



## Design, fabrication and geometric optimization of microchannels for wearable sensors

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### ARTICLE INFO

**Article Type:**  
Original Research

**Received:** 09.19.2024  
**Revised:** 10.21.2024  
**Accepted:** 11.12.2024

**Keyword:**  
Wearable sensors  
microchannels  
polymethyl methacrylate  
(PMMA)  
agarose nanoparticles  
hydrophilicity

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### ABSTRACT

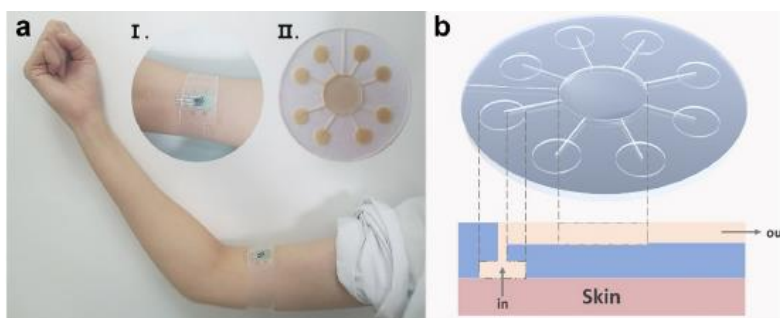
In recent decades, wearable sensors have played a significant role in enhancing personal health management as advanced tools in the medical field and health monitoring. These sensors utilize microchannels to direct fluids for accurate physiological data collection. Microchannels are crucial in improving the precision and efficiency of sensors due to their ability to control fluid flow. Polymethyl methacrylate (PMMA) is one of the widely used materials in the fabrication of these microchannels; however, its hydrophobic nature can disrupt fluid flow. To address this issue, coating with agarose nanoparticles has been proposed as an effective solution. Agarose nanoparticles, due to their biocompatibility and ability to improve the hydrophilicity of surfaces, facilitate fluid flow and enhance sensor accuracy. Experimental testing showed that the optimized microchannel design, with a length of 10 millimeters, a depth of 300 microns, and a constant width of 200 microns for all microchannels, including the outlet microchannel Type 1, exhibited the highest fluid velocity of 62.5 millimeters per second. Additionally, computational simulations demonstrated that optimized geometrical shapes can significantly improve sensor performance. This study examines the effects of geometry, nanostructured materials, and integrated optimization methods in microchannel design, providing strategies to enhance the performance of wearable sensors. The results of this research could pave the way for the development of a new generation of high-performance wearable sensors in the healthcare field.



## Introduction

In recent decades, wearable sensors have established themselves as one of the most prominent innovations in the field of health and medical technologies, significantly solidifying their position as advanced tools for health monitoring. These sensors, worn directly on the human body, can provide real-time and continuous data on physiological parameters such as heart rate, blood pressure, blood glucose levels, body temperature, and even brain electrical activity. The ability of these technologies to perform non-invasive and continuous monitoring allows both patients and healthy individuals to track their health status in real-time and quickly detect any abnormal changes or early signs of disease. These features have significantly contributed to the advancement of personalized medicine and the improvement of personal health management [1].

Wearable sensors, with their wide-ranging applications in healthcare, sports, public health, and environmental monitoring, have successfully collected and analyzed highly accurate data from the human body and the surrounding environment [2]. A key component of these sensors is microchannels, which serve as pathways for guiding and transporting biological and chemical fluids to different parts of the sensor. With their precise design and microscopic dimensions, these microchannels are responsible for guiding fluids with minimal resistance and high efficiency. In sensitive medical and biological applications, the optimal design and construction of these channels are particularly important, as their proper functioning contributes to the accuracy of measurements and the overall efficiency of the sensors [3]. Figure 1 illustrates an example of a wearable sensor and its microchannel sections.



**Figure 1.** a) An image of the wearable sensor configuration applied to the subject's arm. The insets show enlarged views of specific parts of the microfluidic device. b) A schematic representation of the microfluidic system for sweat collection and on-skin operations, shown in top-down and cross-sectional views [4].

