Digital Medical Education Empowered by Intelligent Fabric Space

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Abstract

Medical education plays an important role in promoting the development of global medical science. Nevertheless, the intrinsic gap existing between institutional medical teaching and practical clinical tasks causes low education efficiency and students' weak initiative. Recent developments of sensing fabric and embedded computing, along with the advances in Artificial intelligence (AI) and digital twin technology are paving the way for the transformation of medical research towards digitization. In this work, we present an intelligent fabric space based on novel functional fabric materials and digital twin networking enabled by 5G and Internet of Things (IoT) technologies. In this space, medical students can learn knowledge with collaborative mapping of the digital and real world, cyber-physical interaction and real-time tactile feedback. And the proposed service system will evaluate and feedback students' operational behaviors to improve their experimental skills. We provide four typical applications of intelligent fabric space for medical education, including medical education training, health and behavior tracking, operation playback and reproduction, as well as medical knowledge popularization. The proposed intelligent fabric space has the potential to promote innovative technologies for training cutting-edge medical students by effective and efficient ways.

Key words: medical education, intelligent fabric, digital twin, tactile interaction.

1. Introduction

Medical education aims to cultivate the skills and expertise of medical students, spread medical knowledge and promote the development of global medical science [1, 2]. However, it is a challenge to solidify medical knowledge dissemination due to its practicality and complexity.

Advances in computing and communication technologies, such as artificial intelligence (AI), digital twin networking, 5G and Internet of Things (IoT) are enabling the design and development of next generation digital medical education. In the past few years, much of the medical research has focused on issues related to various aspects in the clinical setting, such as patient monitoring and healthcare, personalized medical treatment and robot surgery [3, 4]. At present, the following shortcomings are observed during the training of medical students:

(1) Offline knowledge acquiring, examination, diagnosis and management: Currently, the medical knowledge acquisition mainly relies on offline efforts, e.g., reading papers and watching recorded videos, which is difficult to be integrated with practical scenarios. Such situation incurs with the sharp shortage of medical training resources, since online medical resources usually are not conductive to the training of doctors.

(2) Deficiency of on-spot medical operation standardization: The situations faced by doctors in the clinic are complex and variable. Accreditation Council for Graduate Medical Education (ACGME) is a representative standard for the existing medical education system in the clinical practice [5]. However, setting a standard to evaluate doctors in non-clinical exercise is difficult.

(3) Coarse evaluation through video recording without multiple physical parameters retrieval, e.g. detailed tactile interaction during operation: It's difficult to implement a cooperative perception of multiple physical quantities. Thus, for medical education, there is currently a lack of multimodal sensing and visualization equipments for the monitoring and feedback of the physiological status of doctors and patients during operation.

After decades of research, various electronic products are gradually exhibiting the features of miniaturization, softness and wearable intelligence [6]. Meanwhile, recent advances in fiber technologies have produced a variety of special fiber structures and functions, such as biosensors [7], supercapacitors [8, 9], batteries [10-12], piezo or triboelectric generators [13], solar cells [14], light-emitting electrochemical cells [15] and light-emitting devices [16-17], etc. Intelligent fabric sensors [18] have also been applied to monitor motions and external stimuli, especially in the surgical or micro-nano manipulation fields. And it is critical to achieve accurate motion detection and tactile sensing [19-23]. Gloves based on the stretchable and flexible sensors have been recently investigated [24-28]. In our work, a variety of perceptions of physical quantities (sound, light, electricity, heat, magnetism, force, etc.) are realized through intelligent fabric. The metrics and regulation of these physical quantities are the foundation of digitized intelligence. The progress in the field of materials science provide strong support for the construction of medical education platforms.

Digital twin involves the establishment of a spatiotemporal, multidimensional, multi-disciplinary and dynamic model for mapping the physical entities of real space in a digital way, to simulate the attributes, behaviors and rules of such physical entities [29, 30]. It can be used to describe complicated conditions in medical scenarios and the fusion state between the physical world and information space. The status of medical personnel and environment is first reflected on the simulation space. Then, the feasible actions in the virtual world are fed back to the physical world [31]. The potential real-time skill evaluation technologies with low latency and high interoperability for future medical education are explored in this article.

