A Review of Wearable Technology

Moving Beyond the Hype: From Need through Sensor Implementation

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***Abstract*— Wearable devices have garnered increased attention over the past years by the sports industry, military, and general public for everyday use. Technological advancements have enabled athletes, sports teams, soldiers, and physicians to track functional movements, workload, biometric and bio-vital markers to maximize performance and safety while minimizing the potential for injury or accidents. Wearable monitoring systems can provide continuous physiological data thus enabling accurate treatment plans and specific recovery programs. Herein, we present a review of the wearable sensors field in sports and emergency medicine and highlight our current work and collaborations which bridge academia, healthcare professionals, sports team physicians, Life Flight operations, and ED/trauma operations. A key outcome of this work is the identification of crosscutting themes that indicate critical path items for future research.**

Keywords*— *Wearable Technology; MEMS; Flexible Electronics; Sports Medicine; Data Analytics; Internet of Things (IoT)

I. Introduction

The human skin is the largest organ in the human body. Its epidermal and dermal layers serve as the outer envelope to contain all bodily fluids and tissue constituents and serve as a protective layer for pathogens, environmental hazards, and toxins. Physiological measurements that utilize the skin surface have garnered interest over the years as evidenced by the increase in research and development efforts in this area. Wearable electronics are devices that are near the body or on it, adhered to the skin surface. These devices monitor physical and chemical signals (i.e. respiratory rate, heart rate, electrocardiograms, skin temperature, bodily motion, brain activity, and blood pressure) generated by the human body and transmit these signals (preferably by wireless) to a device or the web thereby providing an avenue for health monitoring, disease diagnosis, or therapy. Currently, majority of wearable devices can detect a single measurement at a time (i.e. physical or electrophysiological) thereby significantly limiting and hindering monitoring and diagnosis opportunities. To produce wearable physical sensors, large-area integration and conformal lamination onto irregular and coarse structures on the human body are needed. Additionally, maintaining adhesion between the sensor and skin is vital for sensor reliability and function. The growth and adoption of mobile health-care technology and application development (i.e. iOS and Android) is promising to enhance the quality of life for elderly, chronic disease, and healthy patients due to wireless transmission of data. Pedometers, accelerometers, gyroscopes, electrocardiogram monitors, and heart-rate monitors have been packaged into personal devices for a variety of applications ranging from ambulatory monitoring in elderly patients for falls to the development of exercise programs, to monitoring vitals of soldiers on the battlefield, and to sports medicine. On the sports medicine front, wearable technology has been widely utilized by athletes to monitor their endurance levels, player movement, workloads, mechanical forces (i.e. stress/strain), impact, and biometric markers. Monitoring these variables may allow for identifying biomechanical fatigue and early intervention to prevent injury and maximize player output and performance. Additionally, there is interest in developing wearable devices as a diagnostic platform to measure stress in drone pilots. Sensor fabrication, material selection, sensor packaging, electrochemical and mechanical response, adhesion, and data transmission are all factors imperative for device success, accuracy, and longevity. Translation of the detected stimuli into a signal that can be interpreted by a physician or necessary individual is imperative for successful translation as illustrated in figure 1. Herein, we review the utility and applicability of biomedical sensors in the fields of sports medicine, emergency medicine, and trauma care and introduce solutions to overcome current hurdles facing these fields.

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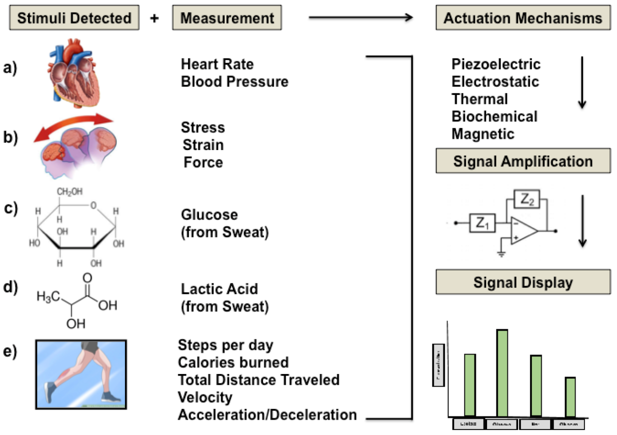

