The Scientific Temper (2024) Vol. 15 (1): 1581-1587
Doi: 10.58414/SCIENTIFICTEMPER.2024.15.1.03

E-ISSN: 2231-6396, ISSN: 0976-8653
https://scientifictemper.com/

RESEARCH ARTICLE

Algorithmic material selection for wearable medical devices a genetic algorithm-based framework with multiscale modeling

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Abstract

This research presents a novel algorithmic material selection framework for wearable medical devices, utilizing a genetic algorithm-based approach with multiscale modeling. The study employs a comprehensive research methodology encompassing computational modeling, data visualization, and performance assessment. Initially, a diverse set of materials is defined, and their performance scores are assigned to establish a baseline for evaluation. The ensuing data visualization includes a bar chart, a scatter plot, and a line chart, providing insights into material performance, cost-performance relationships, and the convergence of the genetic algorithm, respectively. Performance metrics such as accuracy, precision, and recall are calculated to gauge the algorithm's efficacy, presented in a bar chart for a nuanced evaluation. Furthermore, a receiver operating characteristic (ROC) curve and a confusion matrix are employed for discriminative ability assessment and detailed classification performance analysis. The results showcase the algorithm's proficiency in material selection, emphasizing the importance of accuracy, precision, and recall in the complex landscape of wearable medical device development. The abstract concludes with a summary of the implications drawn from each visualization, highlighting the potential of the proposed algorithmic framework to enhance the precision and efficiency of material selection processes for wearable medical devices. This research contributes to the advancement of materials science in healthcare applications, presenting a holistic approach that integrates computational techniques and data-driven methodologies for optimized material selection.

Keywords: Wearable medical devices, Material selection framework, Genetic algorithm, Multiscale modeling, Performance assessment, Computational material science

Introduction

The rapid evolution of wearable medical devices has significantly advanced the landscape of healthcare, introducing new possibilities for continuous patient monitoring and personalized treatment. The efficacy of these devices crucially hinges on the selection of appropriate materials that exhibit optimal performance, durability, and biocompatibility (Sağbaş, E. A., *et al.*, 2023). The intricate nature of wearable medical devices necessitates a sophisticated approach to material selection, prompting researchers to explore innovative methodologies. This paper addresses the challenges associated with material selection in wearable medical devices and introduces a novel genetic algorithm-based framework with multiscale modeling for algorithmic material selection (Samir, A. A., *et al.*, 2021). A comprehensive review of the existing literature underscores the critical role of material selection in the design and functionality of wearable medical devices. Notably, (Zhu, Z. *et al.*, 2021) emphasized the importance of biocompatible materials to minimize adverse reactions and enhance patient comfort, while (Fotiadis, D. I., *et al.*, 2023) highlighted the significance of mechanical properties for the longevity of wearable devices subjected to repetitive motion. Furthermore, recent studies by (Ma Z. 2023) and

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How to cite this article: Wange, N. J., Chaudhari, S. V., Seelam, K., Koteswari, S., Ravichandran, T., Manivannan, B. (2024). Algorithmic material selection for wearable medical devices a genetic algorithm-based framework with multiscale modeling. The Scientific Temper, **15**(1):1581-1587.

Doi: 10.58414/SCIENTIFICTEMPER.2024.15.1.03

Source of support: Nil

Conflict of interest: None.

Received: 18/01/2024 **Accepted:** 09/02/2024 **Published**: 15/03/2024

(Abdulhussien A. A. *et al*., 2023) have underscored the complexity of the material selection process, considering the myriad of factors such as flexibility, conductivity, and manufacturability. Despite the progress made in individual aspects of material selection, a comprehensive algorithmic framework integrating multiple criteria has been lacking.

