for chrono-sampling of sweat; **(A**) **b**. pressure naturally induced by the sweat glands drives sweat through a microchannel to chrono-filling 12 micro-reservoirs under micro-valves' control; **(A) c**. the circular construction is beneficial to use centrifugation for extraction of sampled sweat[11]; **(B) a.** waterproof skin-interfaced microfluidic system for sweat analysis in aquatic settings (inset: microfluidic inlet and outlet ports); **(B**) **b.** a dye composed of blue and red water-soluble particles that dissolve at different rates results in a volume-dependent color gradient to visualize total sweat loss as the device fills with sweat; **(B) c.** a swimmer wearing a skin-interfaced microfluidic system that quantifies local sweat chloride concentration (inset: optical image of the waterproof microfluidic system)[20]; **(C) a.** skin-interfaced microfluidic system for colorimetric analysis of biomarkers in sweat; **(C) b.** a paper-based enzymatic or chemical assay for colorimetric analysis of creatinine and urea concentrations and pH[10].

The researchers attached the system to the subject's body surface and allow the system to undergo a hot water bath of 5–15 minutes (temperature: 38–42 °C). Thereafter, the results were then obtained through mobile phone image analysis: This system adopts the import and export mode from Reeder et al.[11] study, while the use of blue dye dissolved in sweat to visualize the total sweat volume and the method of the enzyme reaction and chemical reaction color development was based on the test paper used in the study by Koh et al.[7]. Through image analysis, creatinine, urea concentration, and pH in the subjects' sweat were quantified against standard color charts on the microfluidic chip (**Figure 5C. b**). Significance of this study: Firstly, it expands the applicability of the microfluidic system for surface sweat analysis; secondly, the sweat analysis results of this system can be used to evaluate the user's renal function (when kidney function is abnormal, especially when glomerular filtration function is abnormal, the concentration of creatinine and urea in blood and sweat will increase, and pH value will also be affected).

3. Wearable hybrid micro-system

In recent years, some scholars have proposed the concept of a hybrid system, which refers to the combination of two quantitative analysis systems; microfluidics and micro-sensors and exert their respective advantages. Bandodkar et al.[12] developed a hybrid microsystem that can simultaneously perform electrochemical, chromogenic, and volumetric quantitative analysis of sweat. The system consists of a disposable microfluidic subsystem (**Figure 3A. a**) and a near field communication (NFC) subsystem (**Figure 3A. b**). In the microfluidic subsystem, one ring-shaped channel with soluble blue dye produces the visualization and quantification of total sweat volume and sweat rate, while two channels connected with six color reaction chambers combined with micro-valves were used to introduce sweat into the reaction chamber in chronological order (a standard colorimetric card is attached to the side of the chamber) to produce the quantitative analysis of the color reaction of pH value and chloride concentration. Additionally, two slightly larger sweat inlets were used to embed micro-sensors to achieve real-time monitoring of glucose and lactic acid concentrations. The NFC subsystem is tightly coupled with the microfluidic subsystem through a magnetic force, which not only provides enough magnetism to keep it from falling off during vigorous exercise but also makes it easy to remove for next use, saving testing costs. **Figure 3A.c** shows the process of sweat analysis by the system. The results of the color reaction can be obtained through mobile phone image analysis, and the power supply and data transmission of the electrochemical analysis was completed through the NFC subsystem connected to external devices (**Figure 3A. d**). The experimenters also conducted the analysis on the trend variation of glucose and lactate concentrations in sweat obtained by micro-sensor analysis (represented by the black dashed line in the figure), and the variation trend of glucose and lactate concentrations in the blood obtained by the blood test (represented by the red dashed line in the figure). For comparison (**Figure 3B**), it was found that the data were close in most cases with the results consistent with previous studies[16,25,28,29], demonstrating the feasibility of sweat analysis to obtain semi-quantitative data and its application prospect in non-invasive exercise monitoring and analysis.