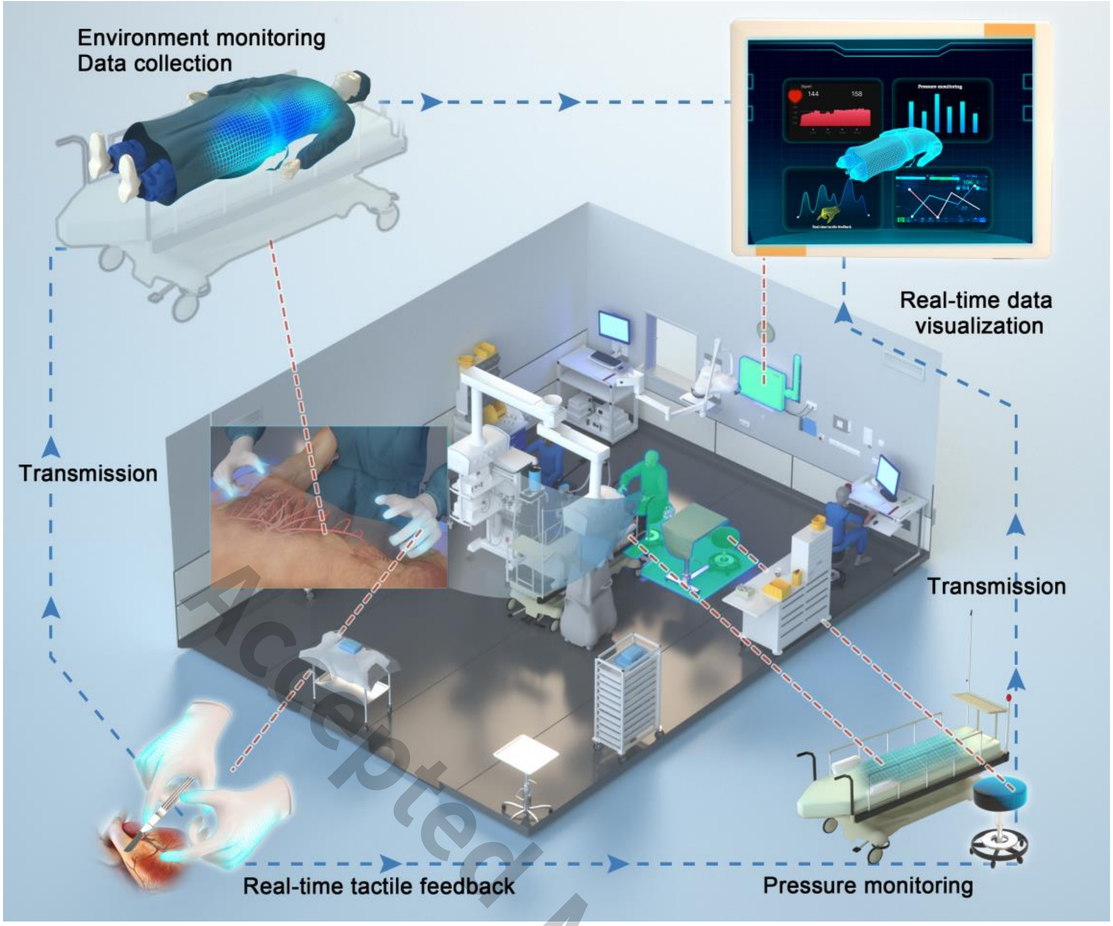

Fig.1 Digital Medical Education Empowered by Intelligent Fabric Space. An intelligent fabric space is created with collaborative mapping of the digital and real world, cyber-physical world interaction and real-time tactile feedback for medical education.

Fig. 1 shows an intelligent fabric space created with digital twin technology. Such space brings digitization into medical education. In the intelligent medical space, fabrics with detection, simulation, and interactive functions allow medical students to experience immersive operations. It is a digital method to monitor the behaviors and states of both patients and doctors and standardize the practice of medical students through simulation and evaluation, improving the quality of medical education and ensuring the smooth completion of surgery practice.

2. Intelligent Fabrics Enabled Digital Medical Education

The advantages of non-inductive and multi-extensible fabrics with high sensitivity can address the problems of data collection and operational action evaluation in the field of medical education. When 5G networks and AI meet sensing fabrics, a comprehensive network infrastructure with powerful processing capabilities can be provided for medical education scenarios [32, 33]. The architecture of intelligent fabric space is presented in this section.

2.1 Architecture of Intelligent Fabric Space

To achieve digitization of medical education in an intelligent fabric space, the actions and behaviors of the executor first need to be collected, evaluated and simulated. Fig.2 shows the system architecture of the intelligent fabric space. When integrated with 6G intelligence networking technology [37], 6G intelligent fabric space can renovate a wide range of future applications in terms of smart cities, smart living, medical care and education.

