Carbon Nanotube-Coated Thread for Wearable Proprioception Sensing

Dedy H.B. Wicaksono[a*], Bilhan Benhanan[a], Deby Erina Parung[a], Putri Indes Oktabriani[a], Fuad Ughi[a], Aisyah A. Shafi[b], Vitriana Biben[c], Novitri Maulana[c], Farida Arisanti[c], Yuliati Herbani[d], Brian Yuliarto[e,f] & Hermawan K. Dipojono[e,f]

[a]*Department of Biomedical Engineering, Faculty of Life Sciences and Technology, Swiss German University (SGU), Tangerang, Indonesia*
[b]*School of Biomedical Engineering and Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), Malaysia*
[c]*Dept. of Physical Medicine and Rehabilitation, Faculty of Medicine, Universitas Padjadjaran (UNPAD) / dr. Hasan Sadikin Hospital, Bandung, Indonesia*
[d]*Research Center for Physics, Indonesian Institute of Sciences (LIPI), Tangerang Selatan, Indonesia*
[e]*Department of Engineering Physics, Institut Teknologi Bandung (ITB), Bandung, Indonesia*
[f]*Research Center for Nanosciences and Nanotechnology, Institut Teknologi Bandung (ITB), Bandung, Indonesia*

*corresponding author: dedy.wicaksono@sgu.ac.id

Abstract: This paper focuses on the development of thread-based sensor for proprioception sensing in finger and knee. The thread sensor is made by dipping cotton thread into carbon nanotube (CNT) dispersion. The electrical and electromechanical properties of the thread change depending on the dipping parameters. The resistance of the CNT-Coated threads changes due to in-plane force, exhibiting a piezoresistive-like mechanism. The CNT-coated thread functioning as strain gage is sewn into hand glove and yoga pants. The thread sensor will stretch upon finger or knee bending, and its resistance will change accordingly. Using this wearable sensor, proprioception detection is conducted for finger bending and sit-to-stand movement.

Keywords: Carbon Nanotube, Cotton Thread, Proprioception, Wearable Sensor

5. Introduction

Proprioception is the sense of the effort to make movement of one's parts of the body (Elsevier, 2013). The loss of proprioceptive sense may affect muscular control. Many neurological and orthopedic conditions are related to proprioception such as stroke (Kenzie et al., 2014). Therapies have been applied and proven to be effective (Aman, Elangovan, Yeh, & Konczak, 2015). Therapies can be assisted by using orthosis, or prosthesis in the case of missing body part. In order that an assessment can be done during the therapy, there is a need to detect and sense the relative position of one's part of the body to the others, hence proprioception sensing.

For therapy assessment purposes, this can be carried out using camera and image recognition system, called as visual proprioception monitor (Pauwels & Kragic, 2015). However, such system is complex and cumbersome. Furthermore, it cannot be made portable, let alone wearable by the person undergoing the treatment. Previously, silver nanoparticles (AgNP) have been patterned on cotton fabrics to develop stretchable sensor for finger's proprioception sensing (Yuen et al., 2014). While the sensor performs quite well, AgNP is a rather expensive nanomaterial with potential toxicity towards human's body. In 1991, Carbon Nanotube (CNT) was discovered by Iijima (Iijima, 1991). CNT has fascinating electronic, and mechanical properties. The atoms bonding on CNT is very strong and CNT has high electrical conductivity. CNT has been applied in several applications. CNT has also been used to coat thread for finger proprioception sensing (Shafi & Wicaksono, 2017). CNT-coated thread offers a lower cost, stretchable and wearable sensor for proprioception sensing.

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In this work, we extend further the application of CNT-coated thread to sense proprioception, in different parts of the body, namely the fingers and the knee. The CNT-coated thread is sewn into glove and stretchable yoga pants to function as wearable sensor for detecting finger flexion, and sit-to-stand postural change.