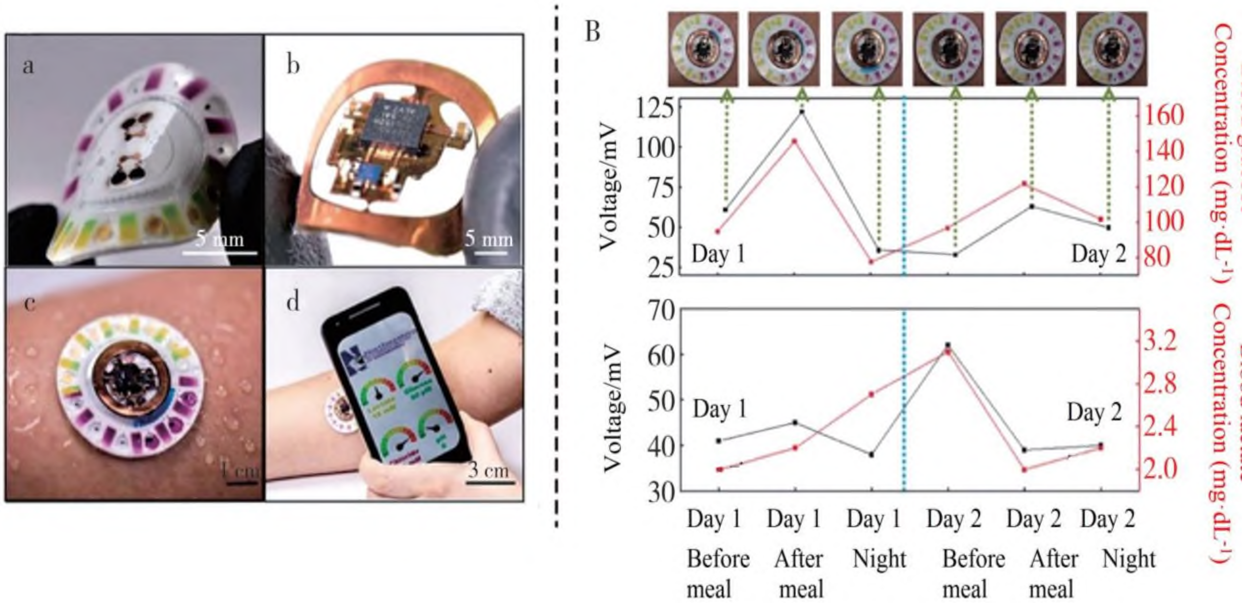

Figure 3. Hybrid microsystem integrating microfluidics and micro-sensors: human trials that compare concentrations of glucose and lactate in sweat and blood; **(A) a.** microfluidic subsystem with embedded sensors' anodes and cathodes; **(A) b.** NFC subsystem; **(A) c.** hybrid microsystem for electrochemical, colorimetric and volumetric analysis during sweating; **(A) d.** wireless power supply and data transmission via external devices; **(B)** correlation of data acquired from glucose and lactate sweat sensors (black line) with that acquired from blood glucose and lactate meters (red line), respectively[12].

In summary, the wearable body surface microfluidic system provides a platform for accurate quantification and real-time monitoring of sweat analysis, and at the same time, it can achieve targeted physiological and biochemical analysis through technology accumulation and the combination of micro-sensors and other technologies. This system not only can be used for the formulation of traditional energy supply schemes for athletes in sports and to promote the innovation of sports technology analysis methods but also to provide scientific and technological assistance for real-time physiological state monitoring of diseased populations in formulating and implementing sports rehabilitation plans. Taken together, these applications demonstrate that microfluidic technology has broad development space and huge market potential in the field of sports.

4. Wearable microneedle system

Traditional drug delivery methods are mainly subcutaneous[30] and intravenous injections[31]. Meanwhile, blood tests have become common means of physical condition detection[32], disease diagnosis[33], and even athlete motor function monitoring[19].

At present, invasive detection methods such as blood drawing not only require professional personnel to operate[30], but the athletes also experience pain, discomfort or fear of needles[30,31,34]. Therefore, achieving efficient drug delivery or painless body fluid collection has become a hot research topic. The development of wearable microneedle chips provides new solutions for sports replenishment, motion monitoring in diseased populations and sports injury treatment. Accurate, efficient, and safe physiological condition monitoring and drug delivery can be achieved through wearable microfluidic chips combined with microneedle arrays or micro-sensors[30,36].

