Insole Gait Analysis System for Monitoring Plantar Pressure

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Abstract

Gait Analysis system widely used in medical diagnostics, chiropractic, osteopathy, athlete performance evaluation and biometric verification monitors the plantar pressure. However, insole systems utilising polymer nanocomposites which can enhance the sensitivity and accuracy is scarcely reported. The objective of this research was to parametric optimisation of PVDF / nanofiller films for gait analysis using solution casting. The films were characterised using FTIR and nanoindentation. Machine Learning algorithms were employed to select the optimum films based on load vs. displacement data. PVDF/ Halloysite (0.2wt.%) films showed superior β phase, voltage output, and average classifying accuracy to those of PVDF/TiO_2 and PVDF/ ZnO.

Keywords: *GAIT analysis, PVDF/nanofiller, Machine Learning*

1.0 Introduction

Human walking involves repetitive actions and periodic body segment movement. The gait phase is used to define a full walking period and better understand this periodic walking process. The Rancho Los Amigos gait analysis committee developed a generic terminology for the functional phases of gait to avoid difficulties and confusion in defining gait stages. This terminology is useful for individuals with gait abnormalities, such as paralysis or arthritis, where traditional definitions may not apply. The committee's terminology provides a more inclusive and adaptable framework for understanding gait phases in various populations [1].

Analysis of the human walking pattern by phases more directly identifies the functional significance of the different motions generated at the individual joints and segments. A normal walking gait cycle is divided into eight different gait phases, such as initial contact, loading response, mid stance, terminal stance, pre-swing, initial swing, mid-swing, and terminal swing [2-3].

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Measuring gait provides valuable insights into underlying health problems and helps in designing and evaluating clinical interventions [4-6]. Gait analysis allows for the identification of deviations from normal gait patterns and the assessment of gait mechanics. It can be used to quantify overall gait quality and quickly identify abnormal gait patterns, which may be indicative of health issues [7].

These systems provide objective measures of motion function, allowing for more accurate evaluation and tailored gait and balance training for patients with neurological disorders [8]. Recent advancements in computer vision and deep neural networks have also shown promise in using monocular RGB cameras for cost-effective and efficient clinical gait analysis offering potential applications in remote rehabilitation and patient monitoring [9-10].

Additionally, artificial neural networks, fuzzy logic, and multifractal analysis have been utilized to develop computational models for gait analysis, particularly in post-stroke patients [11].

Insole-based gait analysis systems have a wide range of applications in medical diagnostics, chiropractics, osteopathy, athlete's performances, and biometric verification. These systems use inertial measurement units (IMUs) and plantar pressure insole sensors to collect information on joint angles and plantar pressure during walking. The collected data is then used for gait division, feature extraction, and analysis using machine learning algorithms such as random forest. The results show that wearable devices have good accuracy for gait assessment and the collected data has good repeatability. Gait analysis systems, including non-wearable sensors and laboratory systems, provide objective measures of motion function and can be used for tailored and specific gait and balance training in neurological patients [12]. Additionally, a computer vision-based system for gait analysis has been developed, which provides acceptable precision and accuracy at a low cost [9].

Gait analysis systems have a high market demand, especially during the COVID-19 pandemic. However, these systems are commercially expensive, making them inaccessible to the general public [13-14]. The monitoring of plantar pressure is a crucial parameter in gait analysis, extensively used in analysing various problems [15].

Different types of electromechanical devices, such as piezoresistive, piezoelectric, and capacitive sensors, are used in sensor systems for gait analysis [16]. These devices have been reviewed by Homayounfar et al., who also defined key metrics for quantitating, comparing, and optimizing their efficiency [17]. They highlighted state-of-the-art examples of these technologies [18]. However, more comparative studies are needed to evaluate the cost, ease of fabrication, and toxicity of different materials used in these sensors [19].

Polymer films made from PMMA and PVDF using the solution casting process were investigated for their structural, spectroscopic, and morphological attributes [20]. PVDF films were found to have low dielectric constant, low elastic stiffness, and low density, making them suitable for sensor applications [2-3]. PVDF films with 86% β-phase were obtained by preparing specimens at specific spinning speed, spinning duration, and annealing temperature [21].