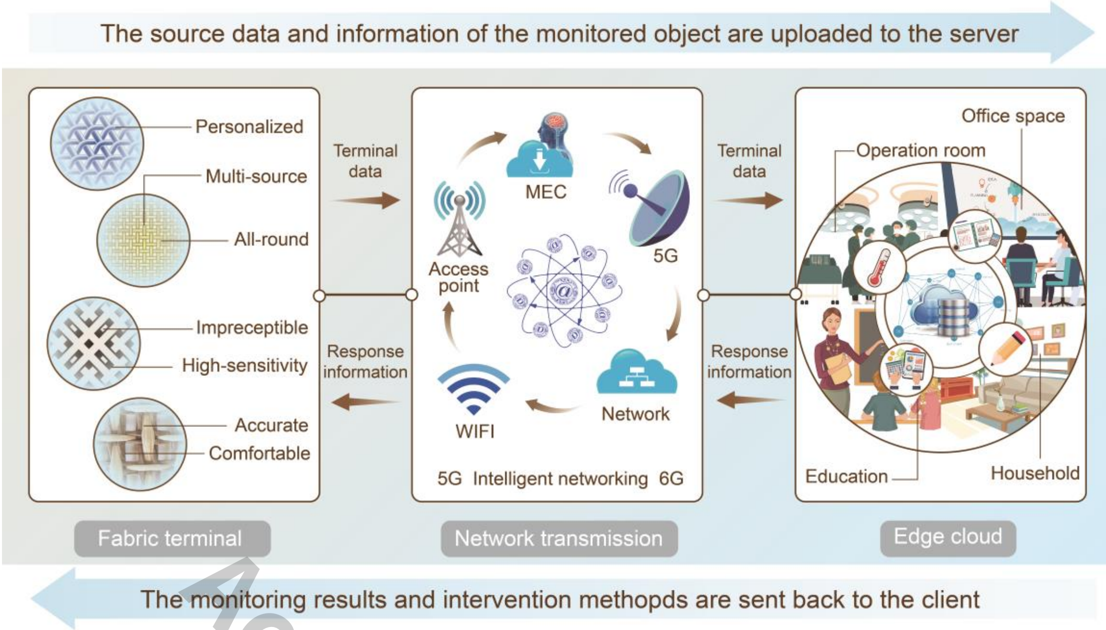

Fig.2 System architecture of the intelligent fabric space includes fabric terminal layer, network transmission layer and edge cloud layer. The first layer is responsible to perceive information from object and environment. The second layer transmits data to the first layer and the third layer. And the third layer deploys AI algorithms to process data on server.

As shown in Fig. 2, the first layer is fabric terminal layer, including a variety of intelligent fabric sensor nodes. In general, flexible fabric nodes are characterized by strong tensile performance, high sensitivity and low responsive delay. In contrast to conventional sensory devices, fabric sensors can be embedded into any clothing, furniture, dummy body and other flexible items to collect multi-source data in a nearly imperceptible way. The different kinds of fabric materials include piezoelectric [34-36], triboelectric [37-39], magnetoelectric [40, 41], textile piezoresistive sensor [42, 43], temperature transducers [44], optical sensor [45] and capacitance sensors [46]. They exhibit great potential in environmental perception, human health monitoring and behavior recognition. In the future, invisible fabric nodes will become a novel way for interaction between humans and computers in daily life.

The second layer is network transmission layer. It is responsible for the low-latency and high-reliability communication for massive data [47]. In 5G networks, some challenges, such as the highly dynamic changes of the transmission link, will be handled for providing real-time connection services. Efficient intercommunication among humans, machines and objects is established in this layer to improve perception accuracy with various distance [48]. In order to meet the requirements of distributed fabric signal acquisition and algorithm analysis, the network transmission layer ensures the reliable sensing of the first layer and the timely feedback of computation result in the third layer.

The third layer is edge cloud layer which has two major tasks, i.e., real-time data analysis and situation recognition for diverse scenes. Typically, terminal nodes are lack of computing power with limited local storage, and hard to meet the quality of service requirements in terms of delay and accuracy. For tasks with low latency tolerance, lightweight models are deployed on the edge server and the calculated results are fed back to the terminal nodes. Tasks requiring high computing power are processed on the cloud with the high performance server [49]. The advances in graphic processing unit and the development of deep learning have significantly enhanced the processing capabilities and expanded the analysis methods for multi-modal data in many fields, which also become a strong support for the analysis of large scale fabric sensing data [50].

2.2 Medical Education Driven by Digital Twins

Based on the architecture of intelligent fabric space, a variety of application scenarios can be designed for medical education. To provide an adequate and vivid clinical operating environment, the digital twin technology is employed to establish the virtual experimental platform by combining the physical world and virtual space.

