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RESEARCH & DEVELOPMENT

Development of a Multifunctional Intelligent Elbow Brace (MIEB) Using a Knitted Textile Strain Sensor

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Abstract

Passive smart textiles are the textile structures that can sense stimuli, which may come from mechanical, thermal, electrical, or chemical sources. Textile strain sensors are smart textiles products in which the sensor's resistance changes with applied strain. This study consists in the development of a textile strain sensor and its application on a Multifunctional Intelligent Elbow Brace (MIEB). The hand-knitted sensor was developed using knitting needles. The material used for this sensor was conductive yarn and lycra. The sensor developed was subjected to a stretch recovery test using a universal testing machine,, and the electrical resistance was measured using an electrical multimeter. The sensor developed has good sensing ability against cyclic loading and unloading at a 5%, 20%, 35% strain level. After testing, the sensor was stitched on an elbow brace to develop an MIEB. This study involved the best economical method for measuring the bowling angle of the player using this MIEB without any need for a biomechanical test, which is very expensive. This MIEB can also be used for rehabilitation purposes and for monitoring joint movement.

Key words: *elbow brace, conductive yarn, textile strain sensor, polyester/silver blend, hand-knitted structure, bowling action.*

Introduction

Sports help to maintain the physical ability and different skills of the player. It also provides entertainment to both participants as well as spectators. Various sports are played across the world nowadays, but cricket is one of the games that is watched and played most. Different bowling techniques have been used in cricket [1], however the spin bowling (off-spin and leg spin) technique is one of the tricky and magical techniques that will always have the ability to deceive the batsman. Different rules have been defined by the International Cricket Council (ICC) for spin bowlers, especially for off-spin bowlers. According to one of those rules, the bowling action of the bowler will be considered legal only if the elbow angle of the player will be less than or equal to 15°, otherwise it will be considered an illegal bowling action [2]. With the application of these rules, lots of top quality off-spin bowlers have been penalised for illegal bowling action, as a result of which players have been suspended from bowling in international cricket. The bio-mechanic test is used to assess the bowling action of the player, which requires high-quality cameras, markers, and high-quality machinery [3, 4]. Due to these high-quality cameras and markers, the cost of this test is very high, usually in millions of dollars. In light of this problem, E-textiles can play a vital role that can provide an economical method for measuring the bowling action of a player during practice sessions. E-textiles are textile structures that can be used as sensors (to sense stimuli) or as actuators (to respond to stimuli) [5]. These structures are lightweight as well as conductive. The sensing properties of these structures can be utilised in the field of medical textiles (for health monitoring), sports textiles (for player performance), as well as in the fashion industry (for glowing dresses) [6-9]. Textile strain sensors (TSS) are E-textile products in which the resistance changes with applied stress. These sensors can be produced by the coating of textile material surfaces or by traditional methods such as weaving, knitting, and embroidery. The material used for the manufacturing of these sensors can be conductive yarn [10, 11] or conductive coating [12], which acts as a transmission path. Coating techniques may involve vacuum filtration, chemical polymerisation, and the dip coating technique. Various studies have been conducted on the fabrication of sensors using coating methods. Fan et al. developed fiber-based strain sensors by chemical polymerisation coating techniques, coating polyurethane (PU) fibers with polyaniline (PANI). The results of their study reveal that the fiber-based sensor shows gauge factor (GF) ~3 at 400% strain and G.F~1 at 500% strain. The problem with such a sensor is low stability during cyclic loading and unloading [13]. Eom et al. fabricated a fiber-based strain sensor by coating poly (3, 4-ethylenedioxythiophene) on the surface of polyester fibers, by means of the in-situ polymerisation technique. The fiber-based sensor prepared was encapsulated with PMMA and stitched onto the surface of the fabric to enhance the sensing ability by up to 20% strain. The problem with this sensor is that it has poor stability against cyclic loading and unloading [14]. Wu et al. utilised the layer-by-layer method to developed polyurethane yarn coated with conductive polymer composite. The sensor developed was then embedded in polydimethylsiloxane matrix. This strain sensor possessed excellent sensing ability up to 1% strain, but its sensing ability in response to large strain was low [15]. Chen et al. coated a yarn-based strain sensor by a coating technique. PVDF-TrFE nanofibres were coated on elastic thread by the electrospinning technique, then this thread was dipped in solution of silver nanowires. It was found that the sensor possessed excellent sensing properties up to the large strain of 50% and also had good sensing stability against cyclic loading and unloading [16]. Another sensor was developed by the dip-coating method, Wang et al. coated yarn with single-wall carbon nanotubes and dipped this yarn in a dispersion of graphene oxide to impart conductive properties to that sensor. It was found that this sensor has an excellent sensing range of up to 300% strain [17]. Similarly, lots of researchers have performed studies on the development of knitted strain sensors. Atalay et al. reported that manufacturing parameters have a significant effect on the sensing properties of the knitted sensor, like the gauge factor, and the linearity of the sensor was also affected by the knitted structure. They found that sensors with a low gauge factor value have a low working range [18]. Scilingo et al. developed a fabric that can sense strain. Firstly, they prepared a fabric using elastomeric and cotton yarn and then coated it using carbon loaded rubber and polypyrrole. They found that the fabric coated with carbon loaded rubber showed excellent stretch sensing properties up to 13% strain [19]. Another research was conducted by Xue et al. on the development of a strain sensing fabric developed using nylon 6 and lycra fibers by coating them with polypyrrole. They found that lycra fibers coated with polypyrrole did not give good results, whereas coated nylon fibers have shown excellent sensing properties [20]. Jinfeng et al developed a wearable sensor for measuring different breathing rates, where a weft knitted plain structure was embedded in a seamless garment and a sensor developed using silver plated filament yarn. They found that the sensor gives good results against fast, slow and normal breathing [21]. Another study was conducted by Jinfeng et al. in which they studied the relationship between the strain sensor and its resistance both experimentally as well as theoretically [22]. Alper et al. developed conductive wool fabric for wearable electronic applications. Wool fabric was coated with silver nanowires. Firstly, silver nanowires were synthesised using the polyol method, and after that knitted wool fabric was coated with those nanowires. The fabric prepared was used for an electrode as well as a capacitor [23]. Guo et al. reported that the elasticity of core yarn and the number of twists have a significant effect on the mechanical behaviour of hybrid yarns. They also found that using hybrid yarn in the sensor will result in a reduction in hysteresis loss. A low electrical resistance of the sensor will lead to reliability problems along with high power consumption. They also found that elastomeric yarn improves the dimensional stability of the knitted structure, and the results of such a sample were also reliable [24]. Guo et al. developed different structures of wearable knitted stretch sensors and found that only floating and interlock structures can be used for breathing purposes due to their good sensing properties [25]. Liwen et al. found that in a 1×1 rib structure, with an increase in extension of the fabric, fabric resistance decreased [26]. Shyr et al. studied the influence of hysteresis and contact resistance on the sensing properties of the sensor and found that the smaller the fraction among conductive yarns, the smaller the tensile hysteresis will be. The closeness of the conductive yarn in the webbing affects the contact resistance. The closer the conductive yarns, the lower the contact resistance will be. The conductivity of conductive fibers, the feed ratio and number of conductive yarns, as well as contact resistance influence the resistance sensitivity of webbings [27]. Many studies have been done on the application of textile strain sensors for measurement of the respiration rate [28, 29], rehabilitation [30] and human body motion detection. Cheng et al. prepared a sensor for the detection of finger movement. Polyester fibers were first wrapped on PU-fibers, then GO was coated on the surface. These fibers were used as a strain sensor after chemical reduction, with the sensor showing a GF of 10 within a 1% strain [31]. Zhang et al. developed a strain sensor with superior sensing properties produced from a silk/graphite core-sheath structure. This sensor shows a GF of 14.5 up to 15% strain and can be used for hand motion detection [32]. Ryu et al. developed CNT coated fibers and used them for the development of a strain sensor for finger movement detection [33]. Mattmann et al. developed a strain sensor using carbon particles and thermoplastic elastomer for the detection of upper body posture. They found that this sensor can measure the upper body posture with an accuracy of 97% [34]. Huang et al. utilised four wires to develop a sensing glove sensor. The position of the fingers was detected based on the voltage change [35]. Woven graphene fabric was developed by Wang et al. to detect human motion [36]. Carbonised silk fabric was developed by Wang et al. which acts as a strain sensor. They used this sensor for complex motion detection, such as the rotation of the wrist and knee movement [37].