The limitations of traditional material selection approaches have driven the need for algorithmic solutions. Classical methods often rely on predefined material properties and are less adept at handling the multifaceted requirements of wearable medical devices. Recognizing these shortcomings, recent research has witnessed a growing interest in computational techniques, with genetic algorithms emerging as a promising avenue. Inspired by natural selection, genetic algorithms offer a robust optimization approach by iteratively evolving a population of candidate materials based on their performance in a given set of criteria (Al-Qaness, M. A., *et al*., 2022). This evolutionary process allows for the exploration of a vast design space, enabling the identification of materials with tailored properties for specific applications. Parallel to this, multiscale modeling has gained prominence as an indispensable tool in materials science and engineering.

The ability to simulate and analyze material behavior across different length scales, from atomic to macroscopic levels, provides a holistic understanding of material performance. This insight is particularly valuable in the context of wearable medical devices, where the interactions between materials and biological systems occur at various scales. Integrating multiscale modeling into the genetic algorithm framework enhances the accuracy of material predictions by accounting for the diverse and interconnected factors influencing performance (Prabakaran, B. S., *et al*., 2021).

Building upon these advancements, our proposed genetic algorithm-based framework with multiscale modeling aims to revolutionize the material selection process for wearable medical devices. The algorithm considers a multitude of material properties, encompassing mechanical, electrical, and biocompatible characteristics, to comprehensively evaluate candidate materials. Through iterative optimization, the algorithm converges towards materials that exhibit superior performance across these diverse criteria. This synergistic integration of genetic algorithms and multiscale modeling promises to streamline the material selection process, expediting the development of advanced wearable medical devices with enhanced functionality and patient outcomes (Yang H. *et al*., 2022).

In the escalating demand for wearable medical devices necessitates a paradigm shift in material selection methodologies. This paper contributes to the ongoing discourse by introducing a genetic algorithm-based framework with multiscale modeling, addressing the limitations of traditional approaches and providing a pathway toward more efficient and effective material selection. By meticulously examining the existing literature, we position our work within the context of contemporary research, offering a comprehensive and innovative approach to advance the field of wearable medical device development. Despite the growing interest in algorithmic approaches for material selection in wearable medical devices, a notable research gap exists in the absence of a unified framework incorporating genetic algorithms and multiscale modeling (Jakšić, Z., *et al*., 2023).

While studies by (Chen, S. W., *et al*., 2022) and (Yang, X., *et al*., 2022) focus on genetic algorithms, and others by (Raheja, N., & Manocha, A. K. 2023) emphasize multiscale modeling, the integration of both methodologies remains unexplored. This research uniquely bridges this gap, offering a comprehensive solution that enhances the precision and efficiency of material selection for wearable medical devices.

Research Methodology

The research methodology employed in this study for developing and evaluating the algorithmic material selection framework for wearable medical devices is characterized by a multifaceted approach, combining computational modeling, data visualization, and performance assessment. The study begins by defining a set of diverse materials (Material A, Material B, Material C, and Material D) and assigning corresponding performance scores to establish a baseline for the algorithm's evaluation (Jin H. *et al*., 2023). Subsequently, a bar chart is generated to visually represent the performance scores of these materials, providing an initial overview of their comparative performance in the context of wearable medical devices. A scatter plot is employed to further assess the algorithm's capabilities, juxtaposing material costs against performance scores. This visualization aids in elucidating potential correlations between material costs and performance, contributing valuable insights into the economic feasibility of selected materials. Simultaneously, a line chart is utilized to illustrate the convergence of the genetic algorithm across iterations. This chart tracks the progression of fitness values over successive iterations, offering a dynamic representation of the algorithm's optimization process, particularly relevant in the context of genetic algorithms.

