Design of TPVDF Based Muscular Signal Sniffing Sensor Mechanism for collaborative control system of Human Shoulder Rehabilitation Exoskeleton Robot

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Abstract: The core intention of this research work is to sniff the muscular movement of human shoulder muscles to develop an exoskeleton robot for rehabilitation of physical weak person like elderly, handicapped and stroked one. In this paper we propose a novel design of a sensor mechanism for the sniffing of muscular movement. A piezoelectric phenomenon is used to convert the muscular movement into voltage levels. The thread type Polyvinylidene Difluride (TPVDF) piezoelectric polymer and gold terminal is selected for this purpose after cytotoxicity analysis. This TPVDF is proposed to be stitched or pasted on the human shoulder muscles to sniff the muscular movement. To verify the feasibility of this proposed design two experiments are performed and results are shown.

Keywords: TPVDF, ROM, Cytotocxicty, Exoskeleton

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1. Introduction

Muscular Motion tribulations at upper limb are commonly found not only at old age but also in early ages caused by any accidents. This issue renders a person for permanent aide as clinical recovery through medicines is not possible. The recovery to some degrees is possible only through physiotherapeutic solutions. Traditional limb rehabilitation procedures have inevitable draw backs in the form of cost, efficiency and results [1]. In recent year's biomechanical structures known as powered exoskeletons are preferred to overcome the performance losses observed during manual rehabilitation programs [1-10]. These robotic devices are being designed with considerable features to cover the needs of end users but still the desire for an ideal one are not quenched. Research works are being carried out for an optimal performance product. Among other design issues a critical parameter is the muscular signal sniffing which is the indication of user's intention for an intended movement [1].

Many techniques are available for muscular signal detection but with inherent flaws as indicated for EMG based signal sniffing [1-10]. We have proposed a signal sniffing technique based on relative approach. This is an experimental study whose successfulness will give forth a physical implementation of device. Our hypothesis is based on the fact that TPVDF piezoelectric sensor's response to applied force is identical and matching with PVDF piezoelectric artificial muscle's response on applied force. Artificial fibers of TPVDF polymer will be designed for later stage of physical implementation. These artificial muscles are going to be attached with prime movers of specific shoulder motions. A relative approach is adapted to test and validate the sensor material response with exoskeleton design before its practical implementation on physical limb muscles after surgery.

2. Design of a Sensor

The prime mover (PM) for Human shoulder pitch motion (flexion and extension) is Deltoid Muscle (DM) and the movement is executed when DM contracts and expends. When interior fibers of deltoid muscle (IFDM) contracts and exterior fibers of deltoid muscle (EFDM) expand, flexion movement of human shoulder is executed and vice versa for extension movement. Similarly the yaw motion (abduction and adduction) and roll motion (medial rotation and lateral rotation) of human shoulder execute.

To realize the above mentioned mechanism a thread or fiber type Polyvinylidenedifluride (TPVDF) [11] piezoelectric material has been selected via cytotoxicity analysis for stitching or pasting on the PM muscle by open surgery. All the upper and lower ends of TPVDF are terminated on two gold terminals (upper terminal UT and lower terminal LT) for the extraction of potential difference.

The thread length of TPVDF varies for each subject depends on the muscle size while the thickness is directly proportional to signal strength. To verify the feasibility of this proposed design before implementation on a handicap subject with the help of medical team through open surgery, an alternative procedure is adopted based on two experiments to check the practicability of above proposed design.

2.1 Experiments for Measurement of Muscular Forces

This includes the experimental procedure performed on shoulder ailing person who needs rehabilitations and a set of healthy voluntaries chosen for same BMI to have an analytical study for sniffed signal levels.

2.1.0 Initial Workout

In this phase, an experimental setup was arranged and experiment was performed on a set of healthy subjects along with polio patient having matched BMI's. Polio patient is intended end user of the proposed model.

In this experimental setup, appropriate apparatus was worn on right shoulder and different weights are applied to anticipate the full ranges of motion for shoulder internal and external rotations. This iterative process was performed and data was recorded.