In previous studies, a lot of work was done on the development of textile strain sensors for different applications, however these sensors were not used for cricket applications, and hence there is a need to develop an intelligent elbow brace using a textile strain sensor for cricket purposes. The primary function of this study was to invent an easy and economical method that can facilitate the player in measuring their bowling action during practice sessions without the need for any biomechanical testing laboratory. The first part of this study involved the development of a textile strain sensor using conductive and elastomeric yarns, then this sensor would be used for the development of a multifunctional intelligent elbow brace (MIEB). The second part of this study assessed the functionality of the MIEB with the help of electronic circuits.

Experimental

Materials

In this study, conductive yarn and elastomeric yarn were used for the development of a textile strain sensor which was purchased from Sparkfun Electronics, Colorado, United States and India-Mart, respectively. A knitted elbow brace (OTC brand, Model = 2420L, accuracy = ± 5%) was purchased from the local market. For the development of the electrical circuit, all materials such as resistors, a Xbee, microcontroller, programmer, breadboard, buzzer, transistors and wires were purchased from the local market. Specifications of the material used for the development of the textile strain sensor are given in ***Table 1***, while those of the electronic components are given in ***Table 2***.

Method

Development of textile strain sensor

Two sets of yarns were used for the development of the textile strain sensor: conductive yarn and elastomeric yarn. The textile strain sensor was developed using hand knitting needles. The single jersey structure of the sensor was developed using straight knitting needles (model: CHENG 888) with a length and

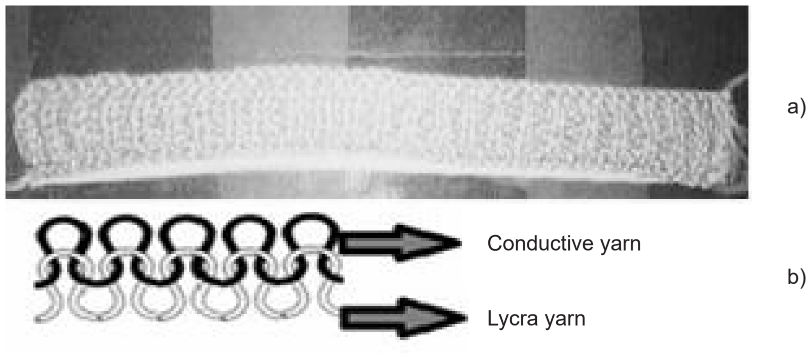

Figure 1. *a) Textile strain sensor (18 cm × 2 cm), b) knitted structure of sensor.*

diameter of 16 cm and 2 mm, respectively. The sample as developed contained one conductive yarn and one elastomeric yarn, where the sample size was kept at 18 cm × 2 cm. The knitted textile strain sensor and its magnified image are shown in ***Figure 1***. Structural parameters of the sensor developed are given in ***Table 3***.