Microchannels, due to their crucial role in wearable sensors, are considered fundamental components in the performance of these devices. These microscopic

channels directly influence the flow and transfer of biological and chemical fluids and can significantly impact the quality and accuracy of the data obtained from the sensors [5]. By precisely controlling fluid flow, microchannels help distribute it evenly towards the sensitive elements of the sensor, thereby enabling more accurate recording and faster responsiveness to environmental changes. These features are particularly important in sensitive measurements, such as biomedical and medical monitoring, where high accuracy and reliability are required [6].

Improper functioning or inefficient design of microchannels can lead to numerous problems. For example, fluid accumulation in specific parts of the channels can create dead zones or imbalanced flows, which can reduce the sensitivity of the sensors and increase the likelihood of errors in the data obtained [7]. These issues may result in serious errors in health data analysis, ultimately leading to incorrect results that could have dire consequences in clinical and medical settings. Additionally, if fluid flow is not properly guided in the microchannels, the sensor's sensitive elements may not respond to rapid changes, leading to decreased sensor efficiency. Therefore, careful and optimal design of microchannels is essential to ensure the best performance of wearable sensors [8].

One of the commonly used materials in constructing microchannels is polymethyl methacrylate (PMMA), also known as Plexiglas. This polymer is widely used in microchannel fabrication due to its desirable properties, such as high transparency, flexibility, and suitable mechanical properties [9]. The high transparency and light transmission ability of PMMA make it suitable for applications requiring direct observation of fluid flow within the channels. Additionally, the flexibility and ease of shaping this material allow engineers to create microchannels with complex designs and diverse geometries. Furthermore, the suitable mechanical properties of this material make it ideal for wearable sensors that require durability and resistance to various environmental conditions [10].

However, a major challenge in using PMMA is its inherent hydrophobicity, which can disrupt fluid flow within the microchannels and reduce sensor efficiency [11]. The hydrophobic surface of PMMA causes fluids to flow over it at a high contact angle, resulting in irregular and higher resistance fluid flow. This characteristic can reduce measurement accuracy and delay sensor responses, which is critical in medical and biological applications. To address this issue, the use of nanoparticles has been proposed as an innovative solution to improve the hydrophilicity of the internal surface of the microchannels [12].

Nanoparticles, due to their high surface-to-volume ratio and ability to modify surface properties, are effective tools for altering the surface characteristics of materials. The use of these particles can modify the surfaces of microchannels to significantly enhance their hydrophilicity. This improvement reduces the contact angle of fluid droplets with the channel surface, facilitating fluid movement within the channels. Enhanced hydrophilicity allows fluids to flow more easily, preventing the formation of dead zones and imbalanced flows [13]. Agarose nanoparticles, due to their biocompatibility, chemical stability, and high efficiency in creating hydrophilic surfaces, have been recognized as a suitable option for use in wearable sensors. Agarose nanoparticles can create a uniform and thin layer on the internal surface of microchannels, which not only improves hydrophilicity but also prevents the accumulation of foreign particles within the channels, thereby increasing sensor accuracy and efficiency. Moreover, due to their biocompatibility, these nanoparticles are highly suitable for use in medical and biological applications that come into direct contact with the human body [14].

Previous research has shown that improving microchannel design and using nanostructured materials can significantly increase the accuracy and sensitivity of wearable sensors [15]. In a study conducted by Lau and colleagues in 2023, the researchers used hybrid materials and optimized microchannel design to enhance the hydrophilicity of the internal surface of these channels. These modifications reduced the contact angle of fluid droplets with the surface, thereby facilitating fluid flow within the microchannels. The improvements resulted in increased sensor accuracy, particularly in applications requiring precise and sensitive measurements. This research demonstrated that the combination of hybrid materials and precise microchannel design could directly impact the performance of wearable sensors and significantly enhance their efficiency [16].

In 2022, Zheng and colleagues investigated the impact of silicon nanoparticles on improving hydrophilicity and reducing fluid friction within microchannels. Silicon nanoparticles, due to their unique properties, such as chemical stability and the ability to modify surface characteristics, were selected as a suitable option for modifying the internal surfaces of microchannels. The results of this study showed that adding these nanoparticles to the internal surface of the channels reduced the friction between the fluid and the channel walls, facilitating fluid flow within the channels. These changes led to increased measurement speed and accuracy, as well as reduced fluid droplet accumulation within the channels, ultimately extending the sensors' lifespan [17].

