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Perspective

Mechanoluminescent materials for athletic analytics in sports science

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Life lies in movement, and sport is one of the most important parts in our life. With the development of advanced science and technology, such as the Internet of Things and big data, sports science has experienced some revolutionary changes [1]. This raises a higher demand to the body and health conditions and promotes various athletic events in terms of entertainments, exercises and competitions. For professional sports, an important link is to improve and sustain performance, especially to explore an effective sport-analytic method. Athletic analytics play an important role in all sports games and competitions as well as physical education and training (Fig. 1a, b). It is usually difficult for the beginners and trainees to estimate athletic positions or postures correctly as a sport goes on. They may tend to fail in controlling the intensity of the applied force, awkwardly estimating the falling point in sports like ball games and competitions. Therefore, to ensure the performance in the process of athletic competition and sport games, it is necessary to explore an effective method for athletic analytics of sports science by combining with smart materials and advanced technologies.

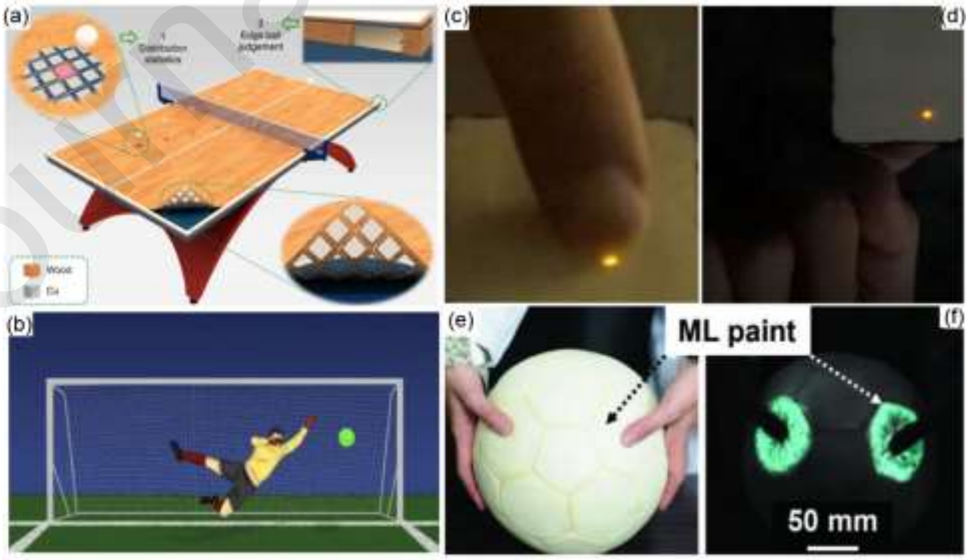

Fig.1 (Color online) (a) Schematic of the smart ping-pong table based on the triboelectric nanogenerator. Reprinted with permission from Ref. [1], Copyright © 2020, Nature Publishing Group. (b) Picture showing a scene where a football player blocks a football. (c, d) Photos of a mechanical-to-

light conversion device for the visible light emission under mechanical stimuli from the front and back sides, respectively. Reprinted with permission from Ref. [2], Copyright © 2020 Wiley-VCH. (e) A routine football coated with a layer of mechanoluminescent materials. (f) The light emitting from the football under external force, showing an intensive visible-emission under fingers pinch, where the position of pinch and the distribution of pressing force can be seen directly by naked eyes from a wide angle of view. Reprinted with permission from Ref. [3], Copyright © 2019 Wiley-VCH.