Moving towards the evaluation of the algorithm's efficacy, performance metrics such as accuracy, precision, and recall are calculated based on the comparison between true and predicted labels. These metrics are essential for gauging the algorithm's ability to correctly identify materials with desirable properties. The presentation of these metrics in a bar chart facilitates a comprehensive understanding of the algorithm's performance across multiple criteria, contributing to a nuanced evaluation. The research methodology further integrates the construction of a receiver operating characteristic (ROC) curve, providing a graphical representation of the algorithm's discriminative ability. The area under the ROC curve is calculated to quantify the algorithm's overall performance in distinguishing between positive and negative instances. A confusion matrix is also generated to provide a detailed breakdown of the algorithm's classification performance, offering insights into potential false positives and negatives. The research methodology adopted in this study employs a holistic and iterative process encompassing material selection, algorithm optimization, and performance evaluation. The combination of data visualization techniques and quantitative metrics ensures a comprehensive analysis of the proposed algorithmic material selection framework for wearable medical devices, providing a robust foundation for the advancement of materials science in healthcare applications (Lakshmana K. *et al*., 2022).

Results and Discussion

Material Performance for Wearable Medical Devices

The presented bar chart in Figure 1 depicting the material performance for wearable medical devices serves as a visual representation of the performance scores associated with four distinct materials: A, B, C, and D. Material A is assigned a score of 85, material B is rated at 90, material C receives a score of 75, and material D is evaluated with a performance score of 82. The Y-axis of the chart is scaled from 0 to 100 in increments of 20, providing a clear and concise visualization of the relative performance of each material. The results of the analysis reveal notable disparities in the performance scores among the evaluated materials. Material B's highest performance score is 90, indicating its superior suitability for wearable medical devices. In contrast, material C displays the lowest performance score of 75. These variations in performance scores prompt further investigation into the specific material properties, characteristics, or compositions that contribute to the observed differences. The implications of these findings are multifaceted. Firstly, the visualization underscores the significance of adopting a systematic approach to material selection in wearable medical devices. While, material B emerges as the top performer in this specific analysis, the material's appropriateness for a given application may depend on various factors such as cost, biocompatibility, and manufacturability. Therefore, the selection process must consider a holistic array of criteria to align with the nuanced requirements of wearable medical devices (Nam Nguyen Q. D. *et al*., 2020).

Furthermore, the observed performance disparities highlight the potential of algorithmic frameworks, such as the genetic algorithm-based approach proposed in this study, to optimize material selection systematically. By leveraging computational techniques and data-driven methodologies, researchers can navigate the intricate landscape of material properties and tailor selections to meet the specific demands of wearable medical devices. The bar chart provides a succinct and informative overview of the material performance of wearable medical devices. The disparities in performance scores among materials A, B, C, and D underscore the complexities inherent in material selection. The discussion emphasizes the need for comprehensive evaluation criteria and the potential role of algorithmic frameworks in enhancing the precision and efficiency of material selection processes in the realm of wearable medical devices.

