Development and evaluation of wearable electro-goniometer for the assessment of repetitive efforts and measurement of joint trajectories during carpet weaving

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Abstract: The aim is to construct, calibrate and validate a low-cost sensor-embedded glove and elbow brace. This article establishes a common thread between electro-goniometry and postural assessment techniques. The output voltages from the sensors were converted into angles by implementing LabVIEW-Interface-for-Arduino based graphical environment. Ten experienced weavers participated in the study. Dynamic recordings of the finger, wrist and elbow bending trajectories were measured using sensory electro-goniometer. Assessment of repetitive task technique was used to identify the postural risks. Based on data output from each sensor, the voltage to angle optimal linear models were obtained for the measurement range of 0°–90° with 5° steps. The accuracy of the sensors was found within the limits of traditional goniometry. The cost-benefit breakdown revealed that wearable electro-goniometer is cost-effective as compared to commercially available electro-goniometers. The low-cost electro-goniometric glove and elbow brace for measurements of hand movements could be a promising tool for postural assessment and safety systems.

Keywords: carpet weaving; sensory gloves; resistive flex sensor; RFS; electro-goniometer; goniometry; assessment of repetitive task; ART; ergonomics; carpal tunnel syndrome; CTS; systems; safety; cost-benefit analysis.

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1 Introduction

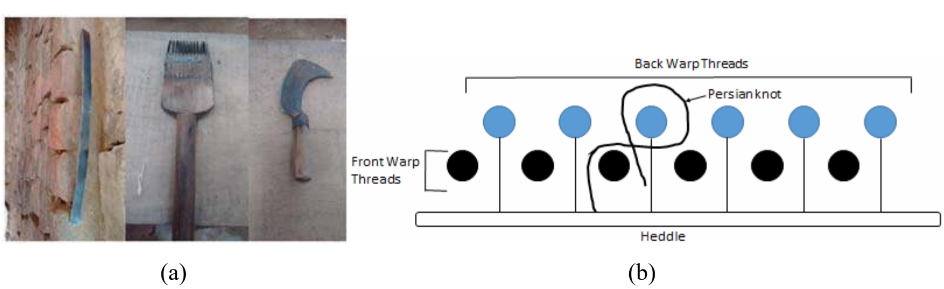
Hand-function assessment is a primary measure of hand rehabilitation, which includes the static muscle strength, hand transmitted vibrations and joint range of motion (ROM) (Chandra et al., 2007; Simone et al., 2007; Singh et al., 2018b). The data acquired from these measurements can be helpful in the assessment of musculoskeletal symptoms and occupational fitness among the industrial workers. These data can also be useful in rehabilitative treatment and design of hand tools (Dipietro et al., 2003; Singh and Khan, 2014).

The traditional goniometers are most suited to the static ROM measurements. This critical limitation of using it during the dynamic tasks make accurate measurements challenging to carry out (Dipietro et al., 2003). Therefore, the dynamic recordings of the wrist and finger bending trajectories are not possible using mechanical goniometers while performing a skilled job. The complexity of hand during the dynamic movements is another limitation. Moreover, the evaluation of hand functions directly in the working environments would provide more practical information than the data gathered in the clinical settings. For that, the selected goniometer should be portable and capable of recording the continuous data over time (Simone and Kamper, 2005). Unfortunately, despite all these claims, practical implications of electro-goniometric gloves for investigating and monitoring hand functions in real-time environment have lacked so far.

According to the National Statistical Commission, 90% of the country's workforce accounts in the informal economy (NSC, 2012; Meena et al., 2013). The nation supports 70 lac people and contributes a substantial part of the total workforce from India (Gopal, 2016). Depending upon the nature of the work and design of hand tool, handicraft operatives can be exposed to awkward posture, forceful gripping, high repetitiveness, noise exposure and hand-arm vibration (HAV) hazard (Atroshi, 2009; Armstrong, 1983; Singh, 2018; Mital and Kilbom, 1992). Therefore, the measurement of hand gesture is vital to workplace safety.

Many jobs in the informal sector (mainly handicrafts) in a lower middle-income country like India, requires the individuals to use their hands as they interact during the daily work. The poor working environment with repetition in tasks can lead to occupational injuries and musculoskeletal disorders (MSDs) among the workers (Mukhopadhyay and Srivastava, 2010; Singh et al., 2018a). Apart from blue pottery, wood crafted products, leather crafts, and imitation jewellery, India is also famous for producing hand-knotted carpets. The country-wise exports of handmade carpets and other floor coverings in 2015–2016 was Rs. 9,481.36 crores which account for 44.2% of the country's total handicraft export (CEPC, 2015; EPCH, 2015). According to Rajasthan Chamber of Commerce and Industries, the different districts within the state of Rajasthan support around 35,000 people and contribute to 40% of the country's wool (Carpet Industry, n.d.).

Figure 1 (a) Weaving hand tools (beater, weaving comb and weaving knife) (b) Tying of Persian knot on vertical warp threads during weaving (TOP VIEW) (see online version for colours)



Note: Figure shows top view of the warp threads/loom.

During weaving, the weavers sat next to each other and wove the carpet as per the provided map using conventional hand tools. These hand tools include weaving knife, weaving comb and a beater [Figure 1(a)]. The weaving knife is used to cut the knot after the completion of each knot. The weaver holds it throughout the process of knotting which leads to forced fisted cylindrical grasping in their dominant hand. They use weaving comb and beater after finishing a row of knots and weft. The continuous hand knotting of Persian knots [Figure 1(b)] causes repetitive movement of digits and wrist.

Our work focuses on evaluating the electro-goniometer to measure finger, wrist and elbow joint (EJ) bending trajectories and repetitiveness during weaving tasks. The Bland Altman plot was used to assess the agreement of joint angles measured between conventional and electro-goniometer. Data from the electro-goniometer, digital photographs and videotapes were used to investigate the postures involved while hand-knotted weaving. We hope this paper helps ergonomists and other researchers to discover common threads between the mechatronics approach and postural assessment techniques. The research also points that further longitudinal work is needed to identify bridges among different aspects of using the hand goniometry in the design of hand tools and exploring postural assessment in various occupations.

2 Literature review

The primary measure of hand function assessment is to calculate the joint ROM using manual goniometry. These measurements are performed by placing the conventional goniometer on the joint for the calculation of flexion/extension angles. Several researchers in the past suggested that electro-goniometers can be used as a diagnostic measure to evaluate the functional status of a person with a musculoskeletal or neurological disability (Afshari et al., 2014; Norkin and White, 2016; Farooq et al., 2016; Bhattacharya and McGlothlin, 2012). Commendable efforts were put forth by Khan et al. (2009, 2010) while demonstrating an evaluation technique which uses electro-goniometer as an indicator of the ROM during wrist articulations and forearm rotation. Also, they have assessed the effect of postural deviations on discomfort levels. Yen and Radwin (2000) showed the comparison between the data from electro-goniometers and actual joint deviations, sustained postures, and repetition rate, and found that direct measurement results were more precise than observational analysis.