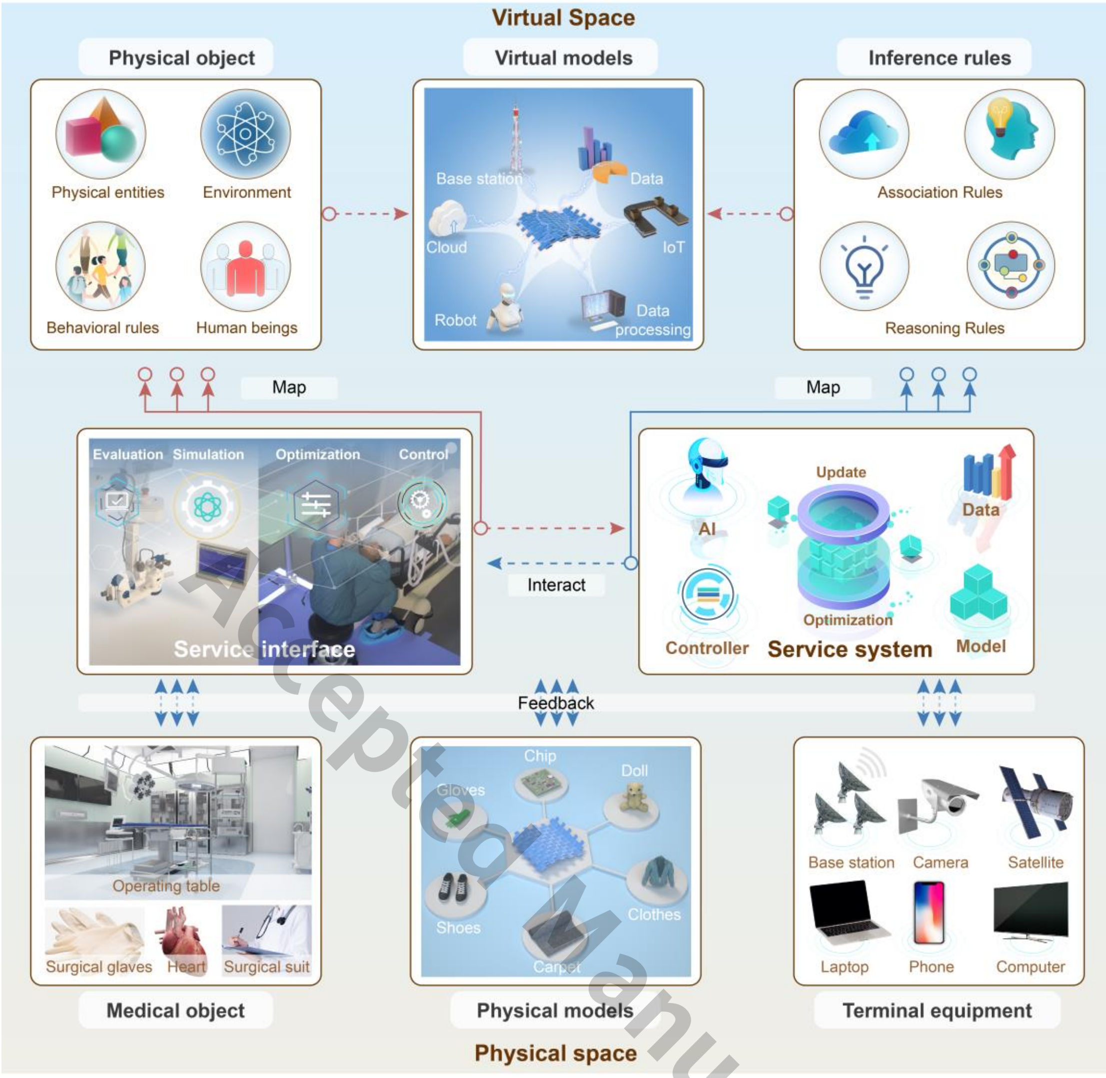

Fig.3 The interactive framework from physical to virtual world, driven by digital twin including four modules. Physical space is the physical world. Virtual space is the simulation world. Service system provides operation functions for executors. Service interface is the interactive interface between physical space and virtual.

We use different fabric materials to construct the medical education environment, which possesses the features of high-resolution, high-sensitivity and non-contact sensing. In this section, a “four-space” model is proposed, which includes physical space, virtual space, service system and service interface [51, 52]. Then, we build a digital twin platform based on the “four-space” model for medical education, as shown in Fig. 3.