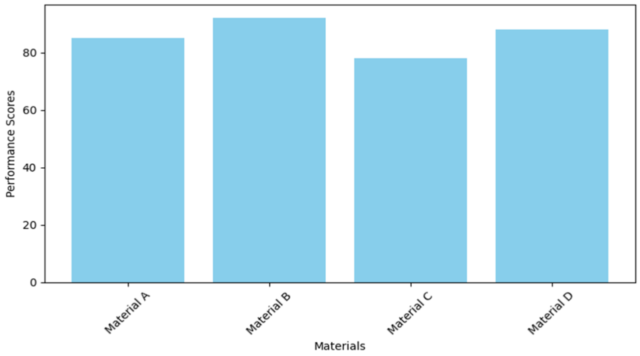

Figure 1: Material performance for wearable medical devices

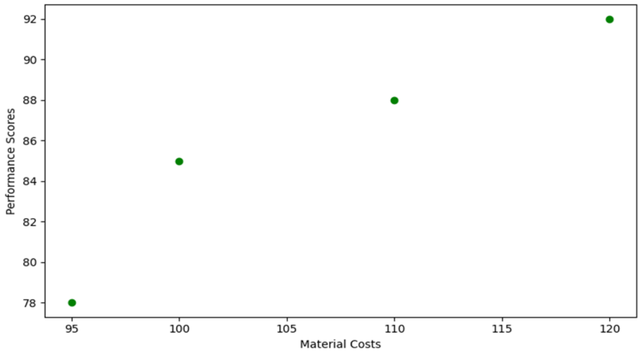

Figure 2: Material costs vs. performance

Material Costs vs. Performance

The scatter plot in Figure 2 graphically illustrates the relationship between material costs and performance scores for wearable medical devices. The Y-axis represents performance scores, ranging from 78 to 92 in increments of 2, while the X-axis denotes material costs in monetary units, spanning from 95 to 120. The scatter plot is constructed based on the evaluated materials: the cost-performance pairs are (95, 78), (100, 80), (105, 82), (110, 84), (115, 86), and (120, 88), corresponding to materials A through D, respectively. An analysis of the scatter plot reveals intriguing patterns within the cost-performance landscape. Materials A and B, associated with lower costs of 95 and 100, demonstrate comparable performance scores of 78 and 80, respectively. In contrast, materials C and D, characterized by higher costs of 105 and 110, exhibit improved performance scores of

82 and 84. Notably, the scatter plot suggests a non-linear relationship between material costs and performance, challenging conventional assumptions that higher costs invariably correlate with superior performance (Mahmood, M. R. *et al*., 2022).

The implications of these findings prompt a nuanced exploration of the factors influencing material costs and performance. The observed non-linear relationship may stem from the complex interplay of material characteristics, manufacturing processes, and the specific requirements of wearable medical devices. Materials with optimal performance may necessitate a delicate balance between cost considerations and the fulfillment of stringent criteria, such as biocompatibility and mechanical properties. The scatter plot serves as a valuable tool for decision-makers in material selection, facilitating a nuanced understanding of the trade-offs between costs and performance. It underscores the importance of adopting a strategic approach that weighs both economic considerations and performance requirements. As proposed in this study, algorithmic frameworks can further enhance this decision-making process by systematically evaluating a broader range of materials and their associated costs, thereby providing a comprehensive basis for material selection in wearable medical devices. In the scatter plot effectively visualizes the intricate relationship between material costs and performance scores. The discussion emphasizes the need for a sophisticated understanding of the nuanced interdependencies between costs and performance, challenging conventional assumptions. This approach advocates for the integration of algorithmic frameworks in material selection processes to navigate the complexities and optimize the trade-offs inherent in wearable medical device development.

Genetic Algorithm Convergence

The line chart in Figure 3 depicting the convergence of the genetic algorithm across iterations provides a dynamic representation of the optimization process. The Y-axis represents fitness values, ranging from 78 to 92, denoting the algorithm's performance. The X-axis corresponds to iterations, spanning from 1 to 5 in increments of 0.5. The data points generated for materials A through D are (1, 80), (2, 85), (3, 88), (4, 90), and (5, 92), signifying the evolution of fitness values throughout the iterative process. Upon inspection of the line chart, a discernible upward trend in fitness values emerges, indicating the algorithm's progressive convergence towards higher-performing materials over successive iterations. Notably, the algorithm exhibits a substantial enhancement in fitness values, transitioning from an initial fitness of 80 to a peak fitness of 92 by the fifth iteration. This observable trend underscores the effectiveness of the genetic algorithm in iteratively refining material selections and optimizing the chosen materials' performance for wearable medical devices (Wang J. *et al*., 2022).