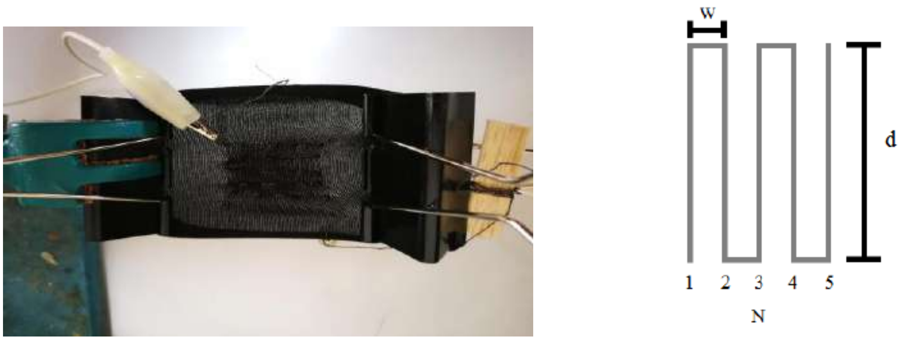
6. Materials and Methods

6.1. Materials

In this project, the CNT-coated thread that was fabricated by Shafi (Shafi & Wicaksono, 2017) was used as the main sensor. Firstly 100% cotton thread was scoured to remove its wax. The scoured thread was then coated with Multi-Walled CNT (MWCNT) dispersion by using facile conventional dipping drying method. The thread was dipped ten times and was then calibrated.

6.2. Dynamometer Calibration Method

The CNT-coated thread was manually sewn to a stretchy cloth, as shown in Figure 1(a), with a strain pattern like shown in Figure 1(b). The strain gage form has 5 vertical lines with 4 horizontal lines. The vertical lines are 2.5 cm and the horizontal lines are 0.5 cm each. Each end of the cloth was clipped with a black paper clip for steadier configuration. As seen in Figure 2, one of the paper clips is being held up by a dynamometer 5N to control the strain given, while the other is firmly held in its position.



(a) (b)

Figure 1. (a) CNT-coated thread sewn to a cloth, (b) the strain gage pattern

The thread will be pulled by 0.5 N, 1 N and 1.5 N with the vertical pull direction from the illustration in Figure 1 (b) (i.e. along the *d* axis). An alligator cable was clipped on each ends of the thread and connected to a multimeter for the resistance reading. The measurement was done repeatedly with different number of thread line and different initial length of the thread.

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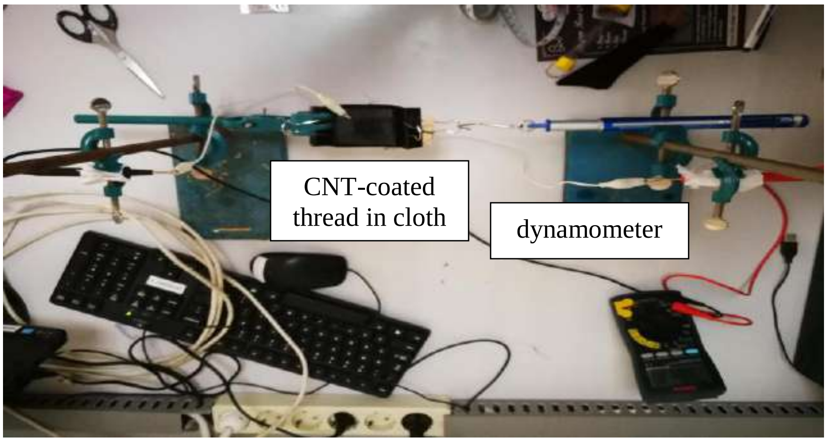


Figure 2. Setup of the dynamometer calibration method

6.3. Glove Calibration

The CNT-coated thread was sewn manually to the index finger part of a glove with a strain gage pattern as shown in Figure 3. The strain gage form has 3 vertical and 2 horizontal lines. The vertical lines are 2 cm long and the horizontal lines are 3 mm and 2 mm respectively. Then each end of the thread near the strain gage pattern was clipped to the alligator clip. The alligator clips were then clipped to digital multimeter where one of the clips was connected to the positive electrode and the other clip was connected to the negative electrode. The glove was worn by a subject. The resistance of the thread was measured at three different positions: straight, 45 degrees bent and 90 degrees bent positions (Figure 4). The measurement was repeated until five times.

