Flexible Piezoelectric Sensors for Miniaturized Sonomyography

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Abstract— **Sonomyography refers to the measurement of muscle activity with an ultrasonic transducer. It is a candidate modality for applications in diagnosis of muscle conditions, rehabilitation engineering and prosthesis control as an alternative to electromyography. We propose a mechanically-flexible piezoelectric sonomyography transducer. Simulating different components of the transducer, using COMSOL Multiphysics® software, we analyze various electromechanical parameters, such as von Mises stress and charge accumulation. Our findings on modelling of a single-element device, comprised of a PZT-5H layer of thickness 66μm, with a polymer substrate (E = 2.5 GPa), demonstrate optimal flexibility and charge accumulation for sonomyography. The addition of Polyimide and PMMA as an acoustic matching layer and an acoustic lens, respectively, allowed for adequate energy transfer to the medium, whilst still maintaining good mechanical properties. In addition, preliminary ultrasound transmission simulations (200 kHz-30 MHz) showed the importance of the aspect ratio of the device and how there is a need for further studies on it. The development of such a technology could be of great use within the healthcare sector, not only due to its ability to provide highly accurate and varied real-time muscle data, but also because of the range of applications that could benefit from its use.**

I. Introduction

The study of muscle activity dates back to the early decades of the 20th century, when the principles of electromyography (EMG) were established. Ever since, this type of functional and anatomical study has been developed and improved to diagnose neuromuscular conditions. Recently, along with these developments in EMG methods, novel techniques that allow for the concurrent study of muscle structure and function with higher spatial resolution than that with the EMG method have emerged, e.g. magnetomyography [1,2] and sonomyography (SMG) [3].

SMG refers to the use of ultrasonic waves to investigate muscle structure and function. This technique was first described in the early 2000s by Zheng *et al.* [3] where they aimed to use SMG to replace EMG-controlled prostheses. This research also pointed out some of the main disadvantages of using EMG, such as its inability to differentiate between the muscle movement of the main muscle and that of neighbouring muscles as well as its inefficiency scanning deeper muscles. This is where SMG could prove to be a better alternative. Other studies have also highlighted its potential as an alternative to the traditionally used electromyography since it can produce very robust signals and can be highly specific [4]. Moreover, ultrasound technologies are currently one of the most researched areas within the biomedical imaging sector. Therefore, this type of technology can potentially allow a major improvement in the quality of the produced images while reducing the costs and complexity of the required devices.

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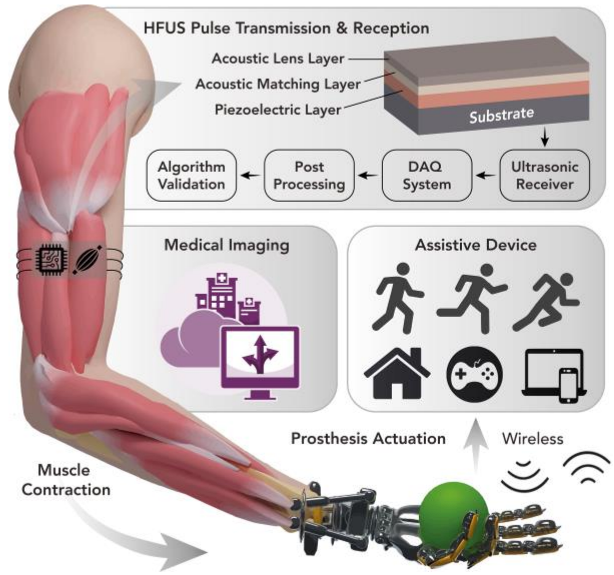

Fig. 1. An overall architecture of the flexible, HFUS sonomyography device. The two main applications: medical imaging, ranging from the diagnosis and analysis of myopathies to spinal cord lesions, and assistive devices, aiding in the control of prosthetic limbs and muscle-computer interfaces.

Furthermore, studies have shown the potential of flexible piezoelectric films within the nanogenerators and energy harvesting sector, but there is a general lack of research within the biomedical engineering sector. Few studies have investigated the use of high frequency ultrasound (HFUS) to enhance the spatial resolution of sonomyography [5]. This poses an opportunity to investigate the potential of combining flexible transducers and HFUS.