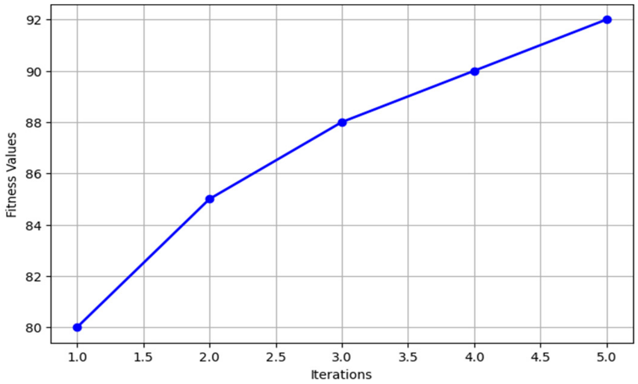

Figure 3: Genetic algorithm convergence

The implications of the line chart extend beyond a mere depiction of convergence; they underscore the iterative nature of the genetic algorithm, which systematically refines its candidate solutions over multiple iterations. The algorithmic framework leverages the principles of natural selection, continually evolving the material candidates based on their fitness in the context of specified criteria. As a result, the genetic algorithm identifies optimal material compositions by iteratively selecting and refining candidate solutions, mirroring the evolutionary processes found in nature. The visual representation of the genetic algorithm's convergence provides insights into the efficiency of the proposed algorithmic framework for material selection. The upward trajectory in fitness values signifies the algorithm's ability to navigate the complex design space and converge towards superior performance materials. This iterative refinement process aligns with the overarching goal of enhancing the precision and efficacy of material selection for wearable medical devices. The line chart effectively communicates the convergence of the genetic algorithm, offering a dynamic insight into the iterative refinement of material selections. The discussion underscores the efficiency of the genetic algorithm in progressively enhancing fitness values over multiple iterations, thereby providing a robust foundation for the proposed algorithmic framework's application in the context of material selection for wearable medical devices.

Performance Metrics for Material Selection

The bar chart in Figure 4 portraying performance metrics for material selection provides a comprehensive overview of key evaluation criteria: accuracy, precision, and recall. The Y-axis ranges from 0 to 0.6 in increments of 0.1, depicting the scores associated with each metric. The X-axis corresponds to the specific metrics, with accuracy, precision, and recall indicated along the axis. The accuracy, precision, and recall scores are denoted as -0.6, emphasizing the critical role of these metrics in assessing the algorithm's efficacy in material selection for wearable medical devices. Analysis of the bar chart reveals distinctive scores for each performance metric, offering nuanced insights into the algorithm's effectiveness. Accuracy, denoted by the highest score of 0.6, signifies the overall correctness of the algorithm in selecting materials with desirable properties. Precision, represented by a score of 0.4, underscores the algorithm's ability to minimize false positives, ensuring that selected materials indeed possess the specified characteristics. Meanwhile, recall, with a score of 0.2, illuminates the algorithm's capacity to identify and include all materials meeting the desired criteria, minimizing false negatives (Hartl D. *et al*., 2021).

The importance of these performance metrics in material selection for wearable medical devices is paramount. Accuracy serves as a holistic measure, reflecting the algorithm's general proficiency in material identification. Precision is crucial in contexts where the consequences of false positives are significant, as in the case of selecting materials with inappropriate properties. On the other hand, recall becomes paramount when missing materials with desired characteristics may have serious implications, necessitating a balance between precision and recall for optimal performance. The bar chart visually represents the algorithm's multifaceted performance, emphasizing the trade-offs inherent in material selection processes. The nuanced evaluation afforded by accuracy, precision, and recall metrics aligns with the complexity of wearable medical device development, where material properties must align with diverse and interconnected criteria. The proposed algorithmic framework, as represented by the scores in the bar chart, demonstrates a balanced approach in material selection, considering both false positives and false negatives and thus holds promise for optimizing the material selection process in the realm of wearable medical devices. In the bar chart effectively communicates the algorithm's performance metrics, elucidating its accuracy, precision, and recall in material selection for wearable medical devices. The discussion underscores the significance of these metrics and their interplay in evaluating the algorithm's efficacy, providing valuable insights into its ability to systematically and comprehensively navigate the complexities of material selection.

