Journal of Engineering Science and Technology
Vol. 13, No. 7 (2018) 2195 - 2210

DEVELOPMENT OF A WEARABLE PRESSURE BANDAGE SYSTEM FOR SCORPION STING

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Abstract

This paper presents a wearable pressure bandage system (ScorpioBand) to discourage unsafe first aid practices by scorpion sting victims. A pressure bandage is utilized to apply pressure over the entire surface around the sting point to reduce the likelihood of scorpion envenomation and pressure transducers were used to acquire bandage pressure signals. A Flexiforce pressure sensor interfaced with a PIC16F873A microcontroller based embedded device are the core components of the wearable system. A real-time simulation using myRIO embedded device and LabVIEW software was used to design the developed system. The developed ScorpioBand prototype was implemented as a waistband and it triggers a visual signal when a safe pressure limit is exceeded during application of the pressure bandage. The performance of the developed system was evaluated experimentally and an average bandage pressure of 48.96 mmHg was achieved with three layers of the bandage in 90% of the trial cases conducted by first-time users. The implication of the results is that inexperienced users in rural communities can apply the developed wearable bandage system to achieve the required bandage pressure for scorpion sting.

Keywords: Pressure bandage, Scorpion sting, Wearable computing.

1. Introduction

Scorpions are venomous animals that cause health challenges to their human victims through injection of a poisonous substance when they sting. Scorpion-stings occur annually and often lead to deaths. Scorpions are eight-legged anthropoids (Fig. 1) belonging to Arthropoda of the class Arachnida. About one thousand four hundred scorpion species exist, belonging to nine living families [1].

The Buthidae is the only family whose members are capable of causing clinically significant envenomation. Every year, more than three thousand deaths occur for every 1.2 million stings [2]. Studies have shown that there is a high rate of scorpion sting in the Middle East [3]. A scorpion sting patient may have to travel several miles, sometimes on foot to access the nearest health care centre. This situation sometimes leads to death due to cardiac and respiratory arrest caused by scorpion-sting [4]. A more problematic situation is when individuals with little or no experience in managing scorpion stings resort to unsafe practices such as tying the limb of the victims out of desperation with the hope of stopping venom flow. Similarly, several traditional remedies for scorpion stings such as eating live scorpions or applying scorpion oil to the sting point have been described in the literature [5].

Fig. 1. A Scorpion of the Scorpio Maurus Townsendi species [6].

A common practice in Nigeria for scorpion-sting victims is to tie a piece of fabric around the affected body part, just above the sting point with the hope of reducing the venom flow. Medical research has shown that this approach is ineffective and dangerous to health if excess pressure is applied [7]. The suggested approach is the use of Medical Compression Bandages (MCBs); however, these bandages have to be applied by skilled health workers [8]. To the best of our knowledge, there is no established scientific method of applying MCBs on the scorpion-sting point with a view to accurately determining the applied pressure. This study addresses this gap through the development of a pressure bandage system for scorpion-stings for victims who cannot access a hospital on time. Rural inhabitants with little or no user experience and support will benefit from this research because it will provide a cost-effective pressure bandage system to manage scorpion-stings without engaging in unsafe practices. The remaining section of the paper is organized as follows: Section 2, presents a summary of the theoretical framework for a pressure bandage system and a summary of related works. Section 3, describes the materials and methods used in this research. A detailed account of the design of the ScorpioBand and experimental validation of results are also presented. The experimental results and discussions are presented in Section 4. Section 5 concludes the paper.

2.` Scorpion Stings

When a scorpion stings, a venom-containing fluid is injected from the glands in its tail. The venom glands produce venom which contains peptides [9]. Scorpions usually inject their venom skin deep to subcutaneous tissue, which is then distributed to other parts of the body by the circulatory system [1]. Venom is almost completely absorbed from sting point in 7 to 8 hours [10]. The concentration of venom in the blood increases from 70% to 100% within 15 minutes and 101± 8 minutes respectively in experimental animals [11]. Scorpion stings cause pain as well as swelling around the sting point and could lead to envenomation which could lead to respiratory failure [12]. Several first aid techniques for venomous stings exist such as constriction bands, cold compress and pressure immobilization method. The most effective techniques for scorpion stings are the pressure immobilization method, keeping the scorpion sting victim still and rapidly transporting the person to a hospital. However, practices such as incision over the scorpion-sting point, chemical application, cauterization, suction, tourniquet and electric shock are harmful because they may cause more tissue injury leading to uncontrolled bleeding [12].