Few studies suggested the use of sensor incorporated gloves to overcome static ROM measurement limitations (Dipietro et al., 2008; Sturman and Zeltzer, 1994; Pantelopoulos and Bourbakis, 2010). In an experimental study, the characteristics of the CyberGlove™ model CG1801 were investigated by the recognition of flexion measurements for the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the thumb and all the digits (Kessler et al., 1995). Oess et al. (2010) developed the NeuroAssess glove embedded with flex sensors and figured out the optimal position of the sensor to the finger joint when non-uniform bending is applied. They used four sensors for the finger flexion and two sensors for the palmar and dorsal wrist flexion monitoring. In their follow-up study, the NeuroAssess glove was used to measure the hand function in the activities of daily living (ADL). For a sensor resolution of 0.5°, intraclass correlation coefficient (ICC) values (0.84 to 0.92) with an accuracy error of about ±5° was obtained (Oess et al., 2012). Wang et al. (2011) introduced step-by-step instructions for designing a low-cost electro-goniometer for the research applications. They opined that the performance of flex sensors used for the index finger, wrist, and elbow was similar to those of commercially available electro-goniometers with a relatively higher durability-to-cost ratio. Among the different types of sensory gloves developed over time, an array of resistive flex sensors (RFS) offer the low-cost, easy to use, and reliable alternative (Oess et al., 2012; Saggio, 2014).

A few, but impactful researches carried out in the past have mostly focused on MSDs, working conditions, and physiological factors among the weavers in the handwoven carpet industry (Choobineh et al., 2004a; Chaman et al., 2015; Durlov et al., 2014; Afshari et al., 2014; Nazari et al., 2012). Besides these factors, the design of hand tools contributes to building up the risks of carpal tunnel syndrome (CTS) (Choobineh et al., 2004b; Motamedzade et al., 2007). Guidelines for ergonomically designed workstations including the design of the chair and carpet looms improved the comfort and working conditions for carpet industry workers (Choobineh et al., 2007; Mahmoudi and Bazrafshan, 2013; Afshari et al., 2015; Singh et al., 2017, 2018a).

A literature review indicates that no significant research has been carried out so far in carpet weaving from the occupational goniometry (measure hand and finger activity) or hand function perspective, despite different tools used. There remains a need to provide a feasible means to assess hand functions in the real work environment. Previous studies suggested that weaving tasks demand high labour-intensive work leading to higher musculoskeletal load (Motamedzade et al., 2007). Therefore, we sought useful to take up the issues of the ergonomic study of female weavers, with objectives to construct, calibrate and validate a low-cost sensor-embedded glove and elbow brace.

3 Methods

3.1 Sensor glove description

A custom made cotton knitted hand gloves was utilised, positioning the carbon ink RFS (Spectra Symbol, Salt Lake City, UT, USA; 2.2 inch) for experimental goniometry. The configuration of the glove was made to support seven unidirectional sensors. Lycra® sleeves were sewn to encase the flex sensors to the respective joint [Figure 2(a)]. The provision was made to accommodate the sensors between the sewn layers. Three 2.2-inch sensors were placed over the index MCP, PIP, and thumb interphalangeal (IP) joints. Four 2.2-inch sensors were used, two of them covered the radiocarpal (RC) joint to measure palmar/dorsal flexion of the wrist. The other two were centred over the groove between the lunate and capitate wrist bones [distal radioulnar joint (DR)] that measures radial/ulnar deviation. However, in this study, bent from distal interphalangeal (DIP) joint was not taken into account to avoid disturbing dexterity while knotting and prevent physical contact between the sensor placed on the distal end of the index digit and the knots. This type of sensor placement could be the limitation of the study. The seven RFSs record angles independently of each other.

The size of the glove was selected as per the female anthropometric data available for Rajasthan region (Agrawal et al., 2013). The size was obtained on the basis of hand length which could be defined as the length from the wrist crease to the distal end of the most projecting point of hand. The additional length is also provided for the change in length due to wrist bending and finger joint bending. Therefore, 22 cm hand size glove was considered appropriate for the study. Additionally, we decided to cut the glove from the distal interphalangeal crease given that we observed that it was not practical to knot the carpet without bare fingers.

3.2 Elbow brace/sleeve description

A bi-layered construction designed with dermophillic cotton and nylon (Tynor, Mohali, India) was used which ensures free movement of the forearm. The RFS (Spectra Symbol, Salt Lake City, UT, USA; 4.5 inch) was positioned at the olecranon eminence of the ulna to measure elbow flexion/extension [Figure 2(b)]. Only one sensor was placed since the typical ROM for EJ does not go beyond 0°. The sleeve was four-way stretchable and selected size of the sleeve was seven-inch circumference. Lycra®/neoprene sleeves were sewn to sandwich the RFS between the sewn layers corresponding to the joint. Medical tape (3M™ Durapore™) was used to hold the sensor to its place while limbs movement.

Figure 2 (a) Configuration of the glove with sewn sleeves to encase the flex sensors
(b) Elbow brace with sewn sleeves at the olecranon eminence of the ulna (see online version for colours)

3.3 Validation of angle measurements

Annexure was given at the end, which includes specific details of the development and calibration procedure of the sensory electro-goniometer. This online annexure was provided to replicate the study and detailing the outcomes from the calibration. Once the placement of the sensors on the glove and elbow sleeve is determined, the accuracy of the glove needs to be assessed for real-time measurements. The sensors were inserted in the sewn sleeve, and their proximal end was fixed by the medical tape to avoid sensor displacement. One female subject wore the glove and elbow sleeve, and ten trials were taken to evaluate the accuracy. The subject was asked to bend each joint by 30°, 60°, and 90°. Traditional goniometers were used to measure these joint angles. The output voltage to joint angle reading was noted for measuring accuracy.

3.3.1 Statistical techniques used to evaluate agreement between angle measurements (Bland-Altman analysis)

Bland and Altman's proposed a method of plotting the differences between values generated by two methods of measurement on the *y-axis* against the average of the values produced by the two methods on the *x-axis* (Bland and Altman, 1986, 2010; Earthman, 2015). In our study, we used Bland Altman plot to evaluate the agreement of joint angles measured between conventional goniometer and electro-goniometer. The mean values of angles by the two methods were plotted on the *x-axis*. On the *y-axis*, the values for the difference between the angle measurements were plotted.

3.4 Participants

Ten healthy female subjects, aged between 22 and 40 (mean 29.20; SD 5.49) and a mean body mass index (BMI) of 19.85 were selected for the experiment from a few workshops of hand-knotted carpet manufacturer. All of them were right hand dominant with no history of neuromuscular or upper extremity disorders. These workshops were situated at different locations in Maanbagh, and Khore regions within Jaipur district. Minimum three year of work experience in the same job and right-hand dominance was the inclusion criteria for this study. Their belongingness was from the state of Rajasthan (India).

The university institutional review board approved all experimental procedures, and the study received written approval from the company before their participation in the study.

The demographic description and general information of weavers related to work depict in tabulated form in Table 1. The nutritional status of the participants was assessed from their BMI values (WHO, 2000), and it was found that the mean value of BMI (19.85 ± 2.99) was within the normal range. The daily hours spent by the participants was 8.1 ± 0.57 hours with rest of 45–60 minutes each day, and weekly workload was 56.7 ± 3.97 hours with seven days working.