Fig. 1. Current electrochemical to signal pathways for wearable sensors

II. WEARABLES FOR SPORTS MEDICINE

Over the last decade or so, athletes were taped via video recording and their stats were analyzed utilizing computer digitization to assess locomotion and to improve sports performance. Unfortunately, many issues exist. These include questionable validity of the acquired data, labor-intensive nature of collecting data, manual hand-notation techniques, and the inability to track athlete position, movement, displacement, and velocity. GPS (global positioning system) and accelerometer technology provided a viable and accurate solution to the aforementioned issues. The development and growth of GPS technology from the 1990s has allowed for the collection of real-time data on human locomotion to examine sport performance in an accurate, reliable, and efficient manner. There are two types of GPS devices that exist today: 1) differential and 2) non-differential with the former being used to obtain speed, position, and distance measurements [1-3]. The latter are preferred due to their low cost, form factor, weight, and simplified data analysis procedure. Recently, GPS have been combined with tri-axial accelerometers to gather data of physical activities conducted during the day. Semiconductor devices based on piezo- resistive, piezoelectric, and differential capacitive technologies are commonly used in accelerometers. Differential capacitors accelerometers are most utilized in sports due to their ability to classify posture, movement, energy expenditure, and balance control. The combination of GPS, accelerometer, and heart rate technology, herein referred to as integrated technology (IT), into one sensor has allowed for a greater understanding of the energy cost and specificity of movement patterns in controlled situations.

Integrated technology was first introduced in 2003 with the SPI-10 and recent models include the MinimaxX OptimEye by Catapult, SPI-Pro, and SPI Elite [3]. The MinimaxX series, the most commonly used IT device, has been utilized in Australian Rugby, Australian Football, soccer, cricket, field hockey, and the National Football League [3]. The OptimEye, the most commonly used model in research, monitors more than 20 measurements ranging from impact load, directional movement, velocity, and activity identification [3]. The use of IT in team sports settings has been deemed reliable and valid. Data collection requires minimal human involvement; thus enabling rapid data collection and analysis compared with previously mentioned video-based analysis. Validation of IT for team sports started occurring over the last half of the decade meaning this analysis strategy requires further research and examination to address its limitations. Recently, a professional sports team utilized the OptimEye sensor to monitor the workload and payload of its players over a specific duration [4]. GPS data of the players was recorded and data showed significant differences in movement profiles between positions in both offensive and defensive teams. The data generated from IT-based wearable devices provides baseline information that may aid in the development of performance programs or injury prevention strategies based on player position [4]. GPS technology in team sports has been limited to outdoor environments as these devices have been unable to track movement patterns in a closed-roof setting. Hence, the use of IT has been limited to field-based team sports. Past work using IT-based devices have determined the speed, position, and distance of athletes during games. Current studies have expanded on this work to measure and interpret physiological data such as heart rate, magnitude, and frequency of contact with the goal of minimizing or preventing soft tissue injuries.

Soft tissue injuries are currently the most common type of injury in athletes and comprise approximately 10% to 55% of all injuries [4]. The majority of muscle injuries (>90%) are contusions or strains [4]. The most severe types can produce chronic pain, dysfunction, recurrence, and even compartment syndrome. Often times such injuries are caused by dehydration, improper treatment, or poor tracking. The next generation of wearable devices can be designed to alleviate this major injury type. Additionally, concussions remain a major issue in sports. Currently, there is no device on the market, which has been qualified to detect and monitor the impact force exerted on the head during a game of American football. Thus, the development of a wearable device to measure impact forces of the head is of great interest to minimize concussions and ultimately decrease the incidence of Chronic Traumatic Encephalopathy (CTE), progressive degeneration of the brain due to repeated trauma, in athletes. The development of an all-encompassing device capable of measuring both biometric (stress, strain, impact forces) and bio-vital signs (i.e. glucose, lactic acid) is needed. These detected stimuli can enable team physicians to gauge the health of players that will help them identify areas of concern and potentially minimize the number of injuries. A recent study by a major American sports network showed that athletes who used wearable technology during their workouts were 60% less likely to experience soft-tissue injuries during the course of the season [4].