Sensing properties of textile strain sensor

After the manufacturing of the sensor, sensing properties of the sample were tested on a universal testing machine (UTM) (LRX PLUS, AMETEK/LLOYD). A digital multimeter (Manufacturer: Uni-Trend, Model: UT-101, accuracy = ± 5%) was also used with UTM to measure the resistance of the samples against different elongations. The textile strain sensor was clamped lengthwise between the stationary and moveable jaws of the UTM. Crocodile clips were used to attach the digital multimeter to the sensor. One clip of the multimeter was attached just below the moveable jaw and the other one just above the stationary clamp of the UTM. The sample was subjected to a constant rate of extension of 20 mm/min. The total levels of strain were 5%, 20% & 35%, after which the specimen was relaxed. During the extension of the sample, the value of resistance was noted against each level of strain. Similarly, values of resistance were also noted when the sample was relaxed. The sample was subjected to a similar test three times and values were calculated each time. It was found that the sample meets the criteria required for the development of a multifunctional intelligent elbow brace.

During the extension, the resistance of the sensor changed, which is an important parameter for the sensitivity of the sensor. The relative change in the resistance of the sensor can be calculated using the ***Equation (1)***,

$$\text{Relative change in resistance} = \frac{\text{Final Resistance } (R_f) - \text{Initial Resistance } (R_0)}{\text{Initial Resistance } (R_0)}, \quad (1)$$

Where,
R_0 is the resistance before the extension,
R_f is the resistance after releasing the extension.

Development of circuits (transmitter and receiver)

For the development of an elbow brace, it requires electrical circuits that can process the signals. Two sets of circuits were developed, one a transmitting circuit and the other a receiving circuit. These circuits were developed by combining different electrical components on the breadboard. The transmitting circuit contained a microcontroller (ATmega328), programmer, and Xbee as the main components of the circuit, which were connected in series and in a parallel combination with each other. In the transmitting circuit, Xbee was responsible for transmitting the signals. The main power supply and textile strain sensor were connected to the transmitting circuit. The textile strain sensor acted as a a sig-

Table 1. *Specification of yarns used for textile strain sensor.* ***Note:*** *S – single, TPI – Twist per inch.*

Type yarn	Specifications
Conductive yarn	Silver Polyester Blended (stretch broken stainless steel, combed Polyester)
Blend ratio in conductive yarn	20:80 (20% Stainless Steel 12 micron and 80% Polyester)
Resistivity of conductive yarn	150 ohm/cm
Conductive yarn count	20S
Tenacity of conductive yarn	26.41 cN/Tex
Twist per inches	16 TPI
Elastomeric yarn	Bare lycra
Pattern of elastomeric yarn	Plain
Linear density of elastomeric yarn	1600 denier

Table 2. *List of components used for preparation of circuits.* ***Note:*** *dBm – decibel milliwatts, V – volt, µF – microfarad.*

Circuit components	Specification/model
Microcontroller	Atmega320
Diode	IN4007
Capacitor	220 µF, 25 V
Power Supply	9 V
Resistor	50 (ohm)
Transistor	BC547
Xbee	63 mW (dBM) transmitting Power
Buzzer	D11

Table 3. *Structural parameters of sensor developed.* ***Note:*** *S – single, TPI – Twist per inch.*

Parameters	Specifications
Wales per centimetre (WPCM)	12
Courses per centimetres	17
Stitch density	204 cm^2
Stitch length	0.235 cm
Mass per unit area of fabric (GSM)	220 g/m^2
Thickness	0.173 cm

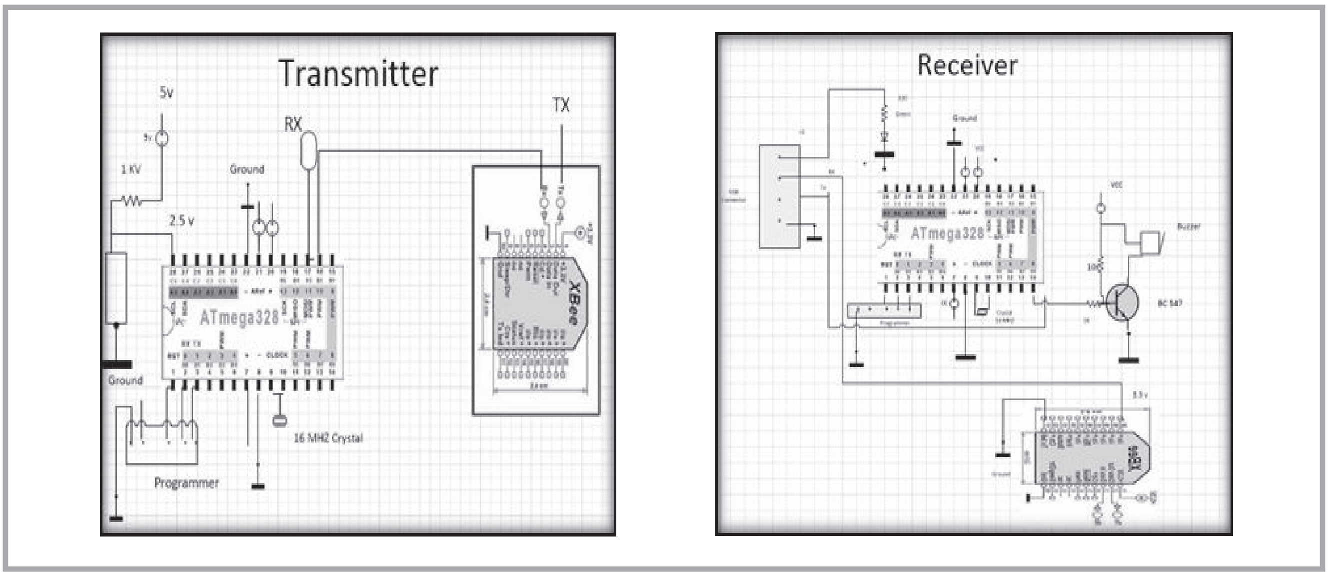

Figure 2. *Circuit diagram of transmitter and receiver circuits.*

nal generator. Similar to the transmitting circuit, the receiving circuit contained a microcontroller (ATmega328), Xbee, and buzzer as the main components. In the receiving circuit, the buzzer acted as an actuator in this circuit, while the Xbee was responsible for receiving the signals generated by the transmitting circuit. The receiving circuit was connected to a laptop display with the help of a data cable. The programming of these circuits was done using the C language, and the software used for this purpose was the Arduino IDE. When the circuit was tested for performance, the same results were found as required. Circuit diagrams are shown in ***Figure 2***.