Table 1 Demographic information of female weavers

Characteristics of samples (n = 10)	*Mean ± SD*
Age of subject (years)	29.20 ± 5.49
Weight of subject (kg)	46.55 ± 8.71
Stature of subject (cm)	152.85 ± 4.32
BMI (kg/m^2)	19.85 ± 2.99
BSA (m^2)	1.40 ± 0.14
Experience (years)	7.1 ± 2.51
Daily workload (hour)	8.1 ± 0.57
Weekly workload (hour)	56.7 ± 3.97

3.5 Experimental procedure

The study aimed to determine the repetitiveness and bending trajectories of the index finger, thumb, wrist, and elbow during the performance of four weaving sub-tasks. The task of carpet weaving was divided into subtasks, i.e.:

- *subtask 1* – knotting (involve use of left and right hand)
- *subtask 2* – knot cutting (involve use of dominant hand)
- *subtask 3* – beating the knots (involve use of dominant hand)
- *subtask 4* – weaving comb (involve use of dominant hand).

The test was performed on the same loom at one of the workshops. Each of the participants was provided with an intermittent weaving task using the conventional hand tools. The experiment was done on 9 × 12 ft^2 sized carpet having 14 counts (14 × 14 knots/inch) using their typical working posture and grip force as they would during normal work. During data collection, we observed each subject and the real-time measurements values until task movements stopped and the self-paced adjustment period ended. The participants wore the RFS-embedded glove and elbow brace and had to perform the subtasks for at least 1 minutes. Angle measurement recordings began just before to each trial and data were collected for the last 30 s of each testing session. The testing sequence for each participant was randomised. For validation purposes, the participant's movements during weaving were captured with a video camera.

Unlike actual weaving, the subtasks were adjusted according to the articulations of interest for acquiring useful data. During knotting and knot cutting subtask, the subjects were instructed to move the joint of interest while making at least 100 knots on the warp threads as they would during daily work. The reason for bifurcating into subtask was to prevent any bias between the angle readings. Beater and weaving comb were used as they were during routine work.

3.6 Postural analysis

The working postures of the subjects were analysed by assessment of repetitive task (ART) technique for the evaluation of repetition of the work process and were only administered to the subtasks during weaving (HSE, 2010). The ART assesses the common risk factors in the repetitive movement of the upper limbs (arms and hands) that contribute to the development of upper limb disorders (Gangopadhyay et al., 2015).

In this technique, the assessment is divided into four stages: stage A assesses frequency and repetition of movements; stage B assesses the level of force exerted with the hand and the amount of time that the force is exerted; stage C assesses the amount of time that the worker spends in the awkward postures; stage D is the assessment of additional factors, such as work breaks, work pace, how much is the tool strikes per minute, requirement of precise movements of the hand or fingers, and task duration. Task scores and exposure scores were calculated by adding the priority scores on the score sheet.

Electro-goniometer, digital photographs, and videotapes were used as data collection tools for the analysis. Only dominant right-hand weavers (n = 10) were selected for the study for minimising any discrepancy in overall priority scores due to hand dominance.

3.6.1 Sampling of postures

The neck posture and back postures were assessed using photographs extracted from the videos. These photographs were analysed in Kinovea 8.15 open source program for measuring angles. The worst working postures in carpet weaving activities were identified through observation and review of the photographs and recorded videos as a retrospective approach (Salmani Nodooshan et al., 2017). Arm/elbow, wrist and digits angles were measured through glove and elbow brace electro-goniometer for each participant.

A total of 90 photographs were extracted from the video recordings (n = 10) during weaving, and 24 of those photographs were screened as extreme reach for knotting and knot cutting in a prospective approach. From these photographs, 12 photographs for knotting (six for rear view and six for side view) and 12 photographs for knot cutting (six for rear view and six for side view) were screened as the worst working postures. The images (n = 30) extracted from video recordings (n = 10) were used to obtain a clearer picture of the weaver's postures (during beater and weaving comb subtasks) in the sagittal plane. They were further analysed using from Kinovea 8.15 open source program, and the mean angles for lower back and neck were calculated (Prairie et al., 2016; Elrahim et al., 2016; Guzmán-Valdivia et al., 2013).

4 Results and discussion

4.1 Validation of angle measurements

Table 2 depicts the variation in mean angles measured by the sensor and traditional goniometer, the average difference between the angles, standard deviation, and the 5th and 95th percent confidence interval (limits of agreement). The mean angular difference by both the methods was –0.265 and the upper and lower limits of agreement came out to be 1.61 and –2.23 which were within the ±3° interval. This range was in line with the previous studies having interval range within ±5° (Williams et al., 2000; Oess et al., 2010).

Table 2 Sensor vs. goniometer angle accuracy evaluation

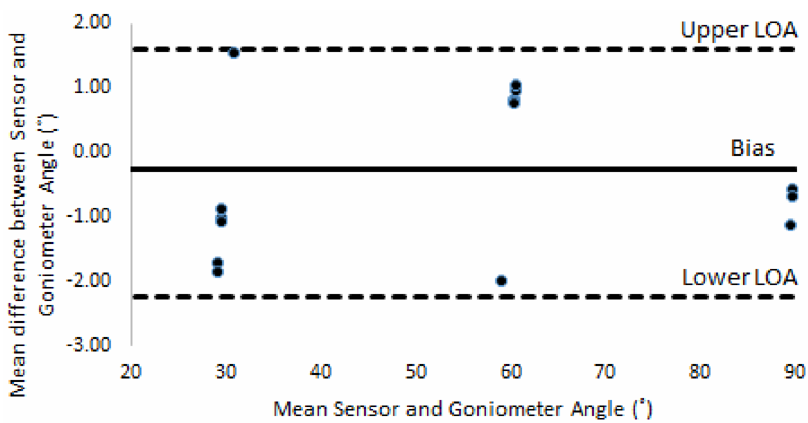
Joint	*Mean angle (goniometer) (°)*	*Mean angle (sensor) (°)*	*Mean difference (°)*	*SD of difference (°)*	*5% confidence interval (°)*	*95% confidence interval (°)*
MCP	30	28.28	–1.72	1.20	–3.32	0.065
	60	60.83	0.83	1.41	–1.63	2.375
	90	89.43	–0.57	1.15	–2.375	0.83
PIP	30	28.98	–1.02	1.59	–3.01	1.31
	60	58.01	–1.99	1.42	–3.395	0.5
	90	90.64	0.64	1.19	–1.15	2.31
IP	30	31.56	1.56	1.91	–1.465	3.54
	60	60.98	0.98	1.68	–2.035	2.785
	90	88.88	–1.12	1.35	–2.81	0.795
RC	30	28.92	–1.08	1.06	–2.365	0.695
	60	60.80	0.8	1.34	–1.185	2.785
DR	30	28.15	–1.85	1.12	–3.42	–0.215
	60	61.05	1.05	1.54	–1.375	3.13
EJ	30	29.14	–0.86	1.24	–2.1	1.155
	60	60.78	0.78	1.59	–1.7	2.785
	90	89.33	–0.67	1.12	–2.285	0.97
	Mean		–0.265	1.37	–2.23	1.61

Notes: MCP – index metacarpophalangeal joint, PIP – proximal interphalangeal joint, IP – thumb interphalangeal joint, RC – radiocarpal joint to measure palmar flexion of the wrist, DR – distal radioulnar joint to measure ulnar abduction, EJ – elbow joint to measure flexion (concentric).