There are several studies on PVDF-based nanogenerators using different nanofillers to enhance the piezoelectric response and performance of PVDF. Sharma and Pedroza [22] reported the enhancement of piezoelectric response in PVDF nanogenerators by incorporating 2D MoS2/1D TiO2 heterostructure as nanofillers. Gunasekhar et al. [23] and Oflaz and Özaytekin [24] focused on improving the piezoelectric properties of PVDF by adding aromatic hyperbranched polyester and various additives, respectively. These studies demonstrate the potential of PVDF-based nanogenerators for energy harvesting applications. However, a specific research work on a PVDF-based insole gait analysis system with the desired combination of properties mentioned in the question has not been reported.

Piezoelectric nanocomposites with different conductive fillers were studied to analyze the effect of filler wt.% change on conductivity and dielectric constant. The nanocomposites included copolymer-reduced graphene oxide, graphene oxide, graphene nanosheets, and halloysite nanotube. The research found that copolymer-reduced graphene oxide nanocomposites showed high crystallinity and electrical and dielectric outputs, making them suitable for practical applications in flexible electronics [25]. Additionally, electrospun PVDF/Hal nanocomposites with lower dielectric constant exhibited higher conversion efficiency or output voltage compared to PVDF/GO and Gr nanocomposites [26]. The study also investigated the effect of nanofiller morphology on piezoelectric response and found that the use of halloysite nanotubes resulted in improved performance [27].

The addition of fillers to polymeric materials has been found to significantly improve their mechanical, barrier, thermal, and electrical properties. One filler that has gained considerable interest as a reinforcing filler in polymer nanocomposites is Halloysite. Halloysite exhibits properties similar to both montmorillonite and carbon nanotubes, making it a versatile filler option. It has a similar chemical composition to montmorillonite and a nanotubular geometry similar to carbon nanotubes. This unique combination of properties makes Halloysite an attractive choice for enhancing the performance of polymer nanocomposites [28].

A novel portable system called the Smart Insole has been developed to integrate low-cost sensors and compute important gait features. This system allows for the transfer of data from the patient side to centralized servers in the medical enterprise, enabling real-time and long-term monitoring of user gait. The Smart Insole utilizes optical fiber Bragg grating (FBG) sensing technology to measure plantar pressure distribution and evaluate body postures. Additionally, a 3D-printed instrumented insole with polymer optical fiber (POF) sensors has been developed for static and dynamic assessments of plantar pressure and ground reaction force (GRF) [29].

Ciniglio et al. proposed that a 16-sensors (1.5 x 1.5 cm) pressure insole to detect plantar pressure distribution during different tasks in the clinic and sport domains [31]. Gao et al proposed smart integration of piezoelectric films providing plantar pressure information to be distributed to the people via the internet [21]. C Prakash et al. presented that machine learning algorithms like supervised learning, unsupervised learning, reinforcement learning, and fuzzy logic-based learning and hybrid approaches can be used for gait analysis [22].

Review of literature [1-29] indicated extensive studies on GAIT analysis and its implications on health monitoring. Different materials with nanofillers are explored for monitoring plantar pressure using ML techniques, which is an important parameter in GAIT analysis. However, a comprehensive research work on PVDF-based insole gait analysis system using a nanofiller with a balanced combination of low cost, light weight, high strength, high impact resistance, process flexibility, and low dielectric constant is not reported. Hence this work was aimed at developing PVDF, PVDF/Nanofiller films with improved beta phase and mechanical properties and to compare and validate the results using ML algorithms and testing the films for plantar pressure.

2.0 Materials and Experimental Details

PVDF pellets (kynar-740), N, N Dimethylformamide, fillers such as Halloysite, Zinc Oxide and Titanium di-oxide were used to fabricate the films using solution casting. The films were characterised using FTIR to assess the beta phase and nano-indentation for mechanical properties. ML algorithms were used to validate the results.