In another study conducted by Xie and colleagues in 2021, computer simulations were used to investigate fluid behavior within microchannels. These simulations enabled the examination of the impact of various geometric parameters of the channels, such as dimensions, cross-sectional shape, and surface roughness. The results showed that optimized geometric design of microchannels could directly influence the accuracy and sensitivity of the sensors. For example, channels with circular cross-sections and smoother surfaces produced more uniform fluid flow, leading to reduced measurement errors and increased sensor accuracy [18].

In addition to these studies, other research has explored using different nanoparticles, such as gold and silver, to improve the surface properties of microchannels. These nanoparticles, due to their antibacterial and anti-corrosion properties, enhance sensor accuracy and increase the devices' lifespan. Overall, this research indicates that optimizing microchannel design and using nanostructured materials can significantly improve the performance of wearable sensors, paving the way for developing a new generation of these devices with more advanced capabilities in various medical and healthcare fields [19].

Despite these advancements, significant research gaps remain in this field. Many studies have focused on theoretical analysis and simulations, but fewer experimental and laboratory studies have been conducted, which could provide more practical results. Furthermore, research that simultaneously examines the effects of both geometric and surface material properties is limited, highlighting the need for more comprehensive and multidisciplinary studies. Additionally, many existing studies have only addressed one aspect of geometric design or surface property improvement, and the integrated optimization of all parameters has not been fully explored [20]. Another research gap is the lack of sufficient attention to the biocompatibility of nanoparticle materials and their potential effects on human health. Although nanoparticles have successfully improved surface properties, the long-term effects of using these particles in the human body have not yet been fully investigated. Alongside these concerns, the possibility of nanoparticle accumulation in the body and their unknown effects on organ function are significant challenges that require more thorough examination. Therefore, more research is needed in this area to fully evaluate the biological impacts and safety of these materials [21].

In general, this article examines the challenges and opportunities in the design, fabrication, and optimization of microchannels for wearable sensors. In this context, the effects of various geometric parameters, structural materials, and nanoparticles on the final performance of these sensors will be analyzed. The primary objectives of this research include evaluating the impact of microchannel

geometry on the performance of wearable sensors, specifically investigating how different shapes and sizes affect fluid dynamics and sensor accuracy, as well as examining the effects of materials and nanoparticles on improving the surface properties of microchannels. To achieve this, experimental tests were first conducted on the microfluidic system, followed by the application of Design of Experiments (DOE) to collect the necessary data. Finally, all of this data was analyzed together, leading to satisfactory results. This research also aims to develop and propose integrated optimization methods that combine geometrical approaches, materials, and nanostructures to maximize sensor performance. The findings of this research could serve as a foundation for developing a new generation of wearable sensors with higher accuracy and efficiency, ultimately contributing to improved healthcare services and quality of life.

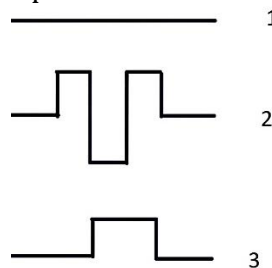
### ***Materials and Equipment***

In this study, polymethyl methacrylate (PMMA) was used as the primary material. This polymer was chosen due to its high transparency, mechanical stability, and precise micro-machinability, making it an ideal choice for fabricating microchannels. The microchannels were created using a precise desktop CNC milling machine, which allows for the fabrication of channels with accurate and controlled dimensions. This machine, guided by CAD design data, precisely defines the length, width, and depth of the microchannels.

After the microchannels were fabricated, their internal surfaces were coated with agarose nanoparticles. These nanoparticles were applied to the inner surface of the channels using a dip-coating method to enhance the hydrophilicity of the surface. The dimensional accuracy of the microchannels was measured and examined using a digital microscope with 1000X magnification to ensure that the actual dimensions matched the original designs.