Bland Altman plot was used to evaluate the agreement of joint angles measured between conventional goniometer and electro-goniometer (Figure 3). The mean values of angles measured between the sensors and traditional goniometer were plotted on the x-axis. The values for the difference between the angle measurements were plotted on the y-axis. The horizontal solid line illustrates the mean difference (bias) between the angles measured by the two methods. The dotted lines represent the 5th and 95th percentile confidence interval boundaries (limits of agreement).

The scatter plot shows no specific trend or pattern of the scattered points around the bias line. The reason for scattering could be that the measurement was performed with a lower resolution of 5° over the broader range of 0°–90°. However, no point was beyond the upper and lower level of agreement. Figure 3 depicts that agreement gets slightly higher as the average of sensor and goniometer angle increases. Furthermore, the variability of point's contracts (less scattered) as the measurement angle tends to 90°, showing the accuracy as the joint angle increases. The reason could be that the participant reported difficulty to keep the limb stable while bending it with small angles.

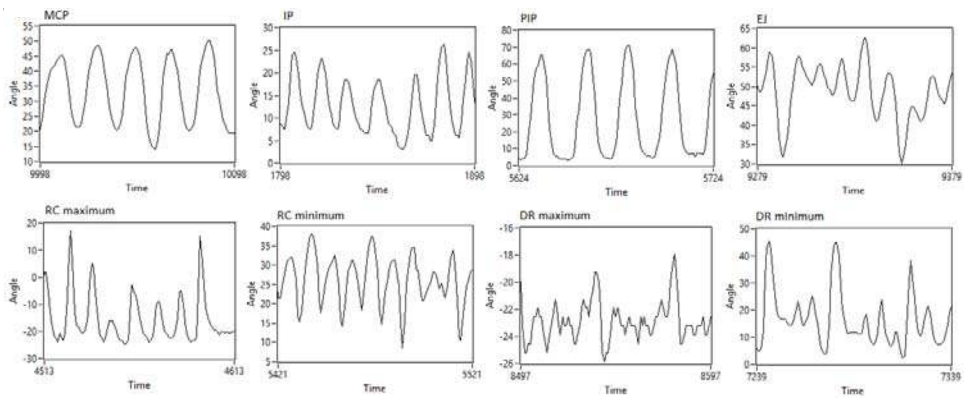
Figure 3 Bland Altman plot for assessment of agreement between the sensor angle and traditional goniometry (see online version for colours)



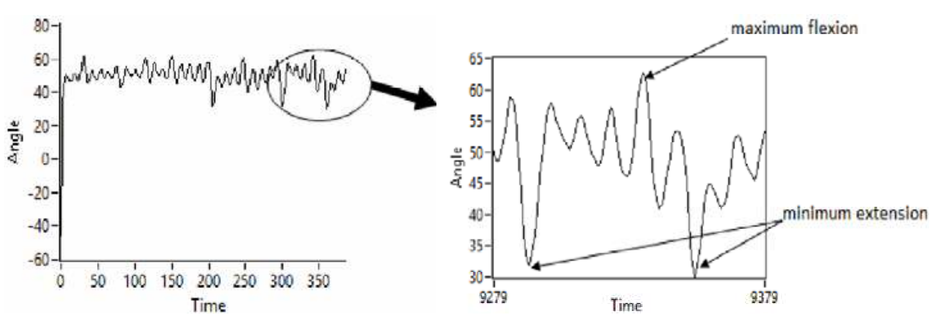
4.2 *Measurement of joint angle and repetitiveness during weaving*

Ten healthy female participants (aged 22–40) volunteered during the weaving subtasks. They underwent each weaving session for at least 1 minute. The sensory outcome for a full range of hand movements (flexion/extension/deviation) of the index finger, thumb, wrist, and elbow during the weaving task was determined. The sensors were affixed to the glove and elbow brace, as described in Section 3.1 and 3.2. The calibration procedure was performed before sensory measurements on each subject. It was observed that knotting requires the continuous movement of index MCP, PIP, and thumb IP joints while the use of weaving knife, beater and comb involves the movement of flexion/extension, ulnar deviation of wrist and elbow extension. The typical sensor readings shown in the Figure 4(a) shows the short segments (last 100 values) of the joint angles sent over to the waveform chart. It depicts the maximum and minimum values of elbow flexion/extension over that short time frame. Figures 4(b) and 4(c) show an example of raw data from the sensor of the EJ (olecranon eminence of the ulna) of one subject during subtask 1 and 2. Figure 5 reports the average of maximum angle induced during knotting and knot cutting subtasks for all the ten subjects. Each value is the average of maximum values for each joint during knotting and knot cutting cycles.

Figure 4 (a) Sample raw angle data over time of the eight different joints of a subject for a single data block collected during the knotting and knot cutting subtasks (b) Sample raw angle data over time of EJ of the same subject during the knotting and knot cutting subtasks (c) Short segment of the joint angles sent over to the waveform chart showing maximum and minimum data points for elbow flexion/extension during the knotting and knot cutting subtasks



(a)

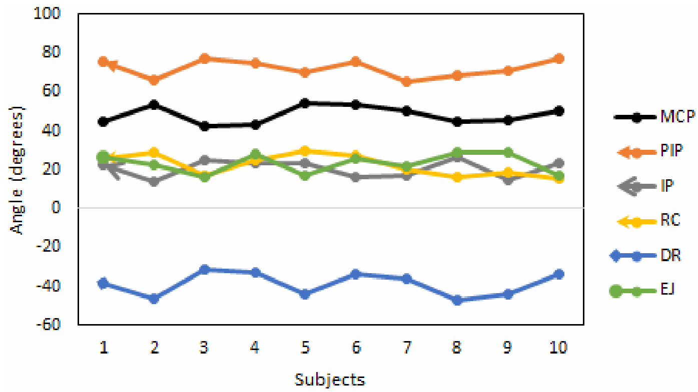


(b) (c)

Notes: Angles are in degrees. MCP – index metacarpophalangeal joint, PIP – proximal interphalangeal joint, IP – thumb interphalangeal joint, RC – radiocarpal joint to measure palmar flexion of the wrist, DR – distal radioulnar joint to measure ulnar abduction, EJ – elbow joint to measure flexion (concentric).

In a study, ICC was computed for reliability analysis of the electro-goniometer gloves (Saggio, 2014). Results showed the ICC were as high as 0.99 for MCP joints of the index finger and 0.86 for DIP and PIP joints. In another study by Simone et al. (2007), random repeated trials were performed, and the average ICC for each MCP joint ranged from 0.933 to 0.980 with an overall average of 0.955 ± 0.091. Some other studies also pointed out that repeatability and reliability of the electro-goniometric sensor glove were high and lies within the acceptable range (Gentner and Classen, 2009). A reliability coefficient value higher than 0.70 could be the standard criteria for acceptance for upper limb function assessment instruments (Van de Ven-Stevens et al., 2009).