2.1. Effect of pressure bandage on venom flow caused by scorpion stings

The human circulation system facilitates venom flow from sting point to organs of the body. The tissue blood flow rate (Q) determines how much blood is supplied to organs of the body. This flow rate is directly proportional to the radius (r) of the vessel carrying the venom-infested blood flowing from the sting point to other parts of the body, Eq. (1).

$$Tissue\ blood\ flow\ rate\ (Q) = \frac{\Delta P \pi r^4}{8L\eta} \tag{1}$$

It can be deduced from (1) that exerting external pressure upon the blood vessels in the circulation system such as arteries, veins and capillaries restricts tissue blood flow and thus venom flow. When the external pressure is generated by a pressure bandage, the relation to calculate sub-bandage pressure is given by (2) [13]

$$P = \frac{T}{C \times W} \tag{2}$$

From (2), it can be deduced that for a bandage of fixed width (W), the tension (T) of the bandage and its circumference (C) affects the surface pressure it generates. The value for sub-bandage pressure obtained when using the relation in (2) is accurate only at the time the bandage is being applied. The European pre-standard for Compression Hosiery (CEN) maintains a standard for pressure levels of pressure bandages [14]. For scorpion-sting, a pressure range of 31 to 43 mmHg (CCI II moderate) is sufficient to constrict venom flow on the subcutaneous tissue and prevent envenomation.

2.2. Common practices of treating scorpion sting in rural areas

There are several unsafe practices associated with a scorpion sting. In Mexico, some of the prevalent treatment includes ingestion of the scorpion venomous glands, drinking alcohol and eating live scorpions at the same time, making an incision in the sting area to induce bleeding and in this way liberating the venom [15]. Discussions with medical doctors during the current research revealed that these practices are unsafe because injection of these substances may increase the blood pressure and help spread the scorpion venom faster. The incision in the sting area could lead to excessive bleeding and infections. Another common practice is the use of a tourniquet. A tourniquet is an apparatus used for constriction of blood vessels in emergencies or during surgical operations. Tourniquet technique is similar to what is practised by individuals who tie the limb of persons stung by scorpions using a piece of cloth, electric wires or twines made from various materials. Studies have shown that tourniquets are ineffective [7], can cause injury [16] and may be dangerous to health due to blood loss and deep vein thrombosis [17]. According to Watt et al. [18], complications due to tourniquets include deteriorating symptoms and respiratory paralysis. There is a potential danger to a patient if compression bandages are not correctly applied. Studies have also shown that compression of the leg veins can lead to a shift in the blood volume with an increase in the preload of the heart [19].

2.3. Related works

Several works have been done in the area of wearable computing applications in medicine. Knight et al. [20] developed the SensVest used for measuring of human movement that can be applied to Newtonian physics. The metric used include force, displacement, velocity and acceleration. The SensVest is not suitable for scorpion sting because it was not designed to measure bandage pressure. A research platform was developed at MIT for context-aware wearable computing. The platform utilizes a wide range of sensors, sufficient computing and communication resources, including a vest [21].

In the area of bandage pressure measurement, Al-Khaburi et al. [22] employed the use of force sensors in a pressure-mapping mannequin leg to determine the pressure gradient and approximate pressure values. The research established how pressure profile of leg could be generated. However, the prototype requires connection of many electrical cables, it is not wearable, not suitable for emergencies and it does not show warning signals when the bandage is misapplied. Hafner et al. [23] conducted a study on compression therapy by evaluating the interface pressure under compression bandages. The pressure sensors used were mostly adapted from the cuffs of sphygmomanometers connected to a system comprising a piezoresistive pressure transducer. The readings were taken in a sitting position with the foot on the floor and the leg in a vertical position. Whereas this is sufficient for compression therapy, it is not sufficient for scorpion-sting situations.