We aim to illustrate the potential of sonomyography as an imaging and assistive technique for assessing muscle activity. This method could lead to a more efficient and accurate diagnosis of myopathies and damage to the peripheral nervous system and optimizing assistive and rehabilitation engineering techniques. We, therefore, designed a flexible and miniaturized HFUS transducer and simulated each stage of the design process with COMSOL Multiphysics® to validate the model that can be used in future SMG applications. Fig. 1 illustrates the proposed design of the overall device, including the flexible transducer and a simple block diagram detailing the electronics and post-processing for the system.

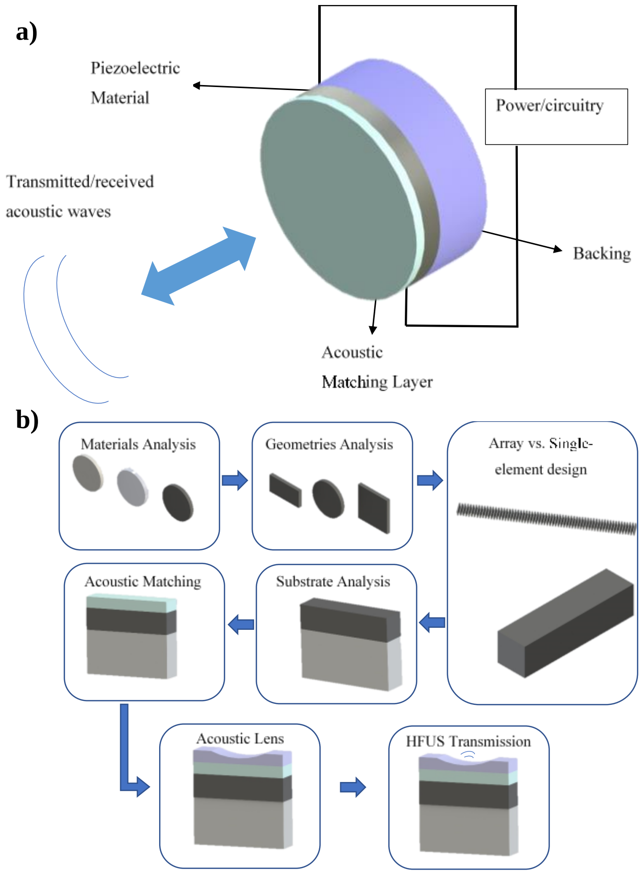

Fig. 2. (a) Single-element transducer design; (b) Detailed methodology for the device's design from the material to HFUS transmission analysis.

II. Piezoelectric Sensor Design

A. Structure and Principle

Ultrasound can be defined as "acoustic waves (sound or pressure waves) propagating within a matter medium at frequencies exceeding the auditory band" [6]. The piezoelectric effect [7], details how certain materials demonstrate an accumulation of electrical charge when a mechanical force or stress is applied to them. The inverse piezoelectric effect indicates that a piezoelectric material deforms when excited with an external electric field. This effect allows transmission and reception of ultrasound waves with piezoelectric transducers.

A simple schematic of a single-element ultrasound transducer is shown in Fig. 2 (a). A key consideration is the choice of the piezoelectric material. Crystalline and ceramics are common piezoelectric materials but the most commonly used piezoceramic is lead zirconate titanate (PZT) [5] due to its high electromechanical coupling coefficient and its very adequate dielectric and elastic properties for biomedical imaging. Other materials of interest inlude polyvinylidene fluoride (PVDF), shown to have great flexibility and biocompatibility [8], and Aluminium Nitride (AIN) which offers higher sensitivity than PZT [9]. These materials were analysed in different studies (Table 1) to evaluate the optimum configuration for SMG applications. In addition, the dimensions and geometries of the piezoelectric element were investigated, with circular, square and rectangular geometries analyzed, as commonly perfomed in the literature [10,11].

Table 1. State-of-the-art studies on flexible piezoelectric sensors

	[10]	**[8]**	**[9]**	**This study**
Frequency range	1.3-5 MHz	0-1 kHz	0-2.8 MHz	20-30 MHz
Piezoelectric material	PZT	PVDF	AlN	PZT
Thickness	0.4-1.5 mm	52 µm (2 layers)	1 µm	66-100 µm
Challenges	Dimensions are too large for HFUS	Relies on FES, low sensitivity at high frequency	Studied on air, low piezoelectric coefficients	Aspect ratio and foreign body response

We evaluated the effect of the backing layer or substrate, the acoustic matching layer and the acoustic lens, as well as an array configuration versus a single-element geometry, as shown in Fig. 2 (b).