(1) Physical space refers to the objective entity that exists in the physical world. In the medical education scene, the physical space includes the operation room, interactive environment, intelligent dummy body and fabric sensors, such as fabric medical gloves and fabric surgical gowns, etc. Compared to the traditional one, our proposed intelligent dummy body deploys sensing fabric sensors on its skin and organs, for enabling real-time tactile feedback during medical education.

(2) Virtual space refers to a mirror of a physical space with a set of interaction rules among the physical objects [53]. The mannequin, medical ontology and user behavior are all digitized to establish a virtual space with evaluation and prediction abilities.

(3) Service system is a backend system that integrates data storage, AI modeling, data analytics, resource optimization, data visualization, and education performance evaluation. In data visualization subsystem, the operation process can be simulated based on data obtained from fabric sensors. Such process can be visualized in screen, as shown in Fig. 3. In the education performance evaluation subsystem, the operation skills of medical students are be evaluated based on various fabric sensory data and the detailed tactile interaction information during operation, in order to improve their operation skill.

(4) Service interface includes the interaction interfaces among physical space, virtual space and service system. It constantly updates the interactive information with the arrivals of real-time data. Service interface provides the personalized access of operation, evaluation and visualization in the physical space and virtual space.

Through "human-machine-fabric" connection [54, 55], the user in the digitized medical education space can receive an immersive operation experience with ultra-low latency and high-fidelity, via the above mentioned four spaces.

3. Typical Applications of Intelligent Fabric Space-Empowered Medical Education

Based on advances of intelligent fabric space and digital twin system, we present four typical applications in the field of medical education as shown in Fig.4.

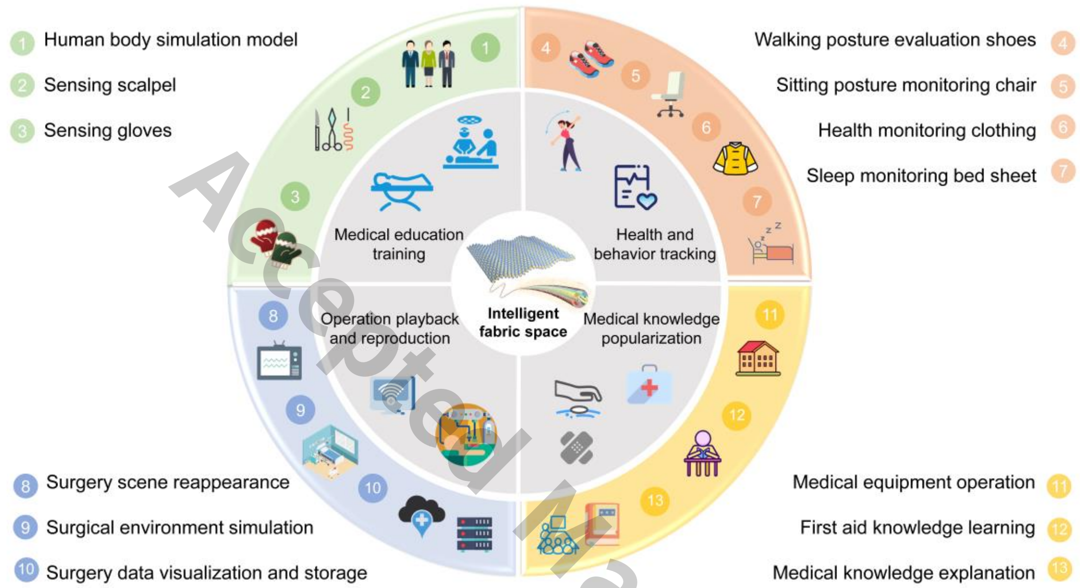

Fig4. Four typical applications in the field of medical education. The platform supports the four typical scenarios, including medical education training, health and behavior tracking, operation playback and reproduction and medical knowledge popularization.

(1) **Medical education training.** Medical students can perform practical exercises to expand their human anatomy knowledge more intuitively through three dimensional visual interfaces in the intelligent space. During experiments, the system can automatically identify the posture of a student holding an instrument, record operation details and present standard evaluation results for the operating student.

(2) **Health and behavior tracking.** Fabric nodes embedded in protective clothing can monitor the physical condition of doctors with indicators such as temperature, heart rate and degree of concentration, and their behavioral information such as gait, sitting

position and the movement trajectories. It will be used to monitor body situations to perform comprehensive operation evaluation when medical students receive medical training.

(3) **Operation playback and reproduction.** The digital twin system can simulate the detailed actions and scenes of the operation to reproduce the surgical scene for both typical and rare cases by means of the recorded data collected by smart gloves and gauze during the operation. This provides doctors with an opportunity to communicate before and after the surgery, solving the problem of insufficient samples in medical learning.