Danielsen et al. [24] carried out a study to compare pressure readings from a long-stretch compression bandage with a short-stretch compression bandage. It was demonstrated that effect of bandage over a long period of time is such that short-stretch bandage does not produce a higher peak working pressure than the long-stretch bandage. A relation based on the use of the Laplace equation was developed for sub-bandage pressure calculation [13]. The relation shows the relationship between sub-bandage pressure, the width of the bandage and number of layers. A recent study has been carried out on automatic scorpion detection using the fluorescence characteristics of scorpion under ultra-violet (UV) light [25]. A major aspect that the ScorpioBand differ from these reviewed works is that it provides a simple wearable device for the measurement and monitoring of pressure bandage applied on the scorpion sting point.

3. Materials and Method

The design goal for the wearable pressure bandage system is to ensure that adequate bandage pressure is applied by continuously monitoring the surface pressure of the applied pressure bandage on a scorpion-sting point. Scorpion venom is injected subcutaneously into the patient, causing it to flow through tiny vessels such as capillaries before getting to the upper part of the body through the vein. We deduce that uniform bandage pressure from a bandage will affect the flow rate of venom-infested blood in the blood vessels.

3.1. Selection of suitable method for automation

The common scorpion sting first aid procedures were identified from the literature and subjected to scrutiny with the assistance of medical experts. The selection process for the best method for automation was done by subjective analysis of each method vis-à-vis the qualitative high-level requirements for the wearable pressure bandage system (Table 1).

Table 1. Scorpion management methods for automation.

Method	Automation	Safety level	Challenges
Cold Ice compress over sting point	Low	High	Non-availability of ice
pressure bandage	High	High	Excessive bandage pressure
Tourniquets	High	Low	Wrong first-aid practice
Injection of antivenom	Medium	Low	Wrong dosage of antivenom for different body size
Electric shock	High	Low	Wrong first-aid practice

The levels namely "High", "Medium" and "Low" in Table 1 are subjective scales to assess the degree of automation possible with the selected methods from the engineering perspective. The scales are also used to assess the degree of effectiveness and safety based on the judgment of medical experts after the proposed automation methods were described to them. After considerations of the possible scorpion management methods for automation, the pressure bandage method was found to be most suitable.

3.2. Design considerations for the wearable pressure bandage system

The pressure bandage was designed to be applied directly over the scorpion-sting point. To facilitate the monitoring of the applied bandage pressure, an embedded device had to be developed as a wearable component of the system. The proper placement of the wearable component of the pressure bandage system was carefully considered. These options are presented in Table 2 along with their strengths and weaknesses. From the positions presented in Table 2, the waistband was selected because it was the most convenient for the intended use for emergencies.

Table 2. Design considerations for wearable component of a pressure bandage system.

Position	Strengths	Weakness
Head Gear	Heads up display for easy monitoring of status of device	Too far away from possible sting point. Expensive Heads up display is required
Vest	A vest can easily be worn	Different vest sizes have to be used for different body sizes
Waist Band	Fast to wear. It can accommodate many body body sizes without affecting circulation.	Relatively far from likely sting point
Shoes	Placement close to sting point because sting often occurs on the feet.	Difficult to get multiple shoe sizes
Belt	Familiar piece of clothing	The buckle can cause injury in emergency situations. Complicated to wear
Socks	Intuitive to use	Socks may not be rigid enough to support electronics

3.3. Design approach for the ScorpioBand

The focal design philosophy for the ScorpioBand is to realize that the device is a wearable, special purpose system for emergencies. The ideal amount of time required to wear the device is in the range of 30 seconds. Accordingly, wearability, ease of use and speed of use were the major design goals considered for the ScorpioBand. The key design specifications were defined under eight headings:

- **Title**: ScorpioBand;
- **Purpose**: standardized pressure bandage application by continuous bandage surface pressure measurements and signalling;
- **Input**: Pressure transducers;
- **Output**: LED to indicate excessive pressure, power on LED, flashing LED to indicate signal transmission;
- **Data**: Pressure readings stored in the internal memory;
- **Performance**: Wearable, continuous monitoring of pressure, no transmission loss, the consistent trigger on excess pressure, no false triggers, always on for duration of use;
- **Power**: A single 9 Volts battery source
- **Physical structure**: Part of a wearable waistband, should not cause discomfort to the wearer or prevent circulation. Should not impose risk to the wearer; and
- **Function**: Sense pressure between 1 mmHg-100 mmHg, process the pressure signals and converts them into appropriate pressure units. Store pressure in non-volatile memory for future reference and optional transfer from a wearable device to a computer using serial-to-USB communication.