Mechanoluminescence (ML) materials are a type of novel luminescent materials that capable of emitting light under the dynamic force/pressure such as pressing, stretching, bending, shaking, peeling, scraping, squeezing, impacting, wind blowing, rain-dropping, and even heart beating [4–15]. Different hosts such as ZnS, $SrAl_2O_4$, and CaZnOS, etc. doped with metal ions such as Mn^{2+} and Cu^+/Cu^{2+} or different lanthanide ions such as Pr^{3+}, Tb^{3+}, Eu^{2+}/Eu^{3+} and Er^{3+} etc. are known to demonstrate efficient ML. Different from the photoluminescence (PL) and electroluminescence (EL) materials, ML materials straightforwardly emit visible light under a moderate external mechanical force without requiring light-excitation or electricity. The representative ML luminous-photos under stretching and pressing are shown in Fig. 1c–f. The phenomenon of ML is also called mechanically induced/excited luminescence, piezo-luminescence, or triboluminescence [2, 4, 5]. ML materials fall into three categories: elastico-mechanoluminescent (EML), plastic-mechanoluminescent (PML) and fracto-mechanoluminescent (FML) materials. Among them, PML and FML cannot repeat stably, while EML materials emit sustainably and repeatedly for over tens of thousands times. Nowadays, there are two kinds of EML materials with self-reproducible performance originating from triboelectric and piezoelectric effect respectively. The former is suitable for triboelectric related devices, while the latter is more proper for strain sensors such as flexible devices. When mixing with some adhesive, ML powders could be coated or paved onto the surface of a solid object. The greater the stress/pressure applied onto the surface covered with ML layered-composites, the higher the ML brightness/intensity can be obtained. EML materials are reported to be even highly sensitive to the pulse pressure induced by heart beating [15]. Since the detection of ML signal depends much on the limit of photodetector, we can improve sensitivity and signal-to-noise ratio by using the advanced single photon detector or integrating with advanced photoelectric detection materials. EML has great potential applications in the fields of stress sensing, display, artificial skin and triboelectric nanogenerator [5]. The performance of EML materials is gradually improved during the past decades. However, there is still room for further improvements. To enhance the ML brightness, we can bring in mechanical-energy harvesting sensitizer to enhance the luminescence, and realize quantum cutting for down-conversion ML to improve the efficiency. For the synthesis of composite reinforced fibers with enhanced mechanical properties and water resistance, we could adopt the method of whisker-composites reinforcement [5], try to develop new structures of EML materials, such as one-dimensional piezoelectric semiconductor [7], and new heterojunction materials [2]. An analogous semiconductor heterojunction lighting mechanism is necessary to be applied in the development of mechanically excited micro-LED for a self-powered stress-emitting cells [2, 3, 7], the stress-emitting semiconductor materials need suitable crystal structures (piezoelectricity is preferable in most cases), beneficial defects, and the accurate synergistic effects of luminous dopants such as transitional metal and lanthanide ions [2,4].

With the rapid development of materials technology and artificial intelligence, EML materials have been developed with the performance of battery-free motion-driven light emission. It can be used on the surface of a moving object to sense the intensity of the applied force, while under dynamic force, the object will emit light in response to the stimuli and the light emission could last for several seconds. When paved into the table, court, racket, it can record the athletic contact position and force distribution. Most inorganic EML materials show stable ML with linear response to the applied force over a wide range (Fig. 2a), as well as strong weather resistance, chemical stability, and operation repeatability (Fig. 2b). Based on EML materials with dynamic properties, a smart approach for athletic stress-visualization and analytics is prospected. On this basis, the hitting or falling positions are judged through the luminous points, while the actual stress is estimated by the emission intensity. These features can be used in athletic analytics by monitoring force position and making force magnitude visible, thereby, the trainees would accurately judge and control games and improve their athletic performance (Fig. 2b). The referees and beginners can conveniently and accurately distinguish and judge a touching position and strength in real-time. It is particularly suitable in sports on campus, gymnasium, indoor and outdoor, as well as some low lighting circumstances. Basically, they are promising in all seasons with varied temperatures, from skating or skiing in winter to swimming or hiking in summer. With few restrictions on places, they can be applied in sports on land, at sea or in the air to achieve stress analysis and even night-vision surveillance and rescue.