Figure 4A shows the principle of microneedle delivery: the length of the microneedle is generally less than 1 mm, and its needle accurately penetrates the epidermis without touching the blood vessels and nerves at the base of the dermis so that exogenous substances can be introduced into the dermis layer by passive diffusion and other methods without pain[31]. **Figure 4A** also shows four typical microneedles[30]: (1) Solid microneedles, which can be used to penetrate the stratum corneum of the skin and form microporous channels to increase the permeability of the skin for subsequent transdermal drug delivery. (2) Coated microneedles, when attached to the body surface, the drug coating on the surface of the microneedles can quickly dissolve into the interstitial fluid. (3) Dissolvable microneedles, the needles are usually encapsulated with drugs and can be completely dissolved in the interstitial fluid of the skin, which can be used for sustained drug release[17]. (4) Hollow microneedles, the tube in the center of the microneedle can be used to continuously inject exogenous substances into the dermis layer. This kind of microneedle usually controls the injection dose per unit time through pressure and can freely achieve fast or slow drug delivery. The above microneedle systems have been widely used in biomedicine and other fields, such as drug delivery[30], interstitial fluid extraction[31,37], disease diagnosis and treatment[16], medical cosmetology[39] and so on. The following summarizes the micro-needling technology that is expected to be applied in the field of sports.

Gowers et al.[15] developed a microneedle array-based sensor for antibiotic concentration monitoring (**Figure 4B**). **Figure 4C** shows the cross-sectional view of each coating on the surface of the microneedle array, the real image of the chip, and the local electron scanning microscope image of the microneedle array.

Its working principle is as follows: the hydrolysis of the antibiotic β-lactam by the β-lactam enzyme plated on the surface of the electrode will produce a change in the pH value of the interstitial fluid. The researchers thus established the correlation between the antibiotic concentration and the pH value, and the pH value is linearly related to the electrical potential in the sensor circuit[15].