The backing layer of an ultrasonic transducer allows for reverberation to be damped and is bonded to the piezoelectric material, as shown in Fig. 2. A mixture of Tungsten powder and a soft-setting epoxy tends to be the common choice within the sector due to its high acoustic attenuation [12]. However, this can challenge the flexibility of the sensor/transducer. There are three possible alternative substrates that serve as a backing for the device: silicon, polydimethylsiloxane (PDMS) and polyimide (PI) [12,13].

Another component of great interest is the acoustic matching layer, which serves as an aid for energy transfer between the piezoelectric material and the surrounding medium, and vice versa. This allows for an improvement in the efficiency of the transducer. A literature review revealed that some studies have shown that certain polymer resins, such as PI, demonstrate satisfactory results when used in lower frequency ultrasonic devices and has the advantage of being quite flexible [14].

The final component of interest to the project is the acoustic lens. Acoustic lenses work in a similar way to optical ones by focusing the ultrasonic waves in order to create the desired beam shape. In terms of the investigated materials, according to the literature, polymethyl methacrylate (PMMA) and PI plano-concave lenses have shown adequate results in high-frequency ultrasound imaging and have the possibility of being micromachined, aiding in the fabrication of the micron-scale components [15].

B. Finite-Element Simulation

In order to design such a transducer, a similar methodology to that provided in recent studies was followed [10], with an additional final stage to analyse the performance of the designed sensor as an ultrasonic transmitter and not just a receiver, as shown in Fig. 3. This was done by using the COMSOL Multiphysics® simulation package. The design process was divided into the stages shown in Fig. 2 (b), with the used parameters shown in Table 2.

The mechanical and electrical parameters of interest were the stress, the strain, the displacement, the electric potential and the charge produced when pressure was applied. In this case, all components were subjected to a pressure of 10 µPa and 10 Pa, and compared to one another. In addition, the electrical impedance spectrum of the different transducer

Table 2. Used parameters for simulations.

Frequency	20 MHz	30 MHz
Piezoelectric material	100 μm	66 μm
Substrate	300 μm	198 μm
Acoustic matching layer	12.5 μm	18.7 μm
Acoustic lens	12.5 μm	18.7 μm

geometries and the safety factor of the substrates were analysed with Eq. (1) and (2), respectively:

$$(1)\ X_C = \frac{\delta}{2\pi f \varepsilon A} \qquad (2)\ Safety\ factor = \frac{yield\ stress}{von\ mises\ stress}$$

where X_c is the electrical impedance, δ is the thickness of the piezoelectric material, f is the operating frequency, ε is the relative permitivitty and A is the surface area of the piezoelectric element.

III. Results

Simulation results showed that even if PVDF has a higher flexibility than PZT-5H (Fig. 3 (a)) and a lower acoustic impedance, its sensitivity is reduced. This is mainly due to the fact that PVDF has a much lower k33 coefficient than PZT-5H, as well as high dielectric loss. In terms of electrical parameters, charge amplifiers are a very common choice for the circuitry design of an ultrasonic transducer [16], meaning that obtaining the greatest charge accumulation was crucial and hence, illustrates the preference of PZT-5H over the other two materials (Fig. 4 (b)). This result was also obtained for the chosen rectangular geometry, as well as an adequate response regarding electrical impedance (Fig. 4(c) and (d)).

The final piezoelectric film was analysed further to evaluate the differences between a single-element and an array design. For the single-element design, the simulation was carried out on the same rectangular PZT-5H element as in the previous section, but this time with a thickness of 66 μm. This thickness, corresponding to 30 MHz, was chosen for the rest of the simulations within the study because a higher frequency allows for better resolution. The decision on whether to use a single-element or an array design depends solely on the application of the sonomyography device. If the device were to be used for prosthesis control, then single-element transducers would be the ideal choice due to their simplicity, cost-effectiveness and accurate output information [5].