Figure 5 Average of maximum angle induced during knotting and knot cutting subtasks for all the subjects (see online version for colours)



Notes: Each value is the average of knotting cycles performed at least for 30 seconds. The maximum values for each joint are used to calculate the average measurement for each subject. MCP – index metacarpophalangeal joint, PIP – proximal interphalangeal joint, IP – thumb interphalangeal joint, RC – radiocarpal joint to measure palmar flexion of the wrist, DR – distal radioulnar joint to measure ulnar abduction, EJ – elbow joint to measure flexion (concentric).

Table 3 depicts the mean ranges of the maximum and minimum data values acquired from the sensors. For EJ joint in subtask 3, the mean (SD) for the minimum value (during flexion of elbow) is 22.1 (4.08), whereas, the maximum value (during extension of elbow) is 74.2 (5.50). Similarly, RC joint of ten subjects performing subtask 1 and 2 showed the mean (SD) of the minimum value (during dorsal flexion of the wrist) as –35.4 (4.45), whereas, the maximum value (during palmar flexion of the wrist) as 22.3 (5.84). Due care has been taken to navigate the extreme points on the plot by using cursor plot function in the waveform graph. For subtask 1 and 2, effort frequency was found 56 to 77 efforts per minute for knotting and knot cutting subtasks for MCP, PIP, RC and DR joints. A smaller value for repetition in thumb IP joint was found since it is only used to guide the thread during knotting. RC and DR joint has the highest ROM since higher wrist deviation is required while using weaving knife during knot cutting. The knife blade can be an essential evaluation measure and should be redesigned so that wrist movement can be minimised (Singh et al., 2018a). RC, DR and EJ joints were having almost close mean repetition values since they are synchronised during cutting knots. Surprisingly, for subtask 3 and 4 (using weaving comb and beater), the ROM for ulnar deviation and wrist flexion/extension was more extensive than elbow flexion/ extension. During the impact of weaving beater/comb on the edge of the carpet, the wrist acts as a fulcrum, and the impact force has a turning effect (moment) about the fulcrum. These tools can be further redesigned by focusing the path of movement of the tool (Singh et al., 2018a). The repetition frequency was higher in subtask 3 and 4 when compared to subtask 1 and 2. It must be borne in mind that this study was only conducted on a small group of workers and some of the variations in the angles are due to the difference in anthropometry of the participants.

Table 3 Mean (°) and standard deviation (°) of the maximum and minimum values from the electro-goniometric glove and elbow brace

Subtask	*Joint*	*Flexion/extension*		*Deviation*		*Repetition per min*
		Minimum	*Maximum*	*Minimum*	*Maximum*	
Subtask 1 and 2	MCP	18.4 (2.35)	48.2 (5.24)	-	-	67.8 (6.03)
	PIP	5.1 (1.83)	72.5 (4.45)	-	-	68.1 (5.43)
	IP	7.3 (2.41)	20.2 (4.65)	-	-	51.4 (4.85)
	RC	–35.4 (4.45)	22.3 (5.84)	-	-	68 (5.04)
	DR	-	-	–38.6 (6.78)	–15.2 (2.50)	67.2 (4.92)
	EJ	32.5 (2.30)	58.4 (3.15)	-	-	69.8 (3.01)
Subtask 3	RC	–25.4 (4.43)	28.3 (3.83)	-	-	141.4 (5.48)
	DR	-	-	–31.2 (4.44)	6.3 (3.61)	141.4 (5.48)
	EJ	22.1 (4.08)	74.2 (5.50)	-	-	138.5 (4.08)
Subtask 4	RC	9.5 (4.10)	45.5 (3.62)	-	-	136.4 (5.52)
	DR	-	-	–29.4 (5.36)	12.3 (4.34)	136.4 (5.52)
	EJ	29.3 (4.65)	56.2 (3.82)	-	-	133.2 (4.84)

Notes: Dominant right-hand flexion/extension, deviation, and repetition for ten subjects performing four subtasks. MCP, PIP, and IP do not involve repetition in the beating and combing tasks. A negative value represents an extension of the joint and/or ulnar deviation of the wrist.

Table 4 Frequency of risk factors (FR, F, AP and AF) of the four different subtasks among the female weavers (N = 10; right hand dominant)

Risk factor	*Sub-factor*	*Subtask*	*Hand*	*Rating criterion*		
				Infrequent (some intermittent movement)	*Frequent (regular movement)*	*Very frequent (continuous movements)*
Frequency and repetition (FR)	Arm movement A1	Subtask 1	L		8 (score 3)	2 (score 6)
			R		8 (score 3)	2 (score 6)
		Subtask 2	L	10 (score 0)		
			R			10 (score 6)
		Subtask 3	L	10 (score 0)		
			R	10 (score 0)		
		Subtask 4	L	10 (score 0)		
			R	10 (score 0)		
	Repetition A2			< = 10 times/min	11–20 times/min	> 20 times/min
		Subtask 1	L			10 (score 6)
			R			10 (score 6)
		Subtask 2	L			10 (score 6)
			R			10 (score 6)
		Subtask 3	L	10 (score 0)		
			R			10 (score 6)
		Subtask 4	L	10 (score 0)		
			R			10 (score 6)

Table 4 Frequency of risk factors (FR, F, AP and AF) of the four different subtasks among the female weavers (N = 10; right hand dominant) (continued)

Risk factor	*Sub-factor*	*Subtask*	*Hand*	*Rating criterion*			
				Infrequent (some intermittent movement)	*Frequent (regular movement)*	*Very frequent (continuous movements)*	
Force (F)	Level of exertion B			Light	Moderate	Strong	Very strong
		Subtask 1	L	10 (G0)			
			R	10 (G0)			
		Subtask 2	L	10 (G0)			
			R		10 (R8)		
		Subtask 3	L	10 (G0)			
			R		1 (A2)	9 (R9)	
		Subtask 4	L	10 (G0)			
			R		6 (A2)	4 (R9)	
Awkward posture (AP)	Head and neck posture C1			Neutral	Bent or twisted (15%–30% of time)	Bent or twisted (> 50% of time)	
		Subtask 1				10 (score 2)	
		Subtask 2				10 (score 2)	
		Subtask 3			10 (score 1)		
		Subtask 4			10 (score 1)		
	Back posture C2			Neutral	Bent forward	Bent forward or twisted (> 50% of time)	
		Subtask 1				10 (score 2)	
		Subtask 2				10 (score 2)	
		Subtask 3		10 (score 0)			
		Subtask 4			10 (score 1)		
	Arm posture C3			Close to body	Raised away from body (part of time)	Raised away from body (> 50% of time)	
		Subtask 1	L			10 (Score 4)	
			R			10 (Score 4)	
		Subtask 2	L			10 (Score 4)	
			R			10 (Score 4)	
		Subtask 3	L	10 (score 0)			
			R			10 (Score 4)	
		Subtask 4	L	10 (score 0)			
			R			10 (Score 4)	

Table 4 Frequency of risk factors (FR, F, AP and AF) of the four different subtasks among the female weavers (N = 10; right hand dominant) (continued)