Development of FANAZA software

FANAZA software was developed for indication of the arm angle during the delivery of the ball. This software was installed on a laptop connected to the receiving circuit. The transmitting circuit, elbow brace, receiving circuit, and FANAZA software were connected. When this software operated on the laptop, it shows a display that contains a circle with three colours (red, green, blue) in the center of the display. On the left side, different pre-set values were shown, which had to be entered before running the experiment. In the set minimum box, the user was required to enter the minimum value of the resistance of the sensor when it was in the rest position. In the set maximum box, the user had to enter the maximum value of the sensor when the sensor was in a fully stretched position. The threshold box indicated the predefined angle, after exceeding which a beep sound was produced by the buzzer. The overall assembly of the FANAZA software is shown in ***Figure 3***.

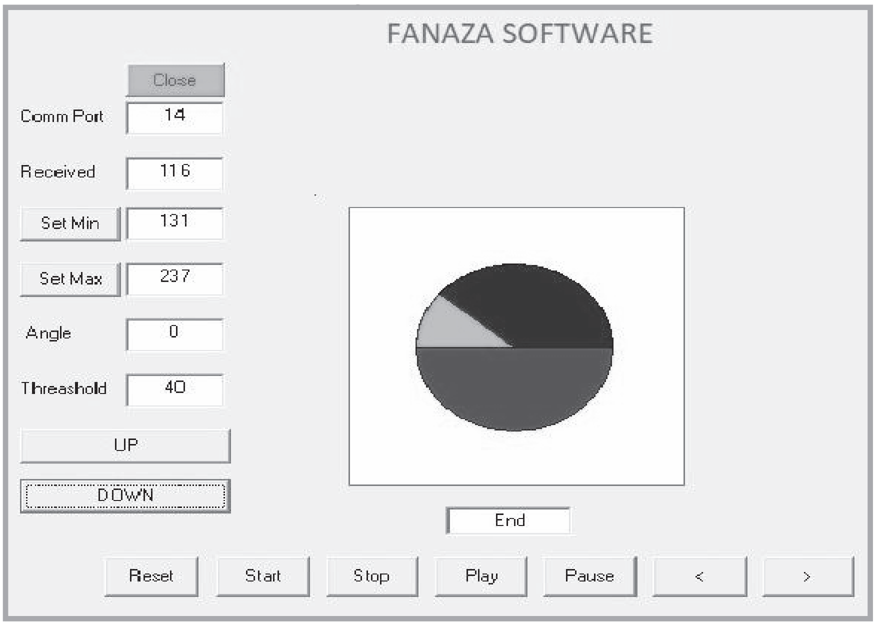

Figure 3. *Display diagram of FANAZA software.*

Development of Multifunctional Intelligent Elbow Brace (MIEB)

A light weight (70 g approximately) intelligent elbow brace was developed by assembling different components. This involved two types of assemblies. Assembly 1: Two sensors of the same design were stitched on the elbow brace using a lock stitch machine. The position of the sensors should be such that when the player wears the brace, the sensors should lie just on the underside of the elbow joint. These sensors were connected to a programmable transmitting circuit, which was further connected to a power supply battery of 9V. A small pouch was also stitched on the top of the brace only on the bicep position. The purpose of the pouch was to hold the transmitting circuit (of weight 60 g) during the functioning of the elbow brace. Assembly 2: This involved the attachment of the programmable receiving circuit to a laptop or display with the help of a data cable. This assembly was responsible for catching the analogue signals generated by the transmitting circuit and converted them to digital signals, shown on the screen of

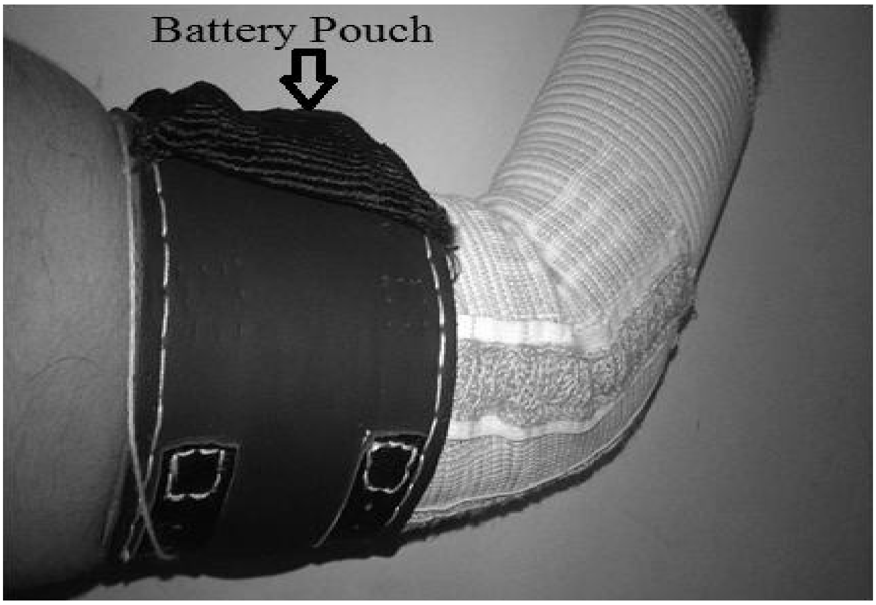

Figure 4. *Prototype multifunctional intelligent elbow brace with use of a textile strain sensor.*