On this front, the utilization of flexible electronics to create a sensor capable of adhering to the surface of the skin to detect bio-vitals is of interest and desired by the sports community. Our rendition of such a sensor is illustrated in figure 2. While these sensors need to be functionally accurate, they must also be power efficient, durable, lightweight and be able to stretch and flex. These requirements are crucial for epidermal electronic devices where the mechanical compliance and integrity with the human skin is crucial for sensor functionality (i.e. sensor material strain needs to exceed 100%) [5]. The application of nanomaterials are drawing heightened attention for functional sensing elements due to their excellent electrical, mechanical, optical, and chemical properties. Polymers such as polydimethylsiloxane (PDMS), silicon and thermoplastic elastomers, are utilized as flexible substrates due to aforementioned criteria [5]. Additionally, graphene, carbon nanotubes, nanowires, and hybrid micro/nanostructures have been utilized to fabricate epidermal sensors.

We are currently not aware of any device that holistically meets the technical and application needs stated above. Researchers at UC Berkeley, University of Cincinnati, and University of California San Diego (UCSD) have developed wearable electronic devices and patches capable of adhering to the skin to detect changes in glucose and lactic acid levels from sweat generated during exercise [6-8]. Sweat contains a variety of biomarkers ranging from electrolytes (sodium, chloride, potassium, calcium) to metabolites (lactate, creatinine, glucose, uric acid) to small molecules (amino acids, DHEA, cortisol) and to proteins (interleukins, tumor necrosis factors, and neuropeptides) [7]. Thus by measuring sweat, researchers can get a thorough understanding of how physical activity and exertion relate to fatigue and injuries. Specifically, measuring lactic acid can provide a useful indicator of a person's ability to cope during rigorous exercise. On this note, researchers from UCSD developed an epidermal tattoo electronic sweat sensor and had subjects wear the device during a simulated exercise routine to measure and determine if a change in lactate can determine when an individual was starting to fatigue [8]. Additionally, researchers from the University of Cincinnati fabricated a wearable device, which utilizes microfluidics to wick sweat from the skin through a membrane that selects for a specific ion such as sodium [6]. In the figure shown in figure 2, the onboard circuitry then calculates the ion concentration and sends the data to a wireless receiver such as a smartphone. There remains a need to design a device that can build off this and other work to measure both bio-vitals and mechanical forces together to give stake-holders and physicians a comprehensive story of the monitored individual.

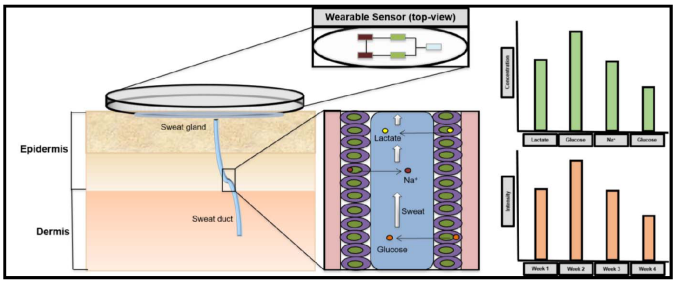

Fig. 2. Epidermal sensor utilizing flexible electronics for analyte detection with resulting analyte and impact force output

Our preliminary work is geared towards the development of a lightweight and non-intrusive sensor able to be adhered to a body or clothing to detect bio-vital and bio-metrics to quantify, track, and monitor performance. Specifically, we seek to measure bio-vital chemistry, detect motion, detect impact and biovital electrical signals. Our proposed device, in whole or in part, can be adapted for other applications as well such as for Life Flight Operations or the ER/Trauma. The fabrication cost of our wearable sensors must be minimized and lower than that of current sensors to enable adoption by a broad market.