(4) **Medical knowledge popularization.** The general public can learn first aid skills in an intelligent fabric medical space, by wearing intelligent fabric equipment for remote learning and practice independently by watching the supporting demonstration operation process. In this way, first aid education will be extended to every household in a low-cost but efficient way.

The digital twin system with intelligent fabrics as the core can nullify the limitations of time and space, allowing experts, medical students and the public to obtain appropriate medical knowledge to support healthy lives.

4. Outlook and Perspectives

Important breakthroughs have been achieved in high-performance fabric materials with flexible tensile strength, strong sensing and high degree of plasticity. Intelligent fabric can be used to realize collaborative perception of multiple physical quantities, with the metrics and regulation of these physical quantities as the foundation of digitized intelligence. The widespread deployment of 5G networks and the perspective of 6G theory have promoted the development of functional fibers, as well as embedded intelligent fabric in the field of medical education. In this article, intelligent fabric and digital twin are combined to create a cyber-physical system of medical scenarios to serve medical students. Based on the architecture of intelligent fabric space, the simulation of medical education scene and the corresponding interactions driven by digital twin technology is realized.

However, the scheme proposed in this work still has limitations in terms of ubiquitous fabric sensing and distributed algorithm processing. The perceiving performance of some fabrics is not stable, which causes difficulty for large scale deployment. Meanwhile, although the advanced network architecture provides real-time data transmission, the current algorithms are still not efficient on processing spatiotemporal multi-dimensional sensory data when facing large amount of computation requirements. This motivates us to constantly strive to solve problems at the aspects of perception, algorithm and deployment.

In the future, the user of medical education will be able to experience an immersive operation with ultra-low latency and dynamic high-fidelity. With fabric sensing materials, the interaction between human and semi-simulated organs can be captured in detail, which also facilitates human body modeling. Driven by computer science and material science, fabric and digital twin technology can create a virtual surgery practice environment to aid medical students to perform comprehensive training for improving education quality while saving medical resources.

5. References

1. J. R. Vitt, C.-H. Sun and P. D. Le Roux *et al*. Minimally invasive surgery for intracerebral hemorrhage. *Current opinion in critical care*, 2020; **26**; 129-36.
2. S. Schilde, K.-S. Delank and D. Arbab *et al*. Minimally invasive vs open akin osteotomy. *Foot & Ankle International* 2021; **42**; 278–86.

3. G. Abhinav and S. N. Subrahmanyam. Artificial intelligence in healthcare. *Journal of Drug Delivery and Therapeutics* 2019; **9**; 164–6.
4. F. Jiang, Y. Jiang and H. Zhi *et al*. Artificial intelligence in healthcare: past, present and future. *Stroke and vascular neurology* 2017; **2**.
5. R. M. Epstein. Assessment in medical education. *New England journal of medicine* 2007; **356**; 387-96.
6. Yan W, Dong C and Xiang Y *et al.* Thermally drawn advanced functional fibers: New frontier of flexible electronics. *Materials Today* 2020; **35**; 168-94.
7. Chen M**,** Zhou J and Tao G. et al. Wearable Affective Robot. *IEEE Access*, 2018; **6**: 64766-64776.
8. R. Hu*, J. Song *et al*. "Machine learning-optimized tamm tmitter for high-performance thermophotovoltaic system with detailed balance analysis," Nano Energy 72, 104687.
9. R. Wang, Z. Du, *et al*. "Magnetic clothing generator for high-performance transduction from biomechanical energy to electricity,"Adv. Funct. Mater. 2107682.
10. S. Zeng, S. Pian, *et al*. "Hierarchical-morphology metafabric for scalable passive daytime radiative cooling," Science 373 (6555), 692-696.
11. Y. Ma, *et al*. "Flexible all-textile dual tactile-tension sensors for monitoring athletic motion during Taekwondo," Nano Energy 85, 105941.
12. Liu L, Zhao F and Liu W *et al*. An electrochemical biosensor with dual signal outputs: toward simultaneous quantification of pH and O2 in the brain upon ischemia and in a tumor during cancer starvation therapy. *Angewandte Chemie International Edition* 2017; **56**; 10471-5.
13. Ma W, Chen S and Yang S *et al*. Hierarchical MnO2 nanowire/graphene hybrid fibers with excellent electrochemical performance for flexible solid-state supercapacitors. *Journal of Power Sources* 2016; **306**; 481-8.
14. Li P, Jin Z and Peng L *et al*. Stretchable all-gel-state fiber-shaped supercapacitors enabled by macromolecularly interconnected 3D graphene/nanostructured conductive polymer hydrogels. *Advanced Materials* 2018; **30**; 1800124.
15. Ren J, Zhang Y and Bai W *et al*. Elastic and wearable wire-shaped lithium-ion battery with high electrochemical performance. *Angewandte Chemi* 2014; **126**; 7998-8003.
16. Ren J, Li L and Chen C *et al*. Twisting carbon nanotube fibers for both wire-shaped micro-supercapacitor and micro-battery. *Advanced Materials* 2013; 25; 1155-9.
17. He J, Lu C, Jiang H *et al*. Scalable production of high-performing woven lithium-ion fibre batteries. *Nature* 2021; **597**; 57–63.
18. Li X, Lin Z H and Cheng G *et al*. 3D fiber-based hybrid nanogenerator for energy harvesting and as a self-powered pressure sensor. *ACS nano* 2014; **8**; 10674-81.
19. Fu X, Sun H and Xie S *et al*. A fiber-shaped solar cell showing a record power