				Rating criterion			
Risk factor	*Sub-factor*	*Subtask*	*Hand*	*Infrequent (some intermittent movement)*	*Frequent (regular movement)*	*Very frequent (continuous movements)*	
Awkward posture (AP)	Wrist posture C4			Neutral	Bent or deviated (part of time)	Bent or deviated (> 50% of time)	
		Subtask 1	L			10 (score 2)	
			R			10 (score 2)	
		Subtask 2	L			10 (score 2)	
			R			10 (score 2)	
		Subtask 3	L	10 (score 0)			
			R		10 (score 1)		
		Subtask 4	L	10 (score 0)			
			R		10 (score 1)		
	Hand/ finger grip C5			Power grip	Pinch or wide grip (part of time)	Pinch or wide grip (> 50% of time)	
		Subtask 1	L			10 (score 2)	
			R			10 (score 2)	
	Hand/ finger grip C5	Subtask 2	L	10 (score 0)			
			R	10 (score 0)			
		Subtask 3	L	10 (score 0)			
			R	10 (score 0)			
		Subtask 4	L	10 (score 0)			
			R	10 (score 0)			
Additional factors (AF)	Breaks D1			1–2 hours	2–3 hours	3–4 hours	> 4 hours
		Subtask 1			10 (score 4)		
		Subtask 2			10 (score 4)		
		Subtask 3		10 (score 2)			
		Subtask 4		10 (score 2)			
	Work pace D2			Not difficult	Sometimes difficult to keep up	Often difficult to keep up	
		Subtask 1			7 (score 1)	3 (score 2)	
		Subtask 2			7 (score 1)	3 (score 2)	
		Subtask 3		10 (score 0)			
		Subtask 4		10 (score 0)			

Table 4 Frequency of risk factors (FR, F, AP and AF) of the four different subtasks among the female weavers (N = 10; right hand dominant) (continued)

Risk factor	*Sub-factor*	*Subtask*	*Hand*	*Rating criterion* *Infrequent (some intermittent movement)*	*Frequent (regular movement)*	*Very frequent (continuous movements)*	
Additional factors (AF)	Other factors D3			No factors present	One factor is present	Two or more factors are present	
		Subtask 1				10 (score 2)	
		Subtask 2				10 (score 2)	
		Subtask 3				10 (score 2)	
		Subtask 4				10 (score 2)	
	Duration D4			< 2 hours	2–4 hours	4–8 hours	> 8 hours
		Subtask 1				10 (multiplier × 1)	
		Subtask 2				10 (multiplier × 1)	
		Subtask 3		10 (multiplier × 0.5)			
		Subtask 4		10 (multiplier × 0.5)			

4.3 Assessment of repetitive task

The exposure score was assessed by the combination of scores in the various categories on the task identification data sheet. Table 4 represents the frequency of risk variables of the four different subtasks among the female weavers. Findings from ART show that let's say for the subtask 2 for the dominant right hand, the frequency and repetition (FR) were high due to higher number of exertion during observed time (score 6), the intensity of exertion (F) was high enough due to high force exertion against the wool knot while swinging the wrist (score 9). Hand/wrist postures were showing deviation from the neutral position with back posture bent forward in most of the cases (score 10). Then there are sufficient reasons to assign a very high priority for change as the combination of scores (HSE, 2010).

Table 5 tries to link the data about the worker's priority scores in different subtasks for both hands. It provides the information that out of ten subjects which were assessed and exposure score was defined had what level of exposure priority in different tasks. It was evident from ART analysis that the combinations of scores for both hands for subtask 1 and 2 were having a very high overall priority score (ES > 22) among all the participants. It has an interpretation that a detailed investigation should be immediately done and possible changes should be required in the level of exertion and present posture.

The duration of effort during knotting and knot cutting was found to be 0.8 to 1.10 seconds during each effort. Effort frequency was found 56 to 77 efforts per minute. These ranges were taken using the data acquired from the electro-goniometer. However, subtask 3 was having a moderate priority score (12 ≤ ES ≤ 21) for dominant hand among nine participants. Subtask 4 was having a moderate priority score for dominant hand among four participants whereas low priority score (0 ≤ ES ≤ 11) for non-dominant hand among six participants (Table 5).

Table 5 Overall priority score between different subtasks among female weavers (N = 10; right hand dominant)

Subtask	*Hand*	*Overall exposure priority (n = 10)*		
		Low (0–11)	*Moderate (12–21)*	*High (≥ 22)*
Subtask 1	L			10
	R			10
Subtask 2	L			10
	R			10
Subtask 3	L	10		
	R	1	9	
Subtask 4	L	10		
	R	6	4	

This is a longitudinal study, and the results from the postural assessment were in agreement with the conclusions of a previous field study which includes the investigation on 75 female weavers (Singh et al., 2018a). They were inspected using the strain index postural assessment technique without the application of goniometric gloves. Strain index is a pen and paper based observational method used for the assessment of physical exposures inherent in mono-task. Digital photographs and videotapes were used as data collection tools for the analysis. The video graphic analysis could be used for calculating the repetitiveness (efforts per minute) in the task, but, it is arduous to quantify the flexion/extension angles accurately. Electro-goniometer could provide us with a clearer picture of postures revealing the ROM in any task (Yen and Radwin, 2000).

4.4 Cost-benefit analysis

The cost-benefit breakdown comparing the fabricated RFS electro-goniometer and commercial electro-goniometer is depicted in Table 6. It could be seen that due to the low-cost components, the total cost of the commercial devices (Biometrics Ltd., 2017) are five times larger than that of wearable electro-goniometer. Also, it should be noted that many of the fixture items (e.g., wiring, male headers, resistors, soldering material, heat-shrinkable tubing, double-sided tape, and adhesive) come in large quantities and can be used to fabricate multiple devices.

Table 6 Comparable cost and benefits analysis of the developed electro-goniometer and commercially available electro-goniometer

Costs and benefits	*RFS electro-goniometer (fabricated in the present study)*	*Electro-goniometer (commercially available)*
Non-recurring costs (INR)		
Sensor (one set)	1,800	52,000[a]
Hardware	1,800	150,000[a]
Software	7,400	
Laptop	25,000	25,000
Fixtures	3,500	500
Recurring costs (INR)		
Labour cost	1,000	1,000
Total cost	*40,500*	*228,500*
Quantifiable benefits		
Accuracy error measured over 90° from neutral position	±5°	±2°
Operating temperature range	–35°C to + 80°C	+0°C to + 40°C
Non-quantifiable benefits		
Dynamic measurement	√√	√√
Time saving	√√	√√
Social benefits and inclusion	√	√
Work effectiveness	√√	√√
Leads to improved quality of the working environment	√	√
Skills required to operate	√	√
Durability	√√	√
Robustness	x	√√
Set-up time	x	√

Notes: The cost of individual components are at the time of publication. All prices are rounded to the nearest INR amount. √ = benefit identified to some extent; √√ = clearly identified benefits; x = lagging behind. [a]Biometrics Ltd., 2017. Fixtures include wiring, male headers, soldering material, resistors, breadboard, heat-shrinkable tubing, double-sided tape, adhesive, etc. Hardware include analogue-digital converter (Arduino Mega R3) for RFS electro-goniometer and data acquisition device with transducer amplifier for commercially available electro-goniometer. Software cost include annual fee of LabVIEW Professional Development System suite for one user.