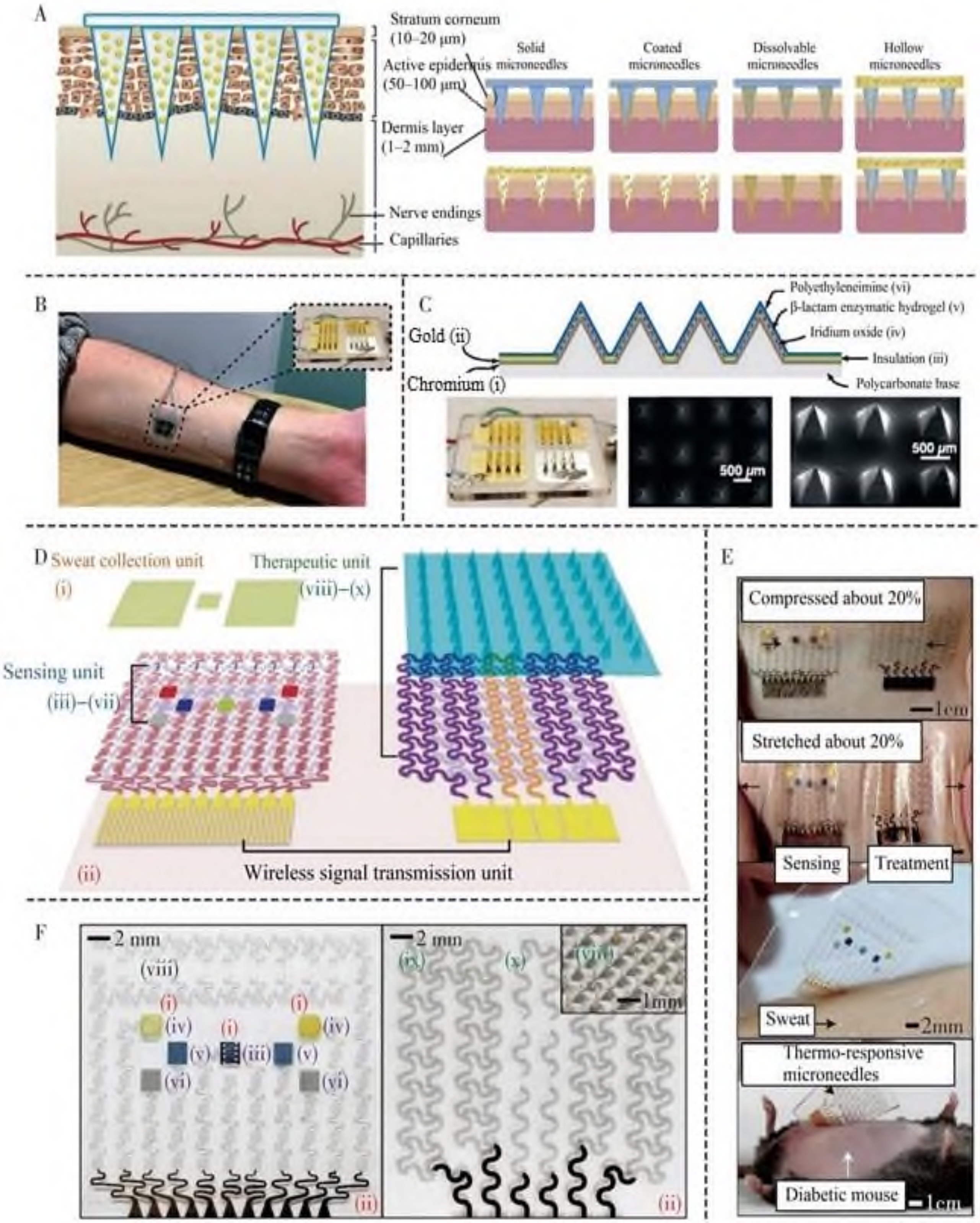

Figure 4. Working principle and application of microneedles: **(A)** common working principle of microneedles for drug delivery and four types of microneedles[30,31]; **(B)** Microneedle-based sensor for continuous monitoring antibiotic concentrations; **(C)** schematic cross-section of working electrode showing each layer, optical image of the microneedles patch, and the scanned electronic microscopy (SEM) image of the microneedle array[15]; **(D)** schematic diagram of the graphene-based electrochemical system with thermo-responsive microneedles; **(E)** the skin-interfaced system with thermo-responsive microneedles under mechanical deformations，electrochemical sensor array on the human skin with perspiration and therapeutic microneedle array laminated on the skin near the abdomen of the diabetic mouse; **(F)** the image of the chip with thermo-responsive microneedles (inset: bioresorbable microneedle array)[16].

To put it in another way, the researchers established the correlation between the concentration of interstitial fluid substances and electrical signals through the combination of microneedle arrays and electrochemical sensors to monitor the changes in the concentration of interstitial fluid substances in real-time through electrical signals and in doing so enable timely delivery of drugs to reduce their side effects[40].

In 2016, Lee et al.[16] unified sweat analysis, micro-sensors, and dissolvable microneedles into a graphene-based electrochemical microsystem (**Figure 4D**), enabling sweat-based diabetes monitoring and feedback-based accurate drug delivery. **Figure 4E** shows its ability to resist deformation during exercise and the sweat analysis module: the micro-sensor is connected to a portable electrochemical analyzer that powers the micro-sensor, transmits data to a smartphone via Bluetooth. It was verified that the system can efficiently deliver the hypoglycemic drug metformin into mice and rapidly reduce the blood glucose level of mice. **Figure 4F** is the physical image of the chip. The microneedles dissolve when the temperature exceeds 41–42 °C. In vitro experiments have shown that the microneedles can release the drug only when the temperature exceeds the thermal response temperature, with precise and controllable drug release being well achieved.

Dissolvable microneedles can be used for precise drug delivery based on thermal response and for the slow release of drugs to achieve long-term therapeutic effects. Li et al.[17] developed a sustained-release effervescent microneedle chip, using the effervescent substrate encapsulated citric acid and sodium bicarbonate (**Figure 5A**). When the microneedle is pierced into the skin, the polyvinylpyrrolidone (PVP) in the effervescent rapidly dissolves in the interstitial fluid, while sodium bicarbonate, citric acid and interstitial fluid react to produce carbon dioxide, resulting in effervescent substrate rupture, achieving rapid separation of microneedle needles and chip substrates (separation efficiency up to 96% ±4%). As shown in **Figure 5B**, the microneedles encapsulated with purple-red fluorescent dyes were pierced into the porcine skin, and the microneedles were left in the porcine skin for sustained drug release. The study also tested the sustained-release process of effervescent microneedle chips loaded with contraceptives (LNG). The results showed that the effervescent microneedle chip that was attached to the mouse body surface for only 1 minute was able to leave the microneedle needle in the mouse skin and slowly release the drug for up to 2 months so that the concentration of LNG in its interstitial fluid was higher than the concentration of human treatment level for more than 1 month. Additionally, there was no erythema, edema or other skin irritation observed and histological analysis also confirmed its good biocompatibility.

