

Application of fuzzy logic for the evaluation of student academic performance in biomedical subjects

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Article Info

Article history:

Received May 4, 2025

Revised Dec 19, 2025

Accepted Jan 1, 2026

Keywords:

Academic performance

evaluation

Biomedical education

Centroid method

Fuzzy logic toolbox

Membership function

ABSTRACT

Conventional educational systems primarily use rigid assessment models that narrowly define student achievement through examination scores, categorizing outcomes into success or failure. Fuzzy logic, a mathematical approach derived from set theory, provides a more flexible framework capable of capturing uncertainty and gradations in performance. Initially applied in engineering and artificial intelligence, fuzzy logic has shown significant promise in educational contexts where nuanced evaluation is essential. This study applies a fuzzy logic-based methodology to the evaluation of biomedical course performance at the Sports University of Tirana, Faculty of Rehabilitation Sciences. Data were collected from fifty students enrolled in biomedical subjects and analyzed through both classical examination grading and fuzzy logic evaluation. Comparative analysis revealed that while classical assessment remains constrained by static calculations, fuzzy logic introduces dynamic adaptability. The findings highlight the superiority of fuzzy logic over traditional methods in providing a multidimensional picture of academic achievement. This approach not only refines evaluation accuracy but also supports fairer and more individualized assessment practices. Consequently, fuzzy logic emerges as a powerful tool for modernizing educational evaluation systems, particularly in biomedical disciplines where learning outcomes often extend beyond conventional metrics.

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1. INTRODUCTION

The evaluation of student performance is a central responsibility of higher education institutions, influencing progression, credentialing, and curriculum design. Traditional approaches, typically based on examination results and numerical averages, often reduce achievement to a rigid success/failure dichotomy [1]. While standardized, such methods inadequately capture the multidimensional, heterogeneous, and uncertain nature of learning outcomes, particularly in biomedical disciplines where competence combines theoretical knowledge with applied practice [2], [3].

Fuzzy logic, first introduced by Zadeh in 1965, provides a robust alternative for addressing uncertainty and gradations of membership in decision-making processes [4]. Unlike classical set theory, which relies on binary classifications, fuzzy sets enable partial membership through linguistic variables, membership functions, and inference rules [5], [6]. This framework has been widely applied across engineering, medicine,

and artificial intelligence, and its adoption in education has grown steadily. Fuzzy inference systems (FIS) allow instructors to integrate diverse indicators into assessment, balancing objectivity with interpretability [7]–[11]. Recent studies reinforce these advantages, demonstrating how fuzzy methods improve fairness, flexibility, and transparency in academic evaluation. Mamdani and Sugeno models were applied to monitor higher education outcomes, confirming the superiority of fuzzy evaluation over classical grading [12]. Another study employed a fuzzy logic model, consisting of three input variables, one output variable, and 20 fuzzy rules, to evaluate the performance of final year engineering students [13]. A fuzzy framework was developed for distance learning [14], while systematic fuzzy evaluation can enhance decision-making in award selection [15]. More recently, fuzzy logic was applied in research to predict performance in physical education, demonstrating its predictive and interpretive value [16]. This approach was extended by incorporating artificial intelligence into a fuzzy evaluation model for physical education teaching [17], while a multi-attribute fuzzy decision-making framework for assessing the impact of artificial intelligence on education was introduced [18]. Similarly, a fuzzy intelligent system to evaluate software project performance was designed [19], and the adaptability of fuzzy methods for general student assessment was confirmed [20]. Collectively, these studies demonstrate that fuzzy-based evaluation offers both predictive accuracy and transparency, especially when compared to purely statistical methods.

Against this background, the present study introduces a Mamdani-type FIS specifically tailored for biomedical education. Its novelty lies in three aspects: i) the domain-specific adaptation of fuzzy logic to four biomedical subjects—biomechanics, anatomy, physiology, and kinesiology; ii) the development of a compact and interpretable rule base of ten IF–THEN rules, employing triangular membership functions that penalize marks under 5 and reward those above 5; and iii) a comparative evaluation of fuzzy logic against the classical averaging method using real student data. By situating fuzzy evaluation within the biomedical domain, this study addresses the growing demand for fair, adaptable, and explainable assessment frameworks in higher education [1], [21], [22].