The design process for the ScorpioBand started with a focus on the functionality. The constraints introduced by the functional requirements formed the bases for considering the ScorpioBand from the wearability point of view. Accordingly, ergonomic considerations were carried out with an emphasis on safety and functionality first, before acceptability and ease of use.

3.4. Architectural design for the wearable pressure bandage system

The system architecture of the ScorpioBand is presented in Fig. 2. The components of the system are described as follows:

- **Pressure bandage:** The pressure bandage is utilized for pressure application to constrict the scorpion venom in the subcutaneous tissue around the sting point.
- **Pressure transducers:** The pressure transducer functions as a means of measuring bandage pressure. The transducer actually detects pressure changes [26], additional circuitry was required to convert the detected pressure changes into signals that can be used for the system.
- **Wearable device:** Consist of embedded electronics, signalling component and battery:
- **Embedded electronics:** The function of the embedded electronics is to compute bandage pressure by processing the conditioned signal from the pressure transducers. It also coordinates the entire pressure bandage device.
- **Signalling component**: Light Emitting Diodes (LEDs) were used as the major signalling component.
- **Battery**: a 9 Volts battery was used to power both the wearable device and the optional detachable accessory:
- **Detachable accessory:** It is an interface circuit between a general-purpose computer and the embedded electronics. It is not required for the operation of the device. It only provides a means of visualizing the stored pressure measurements using a computer in situations where the victim is able to make it to the hospital. It is also used for testing the functionality of the wearable device.
- **Computer interface circuit:** Transmits signals from the wearable device to the computer using a serial-to-USB interface circuit.
- **USB port:** The USB port was used to provide the connection to the computer using a standard USB cable.
- **Computer analysis software**: It serves the purpose of visualizing logged data from the device on a general purpose computer running the windows platform.

The system utilizes the pressure applicator on the affected limb of a scorpion-sting victim, thereby reducing the likelihood of scorpion envenomation and ensuring that the required pressure is applied, for the right duration and within safe limits to avoid associated hazards. The wearable device triggers a visual signal when a safe pressure limit is exceeded during application of the pressure bandage. Visual signals indicate when pressure is at the desired level by blinking a green LED and excess pressure is indicated by a red LED turns on. Pressures below the desired level is indicated by a green LED staying ON. Design tools used for this process includes Microsoft Visio® for flowcharts, Microsoft Excel® Software for computation of design values, LabVIEW® for real-time blood flow model simulation, and Proteus® Software for hardware operation simulation.

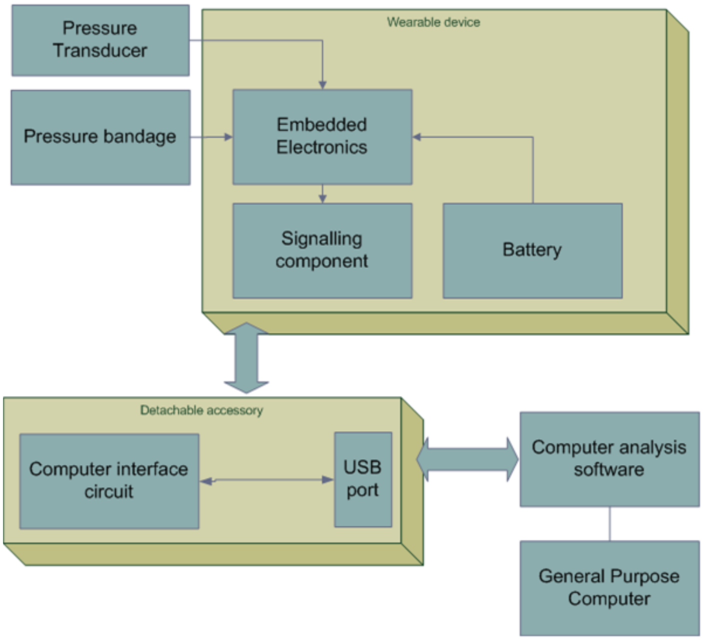

Fig. 2. Block diagram of the pressure bandage system.