Figure 3. CNT-coated Thread Sewn to a Glove

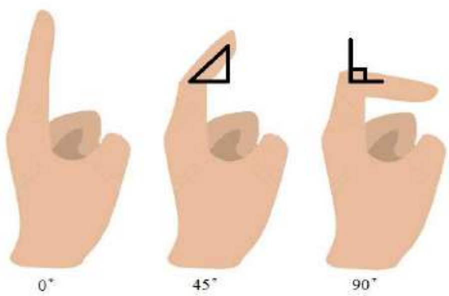


Figure 4. Index finger bend position

6.4. Pants Calibration

First, the CNT-coated thread was stitched manually to the knee part of a stretch/yoga pants as shown in Figure 5. Alligator cable was clipped on each end of the CNT thread. The digital multimeter was connected to the alligator cable with one clip connected to the positive electrode and the other one to the negative electrode. The resistance of the CNT thread strain during sitting position was measured. The subject was moved to half stand position (the knee joint bent is approximately 45 degrees). The resistance of the CNT thread after the strain was measured. The subject was moved to standing position. The resistance of the CNT thread during standing position was measured. The measurement was then repeated until five times. The measurement was then repeated with the pants during sit position adjusted until the resistance value is similar to the first sitting value. Figure 6 shows the sit-to-stand movement.