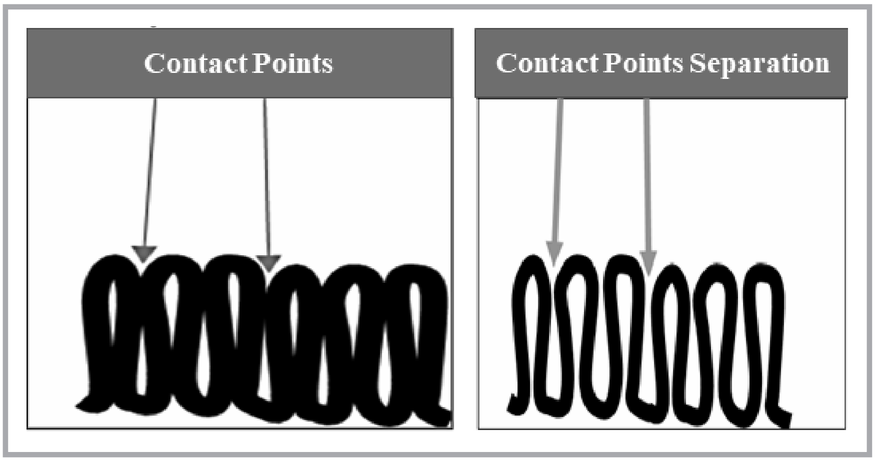

Figure 5. *Contact point behaviour during relaxation (left) and the stretch state of the sensor (right).*

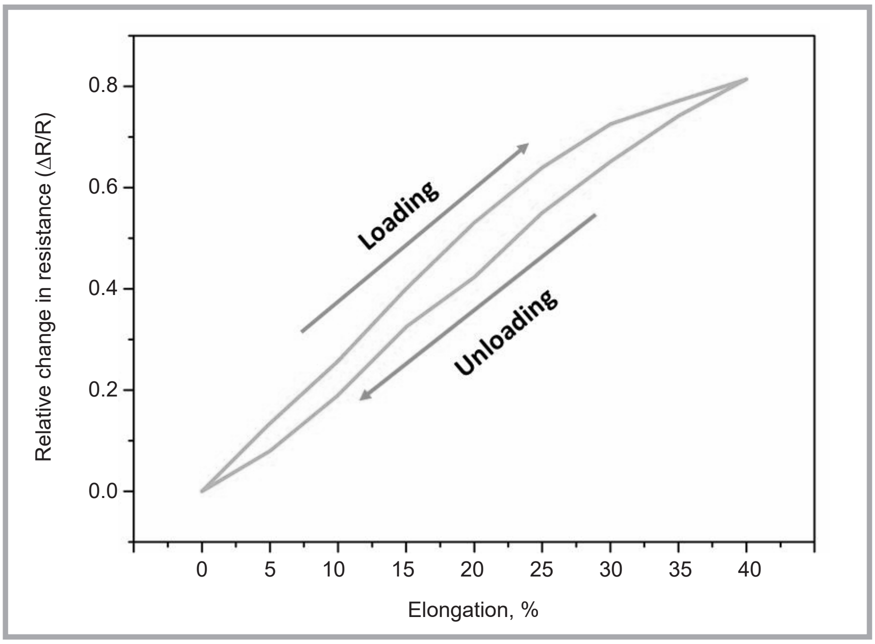

Figure 6. *Relative change in resistance with applied strain.*

the laptop. The basic working principle of this device is that, as extension is produced in the sensor, the resistance value of the sensor will change. Each resistance value represents a specific value of the angle in the receiving circuit. Thus, when the resistance exceeds the preset value, it means that the angle of the elbow has also increased, as a result of which a beep will be heard, being an indication that the elbow angle has started to exceed the preset value. The prototype MIEB is shown in ***Figure 4***.

Results and discussion

Sensing behaviour of textile strain sensor

When the sensor stretches, the contact points of the conductive yarns get separated, as a result of which the electrical resistance changes, as described in a previous study [38]. This separation and rearrangement of the contact point are the main factors of the sensing properties of the sensor, as shown in ***Figure 5***.

The relationship between relative resistance and elongation can be explained by Holm's contact theory, expressed by the formula:

$$R_c = \frac{\rho}{2}\sqrt{\frac{\pi.H}{nP}}, \qquad (2)$$

Where,
R_c = Contact resistance
H = Hardness of material
n = Number of contact points
P = Contact pressure

Here, for the given sensor, the contact pressure of the materials is variable and depends upon the structure of the sensor, whereas the electrical resistivity and hardness of the material remain constant. By increasing the contact pressure, the contact points between the loops of the conductive yarn also increase, and because of which the contact resistance will decrease. Hence, during the application of tensile force up to 40% strain, the contact pressure between the conductive loop decreases, due to which the contact point decreases, and ultimately the overall electrical resistance of the sensor increased due to an increase in the contact resistance (1), as shown in ***Figure 6***.