3.0 Fabrication of PVDF and PVDF/Nanofiller films

PVDF was dissolved in 22ml of DMF solvent and stirred using magnetic stirrer till a clear solution appeared for solution casting. Generally, a single magnetic bead is used as 2 beads leads to turbulence. After a clear solution is prepared, it is poured on a glass slab and kept for drying for 24 hours (Fig. 1)

Nanofillers namely Halloysite, Zinc oxide and Titanium dioxide were incorporated. PVDF and solvent were taken in a beaker. After the filler solution forms a homogeneous mixture, it is poured into the PVDF solution and stirred again. The solvent used is DMF along with Acetone as the Fluorine atom from PVDF having high electronegativity easily bonds with DMF. Acetone aides in improving the $\boldsymbol{\beta}$ phase formation. The weight percentage of filler is kept at 0.2% as higher values led to bead formation. It is then put in a hot air oven at 80ºC for four hours to further remove air bubbles from the solution and for improving beta phase formation. The filler is dissolved in solvent of DMF & Acetone (6:4 ratio, ratios are changed subsequently) and kept in stirrer separately. Different weight proportions of PVDF have been carried out in experiments ranging from 8 to 25%. Table 1 illustrates different experiments and parameters associated with it.

Fig.1 Glass Slab and films after drying

Table 1. Summary of films fabricated

Exp. No.	Total wt. (g)	Amt. of PVDF (g)	Filler Material (wt.%)	Thickness (mm)	Remarks
1	26	6	-	-	Brittle film, sample failed
2	33	5	-	0.22-0.5	Fragile films, too thin
3	50	5	-	0.35-1.29	Fragile films
4	50	5	-	0.17-0.512	Films broke during voltage reading
5	30	3	-	0.06-0.08	Brittle, sample failed
6	25	2.5	Halloycite, 0.2	0.442-0.543	Durable films
7	25	2.5	ZnO, 0.1	0.011- 0.016	Thin films
8	25	2.5	$Ti0_2$, 0.1	0.024- 0.513	Good film
9	35	3.5	Zn0, 0.2	0.352- 0.432	Good film
10	25	2.5	Halloysite, 0.2	0.342- 0.441	Good film
11	30	2.4	-	0.243- 0.446	Good Film

After drying, the films were peeled off using Powered Distilled Water (PDW) and cutter. Peeled films are shown in Fig. 2.

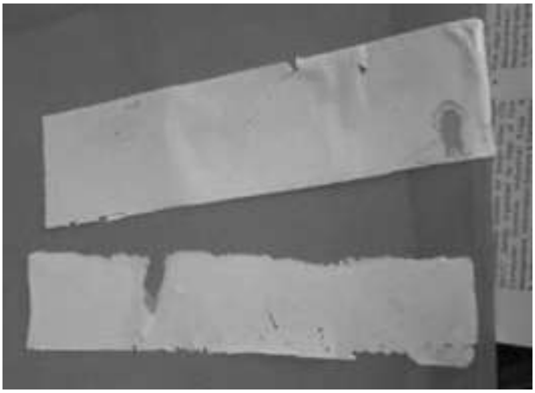

Fig. 2 PVDF Films

PVDF with 10 wt. % solution showed best result of 2.2 V peak output, measured by designing an electric circuit involving copper films attached to the upper and lower sides of films (Fig. 3). Voltage output was measured for a known force on the film.

Fig. 3 a) Setup showing electronic connection and b) Voltage output

4.0 FTIR

FTIR was used to identify the crystalline phases of the films. Amount of β-phase was computed using the Lambert-Beer Law (equation 1).

$$F(\beta) = \frac{A_\beta}{(K_\beta/K_\alpha)A_\alpha + A_\beta} \quad \text{..............Equation (1)}$$

where A$\boldsymbol{\alpha}$ is Absorbance at 840 cm^{-1}, A$\boldsymbol{\beta}$ is Absorbance at 767 cm^{-1}, K$\boldsymbol{\alpha}$ and K$\boldsymbol{\beta}$ are absorption coefficients at wave numbers 767 and 840 cm^{-1} with peak values 6.1 × 104 and 7.7 × 104 $cm^2\,mol^{-1}$ respectively.