Based on spectra symbol RFS data sheet (Flex Sensors, 2018), the lifespan of the flex sensor is more than 1 million flexions/extension cycles. We have used the goniometric gloves multiple times during calibration as well as during the field study on ten participants over the course of two months, without any sensor replacement. Wang et al. (2011) during their investigation revealed that commercial strain-gauge based electro-goniometers make no claims to durability due to their spring-loaded compensation mechanism. The accuracy error, robustness and set-up time required for initialising experiment are the improvement areas to work upon in future studies. Overall, the wearable sensor-based electro-goniometer is sufficiently inexpensive and may help the ergonomists in achieving more accuracy than the conventional ways of conducting postural assessments relying only on observational grounds.

This is the first attempt to investigate the occupational goniometry among handicraft workers using non-powered hand tools. Moreover, our observations suggest that the developed wearable electro-goniometer is lightweight and cost-effective as compared to electro-goniometers available in the market. Most of the previous studies (Singh et al., 2018a, 2017; Gangopadhyay et al., 2015) related to postural and repetitive assessment used pen and paper-based observations, videos, and photographs to determine wrist postures and frequency of exertion. Postural assessments utilising the wearable electro-goniometer could provide more reliable test results than the observational scoring.

5 Business implication

This study provides several important implications including human factors and productivity. The effective use of diagnostic tools in healthcare technology significantly increases comfort and satisfaction among the patients. However, most of those equipment's for health assessment are quite expensive (Peregrin and Jablonsky, 2016). By developing an RFS based goniometer helps to provide a better understanding of postural assessment at a relatively lower cost. Moreover, the sensory glove and elbow brace could be used for any type of hand intensive work industry. This can be an essential evaluation measure to minimise the wrist and/or elbow movement close to neutral postural position. It further is useful in designing hand tools by focusing the path of movement of the tool.

Poor work system design in handicraft industries is responsible for worker's stress and fatigue resulting in lower productivity. Ergonomic interventions could reduce MSDs, increase the work performance and productivity among the workers (Meena et al., 2014).

6 Conclusions

An array of RFS was embedded to develop a simple and low-cost electro-goniometer with its application in the joint angle monitoring. The data acquired from the sensors in the current report provide reliable, linear, highly accurate joint angle values. The voltage-angle pair showed linearity for the measurement range of 0°–90°. The sensory glove and elbow brace provide a dynamic evaluation of ROM during their normal weaving activities. RFS were chosen for their lightweight and cost-effectiveness. The accuracy validation of the sensors shown a favourable agreement with traditional goniometry. The combinations of scores from the ART technique revealed that detailed investigation is required to the level of exertion during carpet weaving.

6.1 Limitations of the study

The RFS (make: spectra symbol) limits the effective length of flex sensors to 2.2” and 4.5”, thereby limiting its application as the electro-goniometer to relatively smaller or larger joints. Therefore, for measurement of lower back and neck angles, we have used static analysis (Kinovea 8.15). Furthermore, we have not measured distal interphalangeal joint as the shorter length of the sensor was not available at the time of publication. It should be noted though; the same techniques apply to the RFS with relatively longer or shorter length.

The design constraints of the RFS make the electro-goniometer ideally suited for measuring a single degree of freedom. Nevertheless, on careful examination of bending trajectories, it was seen that the measurement trajectories were in agreement with the actual movements of the respective joint (Table 2 and Figure 3). It signifies that the measurements from the electro-goniometer will be accurate as long as we perform the calibration procedure correctly.

6.2 Future scope

The present intervention of the sensory glove and elbow brace was restricted to a total of eight sensors. The number of sensors can easily be expanded with stitching sleeves, additional sensor inputs to the microcontroller and a small change LIFA program. Presently, proper monitoring should be done by the examiners ensuring the precise position of the sensor to achieve accurate calibration. Future directions include repeatability assessment over multiple days.

While the future research directions remain open to discussion, the next phase of the study includes the calibration of the developed goniometer with commercially available strain gauge goniometers. Nevertheless, the results from this study can be useful in designing hand tools in the future. The knife blade can be an essential evaluation measure and should be redesigned so that wrist movement can be minimised. During the impact of weaving beater/comb on the edge of the carpet, the wrist acts as a fulcrum, and the impact force has a turning effect (moment) about the fulcrum (Singh et al., 2018a). These tools can be further redesigned by focusing the path of movement of the tool. Furthermore, authors are intended to work on developing a much more robust system with which the users can use their usual hand dexterity without restrictions created by the fear of damaging the device. Limited portability, accuracy error, and tedious calibration are the other area needed to work upon. Further research is hence needed to explore the better ergonomic interventions.

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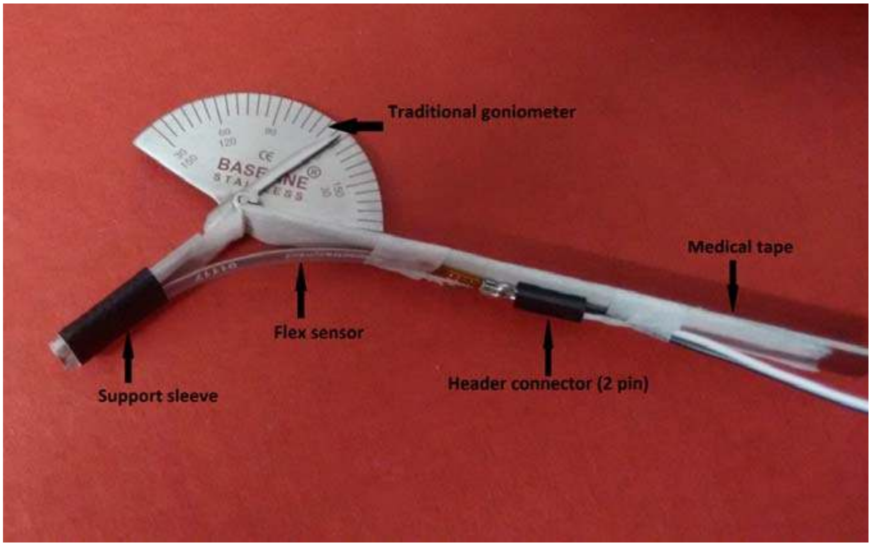
Annexure

Sensor selection, evaluation/calibration and electro-goniometer development

RFSs are based on variable resistive characteristics of a substrate material (carbon ink) and operate on the same principle as strain gauges. It is a passive device which does not require any power source to work. When it is flexed, the substrate is consequently compressed, and the conductive layer stretches, thereby increasing up to a maximum value of resistance corresponding to the maximum measurable angle of deflection (Saggio et al., 2015).

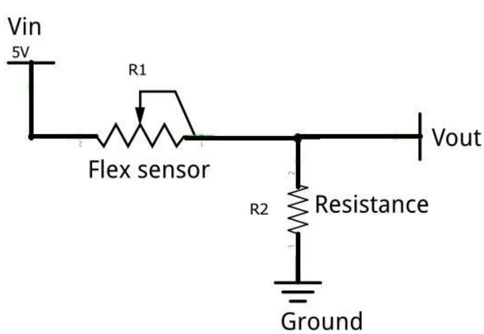
Therefore, calibration is necessary for converting the voltage output from the RFS to joint angles. A LabVIEW-based code was developed to calibrate the glove and elbow brace electro-goniometer. The angle measurements were done using a conventional goniometer (make: baseline; model: 12-1015). The direct physical contact between the exposed surface of the sensor and goniometer arms was prevented by medical tape (3M™ Durapore™) (Figure A1). The calibration angles were set 5° degrees apart till 90°, and the corresponding output voltages from the sensors were measured. The linear or nonlinear relationship from voltage to angle pairs could be obtained for converting the output voltage to the joint angle by interpolation.