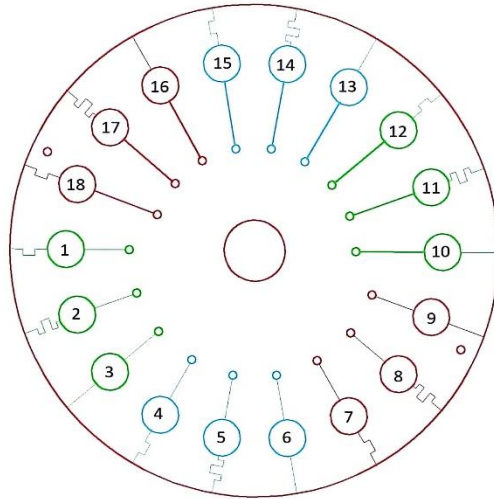
### ***Design and Fabrication of Microchannels***

The microchannels were designed to direct the analyte to a circular reservoir where the sensor is located, followed by an exit through an outlet microchannel configured in three different shapes.



**Figure 2.** Three different configurations of the outlet microchannel.

The initial design of the microchannels was carried out using a CAD software such as SolidWorks. This design included precise geometric specifications for the microchannels, with all channels having a width of 200 microns, lengths of 10 and 15 millimeters, and depths set to 100, 200, and 300 microns.

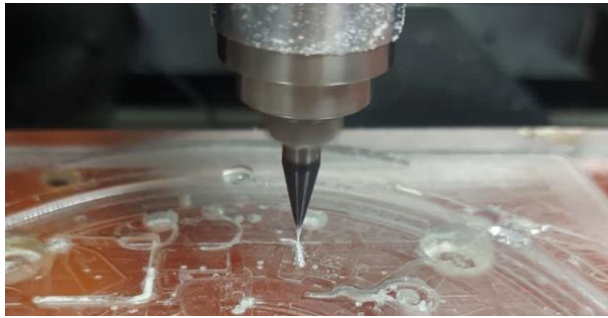


**Figure 3.** CAD layout of the different microchannel configurations with varying dimensions, the collection reservoir, and outlet microchannels.

**Table 1.** Geometric specifications of the microchannels numbered in Figure 3.

Microchannel Number	Microchannel Length (mm)	Microchannel Depth ( $\mu\text{m}$ )	Outlet Microchannel Type
1	10	100	3
2	10	100	2
3	10	100	1
4	10	200	3
5	10	200	2
6	10	200	1
7	10	300	3
8	10	300	2
9	10	300	1
10	15	100	1
11	15	100	2
12	15	100	3
13	15	200	1
14	15	200	2
15	15	200	3
16	15	300	1
17	15	300	2
18	15	300	3

After the design, micro-machining was carried out using a precise desktop CNC milling machine. Following machining, the internal surfaces of the microchannels should be polished with special PMMA polishing materials to ensure a smooth and glossy finish, allowing the fluid flow to proceed smoothly and without interference.



**Figure 4.** The desktop CNC milling machine engraving microchannels on a PMMA sheet.

### ***Coating with Agarose Nanoparticles***

To enhance the hydrophilicity of the internal surfaces of the microchannels, deep coating with agarose nanoparticles was used. Agarose is a natural polysaccharide extracted from seaweed, and due to its gelling properties and high biocompatibility, it is widely utilized in biotechnology and materials engineering. Agarose nanoparticles, due to their small size and high surface-to-volume ratio, can significantly alter the surface properties of the microchannels [22].

To prepare the coating solution, agarose nanoparticles were dissolved at a concentration of 0.05 grams in 10 grams of distilled water. The solution was then thoroughly mixed and microwaved for 30 seconds to ensure that the nanoparticles were uniformly dispersed throughout the solution. After preparing the solution, the microchannels were immersed in it for 5 minutes to allow the nanoparticles to evenly adhere to the internal surfaces of the microchannels. This immersion step aimed to create a thin layer of agarose nanoparticles on the walls of the microchannels (Figure 5).