2. METHOD

2.1. Fuzzy logic

Fuzzy logic provides a mathematical paradigm for modelling uncertainty and gradations of truth in decision-making processes. Fuzzy set theory was first introduced in 1965 and diverges from classical set theory by permitting partial membership in the interval [0,1], defined by the membership function $h(x)$, rather than restricting classification to binary extremes of 0 or 1 [4], [23]. This paper employs trapezoidal membership functions, which are delineated by the expression (1) [24], [25].

$$h(x) = \begin{cases} 0, & x \leq l_1 \\ \frac{x-l_1}{l_2-l_1}, & l_1 \leq x \leq l_2 \\ 1, & l_2 \leq x \leq l_3 \\ \frac{l_4-x}{l_4-l_3}, & l_3 \leq x \leq l_4 \\ 0, & l_4 \leq x \end{cases} \quad (1)$$

This study uses the centroid method for the defuzzification process. We compute the centroid of gravity using (2).

$$t^* = \frac{\int h_A(t) \cdot t dt}{\int h_A(t) dt} \quad (2)$$

Where t^* is the centre of gravity or a numerical value of the output of the system, and is denoted by point k's membership value in the fuzzy output set [25]–[27].

This flexibility makes fuzzy logic particularly useful in domains characterized by ambiguity and heterogeneous inputs, including education, medicine, and artificial intelligence [5], [6]. In educational assessment, fuzzy expert systems replicate human reasoning by encoding linguistic variables (e.g., “low,” “medium,” and “high”) into computational rules. Such systems enable nuanced evaluations of student performance that account for uncertainty, borderline cases, and multiple dimensions of achievement [7], [14].

2.2. Model design

To evaluate biomedical students' academic performance, a Mamdani-type FIS was constructed. The model was selected because of its interpretability and widespread use in decision-support systems in educational contexts [12], [17]. The system design is summarized as follows:

- Input variables: four subjects central to biomedical education were chosen as inputs—biomechanics, anatomy, physiology, and kinesiology. These reflect both theoretical and applied aspects of student competence.
- Membership functions: each input variable was represented by trapezoidal membership functions labeled unsatisfactorily, satisfactorily, good, and excellent. The trapezoidal design was preferred for its computational simplicity and interpretability in academic settings [21]. Importantly, the membership functions were calibrated to penalize scores under 5 and reward those above 5, thereby aligning with institutional grading standards.
- Rule base: the FIS employed a compact and interpretable rule base of ten IF–THEN rules. For example, one representative rule states: IF biomechanics, anatomy, physiology, and kinesiology are good, THEN performance is good. This rule-based structure allows evaluators to transparently trace how input grades influence overall performance [8], [19].
- Defuzzification: to convert fuzzy outputs into crisp values, the centroid method was applied. The centroid approach was selected because it balances sensitivity with stability, producing performance scores that are robust to small variations in input while preserving interpretive depth [17].

Figure 1 and Figure 2 (see Appendix) illustrate the overall structure of the FIS, and the membership functions of the input variables from biomechanics (Figure 2(a)), anatomy (Figure 2(b)), physiology (Figure 2(c)), and kinesiology (Figure 2(d)). Figure 3 shows the rule viewer. Additionally, surface viewer plots (Figure 4) provide a visual representation of the relationships between paired inputs and the output variable, thereby improving the interpretability of the model for educators; Figure 4(a) shows the membership function of the output variable “student performance”, Figure 4(b) shows the performance vs. biomechanical and anatomy, and Figure 4(c) shows the performance vs. biomechanical and kinesiology.