Table 4, shows the linear regression equation for the elongation to resistance, with a coefficient of determination R^2 = 97.14%. where Y stands for relative resistance, and X for elongation. The re-

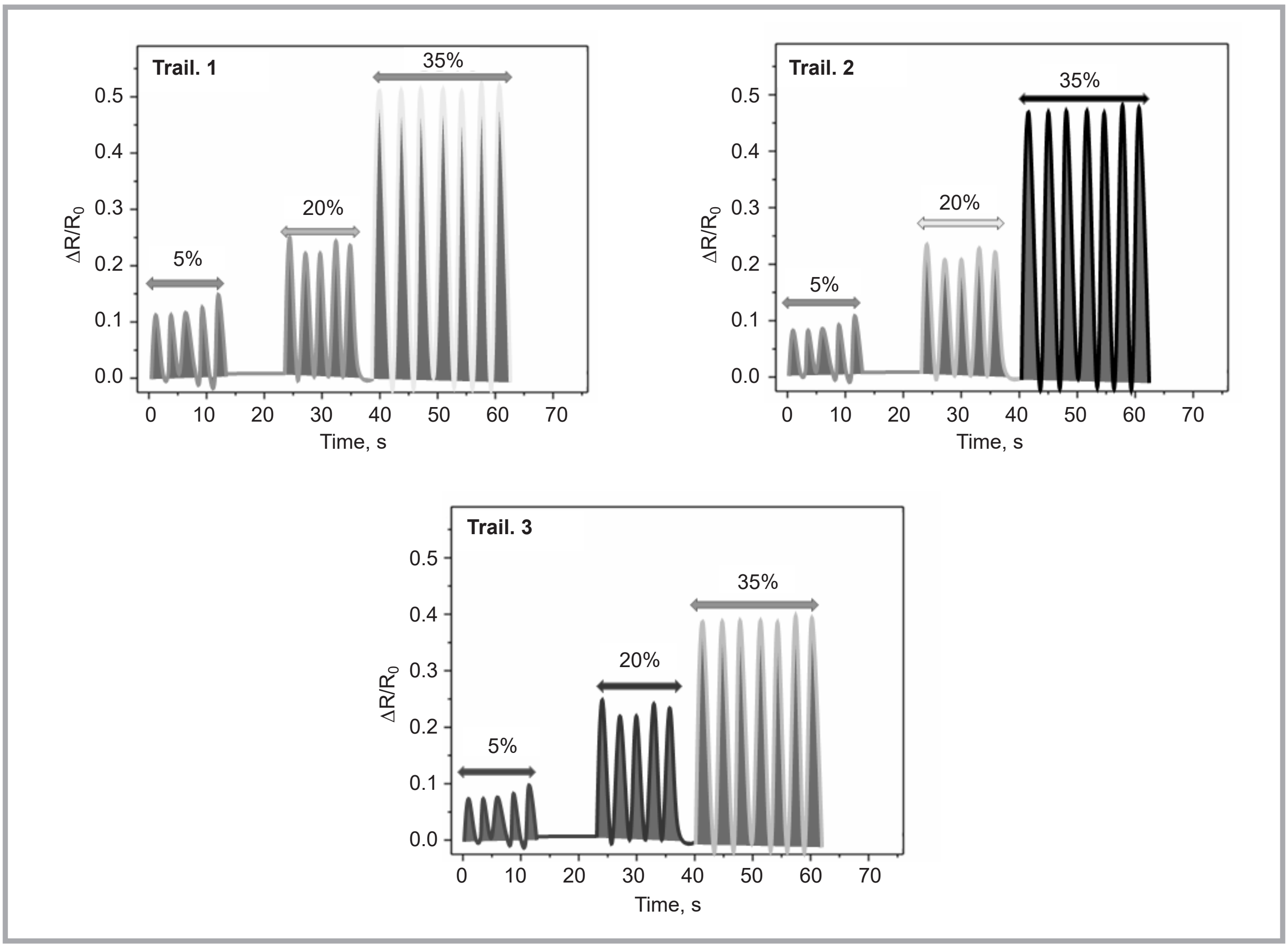

Figure 7. *Sensing stability of textile strain sensor at different strain levels.*

gression equation shows that elongation has a positive effect on the relative resistance of the sensor. This means that as the value of elongation increases, that of the resistance will also increase, and hence the sensing property of the senor will also change due to a change in the contact pressure between the loops (***Equation (2)***). The slope of the regression line determines the gauge factor (sensitivity) of the sensor, which is an important property of the device. The gauge factor for the sensor prepared was 4.069 ± 5, which was calculated using the following formula:

$$Gauge\ factor = (\Delta R/R_0)/\varepsilon \qquad (3)$$

Where,

ΔR = Change in resistance when strain is applied,

R_0 = Initial Resistance of the sensor when there is no strain applied on the sensor,

ε = Strain applied to the sensor.

Table 4. *General regression equation*

Sample	Regression equation	R^2 value	P-value
Sensor	Y= 0.0519 + 0.02114X	97.14%	P < 0.05

Sensing stability of textile strain sensor

To check the stability and regularity of the textile strain sensor, the sensor was subjected to a stretch and recovery test. Cyclic loading and unloading were performed. Three trials were performed on the sensor at three different strain levels (5%, 20%, and 35%). During each strain level, the sensor was subjected to 5 stretch and recovery cycles. The results in ***Figure 7.a*** reveal that as the force is applied, the value of ΔR/R0 changes and the sensor shows excellent stability and regularity under continuous stretch and recovery cycles. To check the stability of the sensor after prolonged tension, the sensor was subjected to loading for 60sec before relaxation. ***Figure 7.b*** and ***Figure 7.c*** show the results for the same sample, on which trial 1 was done to check the durability of the sensor. From trial 2 and trial 3 results, it can be concluded that the amplitude of the peaks slightly decreases as compared to trial 1, which means that the performance of the sensor will be slightly changed after three trials. The possible reason behind this is that the contact pressure between the yarns may change due to continuous stretching. From these graphs, it is clear that the continuous bending and stretching of the arm will not affect the sensing property of the sensor.