As touched upon earlier, an additional area we are interested in focuses on wearable technology for head-injuries. Concussions remain a major concern in contact-laden sports such as rugby and American football, as quantified in figure 3a. Current technology utilizes quantitative electroencephalogram (QEEG) wherein signals from the brain are detected via epidermal-electrodes and the resulting signal is relayed and processed via algorithm which calculates and correlates abnormalities in the EEG signal associated with the pathology of brain injury. Though this technology has shown promise, it cannot be utilized during live-game action. Thus, a wearable sensor capable of detecting impact forces on the brain is of interest. A potential strategy as detailed in figure 3c could involve a polymeric and flexible sensor which can relay an impact force on the sensing layer to a chance in voltage. This change in voltage can initiate a signal to the team physician or independent neurological consultant indicating the severity of the hit received. This signal could greatly expedite current protocols and dramatically increase player safety for the short and longterm.

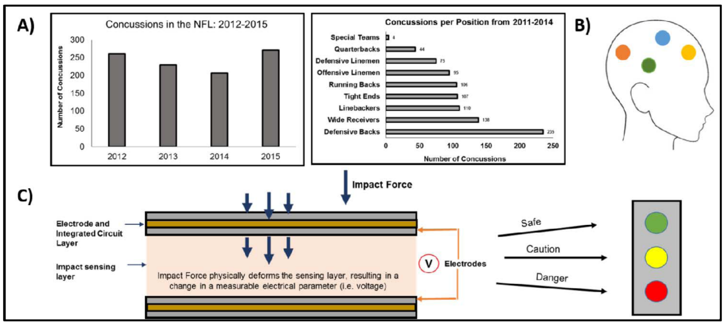

Fig. 3. a) Concussions in the NFL and per position over the last five years, b) Current EEG technology to monitor trauma and stress, c) Our proposed schematic utilizing flexible electronics for impact monitoring towards CTE prevention

III. WEARABLES FOR DEFENSE AND ICU APPLICATIONS

The use of drones in aerial warfare has significantly increased over the last few years. Drone pilots are often overworked leading to fatigue thus at times impairing their decision-making ability. Additionally, studies from the US Air Force have shown that drone pilots experience the same mental stress (PTSD, depression, and anxiety) exhibited by soldiers or aerial pilots at the battlefield. There is a growing need to monitor the stress levels of drone pilots to moderate their workload to prevent on the job fatigue and accidents from occurring. In addition to funding the aforementioned research, the Department of Defense has also exhibited immense interest in developing wearable devices utilizing smart textiles (integrated electronics in clothing and fabrics) to detect and relay vital signs from the battlefield to a centralized location thereby constantly monitoring the physical state of the soldier or pilot.

Stress monitoring can also be translated to those working in an ICU dealing with the medical transport of patients. The use of medical transport has increased dramatically and will continue to grow as health care costs drive community hospitals to consolidate costly services [9]. Effective medical transport requires and necessitates the practitioner to have situational awareness and manage the needs of the patient in an unstructured, uncertain, and stressful environment. Medical transport teams need to be trained in effective communication and handoffs as they provide a crucial link between healthcare settings as patients are moved from one arena to another. The World Health Organization has identified communication during patient handoffs (transfer of information from one provider to another) as a priority patient concern [9]. Protocols are in place to ensure that handoffs are structured; however, often times that is not the case. Failure to communicate in an effective manner leads to poor coordination, increased errors in diagnosis, and adverse events. Researchers have felt the need to analyze patient handoffs during joint training simulation exercises between pre-hospital rescue and air medical transport crews to identify gaps in communication and uncover information needed for a successful handoff [9]. Wearable technology can play a vital role in decreasing handoff related errors. By monitoring the stress patterns and correlating them with the moments when key decisions are made, medical personnel can tailor the training regimen to ultimately decrease handoff errors caused by the practitioner. Specifically, by correlating and matching periods of high stress in practitioners with that of key decision-making periods during handoff, medical personnel can help identify gaps in judgment [10]. Analysis and translation of acquired data are imperative for this to occur, thus further work on the analytics side is imperative for wearable technologies to make their mark in the sports medicine, military, or ICU front.