After this step, the microchannels were dried at room temperature for 24 hours. This drying process allows the nanoparticles to fully adhere to the surface of the microchannels, creating a uniform and stable coating. Coating with agarose nanoparticles enhances the hydrophilicity of the microchannel surfaces, improving fluid flow within the channels and reducing hydrodynamic resistance. Additionally, this coating can prevent the adhesion of suspended particles to the channel walls, thereby increasing measurement accuracy.



**Figure 5.** A representation of the equipment required for coating the PMMA chip with a solution of water and agarose nanoparticles to enhance hydrophilicity.

### ***Governing Equations of Fluid Flow***

In this paper, several fundamental equations in fluid dynamics are used to analyze fluid flow in microchannels. These equations specifically describe the behavior of the fluid within the microchannels and address the impact of various parameters on flow, pressure drop, and the effects of surface forces at the micro scale.

### ***Continuity Equation***

The continuity equation is used for incompressible fluids and indicates that the volume of fluid entering any point in the microchannel is equal to the volume of fluid exiting that point [23].

$$\nabla \cdot V = 0 \tag{1}$$

In this equation,  $V$  is the velocity vector of the fluid, which represents the speed and direction of the fluid flow at any point in the microchannel, and  $\nabla \cdot V$  is the divergence of the velocity vector, indicating the volumetric changes in the fluid flow at a point.

This equation examines the variations in fluid density over time and ensures that fluid is neither accumulating nor disappearing at any point in the channel. It is specifically used to analyze the uniform distribution of fluid flow along the microchannels and to ensure that no point in the channel experiences constriction or accumulation.

### **Mass Conservation Equation**

The mass conservation equation states that changes in fluid density over time and space must correspond with the fluid flow at that point. This equation is applicable in systems where density variations occur (such as compressible flows) [23].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \quad (2)$$

In this equation,  $\rho$  is the fluid density,  $\frac{\partial \rho}{\partial t}$  is the temporal derivative of density, which represents changes in fluid density over time and  $\nabla \cdot (\rho V)$  is the divergence of the mass flux, indicating spatial changes in the mass flux.

The mass conservation equation is used to ensure that changes in fluid density within the microchannels are properly accounted for, especially in scenarios where fluid density might vary due to changes in temperature or pressure.

### **Navier-Stokes Equation**

The Navier-Stokes equation describes the behavior of fluid flow under the influence of various forces such as pressure, viscosity, and external forces. This equation is fundamental to analyzing complex flows, such as those occurring within microchannels [24].

$$\rho \left( \frac{\partial V}{\partial t} + (V \cdot \nabla) V \right) = -\nabla p + \mu \nabla^2 V + f \quad (3)$$

In this equation,  $\rho$  is the fluid density,  $\frac{\partial V}{\partial t}$  is the temporal derivative of the velocity vector,  $(V \cdot \nabla) V$  represents the convective acceleration,  $\nabla p$  is the pressure gradient,  $\mu$  is the dynamic viscosity of the fluid,  $\nabla^2 V$  is the Laplacian of the velocity vector and  $f$  represents external forces acting on the fluid.

In this study, the Navier-Stokes equation is used to simulate and understand fluid dynamics in microchannels, including how pressure and viscosity affect flow patterns. This equation aids in designing microchannels with optimized flow characteristics.

### **Hagen-Poiseuille Equation**

The Hagen-Poiseuille equation is used to calculate pressure drop in a straight and simple channel. The pressure drop is a function of the fluid viscosity, channel length, flow rate, and channel radius [25].

$$\Delta P = \frac{8\mu LQ}{\pi R^4} \quad (4)$$

In this equation,  $\Delta P$  represents the pressure drop along the microchannel,  $\mu$  is the dynamic viscosity of the fluid,  $L$  is the length of the microchannel,  $Q$  is the volumetric flow rate of the fluid, and  $R$  is the radius of the microchannel. This equation is used to estimate the pressure drop in designed microchannels, specifically helping in determining the optimal channel dimensions to minimize pressure drop and ensure efficient fluid flow.