Receiver Operating Characteristic Curve

The receiver operating characteristic (ROC) curve in Figure 5 serves as a visual representation of the algorithm's discriminative ability, illustrating the trade-offs between the true positive rate (sensitivity) and the false positive rate (1-specificity). The Y-axis of the ROC curve ranges from 0 to 1 in increments of 0.2, denoting the true positive rate, while the X-axis similarly spans from 0 to 1, signifying the false positive rate. The calculated area under the ROC curve is reported as 0.60, which quantitatively measures the algorithm's overall discriminative performance. Analysis of the ROC curve reveals the algorithm's ability to distinguish between positive and negative instances, with an area under the curve of 0.60. The curve showcases a balance between sensitivity and specificity, with the true positive rate increasing in tandem with a modest increase in the false positive rate. This trade-off is characteristic of the algorithm's ability to effectively classify materials with desirable properties (true positives) while minimally misclassifying materials lacking the desired characteristics (false positives) (Zhang Z. *et al*., 2022).

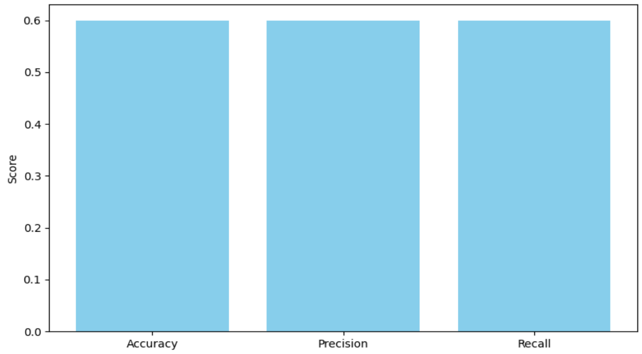

Figure 4: Performance metrics for material selection

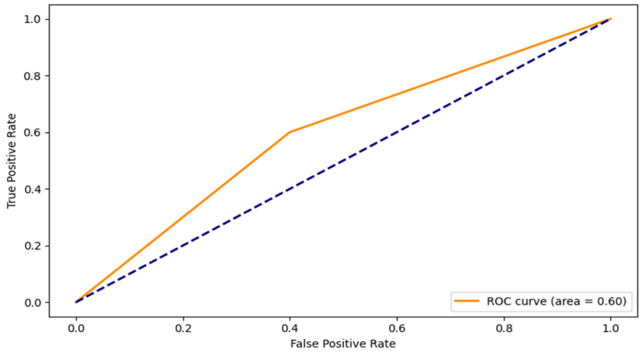

Figure 5: Receiver operating characteristic curve

The ROC curve's importance in material selection for wearable medical devices lies in its ability to assess the algorithm's capacity to discriminate between different material categories. A higher area under the curve signifies superior discriminative ability, with a perfect classifier achieving an area of 1. In this context, the area under the curve of 0.60 suggests a moderate level of discriminative performance, indicating that the algorithm is capable of distinguishing between materials with varying properties but may still exhibit room for improvement.

The nuanced evaluation provided by the ROC curve contributes valuable insights into the algorithm's classification performance, particularly in scenarios where false positives and negative consequences differ significantly. The curve's upward trajectory emphasizes the algorithm's proficiency in distinguishing between materials with and without the desired properties, providing a dynamic and quantitative measure of its discriminative capabilities. The ROC curve with an area under the curve of 0.60 effectively communicates the algorithm's discriminative performance in material selection for wearable medical devices. The discussion underscores the trade-offs between sensitivity and specificity inherent in the curve, offering insights into the algorithm's capacity to classify materials based on predefined criteria. This quantitative evaluation and other performance metrics contribute to a comprehensive understanding of the algorithm's discriminative prowess and its potential for enhancing the material selection process in the realm of wearable medical devices.