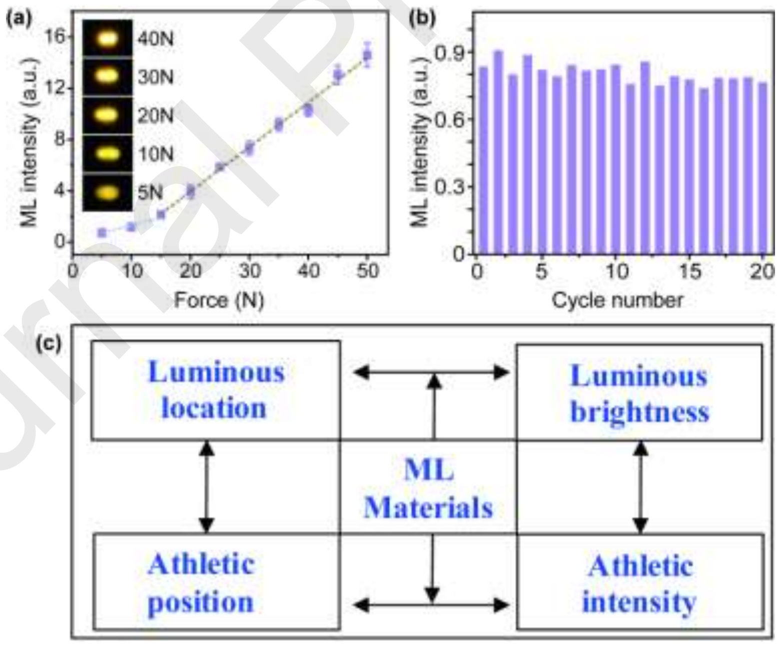

Fig.2 (Color online) (a) Linear relationship between the applied force magnitude and the ML intensity of the developed materials. (b) Repeatability of the EML composite films under continuous mechanical excitation at 10 N. Reprinted with permission from Ref. [2], Copyright © 2019 Wiley-VCH. (c) Schematic diagram representing the teaching and training process by using ML materials. Under the movement force, the luminous intensity (horizontal axis) of ML materials is linearly related to the applied dynamic pressure (vertical axis), and the luminous intensity increases gradually with the

growth of the applied pressure. Due to the repeatability and self-recovery luminescence under mechanical stimuli, this principle can be used in athletic analytics for sports science.

Besides building of a new method for athletic analytics, it may also bring pleasure to the teaching and training, and improve the training results of various sports. Record ML by photos taken by a camera, subtract the background from the environment, and then the gray value of the image could represent the relative emission intensity and further the relative stress owing to a linear relationship. Generally, the effect will be better in dark or low-light environment. However, if utilizing the ML phenomenal materials with the emission insignificantly overlapping to the solar spectrum, such as solar-blind infrared or ultraviolet light, they can be used under natural sunlight. The ML units can be directly integrated with photosensitive devices such as photoresistors in the sport field to real-time sense light signals over a comprehensive device with remote data processing. Owing to the capable of direct mechanical-to-light conversion with linear response and good repeatability, EML materials can be adopted to various ball-related sports such as basketball, volleyball, tennis, golf and table tennis as well as the stress judgment and positioning training in various hitting sports. First of all, the basic and relatively simple step is coating the object with the touching self-luminous powder epoxy, the rest goes into sport movement and athletic analysis. Meantime, the athletic position can be distinguished or judged by the EML. The stressed position of the objects can be judged by movement action such as touching/hitting point of the stimuli-luminous emergent area. Simultaneously, the athletic strength can be monitored by the brightness/intensity of emitting light. Thus utilizing novel ML materials and following new approaches for their applications, it is possible to evaluate the amplitude of applied force and gradually controls the sport in motion in order to improve the athletic performance. We believe that such methods are prospective to be used as a general rule to guide athletic analytics for sports science.

Currently, the brightness value of 200–300 cd/m^2 can be achieved under a moderate mechanical force (finger drive, brightness is proportional to pressure). It can be close to the brightness of ordinary LCD and mobile phone display. However, there are still lots of issues to be addressed and improved. At present, there are few systematic and direct experimental evidences explaining the luminescence mechanism of EML, including the type of carrier, and the confirmation of repeated charge transfer and energy cycle transfer driven by stress. Yet, some aspects are not clear, accomplishing certain limitations on the prediction of materials. It is like LEDs are not just hanging on trees for people to enjoy its glistening. In future, with the introduction of new mechanisms and models such as the self-powered stress LED with semiconductor herojunctions as well as with the help of dynamic microscopy such as the in-situ stress-loading characterization of its structure (atomic displace and dislocations), electrical and optical properties, it will be expected to realize a crucial improvement of ML material performances. Thereafter, we believe ML will show its unique advantages in more and more areas of life.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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