Figure A1 Calibration setup for converting the voltage output from the RFS to joint angles (see online version for colours)



Among the different commercially available sensors, we chose spectra symbol carbon ink RFS (Salt Lake City, UT, USA) because of its higher signal stability over time in comparison to other sensors (Simone and Kamper, 2005). These inexpensive sensors change their resistance when subject to bent. Here, the 'bent' is a relative term which refers to the angle made by the curvature of RFS and measured in degrees. To facilitate secure connection, RFS terminals were soldered by the male headers with 10 mm × 0.64 mm pins (2.54 mm spacing; make: Robo India, Rajasthan, India). 2.54 mm square female headers (2 × 1 configuration; make: Robo India, Rajasthan, India) were arranged back-to-back with the male headers. Polyolefin heat shrink insulating tubing (5 mm; shrink ratio: 2:1; make: Robo India, Rajasthan, India) was applied to the headers to prevent environmental exposure.

Figure A2 A schematic circuit for converting flex sensor into voltage divider (potentiometer) (circuit made on Fritzing open source software version 0.9.3)



The resistance of 2.2-inch RFS varies from about 20 kΩ, when in a straight position, to 65 kΩ, when bent to 90°. For 4.5-inch RFS, the resistance value changes from 10 kΩ to 18 kΩ, when bent from 0° to 90°. The trajectory of bending is the angle between tangential lines at the finger, wrist or the EJs. As it straightens out again, the resistance returns to its original value. The simplest way to acquire voltage is to convert the sensor into voltage divider (potentiometer), by incorporating a suitable resistance into the circuit that yields the best range of voltage output (Figure A2).

To make the RFS work in the scenario that we can use analogue to digital converter (ADC), we need to apply voltage divider formula:

$$V_{out} = V_{in}\left(\frac{R_1}{R_1 + R_2}\right) \tag{1}$$

Here

V_{in} is the input voltage, i.e., 5V in this case

V_{out} is the output voltage for 0° and 90° bend

R_1 is the resistance of the flex sensor for 0° and 90° bend

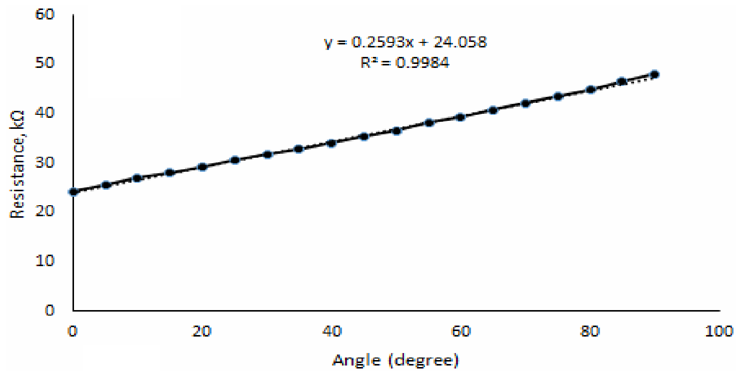
R_2 is the suitable resistance into the circuit that yields the best range of voltage output.

Here, R_1 is the varying resistance of the RFS which is known. Unfortunately, in this case, R_2 is going to be constant. As we can see from equation (1), this condition will limit our V_{out} since we cannot change the value of R_2 as in potentiometer. So, we have selected a range of 10 k to 65 kΩ resistance values with a step of 1 kΩ to yield the best range of voltage output. After trial-and-error calculation for establishing the threshold range of voltage difference, 28 k, 34 k, 35 k, 53 k and 46 kΩ series resistors for 2.2-inch RFS and 13 kΩ resistor for 4.5-inch RFS were chosen to hookup on the ground side. The terminals of each sensor were connected to an analogue-digital converter (ADC) (16 analogue input channel, operating voltage 5V, Arduino Mega R3) based on the ATmega2560 (D'Ausilio, 2012). The ADC was plugged into a laptop via USB cable, and the sensor signals were sampled continuously at 100 Hz using LabVIEW interface for Arduino (LIFA) that allows acquiring data from the Arduino microcontroller. The signals were processed in the LabVIEW version 13 graphical programming environment (NI Corp., Austin, TX).

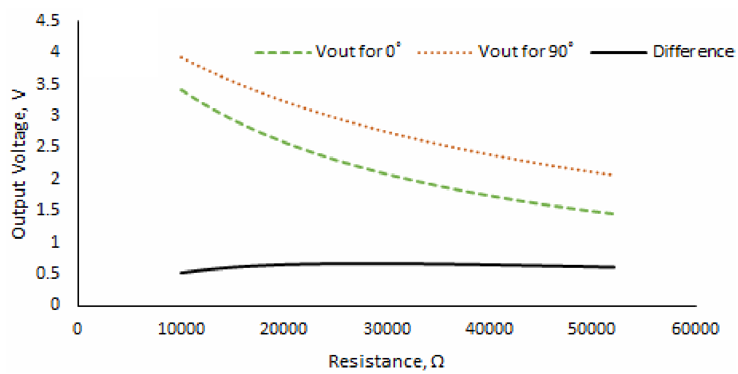
Results from sensor evaluation/calibration

Simone et al. (2007) and Williams et al. (2000) claimed a nonlinear relationship between voltage and angle using flex sensors. Contradictory to their study, a few studies showed linearity in voltage angle pairs (Oess et al., 2010, 2012; Gentner and Classen, 2009). Oess et al. (2012) in their study, opined that from 0° to approximately 100°, the voltage and angle had a linear relationship, and from 100° to 120°, saturation region that cannot be used for measurements.

Figure A3 (a) Linear interpolation trend line obtained for angle vs. bend resistance of one of the 2.2-inch sensor. Bend resistance varies from 24 kΩ, when in a straight position, to 48 kΩ, when bent to 90° (b) Selection of resistance to convert the sensor into a voltage divider (see online version for colours)



(a)



(b)

Note: Trial-and-error calculation for establishing the threshold range of voltage difference, i.e., 28 kΩ series resistor for one of the 2.2-inch flex sensor was chosen to hookup on the ground side.

The RFS were embedded to a conventional goniometer for calibration purposes, as described in Section 3.3. A sample interpolated curve with voltage-angle pairs are shown in Figure A3(a). Based on calibration data, a voltage to angle optimal linear model was found by minimising the sum of squared deviation for the angle-resistance combination for each sensor. Figure A3(b) depicts the plot of trial-and-error calculation for establishing the threshold range of voltage difference, i.e., a 28 kΩ series resistor for one of the 2.2-inch RFS. For other sensors, the threshold range of voltage difference, 34 k, 35 k, 53 k and 46 kΩ series resistors for 2.2-inch RFS and 13 kΩ resistor for 4.5-inch RFS were chosen to hookup on the ground side. As we can see from Figure A3(b), the output voltages in both straight and 90° bent position show an exponential decay as the resistance values increases. The difference in output voltage for 0° and 90° has a threshold point at 28 kΩ resistance beyond which the output voltage difference again tend to decrease.