Regarding substrate analysis, a compromise between the safety factor and charge accumulation results was required (Fig.4 (e) and (f)), hence PI was the material of choice. For the acoustic matching layer, the thickness was the first parameter that needed to be calculated. In terms of the acoustic matching layer, since it has been demonstrated in the literature that an ideal acoustic layer thickness is ¼ the wavelength of interest [14]. Therefore, the thickness of the acoustic matching layer was calculated to be between 18.75 μm and 12.5 μm for a frequency range of 20-30 MHz, respectively, with an ideal acoustic impedance of 6.7 MRayl. In order to obtain such an acoustic impedance, it is common to chemically characterise the material of the matching layer by using powders containing different concentrations of materials such as Tungsten. This could be performed on a material like PI, which allows for flexibility and has been shown to perform well in high-frequency settings [14]. As for the acoustic lens, it was seen that a PMMA plano-concave lens with a radius of curvature of 7.4 μm, could allow for a simpler fabrication process and an effective transfer of energy to the medium.

In terms of the ultrasound transmission simulation results (Fig. 3 (d) and (e)), we showed that the high aspect ratio of the piezoelectric film prevented acoustic waves to be transmitted properly and should be revisited in future work.

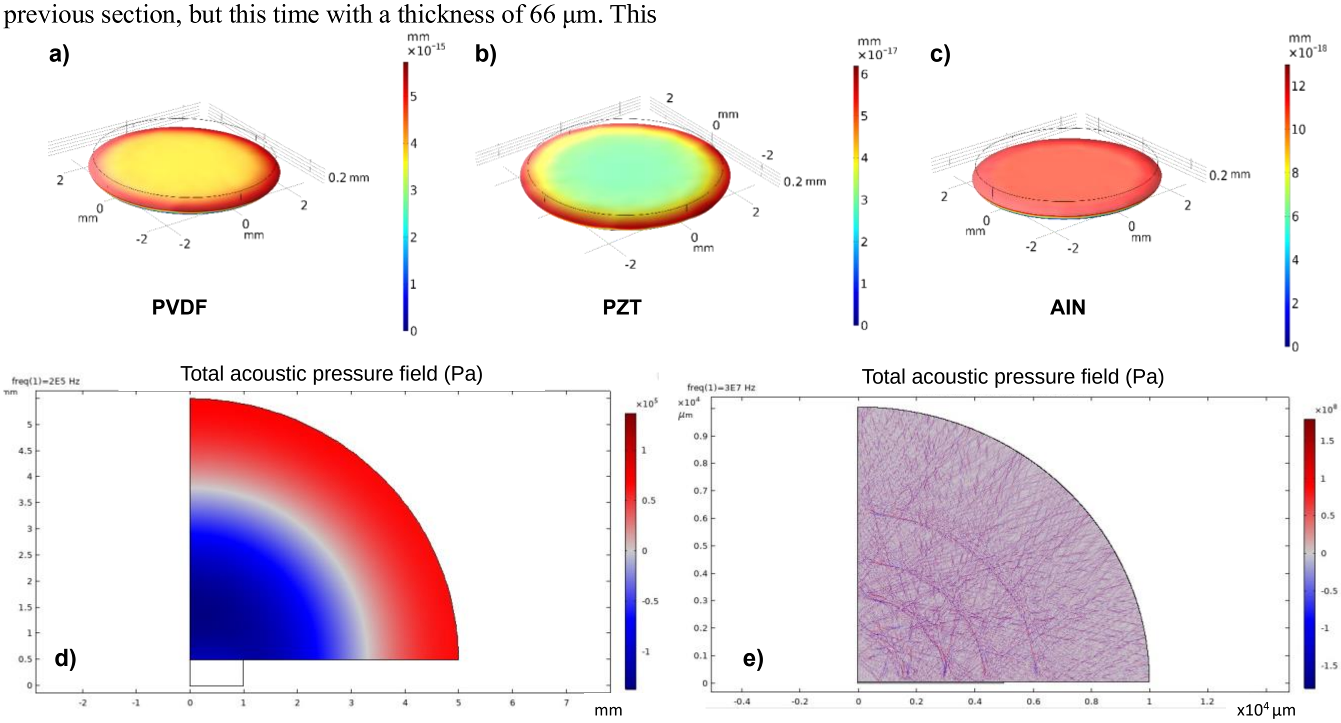

Fig. 3. Analysis of materials with (a) PVDF, (b) PZT and (c) AlN; (b) Acoustic pressure parameters analysed for a two-dimensional PZT rectangular film of dimensions 1 × 0.5 mm and 5 mm × 66 μm at the frequency (c) 200 kHz and (d) 30 MHz, respectively.