Compared with keeping the drug in the body for slow release, Di et al.[18] developed a stretch-induced drug delivery microneedle chip that can be attached to the joint and store a drug in a microgel chamber on the chip, which releases and delivers the drug into the skin when needed. **Figure 5C** shows the principle of drug storage and release: the microgel drug compartment is used to load the polymer nano-drug particles and bind them to the stretchable elastic membrane. When the elastic membrane is deformed by the joint movement, the microgel drug cartridge releases the nano-drug particles into the microgel matrix, which is then injected into the skin on the joint surface by the microneedle array on the chip (**Figure 5D**). The microneedle system is expected to be applied to long-distance events, such as marathons, where anti-inflammatory drugs[18] can be delivered into interstitial fluid on the surface of the joint body by using traction caused by joint movement during exercise, alleviating joint inflammation in athletes in long-distance sports.

In summary, the wearable microneedle system can achieve painless, minimally invasive and precise transdermal drug delivery. It can also be combined with microfluidics and micro-sensor technology to achieve individualized closed-loop feedback therapy, which enables it to have broad prospects in the field of sports and health. The system can monitor the sports performance of athletes, treat sports injuries and provide nutritional supplements in sports and also facilitate the exercise intervention made by sports coaches and researchers in the field on disease populations (such as hypertension, diabetes, arteriosclerosis patients). It has greatly promoted the integration of scientific training and physical medicine, thus providing technical support for Healthy China 2030.