### **Surface Tension Equation**

The surface tension equation is defined as a function of surface stress and surface curvature. At the microscale, surface tension significantly impacts fluid behavior and can lead to the formation of droplets and bubbles [26].

$$\gamma = \frac{1}{2} \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (5)$$

In this context,  $\gamma$  is the surface tension,  $\sigma$  is the interfacial tension, and  $R_1, R_2$  are the radii of curvature in two different directions.

In this article, the surface tension equation helps to understand how surface forces affect the behavior of fluid in microchannels, including droplet or bubble formation and their interaction with the walls of the microchannel.

### **Young's Equation**

The Young's equation is a relationship that relates the contact angle ( $\theta$ ) formed at the three-phase contact line between a liquid and a solid to the involved surface tensions. This equation describes the balance of forces at the three-phase contact line where liquid, solid, and vapor meet. The Young's equation is expressed as follows [27]:

$$\cos \theta = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} \quad (6)$$

In this equation,  $\sigma_{sv}$  is the surface tension force between the solid and vapor,  $\sigma_{sl}$  is the surface tension force between the solid and liquid,  $\sigma_{lv}$  is the surface tension force between the liquid and vapor, and  $\theta$  is the contact angle formed at the interface between the liquid and solid surfaces.

### Capillary Equation

The capillary equation describes the height to which a fluid rises or falls within a channel due to surface tension forces and the contact angle. These forces can assist in fluid transport on a microscale [28].

$$h = \frac{2\gamma \cos \theta}{\rho g R} \quad (7)$$

In this equation,  $h$  is the height of fluid rise in the microchannel,  $\gamma$  is the surface tension,  $\theta$  is the contact angle,  $\rho$  is the fluid density,  $g$  is the gravitational acceleration, and  $R$  is the radius of the microchannel.

The capillary equation is used to analyze how capillary forces affect fluid distribution in microchannels, particularly in designs where fluid movement relies on capillary forces to guide flow or manage fluid distribution.

### Experimental Design

The Design of Experiments (DOE) method was used to optimize the depth, length, and outlet shape of the microchannels. In this study, the geometric parameters, including length (10 and 15 mm), depth (100, 200, and 300 microns) and outlet channel shape (three types of outlet microchannels shown in Figure 2), were examined. In all cases, the microchannel width was kept constant at 200 microns. A total of 18 different experiments were designed and conducted, in which the flow rate was empirically measured, and the results were analyzed using the Box-Behnken response surface methodology in Minitab software. The reason for using the Box-Behnken method is that many researchers, such as Kavitha Jayakumar [29], Shiva Khurshid [30] and Minimin [31], have used this method in their articles to evaluate optimal conditions.

### Results and Discussion

Initially, using experimental testing, the time it took for the fluid to travel from the moment 2 microliters of fluid were injected into the microchannels by a sampler until it reached the main reservoir was recorded. The fluid velocity in all microchannels under identical conditions was also measured and reported in Tables 2 and 3.

**Table 2.** Recorded velocities from experimental testing for microchannels with a length of 10 millimeters.

Microchannel Depth ( $\mu\text{m}$ )	Outlet Microchannel Type	Fluid Velocity ( $\text{mm} / \text{s}$ )
100	3	42.9
100	2	42

100	1	43.3
200	3	47.1
200	2	45.9
200	1	48.6
300	3	57.4
300	2	53.6
300	1	62.5

**Table 3.** Recorded velocities from experimental testing for microchannels with a length of 15 millimeters.

Microchannel Depth ( $\mu\text{m}$ )	Outlet Microchannel Type	Fluid Velocity ( $\text{mm} / \text{s}$ )
100	1	53.2
100	2	50.8
100	3	51.9
200	1	55.3
200	2	54.9
200	3	54.1
300	1	59.7
300	2	56.4
300	3	58.9

Based on the reported velocities in various scenarios, the microchannel with a length of 10 millimeters, a depth of 300 microns, and Type 1 for the outlet microchannel exhibited the highest velocity, 62.5 millimeters per second, making it the most optimal compared to other recorded values.

In this section, the impact of various parameters on the results is analyzed using the Response Surface Methodology (RSM) and Box-Behnken design in Minitab software, with the goal of achieving the highest velocity in the microchannels. The parameters include a fixed width of 200 microns, three depths of 100, 200, and 300 microns, two lengths of 10 and 15 millimeters, and three outlet channel types (1, 2, and 3).