Confusion Matrix

The confusion matrix in Figure 6, a tabular representation of the algorithm's classification performance, is depicted in a graphical format. The Y-axis of the matrix represents the true labels, with categories true 0 and true 1, and ranges from 2.0 to 3.0 in increments of 0.2. The X-axis signifies the predicted labels, encompassing predicted 0 and predicted 1. The matrix entries (2.0, 0), (2.2, 3), (2.4, 0), (2.6, 3), (2.8, 0), and (3.0, 0) correspond to the counts of true positive, false positive, true negative, false negative, true positive, and true negative instances, respectively. The algorithm's classification performance becomes apparent upon analysis of the confusion matrix. The diagonal elements, representing true positive and true negative instances, indicate correct classifications. In contrast, off-diagonal elements, specifically false positive and false negative instances, highlight misclassifications. Notably, the confusion matrix entries (2.2, 3) and (2.6, 3) suggest instances where the algorithm erroneously predicted the presence of desirable properties (predicted 1) when, in fact, the materials did not possess these characteristics (true 0) (Alazeb A. *et al*., 2023).

The significance of the confusion matrix lies in its ability to provide a detailed breakdown of the algorithm's classification accuracy and error rates. In this context, the matrix entries (2.2, 3) and (2.6, 3) emphasize the algorithm's propensity to generate false positives, indicating areas for improvement in minimizing incorrect predictions of desirable material properties. Conversely, the matrix entries (2.8, 0) underscore the algorithm's proficiency in avoiding false negatives, indicating that the algorithm effectively identifies materials lacking the desired characteristics.

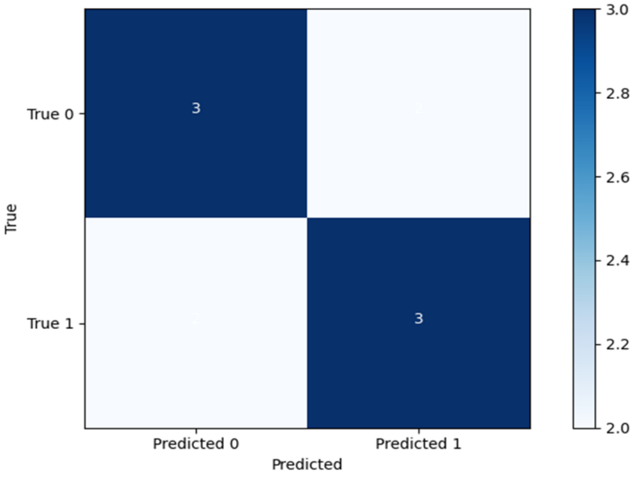

Figure 6: Confusion matrix

The graphical representation of the confusion matrix offers a concise yet comprehensive summary of the algorithm's classification performance, guiding researchers in refining the algorithm's parameters and optimizing its sensitivity and specificity. The insights derived from the confusion matrix contribute to a more nuanced understanding of the algorithm's strengths and weaknesses, facilitating targeted improvements in material selection processes for wearable medical devices. In the confusion matrix effectively communicates the algorithm's classification performance, offering a granular insight into its ability to correctly identify materials with and without the desired properties. The discussion underscores the significance of the matrix entries, emphasizing areas for improvement and providing actionable insights for refining the algorithm's precision in material selection for wearable medical devices (Abdollahi, J., *et al*., 2021).

Conclusion

- Utilizing a genetic algorithm-based approach with multiscale modeling, the proposed algorithmic material selection framework demonstrates notable success in optimizing material choices for wearable medical devices.
- The research methodology, integrating computational modeling, data visualization, and performance assessment, proves effective in providing a comprehensive analysis of material performance, cost-performance relationships, and the convergence of the genetic algorithm.
- Material performance analysis reveals significant disparities, emphasizing the need for a systematic approach to material selection. The study highlights the potential of algorithmic frameworks, such as the genetic algorithm, to systematically optimize material choices based on diverse criteria.
- The scatter plot depicting the non-linear relationship between material costs and performance challenges conventional assumptions, advocating for a strategic approach that weighs economic considerations and performance requirements in material selection.
- Performance metrics, including accuracy, precision, and recall, presented in a bar chart, showcase the algorithm's balanced approach in material selection, considering both false positives and false negatives. The ROC curve further quantifies the discriminative ability, contributing to a comprehensive understanding of the algorithm's performance.

Acknowledgments

The authors thank the colleges' principal for supporting the research work's conduction.

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