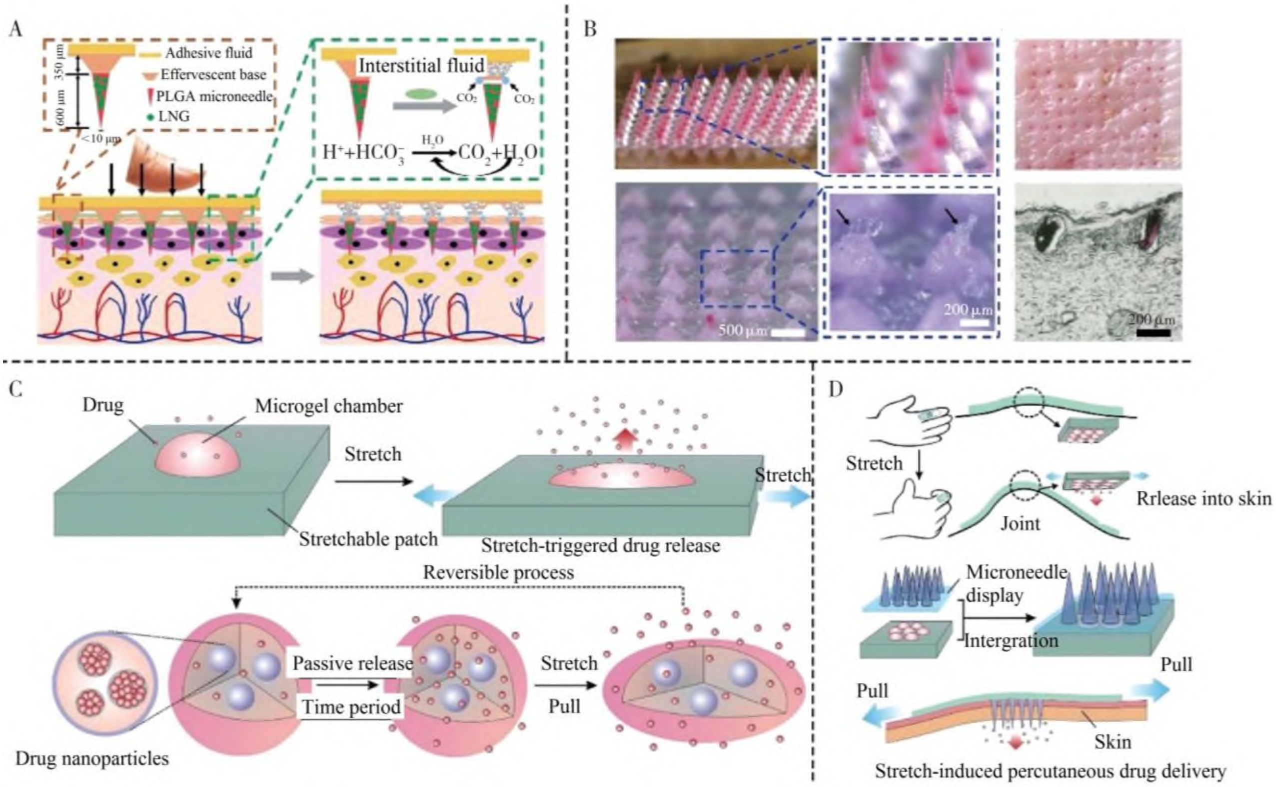

Figure 5. Two long-acting microneedle patches and their working principle: **(A)** schematic drawings of the process of microneedle patch application to the skin to rapidly deliver microneedle tips into the skin by the fast dissolution of the effervescent backing; **(B)** images of an effervescent microneedle patch with microneedle tips containing red fluorescent dye (Nile red) and photos took after microneedle tips separated from the effervescent patches; representative bright-field microscopy images of porcine skin after microneedle patch insertion and microneedle tip detachment in porcine skin and a corresponding image of a histological section of porcine skin (bright-field)[17]; **(C)** stretch-triggered drug delivery microneedle patch and its working principle of drug storage and release; **(D)** stretching of the patch induced by joint movements promotes the drug release and diffuse into the microneedle for transcutaneous drug delivery[18].

5. Conclusions

The wearable body surface microfluidic system combines the principles of physiological and biochemical analysis, with its in situ, real-time, non-invasive and other characteristics to continuously collect and analyze various indicators of the human body and monitor the health status of sports athletes. Coupled with the promotion of 5G and the widespread establishment of big data processing capabilities, a new generation of microfluidic systems supported by cloud databases is expected to achieve accurate quantitative analysis based on big data.

With the increasing demands of athletes' kinesiology monitoring, scientific training, and exercise intervention for diseased populations, the application of wearable body surface microfluidic systems in sports in the future is expected to achieve breakthroughs in the following aspects. (1) Sweat analysis: The wearable microfluidic chip can accurately measure the concentration of glucose, lactate, sodium ions and potassium ions in sweat, which can be used to judge the training intensity, exercise energy consumption, hydration state and thermal regulation state of athletes. The microfluidic chip on the body surface interacts with the mobile phone to display information such as the intensity of the exercise in real-time and give scientific nutritional supplement suggestions after the exercise.

In addition, with the help of the corresponding relationship between the concentration of substances in sweat and the concentration of substances in the blood, we can also establish the connection between sweat analysis results and clinical blood analysis data. Sweat analysis microfluidic chip gradually replaces blood sample detection and achieve true non-invasive exercise monitoring and analysis. (2) Exercise intervention for the diseased population: the wearable microfluidic system can also achieve real-time monitoring of the physiological indicators of the diseased population while being able to be combined with the microneedle chip to enable drug delivery. It is expected that microfluidic chips can be developed further for people with hypertension, diabetes, hypoglycemia and other populations in the future so that they can exercise more scientifically and safely. At the same time, the system may also be used to predict exercise-induced coma and falls, thereby helping to promote a healthy China. (3) Minimally invasive and precise drug delivery: the combination of micro-sensors and dissolvable microneedles can monitor the concentration of substances in sweat and interstitial fluid, thereby enabling precise, painless, and portable drug delivery in an individualized manner. By developing such microneedle chips, we can deliver a wide variety of drugs, not just diabetes and anti-inflammatory drugs. The new microneedle chip developed in the future is expected to solve the problems of needle fear, repeated injection, and adverse reactions caused by the traditional drug delivery injection process. In addition, such microfluidic and microneedle products are small in size, which is convenient for storage, transportation, and distribution, and reduces circulation costs. Athletes or users only need to put them in their pockets or backpacks before exercising, and they can be attached to the body surface when they need to be used, which provides great convenience to users and facilitates promotion and use.

At the same time, there are still some constraints and difficulties in the application of microfluidic technology in sports, such as: (1) To complete a series of complex fluid manipulation and biochemical reactions on a microfluidic chip, professional designers and chip processing equipment are required. (2) Microfluidic chips are still in the stage of small-scale application testing in the field of sports and are gradually being industrialized and commercialized. Physiological and biochemical researchers also lack opportunities to collaborate with medical engineering researchers. (3) At this stage, the performance of wearable body surface microfluidic systems is increasingly getting better with the test data is getting more and more accurate. However, the golden standard for sweat analysis has not yet been established.