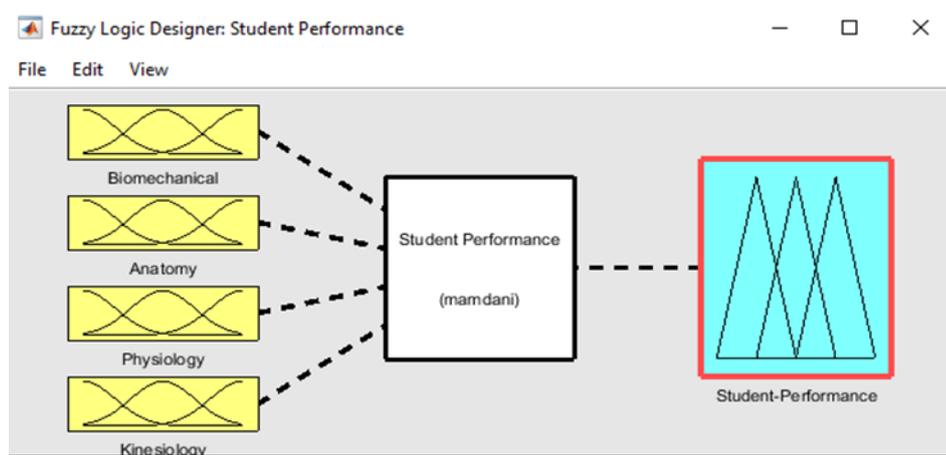


Figure 1. Mamdani FIS model

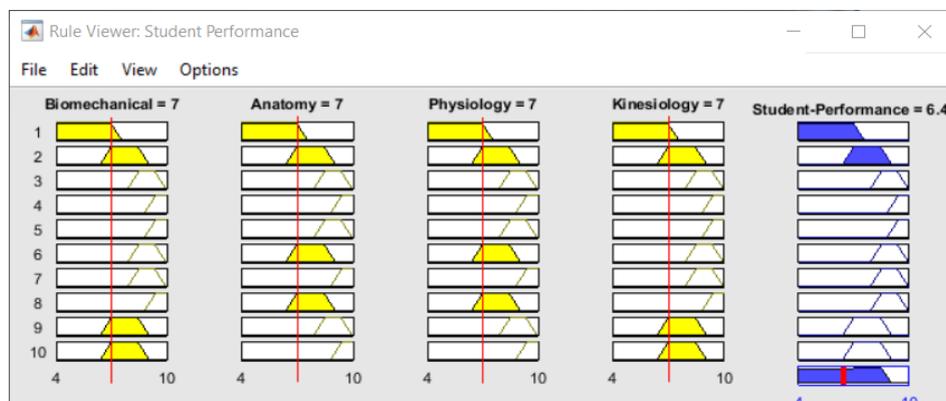
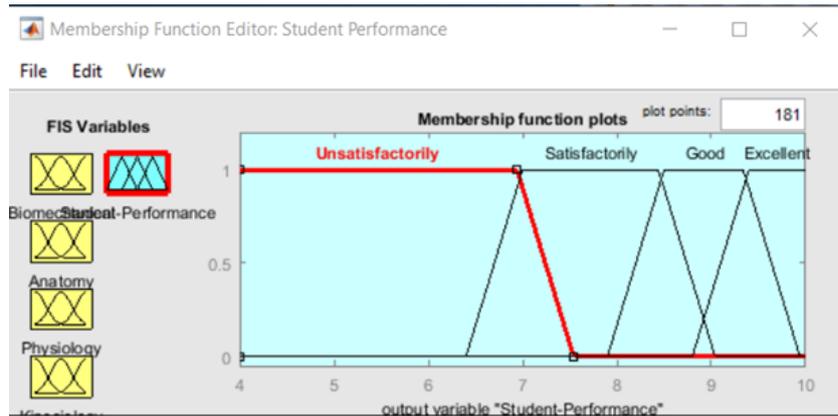
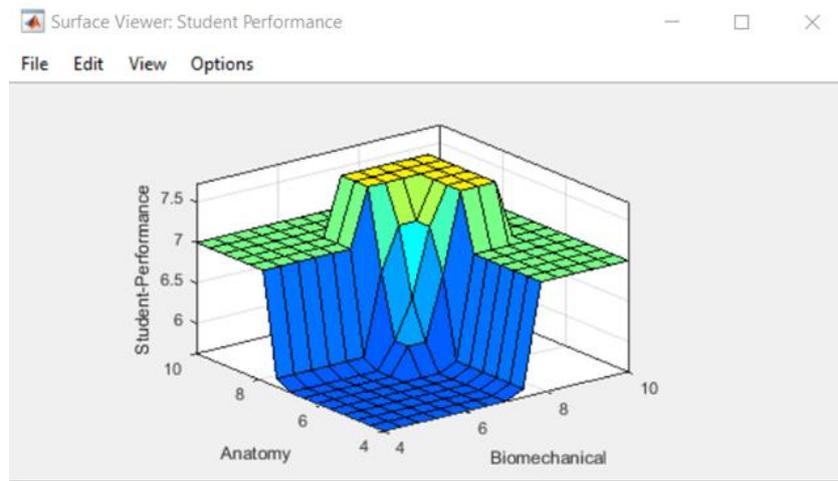