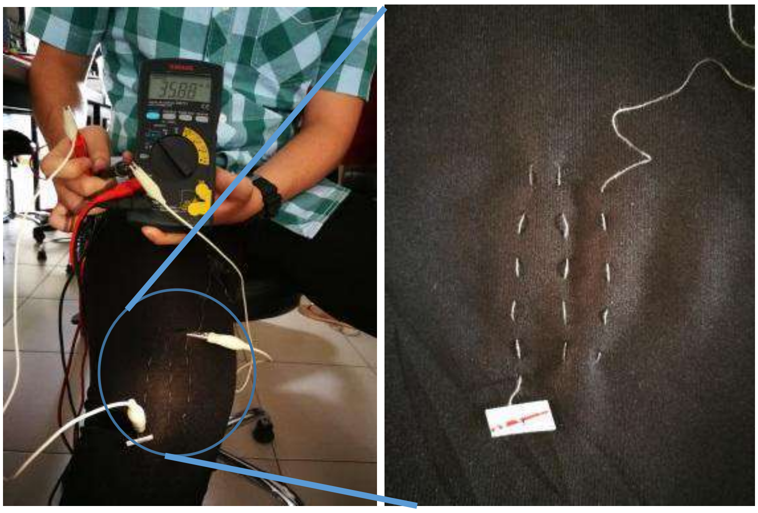


Figure 5. Stitched CNT-coated thread to knee part of a stretch/yoga pants

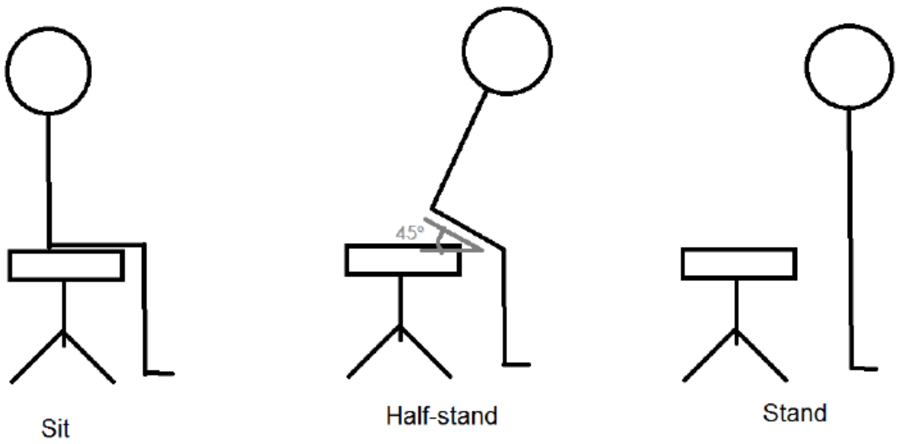


Figure 6. Sit to stand position

7. Results and Discussion

The strain gage was calibrated with the in-plane stress. The parameters obtained from the measurements are: force (F), number of lines (n), initial resistance (R_i), final resistance (R_f), initial length (l_i) and final length (l_f). The parameters obtained from the calculations are: resistance difference (ΔR), length difference (Δl), relative resistance change ($\Delta R/R_0$), normal strain (ε), and gage factor (*GF*). Equation (1) shows the formula for calculating resistance difference. Equation (2) shows the formula to calculate the length difference.

$$\Delta R = R_f - R_0 \tag{1}$$

$$\Delta l = l_f - l_0 \tag{2}$$

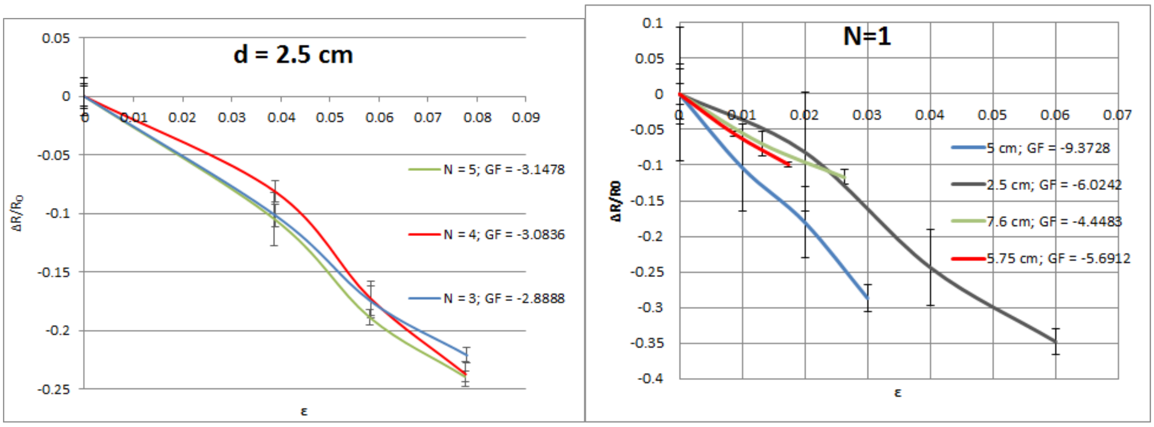
The relative resistance change can be determined from its symbol if the corresponding data is available or using the equations (3) and (4), where it is the result from multiplying the normal strain with gage factor.

$$\varepsilon = \Delta l / l_0 \tag{3}$$

$$\Delta R/R_0 = \varepsilon \text{ x } GF \tag{4}$$

7.1. Dynamometer Method

The graph in Figure 7(a) shows the relationship between the change in resistance and the change in relative strain of the thread design. The experiment was done repeatedly on the same distance value, 2.5 cm, but with different number of designed turns each time. The relative strain for the different designs are the same when given the 0.5, 1 and 1.5 N. The gage factor value for the designs with 3, 4 and 5 lines are relatively close together with a mean of -3.0398 ± 0.1353.