In summary, wearable microfluidic systems have broad application space in the field of sports, whether it is in kinesiology monitoring, exercise training effect evaluation, or intervention in drug delivery, in which all of them provide new possibilities. In the future, the research and development of wearable sports equipment, especially in combination with microfluidic technology, will introduce a multi-index, non-invasive or minimally invasive, real-time data analysis, cloud database support, feedback drug delivery and high-speed wireless data transmission functions. The wearable body surface microsystem provides strong scientific and technological support for preparing for the Olympic Games and a healthy China.

Conflict of interest

The authors declare no conflict of interest.

References

1. Lee BC, Chen S, Sienko KH. A wearable device for real-time motion error detection and vibrotactile instructional cuing. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2011; 19(4): 374–381.
2. Villa F, Magnani A, Maggioni MA, et al. Wearable multi-frequency and multi-segment bioelectrical impedance spectroscopy for unobtrusively tracking body fluid shifts during physical activity in real-field applications: A preliminary study. Sensors 2016; 16(5): 673.
3. Maier D, Laubender E, Basavanna A, et al. Toward

continuous monitoring of breath biochemistry: A paper-based wearable sensor for real-time hydrogen peroxide measurement in simulated breath. ACS Sensors 2019; 4(11): 2945–2951.
4. Feng S, Caire R, Cortazar B, et al. Immunochromatographic diagnostic test analysis using Google Glass. ACS Nano 2014; 8(3): 3069–3079.
5. Liu Y, Pharr M, Salvatore GA. Lab-on-skin: A review of flexible and stretchable electronics for wearable health monitoring. ACS Nano 2017; 11(10): 9614–9635.
6. Heikenfeld J, Jajack A, Rogers J, et al. Wearable sensors: Modalities, challenges, and prospects. Lab on a Chip 2018; 18(2): 217–248.
7. Koh A, Kang D, Xue Y, et al. A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. Science Translational Medicine 2016; 366(8): 165.
8. Choi J, Xue Y, Xia W, et al. Soft, skin-mounted microfluidic systems for measuring secretory fluidic pressures generated at the surface of the skin by eccrine sweat glands. Lab on a Chip 2017; 17(15): 2572–2580.
9. Sekine Y, Kim SB, Zhang Y, et al. A fluorometric skin-interfaced microfluidic device and smartphone imaging module for in situ quantitative analysis of sweat chemistry. Lab on a Chip 2018; 18(15): 2178–2186.
10. Zhang Y, Guo H, Kim SB, et al. Passive sweat collection and colorimetric analysis of biomarkers relevant to kidney disorders using a soft microfluidic system. Lab on a Chip 2019; 19(9): 1545–1555.
11. Choi J, Kang D, Han S, et al. Thin, soft, skin-mounted microfluidic networks with capillary bursting valves for chrono-sampling of sweat. Advanced Healthcare Materials 2017; 6(5): 1601355.
12. Bandodkar AJ, Gutruf P, Choi J, et al. Battery-free, skin-interfaced microfluidic/electronic systems for simultaneous electrochemical, colorimetric, and volumetric analysis of sweat. Science Advances 2019; 5(1).
13. Kim SB, Lee KH, Raj MS, et al. Soft, skin-interfaced microfluidic systems with wireless, battery-free electronics for digital, real-time tracking of sweat loss and electrolyte composition. Small 2018; 14(45): 1802876.
14. Kim SB, Zhang Y, Won SM, et al. Super-absorbent polymer valves and colorimetric chemistries for time-sequenced discrete sampling and chloride analysis of sweat via skin-mounted soft microfluidics. Small 2018; 14(12): 1703334.
15. Gowers SAN, Freeman DME, Rawson TM, et al. Development of a minimally invasive microneedle-based sensor for continuous monitoring of β-lactam antibiotic concentrations in vivo. ACS Sensors 2019; 4(4): 1072–1080.
16. Lee H, Choi TK, Lee YB, et al. A graphene-based electrochemical device with thermos-responsive microneedles for diabetes monitoring and therapy. Nature Nanotechnology 2016; 11(6): 566–572.
17. Li W, Tang J, Terry RN, et al. Long-acting reversible contraception by effervescent microneedle patch. Science Advances 2019; 5(11): eaaw8145.
18. Di J, Yao S, Ye Y, et al. Stretch-triggered drug delivery from wearable elastomer films containing therapeutic depots. ACS Nano 2015; 9(9): 9407–9415.
19. Goodwin ML, Harris JE, Hernández A, et al. Blood lactate measurements and analysis during exercise: A guide for clinicians. Journal of Diabetes Science and Technology 2007; 1(4): 558–569.
20. Reeder JT, Choi J, Xue Y, et al. Waterproof, electronics-enabled, epidermal microfluidic devices for sweat collection, biomarker analysis, and thermography in aquatic settings. Science Advances 2019; 5(1): eaau6356.
21. Ray T, Choi J, Reeder J, et al. Soft, skin-interfaced wearable systems for sports science and analytics. Current Opinion in Biomedical Engineering 2019; 9: 47–56.
22. Alizadeh A, Burns A, Lenigk R, et al. A wearable patch for continuous monitoring of sweat electrolytes during exertion. Lab on a Chip 2018; 18(17): 2632–2641.
23. Gao W, Emaminejad S, Nyein HYY, et al. Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. Nature 2016; 529(7587): 509–514.
24. Choi J, Ghaffari R, Baker LB, et al. Skin-interfaced systems for sweat collection and analytics. Science Advances 2018; 4(2): eaar3921.
25. Emaminejad S, Gao W, Wu E, et al. Autonomous sweat extraction and analysis applied to cystic fibrosis and glucose monitoring using a fully integrated wearable platform. Proceedings of the National Academy of Sciences 2017; 114(18): 4625–4630.
26. Choi J, Bandodkar AJ, Reeder JT, et al. Soft, skin-integrated multifunctional microfluidic systems for accurate colorimetric analysis of sweat biomarkers and temperature. ACS Sensors 2019; 4(2): 379–388.
27. Buono MJ, Lee NVL, Miller PW. The relationship between exercise intensity and the sweat lactate excretion rate. The Journal of Physiological Sciences 2010; 60(2): 103–107.
28. Moyer J, Wilson D, Finkelshtein I, et al. Correlation between sweat glucose and blood glucose in subjects with diabetes. Diabetes Technology & Therapeutics 2012; 14(5): 398–402.
29. Kim J, Campbell AS, Wang J. Wearable non-invasive epidermal glucose sensors: A review. Talanta 2018; 177: 163–170.
30. Kim YC, Park JH, Prausnitz MR. Microneedles for drug and vaccine delivery. Advanced Drug Delivery Reviews 2012; 64(14): 1547–1568.
31. Wang M, Hu L, Xu C. Recent advances in the design