IV. DATA ANALYTICS

Data analytics is imperative for interpreting the large volume of biometric and bio-vital information provided by wearable sensors. Battery power generally limits the volume of data that can be collected and communicated by a wearable sensor. Pre-processing and acting on some data locally on the sensor before transmission will preserve battery life and minimize off-line data analysis. This implies that some data will be discarded or not stored remotely. Thus, there is a trade-off between transmitting all data to a server and preserving battery life. Additionally, interpreting these large data sets poses challenges. Firstly, the data is heterogeneous, originating from various sensing modalities. Another challenge arises from the potentially sporadic nature of the data. Signal processing methods are needed for dealing with non-uniformly sampled data. The large volumes and complexities of big data require the discovery of new relationships and new data mining techniques. The raw sensor data is utilized as a starting point of the data mining procedure [11]. An algorithm is then applied to translate and convert the raw sensor data into concrete data that can be analyzed by a medical professional. To classify stress and other vital signs from wearable sensors, military and hospital officials can use the aforementioned data processing methods for a robust analysis to help soldiers, drone pilots, airmen, and medical practitioners. With the advent of wearable sensors in the sporting industry, data analytics has been utilized to track players' health over a short or long term period thus providing a thorough means for recovery, training, and increased performance. American football teams have utilized this data with wearable sensors to track player load and intensity thereby minimizing soft tissue injuries over training camp and during the course of a season.

V. DISCUSSIONS AND CONCLUSION

Three crosscutting issues dominate the translation of wearable technology into the "next generation" of products: 1) Analysis of voluminous data sets that include natural language processing to enable the conversion of data into actionable knowledge for clinical decision support, 2) test beds for controlled case studies that will provide a foundation for testing specific physiologic hypotheses, and 3) multi-disciplinary teams of investigators– the so-called "team science" approach of the National Science Foundation (NSF) – to ensure critical thinking prevails at the onset of translational work.

In summary, this work sought to review the wearable technologies field and suggest promising approaches to overcoming current drawbacks to improve patient outcomes. Flexible electronics as substrates for epidermal sensors enable detection in a non-intrusive manner thereby improving their utility. As shown in figure 4, technology readiness levels (TRL) for wearable devices highlight the infancy of this field thus detailing the promise and opportunity for future work, collaborations, and commercialization.

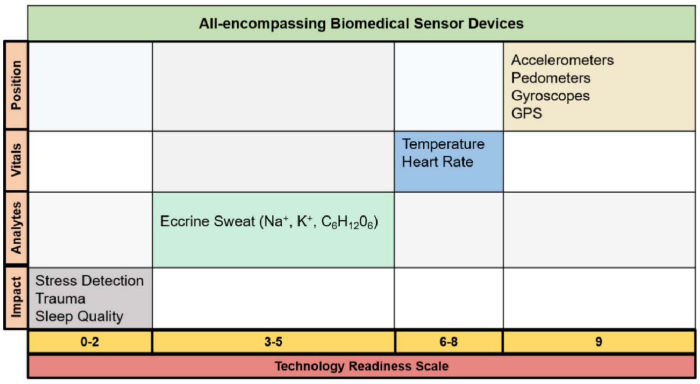

Fig. 4. Technology readiness scale for the wearable technology field

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