Effect of tensile rate on sensing properties of textile strain sensor

To investigate the effect of the tensile rate on sensing properties of the sensor, the sensor was subjected to a stretch and recovery test. 35% strain was maintained while varying the tensile rate from 20 mm/min to 100 mm/min. In ***Figure 8***, the results reveal that the amplitude of the peaks remains constant when a 20 mm/min and 40 mm/min tensile rate was applied, while when the tensile rate was increased to 70 mm/min and 100 mm/min, the am-

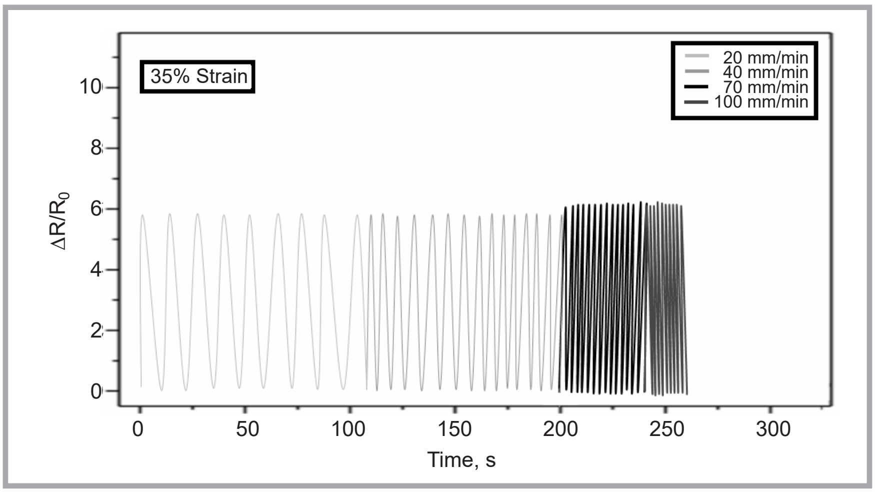

***Figure 8.** Effect of tensile rate on the sensing properties of textile strain sensor.*

plitude of the peaks vary slightly from the previous amplitude, but this effect is still negligible. This means that the tensile rate does not affect the sensing properties of the textile strain sensor, hence the sensor remains stable under different external stresses applied at different frequencies.

Functionality of Multifunctional Intelligent Elbow Brace (MIEB)

Control circuits (receiver and transmitter) were designed at the electronic laboratory of BUITEMS Quetta. The major components of these circuits were a microcontroller (ATmega328) and Xbee. These control circuits were designed using a microcontroller. In the transmitting circuit, the output of the textile stretch sensor was sent to the microcontroller. The output of this microcontroller was then sent to the receiver microcontroller, which in turn sends the signal to the LCD, from where the output is displayed As mentioned above, the extension causes changes in resistance, therefore each resistance value represents a specific value of the angle in the receiving circuit. Thus, when the resistance exceeded the preset value, it meant that the angle of the elbow also increased, as a result of which a beep was heard. The working principle of MIEB is given in ***Figure 9***.

All this process is displayed using FANAZA software. FANAZA software shows a circular display that contains three colors: red, green and blue. When the predefined angle is zero degrees or either the receiving or transmitting circuits are off, then two colours will appear on the display screen: the upper half of the circle will appear blue and the lower half – red. It will also indicate that our sensor is in a relaxed position. When a certain value of the angle is entered into the computer, a third color will appear on the display – green; how wide the green colour is will depend upon the value of the predefined angle. The player has to define the parameters by entering the required values, which will appear on the display screen before testing his bowling action. The threshold value will indicate the angle which is to be set by the player before testing his bowling action. When the circuits are ON and the player starts to deliver the ball, stretch will be produced in the sensor, as a result of which the stretch contact pressure between the loops of the conductive yarn will change, which will directly affect the contact resistance of the sensor. When the resistance of the circuit starts changing, the red color will start travelling over the green colour. The travelling of the red colour indicates how many angles have been displayed by the elbow joint. As the red colour starts traveling over the green colour, the value of the angle continuously changes in the angle box, which shows the present value of the angle. When the red colour crosses the range of the predefined green colour, then the buzzer will be heard, which will be an indication that the elbow joint has crossed the predefined limit of the angle. The travelling phase of the red colour is shown in ***Figure 10***.

Testing of (MIEB) by pre-setting different angles

Figure 11 indicates the different angles of delivering the ball by the player. ***Figure 11.a*** shows the legal bowling action as defined by the International Cricket Council (ICC) in their rules where the elbow angle of the bowler should be less than or equal to 15°. The predefined angle is 15°, which is shown by the green portion; thus, when the player delivers the ball, stretch will be produced in the textile strain sensor, as a result of which the resistance will change [40]. Each variation in the value of resistance corresponds to a specific value of the angle [41], where the red colour starts travelling over the green colour; as the green colour is crossed by the red colour, a sound will