Table 2 presents A$\boldsymbol{\alpha}$, and A$\boldsymbol{\beta}$ values along with the β phase calculation for experiments 6,8 and 10 using equation 1 the corresponding graphs are shown in Fig.4.

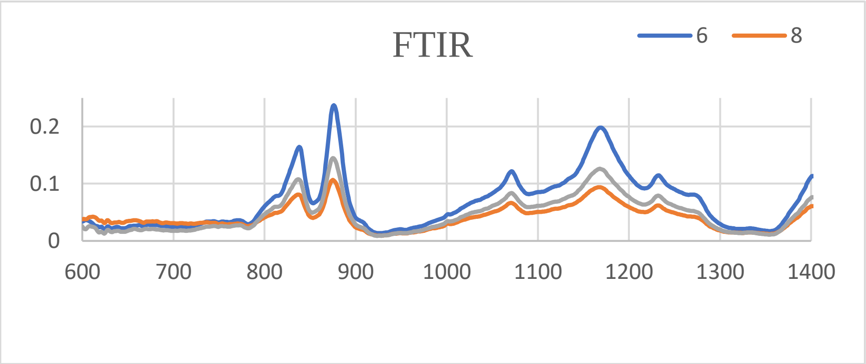

Table 2. β-Phase calculation

Expt. No.	Composition	Aα	Aβ	β (%)
6	PVDF (10%), Halloysite (0.2%), DMF : Acetone (6:4)	0.0352	0.1589	78.17%
8	PVDF (10%), TiO2 (0.1%), DMF:Acetone (7:3)	0.0296	0.0774	67.48%
10	PVDF (10%), Halloysite (0.2%), DMF:Acetone (7:3)	0.0266	0.1025	75.35%

5.0 Nano indentation

For the development of thin films used for the pressure sensor applications, it is important to develop films with some good mechanical properties along with the maximum β-phase. Thus, it is important to investigate various mechanical properties of PVDF thin films for the stretched samples. The mechanical properties were determined using the Agilent nano indenter. Table 3 presents the Maximum value of Load at 1226 nm displacement.

Table 3. Mechanical properties of the films

Expt No.	Composition	Maximum Load at 2126 nm (mN)	Hardness (MPa)	Modulus of Elasticity (MPa)
6	PVDF (10%), Halloysite (0.2%), DMF : Acetone (6:4)	1.24	200	30
8	PVDF (10%), TiO2 (0.1%), DMF:Acetone (7:3)	1.12	300	20
10	PVDF (10%), Halloysite (0.2%), DMF:Acetone (7:3)	1.23	300	30

Fig. 5 shows the load vs. displacement curve for all the experiments. As the displacement of tip is increasing, the load on the sample increases up to a maximum value at 2126 nm and then it starts decreasing steeply. The load–penetration depth curves are all moved to the left side which shows a maximum force for the same displacement.

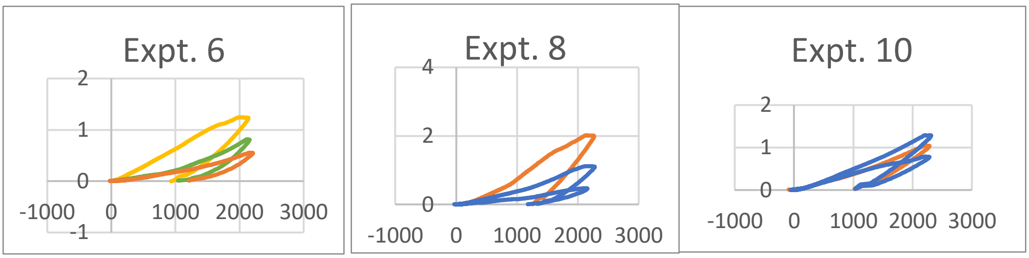

Fig. 5. Load vs. displacement for different film samples

7.0 Applying Different Classification Algorithms on data obtained.

For every experiment, the load data of nanoindentation was imported. The data at different points are concatenated and described as a data frame. The data was defined in two variables, ‘y’ as secim or class and ‘x’ as data without classes. Further data was split into training and test data and different algorithms were trained and accuracy was evaluated,

7.1 Experiment 6 (PVDF-10 wt. %, Halloysite - 0.2wt. %, DMF: Acetone :: 6:4)

Accuracy of different algorithms is summarized for experiment 6 in Table 4.