3.5. Development of the pressure bandage system

The development was carried out in two stages namely: experimental design and implementation.

3.5.1. Experimental design of the pressure bandage system

The myRIO-embedded platform was used to design and simulate the behaviour of the system. The analogue input of the myRIO device was used to capture readings from the pressure bandage through the Flexiforce pressure transducer using the circuit connection in Fig. 3.

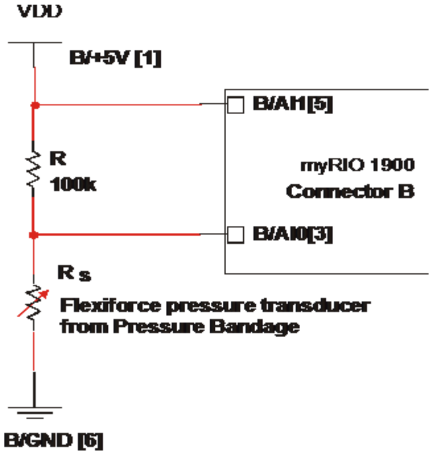

Fig. 3. Connection of the Flexiforce transducer to myRIO embedded device.

The LabVIEW front panel of the wearable pressure bandage system simulation is shown in Fig. 4. The front panel consists of controls for adjusting simulation parameters at run-time. Waveform charts were used to display instantaneous pressure readings from the pressure bandage. The blood flow rate and venom flow rate were simulated using three tanks: the first tank indicates blood volume in the body, the second tank indicates blood volume in the leg, while the third tank indicates the volume of venom in the body. Three light indicators were included in the design to give-off visual signals regarding the intensity of bandage pressure. Accordingly, three levels are indicated namely: high, normal and low. The readings (in Volts) were converted to pressure values and the theoretical value for bandage pressure was computed using the parameters: leg circumference, bandage width and a number of bandage layers. The simulation was simplified by using the typical value of 0.55 L/min for blood flow to the leg. The venom flow was investigated by substituting typical values (=0.02 *D*, *U*=500 μm/s, *D*=7 μm, and μ = 1.4×10^{-2} dyn-s/cm) reported in literature [27] into (3).

$$Q = \frac{\left[\left(\mu\frac{U}{h}\right)(\pi D^3)(0.1D)\right]}{16L\eta} \qquad (3)$$

The flow rate (*Q*) is affected by the diameter (*D*) of the blood vessel. Constricting this vessel reduces the flow rate. The LabVIEW platform was used to observe the flow rate (*Q*) and other parameters in real time while the pressure bandages were applied multiple times. The purpose of the observation was to gain insight into the effect of pressure bandage on venom flow.