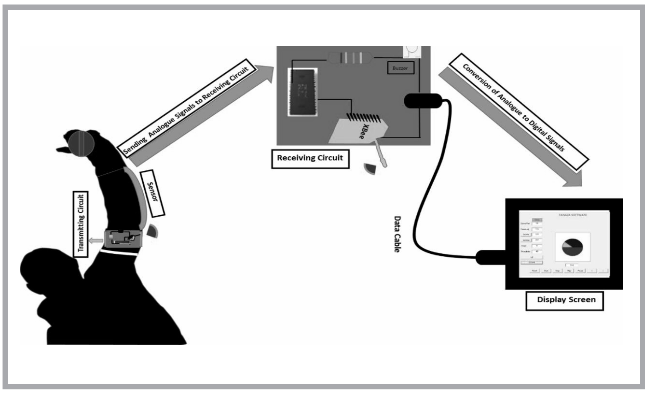

***Figure 9.** Working principle of multifunctional intelligent elbow brace.*

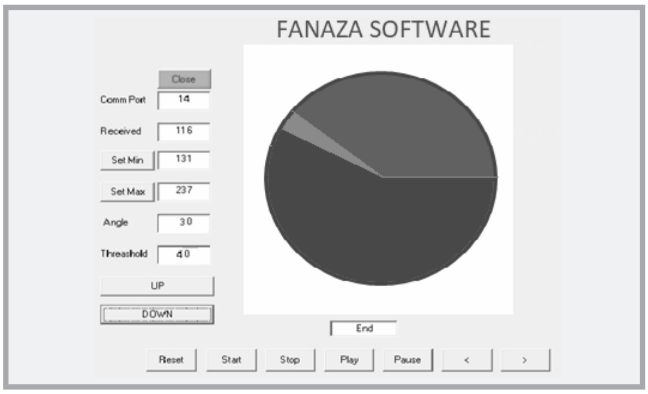

***Figure 10.** Travelling movement of the different colours during the functionality.*

be produced by the buzzer, which will be an indication that the elbow angle has exceeded the pre-set value. In ***Figures 11.b*** and ***11.c***, the predefined angle is exceeded by 30° and 40°, respectively.

Conclusions

In this study, a multifunctional intelligent elbow brace was developed using a textile strain sensor. The sensing stability results show that the textile strain sensor possessed excellent sensing stability at different strain levels. From this study it can also be concluded that the tensile rate does not affect the sensing properties of the textile strain sensor, hence the sensor remains stable under different external stresses applied at different frequencies. The MIEB developed can be used for measuring the legal and illegal bowling actions of players as per the rules defined by the International Cricket Council (ICC). This elbow brace is lightweight and more economical as compared to the biomechanics test, which is used to test the bowling angle of a player. This elbow brace can also be used for the rehabilitation of elbow joints.

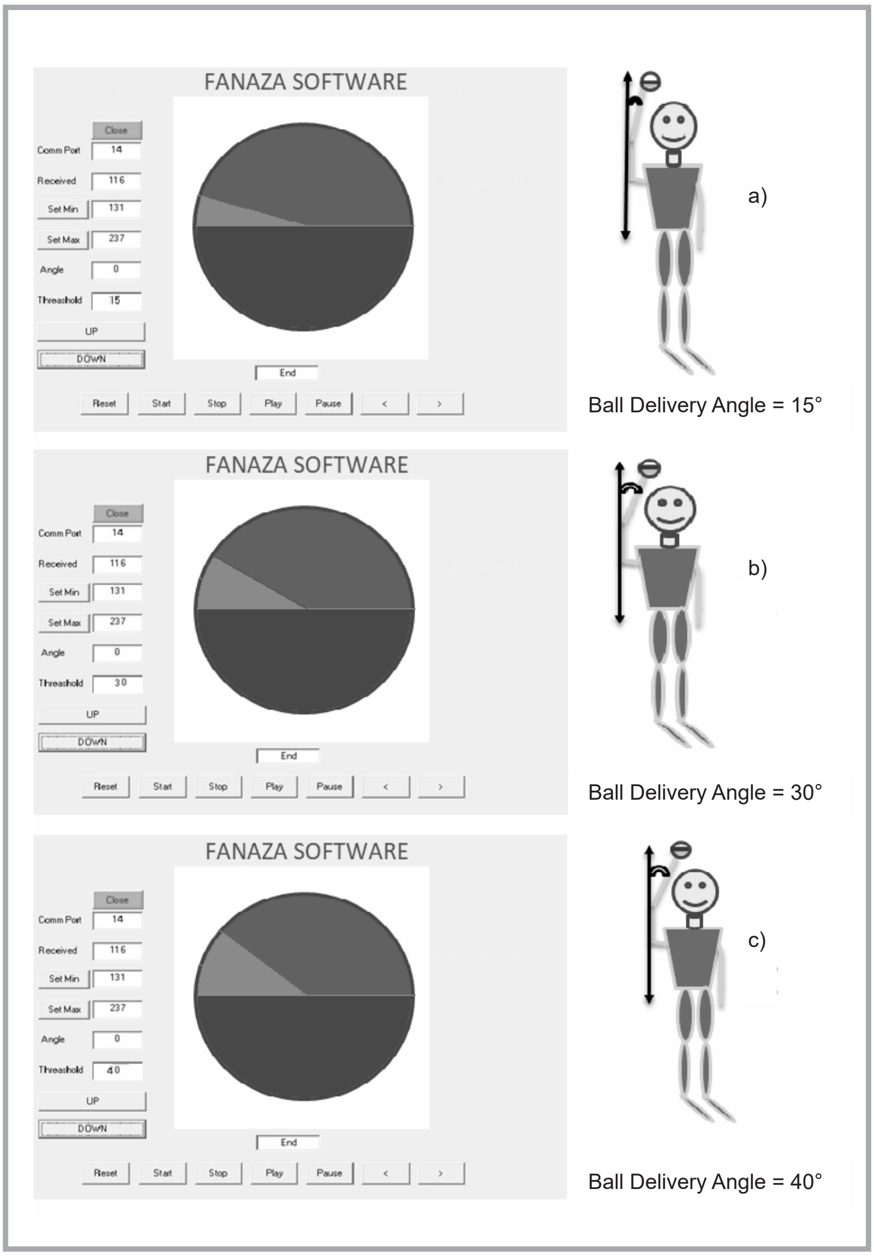

Figure 11. *a) predefine angle 15°, b) predefine angle 30° and c) predefine angle 40°.*

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