Finally the experiment was performed on a polio patient affected at right arm having limited mobility.

Results were recorded and analyzed to build an efficient control system for motion assistance in upper limb. Result table is shown below.

Table 3.2.2.1 Iterations Result

Subject	**BMI**	**Force in Newton**		**Output(mV)**	
		INT-R	EXT-R	INT-R	EXT-R
Healthy	26.5	11.76	12.74	393	401
Polio	26.5	20.58	23.52	420	433

The analysis of above data shows that about double torque is required to generate the internal and external rotation for polio patient as comparison to healthy persons of same BMI. The reason investigated and observed that the muscles of polio patient are quite stiff and hard due to prolonged disease affects; power amplification is required to produce desired rotation as compare to healthy person. The proposed Collaborative Control System for 1-DOF Exoskeleton Robot will be used to realize this motion assistance as well as therapeutic rehabilitation.

Direct double power cannot be provided as it will be harmful and counter-productive for rehabilitation process. A slow and steady therapy in the presence of expert renders an optimal torque application with safe results.

2.2 Experiment for Calculation of Activation Levels

An experiment has been designed to sniff the activation levels against the calculated muscular forces. In this design a sensor fabricated of PVDF piezoelectric material (LDT0-028K) is used as an alternative method to check the feasibility of proposed sensor design and get the activation levels. To insert a controlled force on the LDT0-028K sensor a helical spring is chosen according to the desired requirement.

2.2.1 DESIGN OF THE REQUIRED SPECIFICATIONS OF HELICAL SPRING

The design of helical spring is based on two known parameters:

1. The sensor LDT0-028K can be deflected up to maximum 20mm due to its size, accordingly the helical spring's axial deflection is

$$y = 20mm.$$

2. The maximum muscular force calculated from first experiment is 61.1N, thus it is considered as maximum load for helical spring.

$$F = 70\ N.$$

(Taking some extra force for omission of errors)

Therefore, a carbon steel wire of diameter $d = 1.6mm$ is selected. The diameter of the coil made up from this wire is $D = 11.89mm$. Then the outer diameter of coil is

$$Do = D + d$$

$$Do = 11.89 + 1.6 = 13.49mm.$$

Similarly, the inner diameter of coil is

$$Di = D - d$$

$$Di = 11.89 - 1.6 = 10.29mm.$$

To find the axial deflection we know that

$$y = \frac{8\ F\ D^3\ i}{G\ d^4}$$

Where F is maximum load/force, G is modulus of rigidity or Shear modulus [its value for carbon steel is 11.2 (10^6 psi) or 77 (Gpa)] and i is number of turns. By rearrange the equation for (i):

$$i = \frac{y\ G\ d^4}{8\ F\ D^3}$$

$$i = \frac{20 * \ 7700 * 1.6^4}{8 * 70 * \ 11.89^3} = 10.7\ Turns$$

Free length of helical spring is calculated as:

$$lo \ \geq (i + n)\ d + y + a$$

Where $a = 25\ \%$ is the clearance of maximum deflection and $n = 2$ for squared and grounded end. Thus

$$lo \ \geq (11 + 2)1.6 + 20 + 5$$

$$lo \ \geq 45.8mm.$$

Stiffness or Rate of spring is

$$Fo = \frac{F}{y}$$

$$Fo = \frac{70}{20} = 3.5\ N/mm.$$

and the pitch of helical spring is

$$p = \frac{lo - 2\,d}{i}$$

$$p = \frac{45.8 - 2 * 1.6}{11} = 3.88mm.$$

Therefore the helical spring specification is

Material Carbon Steel

Wire diameter $d = 1.6mm$

Mean diameter $D = 11.89mm$

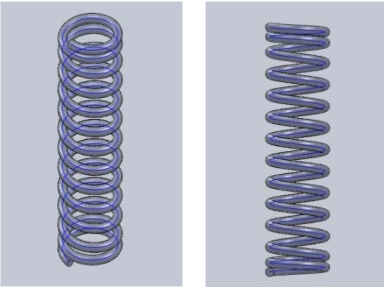
Free length $lo \geq 45.8mm.$

Total number of turns $i = 13\ Turns$

Style of end-squared and ground

Pitch $p = \ 3.88mm$

Rate of spring $Fo = 3.5\ N/mm.$



2.2.2 DESIGN OF A BASE

A base is required on which the designed helical spring will be fixed to perform the desired experiment. The design of base is based on following constraints:

1. The length and width of base must be greater than the outer diameter of the coil of helical spring.

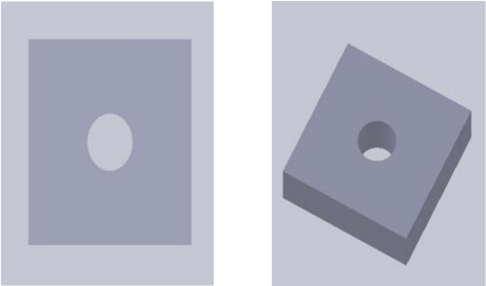
$$Length\ of\ Base\ > Do$$
$$Width\ of\ Base\ > Do$$

It is taken as 18mm for both length and width of the base which is satisfying the above constraint and height B_h is selected as 2mm.

2. There will be a hole in the middle of the base and its diameter must be less than the inner diameter of the coil of helical spring.

$$d_h < D_i$$

So, it is selected 5mm which is satisfying the above constrain.



2.2.3 DESIGN OF A SHAFT

A shaft having tray head at the top end is required to perform the experiment and it is used to apply force on the helical spring. The design of the shaft is based on three constraints.

1. The length and width of tray head of the shaft at the top end must be greater than the outer diameter of the coil of helical spring.

$$Length\ of\ the\ tray\ > Do$$
$$Width\ of\ the\ tray\ > Do$$

So, length and width both are taken as 18mm which satisfies the above constraint and height T_h is selected as 2mm.

2. The diameter of the shaft must be equal to the hole in the base designed above.

$$d_s = d_h$$

So, d_s = 5mm.

3. The length of the shaft must be equal to the sum of free length of helical spring, height of base on which it will be fixed and axial deflection of the helical spring.

$$S_l = lo + B_h + y$$
$$S_l = 45.8 + 2 + 20 = 67.8mm.$$

Therefore, the shaft having tray head at the top end has been designed according to above calculated parameters.

After spring design, the experiment is performed with following experimental setup shown below.

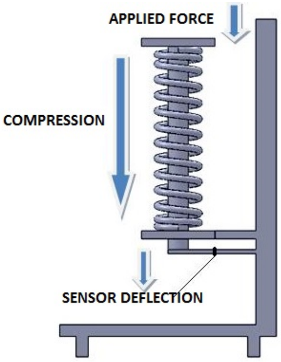


Figure 3.1

Experimental setup Phase-I

2.2.4 Experimental Results

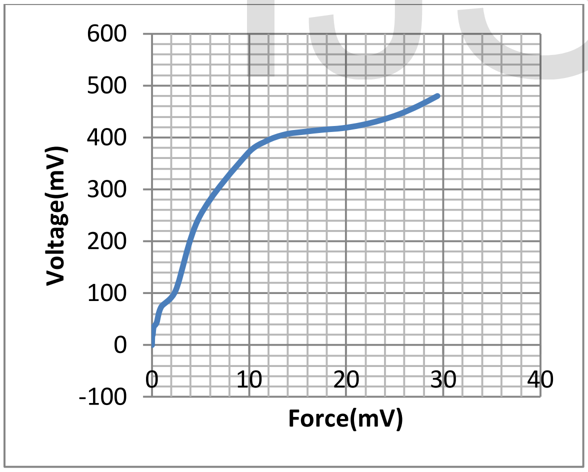
Experiment is performed on the LDT0-028K and resultant output voltages after application of set of forces is shown in below table.

Experimental Data is shown in tabular and graphical form below for analysis purpose.