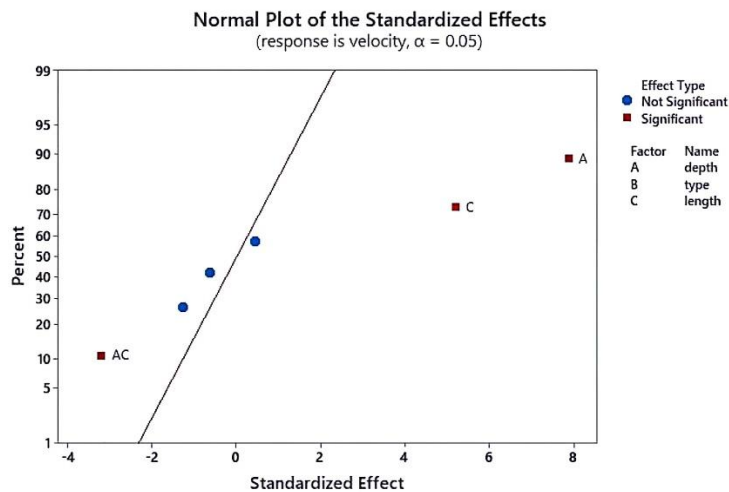
Analysis of variance (ANOVA) assesses the significance of one or more factors by comparing the mean response variable across different levels of the factor. In Table 4, P-values less than 0.05 indicate the most influential parameters. As shown, depth, length, and the interaction between depth and length are the most significant parameters.

**Table 4.** Analysis of Variance (ANOVA) results, highlighting the significance of depth, length, and their interaction.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
<b>Model</b>	6	564.648	94.108	16.94	0.000
<b>Linear</b>	3	504.099	168.033	30.24	0.000

<b>depth</b>	1	345.613	345.613	62.21	0.000
<b>type</b>	1	8.841	8.841	1.59	0.233
<b>length</b>	1	149.645	149.645	26.93	0.000
<b>2-Way Interaction</b>	3	60.549	20.183	3.63	0.048
<b>depth*type</b>	1	2.205	2.205	0.40	0.542
<b>depth*length</b>	1	57.203	57.203	10.30	0.008
<b>type*length</b>	1	1.141	1.141	0.21	0.659
<b>Error</b>	11	61.114	5.556		
<b>Total</b>	17	625.763			

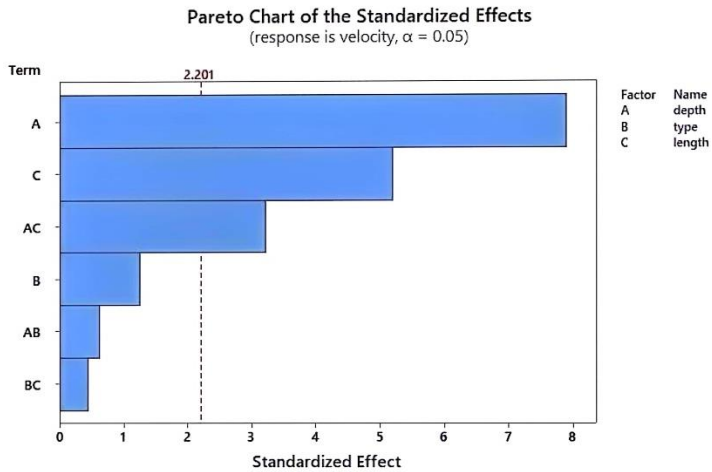
In the Normal Plot, the standardized effects are plotted against a fitted distribution line, representing the scenario where all effects are zero. This plot is used to determine the magnitude, direction, and significance of the effects. The red points indicate the most influential parameters in our experiment, and as seen in the plot in Figure 6, depth, length, and the interaction between depth and length are the most significant factors in this experiment.



**Figure 6.** Standardized Effects Plot displaying the relationship between standardized effects and the fitted distribution line, highlighting the most significant factors, including depth, length, and their interaction, indicated by the red points.