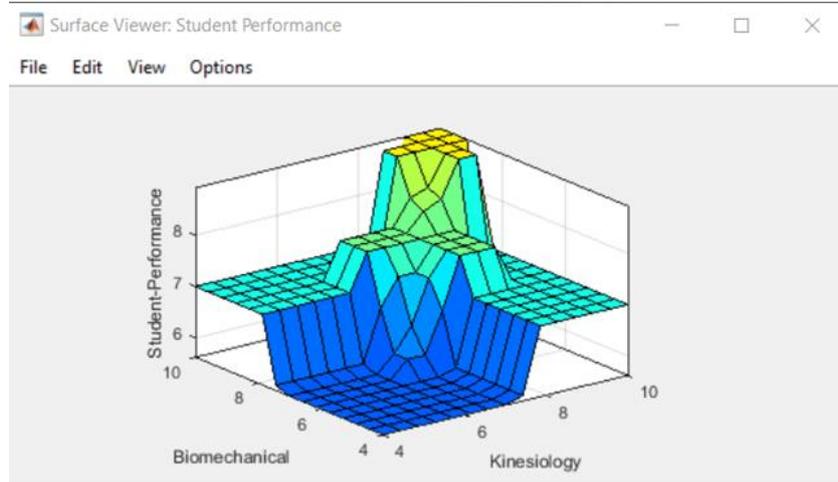
Figure 3. Rule viewer



(a)



(b)



(c)

Figure 4. Visual representation of the relationships between paired inputs and the output variable of (a) membership function of the output variable “student performance”, (b) performance vs. biomechanical and anatomy, and (c) performance vs. biomechanical and kinesiology

3. RESULTS

The proposed Mamdani FIS was implemented using data from 50 undergraduate students enrolled in biomedical courses at the Faculty of Rehabilitation Sciences, Sports University of Tirana. Each student’s

performance was evaluated based on four subject areas: biomechanics, anatomy, physiology, and kinesiology. Results from the fuzzy logic model were then compared with those obtained using the traditional classical averaging method.

3.1. Comparative analysis

The classical approach calculated a simple arithmetic mean of the four subject grades, assigning equal weight to each discipline. In contrast, the fuzzy logic approach incorporated rule-based aggregation that allowed nonlinear interactions among inputs and reflected threshold sensitivity in student performance evaluation. Key distinctions emerged in borderline cases, where student scores clustered near the pass–fail boundary (5-6 range).

For example, student 31 achieved an average score of 5.25 under the classical method, while the fuzzy model produced 5.61, recognizing that consistent minimum-level performance should not be penalized excessively. Conversely, student 50, with a uniform score of 7, received a classical mean of 7.00 but a fuzzy outcome of 6.42. This downward adjustment illustrates the system's calibration to balance nuances, ensuring that students with non-exceptional yet uniform scores do not receive disproportionately favorable results. Such differentiation has also been observed in prior studies, where fuzzy systems emphasized performance distribution rather than relying solely on raw averages [8], [9].