S.R#	F(N)	Voltage (mV)
01	0.0098	0

02	0.0196	0
03	0.049	20
04	0.098	20
05	0.196	35
06	0.49	43
07	0.98	74
08	2.45	105
09	4.9	247
10	9.8	368
11	11.76	393
12	13.72	406
13	15.68	411
14	17.64	415
15	19.6	418
16	21.56	424
17	23.52	433
18	25.48	445
19	27.44	461
20	29.4	480

2.1Results Data Table



2.1Results in Graphical Form

2.3.1 Analytical Technique

Analytical Technique is required to find the output voltages of each motion in response to applied forces required for each movement. Lagrange interpolation formula is used and mathematical equation is developed to find out the required voltages corresponding to applied forces. These voltage levels are used in designing of electronic control system which in turn required for driving the mechanical model of exoskeleton robot.

$$
\begin{aligned}
L(x) = (&-3.61\mathrm{e}^{-10}x^{6} + 9.55\mathrm{e}^{-8}x^{5} \\
&- 9.72\mathrm{e}^{-6}x^{4} + 4.81\mathrm{e}^{-4}x^{3} \\
&- 1.195\mathrm{e}^{-2}x^{2} + 1.45259\mathrm{e}^{-1}x^{1} \\
&- 2.79\mathrm{e}^{-1}x^{0})
\end{aligned}
$$

By using this mathematical equation, set of data points are chosen in the region of interest and corresponding outputs are found by solving equation number of times as per inputs. Region of interest here means the threshold values of forces and corresponding voltage levels required for the maximal and minimal rotations in the healthy and polio subject’s shoulder. Data smoothness is clearly shown in below graph by using Lagrange Equation developed above.

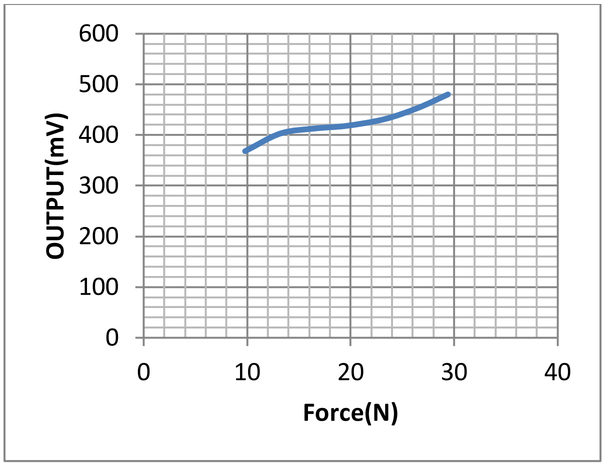


Figure 4.0 Lagrange Equation Data points

3.0 Active Amplifier Design

Input signal for the control system is the most important factor and it is the low voltage signal related to the muscular activity level. Low voltage input signal is amplified using active amplifier. I have virtually related the prime movers of internal and external rotation as input signal producers as mentioned in experimentation phase earlier.

This low voltage signal is amplified through an active amplifier system. Designing of active amplifier requires the threshold values. These values are deduced from the maximum power level required by subject to perform the full intended rotation and the maximum operating voltage levels of *u*-controller. Design values are as follows.

Maximum output voltage of sensor required to produce full Internal Rotation is V_Int. The Maximum voltage level required to produce full external rotation is V_Ext.

Two amplifiers are designed to magnify the low voltages of muscular activity levels for Internal and External rotation.

V_Int = 420mV

V_Ext = 433mV

Output = 5V

G1= 11.90

G2 = 11.54

3.0.1 INTERNAL ROTATION

R4= 1KΩ, R5= 10.54KΩ

3.0.2 EXTERNAL ROTATION

R3= 1KΩ, R2= 10.90KΩ

4.0 CONCLUSION

The successful development of Collaborative Control System for 1-DOF Exoskeleton Robot requires the muscular activity level detection. Muscular Activity detection is made possible by using sensing material externally by applying forces on the sensor and generated voltage levels are recorded. It's assumed that the same sensor material will be used in designing muscle threads that's to be attached with the actual muscles after open surgery of polio patients affected shoulder. Experimental study for signal sniffing from the muscles based on relative approach has been successful. Results are documented. Based on these results electronic control system and mechanical model are designed and simulated.

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