(a) (b)

Figure 7. (a) Graph of relative resistance change to normal strain in strain gage with dia. of 2.5 cm; **(b)** Graph of relative resistance change to normal strain in one thread with different length

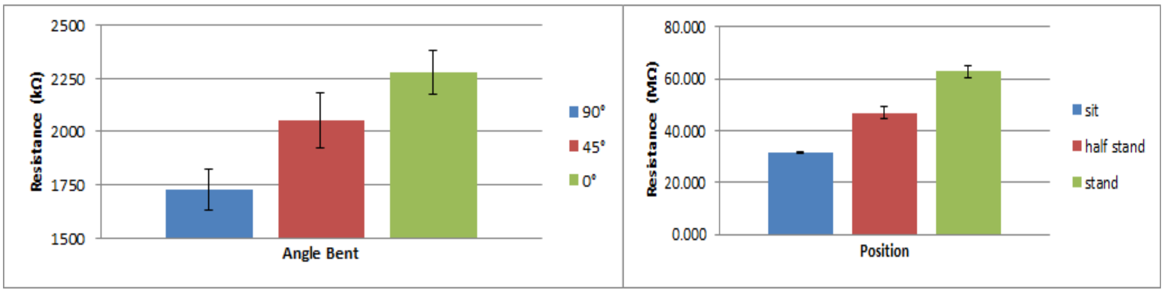
The results show a small increase in *GF* (absolute value) as the number of turns increase. In some cases, when it is required for a low degree of bending or stretching, high *GF* (sensitivity) is needed. More elaborate research on the relationship of the number of lines and *GF* value must be done before acquiring the best design. The result in Figure 7(b) shows the relationship between the change in resistance and the change in relative strain of single threads with different lengths. For the same force given, 0.5, 0.1 and 0.15 N, the relative strain is different for each thread (refer to eq. (3)). The gage factor value of the threads varies greatly. No trend is palpable at this stage, and no correlation is found. The 5 cm thread produced the greatest GF value at -9.3728, while the 7.6 cm thread produced the lowest GF value at -4.4483.

7.2. Glove Calibration

The result in Figure 8(a) shows the resistance characteristic of the thread. As a strain -bending the finger- was given to the thread, the resistance decreases. Based on this method results, the relationship between resistance and strain given is inversely proportional. This pattern is consistent with a value of 1729.143 ± 96.56 kΩ, 2050.154 ± 129.80 kΩ, and 2276.143 ± 102.82 kΩ for respectively 90 degrees, 45 degrees, and 0 degrees of bending. The repeatability is however very low, due to drift. It will have to be calibrated before each usage.

7.3. Pants Calibration

The resistance of the thread decreased as it received strain from the knee bending. The resistances are 33979.375 ± 4056 kΩ, 48043 ± 2988.211 kΩ, 58477 ± 3328.133 kΩ for sitting, half-standing and standing positions, respectively. A calibrated resistance method was used in the hope to increase the measurement repeatability for each position. During the sitting position, the pants are set in certain way that it would mimic the first sitting resistance value. Figure 8(b) shows the resistance for each knee position. The resistances are 31484 ± 358.08 kΩ, 46740 ± 2322.09 kΩ, 62904 ± 2312.69 kΩ for sitting, half standing and standing positions, respectively. It proves to be quite a good method since the values are not as fluctuating as before.



(a) (b)

Figure 8. (a) Graph between angle bent and the corresponding resistance of CNT-coated thread measured in the glove; **(b)** Graph of the resistance over the knee position (standardized in sit position)

8. Conclusion

To conclude, the gage factor is directly proportional to the thread length. The resistance, however, is inversely proportional to the change in length. Current findings show that the increasing number of lines in the strain gage design increase the absolute value of *GF*. The direct correlation between the initial length of a single thread to the resistance, however, is yet to be figured out. To reduce the offset, it is better to do some adjustment before starting a measurement cycle. A more thorough calibration must be done before the CNT-coated thread can be used as a reliable wearable sensor.

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