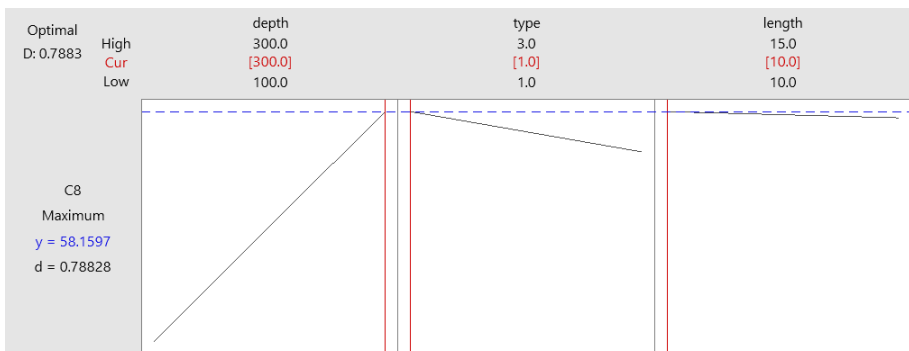
In the Pareto chart, the absolute values of the standardized effects are displayed from the largest effect to the smallest effect. This chart also plots a reference line to indicate which effects are statistically significant. The Pareto chart is used to determine the magnitude and importance of the effects. As mentioned above, depth, length, and the interaction between depth and length are the most significant, while the interaction between length and microchannel outlet type, as

well as depth and outlet type, have the least impact. As individual factors, depth, length, and outlet type have the greatest influence, respectively.



**Figure 7.** Pareto chart of standardized effects ranked from largest to smallest, highlighting statistically significant effects. The chart shows that depth, length, and their interaction are the most influential factors, while the interactions between length and outlet type, and depth and outlet type, have the least impact.

Finally, as seen in Figure 8, the parameter *d* indicates the desirability, which ranges between zero and one. Additionally, the optimal configuration identified by the Box-Behnken method was a depth of 300 microns, a length of 10 millimeters, and outlet microchannel Type 1 from Figure 2.



**Figure 8.** Overall optimization results showing the desirability parameter (*d*) from zero to one. The optimal configuration identified by the Box-Behnken method includes a depth of 300 microns, a length of 10 millimeters, and outlet microchannel Type 1.

As observed in this section, the results of the experimental tests to find the optimal microchannel matched the results obtained using the Response Surface

Methodology (RSM) and Box-Behnken in Minitab software for achieving the highest fluid velocity in microchannels. This alignment of results from both methods increases confidence in the accuracy of the findings.

## **Conclusion**

In this study, the role of microchannels and the impact of their precise design on the performance of wearable sensors were comprehensively examined. Microchannels, as key components in guiding biological and chemical fluids, play a crucial role in the accuracy and efficiency of these sensors. The studies showed that improving the geometric design of microchannels directly affects the performance of the sensors. In this study, the optimal microchannel for wearable sensors was found to have a width of 200 microns, a depth of 300 microns, a length of 10 millimeters, and outlet microchannel Type 1 from Figure 2. Additionally, agarose nanoparticles, by enhancing the hydrophilicity of the microchannels' inner surface, facilitated fluid flow and prevented the formation of dead spots and unbalanced flows. These improvements led to increased accuracy and faster response times for the sensors, reducing the likelihood of errors in the obtained data.

Furthermore, the use of polymethyl methacrylate (PMMA) as the structural material for the microchannels, due to its mechanical properties and high transparency, is considered a suitable choice for wearable sensors. Although the hydrophobic nature of this material posed a challenge, it was significantly addressed through the incorporation of agarose nanoparticles. Overall, the results of this study indicate that optimal design and the use of nanoparticles can pave the way for improving the performance of wearable sensors and developing innovative technologies in the field of personalized medicine.

These findings can serve as an important research foundation for future studies on wearable sensors and their applications in healthcare. Finally, further investigation into the long-term biocompatibility of nanoparticles and the implementation of more extensive tests could contribute to the development of more sustainable and safer technologies.

## **Disclosure statement and funding**

The authors declare no potential conflicts of interest. The present study received no financial support from any organization or institution.

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