conversion efficiency of 10%. *Journal of Materials Chemistry A* 2018; **6**; 45-51.

20. Pei Q, Yu G and Zhang C *et al*. Polymer light-emitting electrochemical cells. *Science* 1995; **269**; 1086-8.
21. Zheng H, Zhang Z and Jiang S *et al*. A shape-memory and spiral light-emitting device for precise multisite stimulation of nerve bundles. *Nature communications* 2019; **10**; 1-14.
22. Shi X, Zuo Y and Zhai P *et al*. Large-area display textiles integrated with functional systems. *Nature* 2021; **591**; 240–5.
23. Shi J, Liu S and Zhang L *et al*. Smart Textile-Integrated Microelectronic Systems for Wearable Applications. *Adv. Mater.* 2020; **32**; 1–37.
24. Bandari N and Member J D. Tactile Sensors for Minimally Invasive Surgery: a Review of the State-of-the-art, Applications, and Perspectives. *IEEE Access* 2019; **8**; 7682–708.
25. Dong B, Shi Q and He T *et al*. Wearable triboelectric/aluminum nitride nano-energy-nano-system with self-sustainable photonic modulation and continuous force sensing. *Adv. Sci.* 2020; **7**; 1903636.
26. Gul J Z, Sajid M and Choi K H. 3D printed highly flexible strain sensor based on TPU-graphene composite for feedback from high speed robotic applications. *J. Mater. Chem. C.* 2019; **7**; 4692–701.
27. Fujiwara E, Dos Santos M F M and Suzuki C K. Flexible optical fiber bending transducer for application in glove-based sensors. *IEEE Sens. J.* 2014; **14**; 3631–36.
28. Dahroug B, Tamadazte B and Weber S. Review on otological robotic systems: toward microrobot-assisted cholesteatoma surgery. *IEEE Rev. Biomed. Eng.* 2018; **11**; 125–42.
29. Hammond F L, Menguc Y and Wood R J. Toward a modular soft sensor-embedded glove for human hand motion and tactile pressure measurement. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, 2014*. 4000-7.
30. Dong B, Yang Y and Shi Q *et al*. Wearable triboelectric–human machine interface (THMI) using robust nanophotonic readout. *ACS Nano* 2020; **14**; 8915–30.
31. Wang W, Yu A and Liu X *et al*. Large-scale fabrication of robust textile triboelectric nanogenerators. *Nano Energy* 2020; **71**; 104605.
32. Wang, Y, Wu H and Xu L *et al.* Hierarchically patterned self-powered sensors for multifunctional tactile sensing. *Sci. Adv.* 2020; **6**; eabb9083.
33. Jin T, Sun Z and Li L *et al*. Triboelectric nanogenerator sensors for soft robotics aiming at digital twin applications. *Nature communications* 2020; **11**; 1-12.
34. Tao F, Cheng J and Qi Q *et al.* Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing*

Technology, 2018, **94**(4).