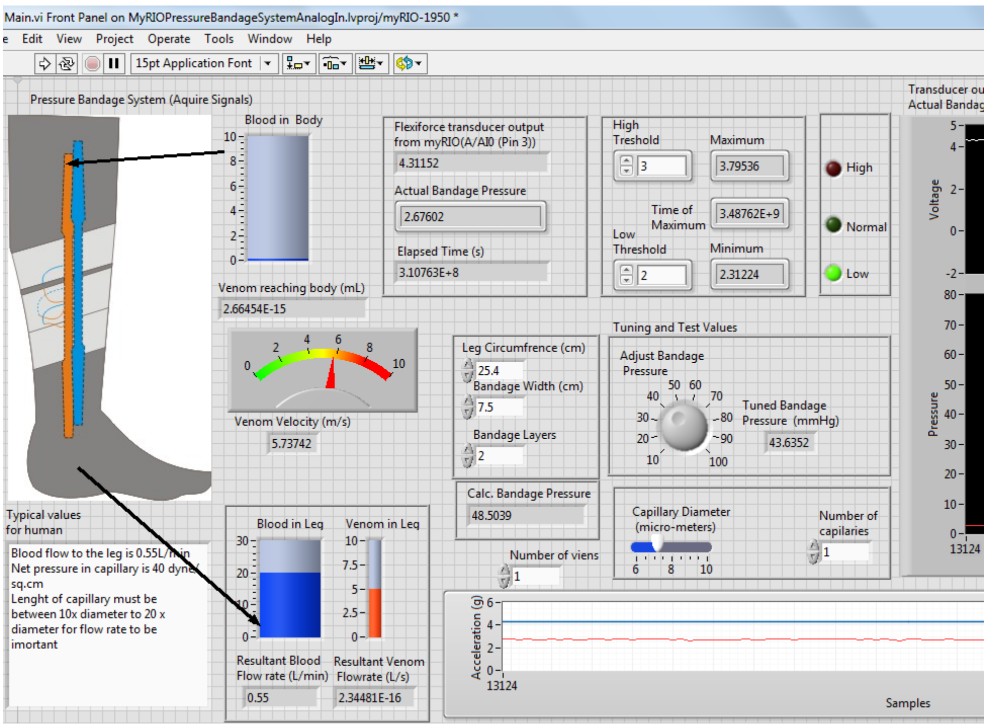

Fig. 4. LabVIEW front panel of the pressure bandage system.

3.5.2. Implementation of the pressure bandage system

The device was implemented using a Flexiforce pressure transducer, a PIC16F873A microcontroller and a pressure bandage. This PIC16F873A microcontroller was selected because it is a high-performance RISC CPU that features up to 368×8 bytes of data memory (RAM) and 256×8 bytes of EEPROM data memory. The inbuilt memory was sufficient for storing pressure readings acquired from the transducer. The flowchart of the PIC16F873A program is presented in *Appendix A*. The pressure sensing method composed of a single Flexiforce pressure transducer manufactured by Tekscan Inc. The circuit diagram is shown in Fig. 5. The pressure transducer was interfaced to the analogue input ports of the PIC16F873A microcontroller through pins 2 and 4. The signalling LEDs were connected to the general purpose ports through pins 13 and 23. The connection between the wearable device and the optionally detachable accessory was achieved using *J1* and *J2* connectors. The pressure readings are transferred using the inbuilt serial communication of the microcontroller. The MAX232 IC was required to provide the required voltage signals for UART/RS232 serial communication standard.

The RS232-to-USB converter module was used because USB connectors are more common than the DB9 connector (CONN-D9M) in most general-purpose computers. The push button was connected to RB0/INT (pin 21) of the microcontroller because it has a built-in interrupt. The purpose of the button is to initiate the transfer of pressure readings.

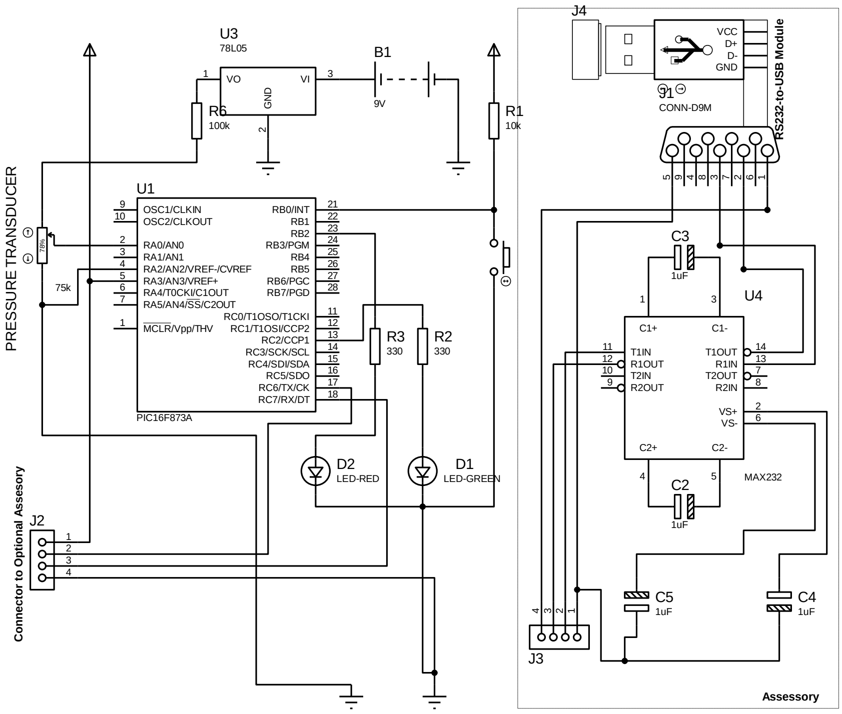

Fig. 5. Circuit diagram of the pressure bandage system.