Table 4. Accuracy of different algorithms and their average (Expt. 6)

Algorithm	Accuracy (in %)
Support Vector Machine	83.06
Naive Bayes Classifier	74.59
Decision Tree Classifier	91.80
Random Forest Classifier	91.20
Logistic Regression	77.32
KNN	95.08
Average Accuracy	85.51

7.2 Experiment 8 (PVDF-10% w/w, TiO2 - 0.1% w/w, DMF: Acetone :: 7:3)

Accuracy of different algorithms can be summarized for experiment 8 in Table 5.

Table 5. Accuracy of different algorithms and their average (Expt. 8)

Algorithm	Accuracy (in %)
Support Vector Machine	77.37
Naive Bayes Classifier	67.63
Decision Tree Classifier	89.47
Random Forest Classifier	93.68
Logistic Regression	75.26
KNN	94.21
Average Accuracy	82.94

7.3 Experiment 10 ((PVDF-10% w/w, Halloysite - 0.2% w/w, DMF: Acetone :: 7:3)

Accuracy of different algorithms is summarized for experiment 10 in Table 6.

Table 6. Accuracy of different algorithms and their average (Expt.10)

Algorithm	Accuracy (in %)
Support Vector Machine	84.25
Naive Bayes Classifier	49.47
Decision Tree Classifier	91.45
Random Forest Classifier	92.95
Logistic Regression	44.37
KNN	92.65
Average Accuracy	75.85

8.0 Testing of Films

From the characterization results and ML accuracy results, it is found that Experiment 6 (PVDF/Halloysite (0.2 wt. %) was found to be the best combination which can be used for Insole Gait Analysis System. For testing of the films for monitoring plantar pressure, an electronic connection was laid out using force sensor, Arduino and breadboard.

8.1 Electronic setup and results

PVDF/Halloysite film was inserted inside a shoe insole and force sensor was placed between sole and the film. Fig. 6 shows the electronic connection connecting different components and the insole.

The unit of the plantar pressure shown by the display device is kg-f (Kilogram Force). Arduino segregated the pressure into 5 types, namely no pressure, light touch, light squeeze, medium squeeze and big squeeze depending on the intensity of the load applied.

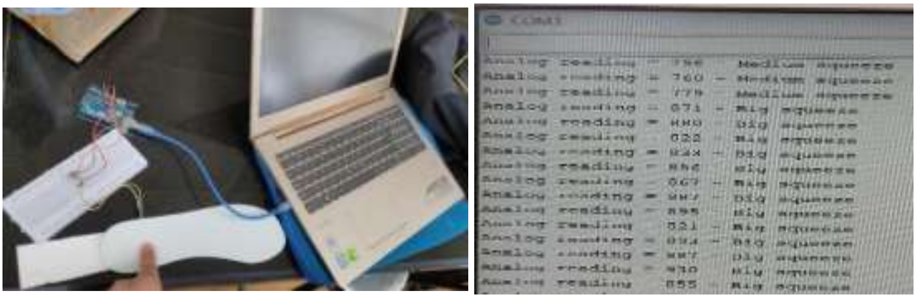

Fig. 6. Electronic setup and the display device producing results of plantar pressure

9.0 Conclusion

The FTIR results highlight the superior piezoelectric properties of Halloysite compared to TiO_2, with Experiment 6 exhibiting a significantly higher β phase. Additionally, Experiment 10 demonstrates a slight decrease in β phase with an increase in DMF concentration in the solvent. Nanoindentation results reveal that Experiment 6 experiences the highest load at 2126 nm displacement, emphasizing its mechanical strength. Interestingly, Experiment 10 shows a comparable Modulus of Elasticity to Experiment 6, indicating minimal influence of DMF concentration on elasticity values. Machine learning algorithms, particularly KNN, proved accurate across all experiments, (85.51%). This comprehensive analysis provides a foundation for understanding and optimizing the properties of PVDF films for various applications.

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