of polymeric microneedles for transdermal drug delivery and biosensing. Lab on a Chip 2017; 17(8): 1373–1387.
32. Petchakup C, Tay HM, Li KHH, et al. Integrated inertial-impedance cytometry for rapid label-free leukocyte isolation and profiling of neutrophil extracellular traps (NETs). Lab on a Chip 2019; 19(10): 1736–1746.
33. Sharma A, Smyrk TC, Levy MJ, et al. Fasting blood glucose levels provide estimate of duration and progression of pancreatic cancer before diagnosis. Gastroenterology 2018; 155(2): 490–500.
34. Babity S, Roohnikan M, Brambilla D. Advances in the design of transdermal microneedles for diagnostic and monitoring applications. Small 2018; 14(49): 1803186.
35. Fukushima K, Ise A, Morita H, et al. Two-layered dissolving microneedles for percutaneous delivery of peptide/protein drugs in rats. Pharmaceutical Research 2011; 28(1): 7–21.
36. Yang J, Liu X, Fu Y, et al. Recent advances of microneedles for biomedical applications: drug delivery and beyond. Acta Pharmaceutica Sinica B 2019; 9(3): 469–483.
37. Wang P, Cornwell M, Prausnitz MR. Minimally invasive extraction of dermal interstitial fluid for glucose monitoring using microneedles. Diabetes Technology & Therapeutics 2005; 7(1): 131–141.
38. Bariya SH, Gohel MC, Mehta TA, et al. Microneedles: An emerging transdermal drug delivery system. Journal of Pharmacy and Pharmacology 2012; 64(1): 11–29.
39. Tasca F, Tortolini C, Bollella P, et al. Microneedle-based electrochemical devices for transdermal biosensing: A review. Current Opinion in Electrochemistry 2019; 16: 42–49.
40. Rawson TM, Gowers SAN, Freeman DM E, et al. Microneedle biosensors for real-time, minimally invasive drug monitoring of phenoxymethylpenicillin: A first-in-human evaluation in healthy volunteers. The Lancet Digital Health 2019; 1(7): e335–e343.