35. Fei T, He Z and Liu A *et al.* Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, 2019; **15**(4): 2405-15.
36. Erol T, Mendi A F, Dogan D. The Digital Twin Revolution in Healthcare. *2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, 2020.
37. Hao Y, Miao Y and Chen M *et al.* 6G Cognitive Information Theory: A Mailbox Perspective. *Big Data and Cognitive Computing*, 2021; **5**(4): 56.
38. Li Q, Xia B and Huang H *et al.* TRAC: Traceable and Revocable Access Control Scheme for mHealth in 5G-enabled IioT. *IEEE Transactions on Industrial Informatics*, 2021.
39. Fei T, He Z and Liu A *et al.* Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, 2019; **15**(4): 2405-15.
40. Liu H, Wu H and Khuong Phuong Ong *et al.* Giant piezoelectricity in oxide thin films with nanopillar structure. *Science*, 2020; **369**(6501).
41. Qin Y,Wang X and Wang Z. Microfibre-nanowire hybrid structure for energy scavenging. *Nature*, 2008; **451**(7180).
42. Han M, Wang H and Yang Y *et al.* Three-dimensional piezoelectric polymer microsystems for vibrational energy harvesting, robotic interfaces and biomedical implants. *Nature Electronics*, 2019; **2**: 26-35.
43. Tang Y, Zhou H and Sun X *et al.* Triboelectric Touch-Free Screen Sensor for Noncontact Gesture Recognizing. *Advanced Functional Materials*, 2020; **30**(5).
44. Chen B, Tang W and Wang Z. Advanced 3D printing-based triboelectric nanogenerator for mechanical energy harvesting and self-powered sensing. *Mater. Today*, 2021.
45. Jin T, Sun Z and Li L *et al.* Triboelectric nanogenerator sensors for soft robotics aiming at digital twin applications. *Nature Communications*, 2020; **11**(1): 5381.
46. Gilbert S, Dmitriy D and Karnaushenko *et al.* Magnetosensitive e-skins with directional perception for augmented reality. *Science Advances*, 2018; **4**(1).
47. Melzer M, Mönch J and Makarov D *et al.* Wearable magnetic field sensors for flexible electronics. *Advanced materials (Deerfield Beach, Fla.)*, 2015; **27**(7).
48. Han M, Wang H and Yang Y *et al.* Three-dimensional piezoelectric polymer microsystems for vibrational energy harvesting, robotic interfaces and biomedical implants. *Nature Electron*, 2019; **2**: 26-35.
49. Sundaram S, Kellnhofer P and Li Y *et al.* Learning the signatures of the human grasp using a scalable tactile glove. *Nature*, 2019; **569**; 698-702.
50. Zhang L, Lin S and Hua T *et al.* Fiber-Based Thermoelectric Generators: Materials, Device Structures, Fabrication, Characterization, and Applications. *Advanced Energy Materials*. 2018; **8**: 1-18.

51. Bai H, Li S and Barreiros J *et al.* Stretchable distributed fiber-optic sensors. *Science*, 2020; **370**: 848-52.
52. Cooper C, Arutselvan K and Liu Y *et al.*Stretchable Capacitive Sensors of Torsion, Strain, and Touch Using Double Helix Liquid Metal Fibers. *Advanced Functional Materials*, 2017; **27**(20).
53. Liyanaarachchi S, Riihonen T, and Barneto C *et al.* Optimized Waveforms for 5G–6G Communication With Sensing: Theory, Simulations and Experiments. *IEEE Transactions on Wireless Communications*, 2021; **20**: 8301-15.
54. Fortino G, Savaglio C, Spezzano C, Zhou M. Internet of Things as System of Systems: A Review of Methodologies, Frameworks, Platforms, and Tools. *IEEE Trans. Syst. Man Cybern. Syst.*, 2021; **51**(1): 223-236
55. Chen M, Xiao W and Hu L *et al.* Cognitive Wearable Robotics for Autism Perception Enhancement. *ACM Transactions on Internet Technology*, 2021; **21**(4): Article No. 97.
56. Y, Porambage P and Liyanage M *et al.* A Survey on Mobile Augmented Reality With 5G Mobile Edge Computing: Architectures, Applications, and Technical Aspects. *IEEE Communications Surveys & Tutorials*, 2021, **23**(2): 1160-92.
57. Qiu Y, Yin W and Wang L *et al.* A High-Performance and Scalable NVMe Controller Featuring Hardware Acceleration. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*.
58. Cao K, Hu S and Shi Y *et al.* A Survey on Edge and Edge-Cloud Computing Assisted Cyber-Physical Systems. *IEEE Transactions on Industrial Informatics*, 2021; **99**:1-1.
59. Chen M, Jiang Y and Guizani N *et al.* Living with I-fabric: Smart living powered by intelligent fabric and deep analytics. *IEEE Network*, 2020; **34**(5): 156-163.
60. Ji B. Several Key Technologies for 6G: Challenges and Opportunities. *IEEE Communications Standards Magazine*. 2021; **5**(2):44-51.
61. Hao Y, Chen M and Zhang Y *et al.* Deep Reinforcement Learning for Edge Service Placement in Softwarized Industrial Cyber-Physical System. *IEEE Transactions on Industrial Informatics*, 2021; **17**(8): 5552-5561.