4. Results and Discussion

4.1. The ScorpioBand prototype

The prototype of the ScorpioBand during operation and under test conditions is shown in Fig. 6. The device is worn on the waist of the scorpion-sting victim. A green LED indicates that the device is turned ON and functional. The pressure transducer which is concealed in the fabric is placed anywhere close to the sting point and a pressure bandage is manually applied over the transducer and the sting point. As the pressure bandage is being applied, a green LED indicates whether the pressure is adequate or not. A blinking green LED indicates that pressure is adequate while a steady red LED indicates excessive pressure. The system automatically stores pressure levels in the internal memory of the wearable device.

(a) The Scorpioband during its use.

(b) Wearable device and detachable accessory interfaced with a computer after its use.

(c) Wearable waistband.

(d) Pressure bandage and fabric-based enclosure for transducer.

Fig. 6. Prototype of the Scorpioband.

4.2. Experimental results

Table 3 presents measured pressure for pressure bandages tested on three volunteers using the developed wearable pressure bandage system. The results reveal that pressure increases with the number of bandage layers applied. The leg circumference also affects the effective bandage pressure such that larger circumferences produce less pressure.

Table 3. Bandage pressure for three volunteers using the ScorpioBand.

Parameter	Value (Volunteer 1)	Value (Volunteer 2)	Value (Volunteer 3)
Bandage width (cm)	7.5000	7.5000	7.5000
Number of bandage layers	3.0000	3.0000	4.0000
Leg circumference (cm)	25.400	22.860	25.400
Theoretical pressure (mmHg)	58.205	64.672	77.606
Measured pressure from system (mmHg)	48.965	70.825	89.406

A comparative study was performed using the ReliON sphygmomanometer as a modified pressure sensor. The ReliON sphygmomanometer was adapted for surface pressure measurement by only slightly inflating the bladder and releasing the air valve until there is no visible change. The pressure bandage is then applied over the bladder.

Table 4 shows measured pressure values for typical test scenarios. The results show that the designed pressure bandage system compares favorably with the ReliON sphygmomanometer device. Similarly, the pressure readings are within the range of theoretical values. The required bandage pressure of 48.96 mmHg for scorpion-sting was achieved in 90% of the cases by applying a three-layer bandage of width 7.5cm using the designed system. The significance of this result is that the level of experience of the user did not affect the achieved pressure.

Table 4. Result of comparison between prototype and modified ReliON Sphygmomanometer.

Description of test scenario	Output Pressure using prototype (mmHg)	Output pressure using ReliON (mmHg)	Calculated Pressure Value (mmHg)
Five layer bandage applied on a leg with circumference 25.4 cm.	89.62	95	97.00
Four layer bandage applied on a leg with circumference 25.4 cm.	70.82	80	77.60
Three layer bandage applied on a leg with circumference 25.4 cm.	48.96	52	58.20

5. Conclusions

A wearable pressure bandage system for scorpion sting was developed to provide a standard way of applying uniform pressure bandage within safe limits. Before now, the established safe way of using a pressure bandage for scorpion-sting is to get a medical expert to apply the correct bandage type using standard procedures.

The designed system eliminates guesswork in the application of pressure bandage on scorpion-sting victims by non-experts. The system achieved success in continuously monitoring pressure bandage accurately and giving off warning signals when bandage pressure is inadequate or excessive. The developed wearable pressure bandage system will prove useful in rural communities in the reduction of complications, injuries and fatalities associated with scorpion-sting due to unsafe first-aid practices.

Finally, the designed system will serve as a research tool and the results obtained from this project will serve as inputs to further research in the treatment of scorpion-sting. Future work will focus on improving the design of the wearable pressure bandage system to make it adapt better to various circumstances and faster to apply in emergency cases.

Attention should also be given to miniaturizing the embedded electronics so that, it can be fitted with the pressure bandage. This must be done in such a way that it does not cause any harm to the user.