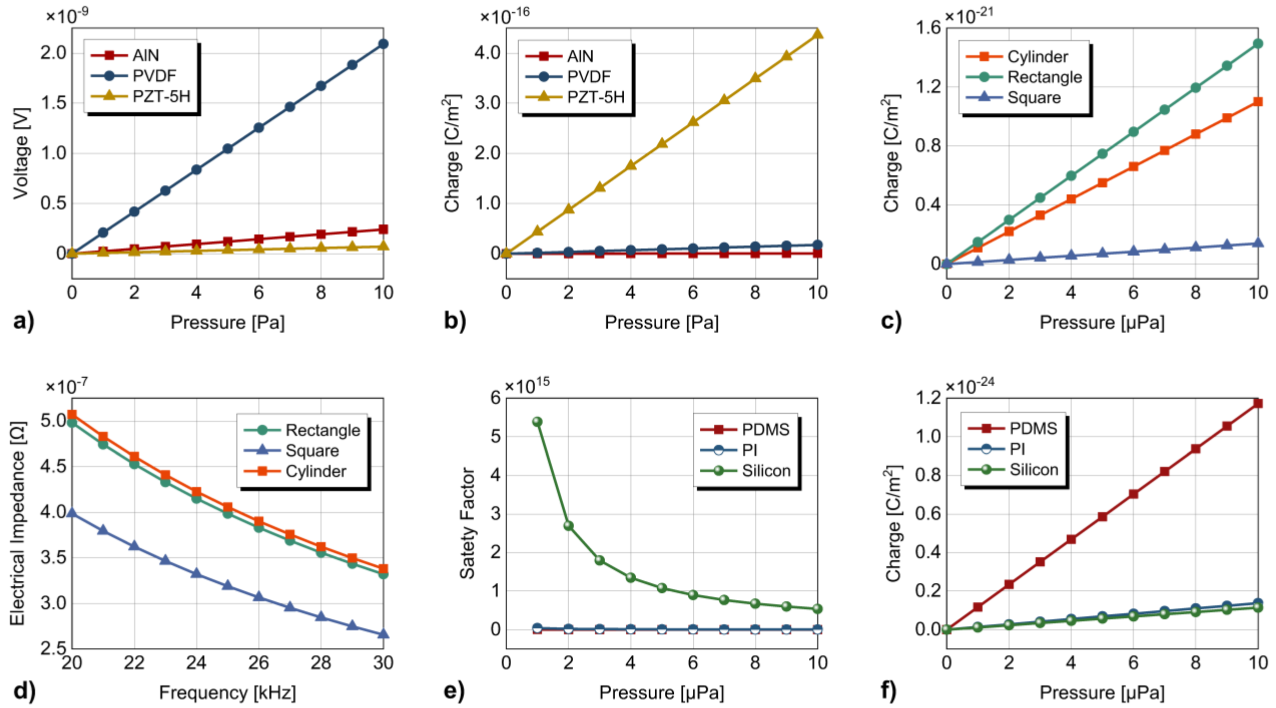

Fig.4. Comparison of electric potential and charge accumulation changes with increasing pressure for the three different materials: (a) Electric Potential (V); (b) Surface charge accumulation (nC/m^2); Further analysis on MATLAB of the electrical impedance and the charge accumulation for the different geometries: (c) Surface charge accumulation (nC/m^2) and (d) Electrical impedance-frequency response (Ω); (e) Safety factor for the three different substrates with changing pressure; (f) Surface charge accumulation for the three different substrates with changing pressure.

IV. Conclusions

A new method for the study of muscle structure and function has been proposed through the use of a high-frequency flexible ultrasonic transducer. With COMSOL Multiphysics® simulations, it was demonstrated that a PZT-5H transducer, with PI for the backing and acoustic matching layer and PMMA as a plano-concave acoustic lens, could allow for high resolution SMG. The application range of this sensor model can range from medical imaging to prosthetics and rehabilitation engineering. Further analysis on the aspect ratio, real-time performance, and micromachining fabrication techniques is required to determine whether SMG can replace EMG as a diagnostic and rehabilitation tool.

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