Nomenclatures

C	Bandage circumference, m
D	Internal diameter of blood vessel, m
L	Length of blood vessel, m
P	Pressure generated by bandage, Pa
Q	Flow rate of blood through blood vessel, m^3/s
R	Resistance to flow ($8L\eta/\pi r^4$), Pa.s/ m^3
r	Internal radius of vessel, m
T	Tension of bandage, Pa
U	Velocity of blood, m/s
W	Bandage width, m

Greek Symbols

η	Viscosity of fluid, Pa.s

Abbreviations

CEN	European Pre-standard for Compression Hosiery

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Appendix A

Embedded Computer Programme

A.1 Programme Flowchart for Embedded Electronics

MikroBasic programming language was used to develop the embedded computer programme. The purpose of the embedded computer program is to monitor bandage pressure, send warning signals if pressure is inappropriate and store pressure readings, which could also be transmitted at the user's request. The main flow chart of the programme is shown in Fig. A-1.

A.2. Programme Design for Computer Analysis Software

The computer analysis software was developed with VisualBasic.NET to run on the Windows operating system. The analysis involves computing the minimum, maximum and average pressure values obtained from the wearable device. The software displays the pressure values graphically. The structure of the programme is given in Fig. A-2.

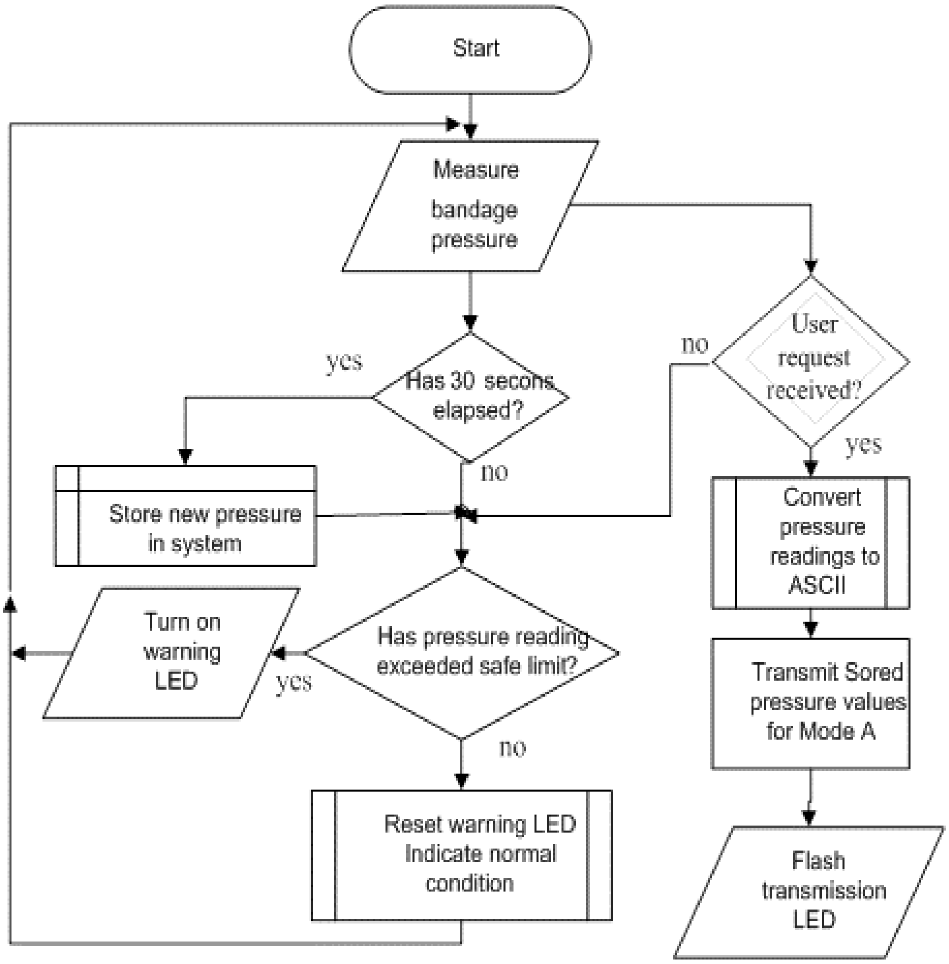

Fig. A-1. Main flowchart for the embedded computer programme.

```
InitializeSerialCommunication()
getPressureReadings()
analysePressureReadings()
displayResults()
```

Fig. A-2. Programme structure for computer analysis software.