3.2. Validation metrics

Validation metrics were employed to ensure reliability, and fuzzy logic outcomes were subjected to comparative statistical validation:

- Pearson correlation coefficient: a strong positive correlation was observed between fuzzy results and classical averages ($r = 0.91$), confirming substantial alignment while capturing meaningful differences. Similar high correlations were reported in recent applications of fuzzy grading systems, suggesting robustness across educational domains [17], [19].
- Mean absolute error (MAE): across all 50 cases, the MAE was 0.34, indicating only modest divergence between the two methods.
- Root mean square error (RMSE): an RMSE of 0.42 was calculated, reflecting low overall discrepancy but supporting the value of fuzzy logic as a complementary tool rather than a duplicate of classical assessment.

These findings validate that the fuzzy system delivers greater flexibility and interpretability while remaining anchored to traditional scoring. By incorporating threshold effects and rule-based reasoning, the fuzzy model provides a richer representation of student performance, consistent with broader evidence in educational data mining and intelligent assessment frameworks [7], [18].

4. DISCUSSION

The results of this study indicate that fuzzy logic enhances the sensitivity and fairness of student performance evaluation by introducing nonlinear and interpretable adjustments to raw scores. The triangular membership functions were deliberately calibrated to penalize sub-threshold outcomes (scores under 5) while rewarding supra-threshold performance (scores above 5). This design explicitly operationalizes institutional grading policies and ensures that borderline cases are handled with nuance. The compact 10-rule base achieved a balance between parsimony and interpretability, which aligns with best practices observed in recent fuzzy-based academic evaluation models [17], [21].

In the context of biomedical education, where competency development integrates theoretical understanding with practical application, fuzzy evaluation provides a more accurate reflection of the multidimensional learning process. Classical averages, by contrast, obscure heterogeneity across disciplines. The outcomes presented here are consistent with prior findings in both higher education monitoring [12] and physical education teaching assessment [16], [17], confirming that FIS represents a flexible and context-sensitive assessment framework.

Another significant contribution of this approach lies in its interpretability, which directly addresses growing concerns around explainability in artificial intelligence applications to education [20]. Unlike black-box models, the transparent structure of the rule base allows instructors and stakeholders to trace how inputs translate into performance scores. This interpretability has been highlighted as essential for trust in educational data mining and intelligent tutoring systems [18].

When compared to hybrid AI systems such as neuro-fuzzy models, which may achieve stronger predictive accuracy [18], [19], the present study emphasizes usability and transparency for instructors. While predictive optimization is valuable, it often comes at the expense of comprehensibility. The proposed Mamdani FIS therefore represents a pedagogically aligned compromise: it improves fairness and adaptability without overwhelming educators with technical complexity. Future work should investigate the integration of hybrid

neuro-fuzzy approaches, provided that interpretability is preserved, thereby combining predictive power with transparent decision-making. Overall, these findings contribute to the ongoing shift toward intelligent, explainable assessment models in higher education. They underscore the value of fuzzy logic in biomedical disciplines, where nuanced judgments and multidimensional performance indicators are indispensable.

In the discussion of this study, it is important to acknowledge several limitations while also highlighting future opportunities and the broader impact of the findings. The research was conducted on a relatively small group of students from a single institution, which restricts the extent to which the results can be generalized to other contexts or disciplines beyond biomedical education. Additionally, although the fuzzy logic-based grading approach provides flexibility and fairness, particularly for borderline cases, its outcomes may initially appear less intuitive to students who are accustomed to conventional grading systems, suggesting a need for clearer explanatory tools and visual support.

Looking ahead, future work should focus on applying the proposed model to larger and more diverse student populations across multiple institutions and academic fields to strengthen its validity and adaptability. The integration of fuzzy logic with machine learning techniques and longitudinal student data also presents promising directions for improving predictive capability while maintaining transparency and interpretability. Despite these limitations, the study makes a meaningful contribution to educational data mining by demonstrating that fuzzy logic can support fairer, more nuanced assessment practices. In particular, it offers a valuable framework for biomedical education, where student performance is inherently multidimensional, and it lays the groundwork for scalable, intelligent assessment and decision-support systems in higher education.

5. CONCLUSION

In conclusion, this study shows that the Mamdani FIS offers a more flexible and meaningful alternative to traditional grading methods for evaluating biomedical students. By using simple triangular membership functions and clearly defined rules, the proposed model allows student performance to be assessed in a way that better reflects real academic judgment, especially in borderline cases where rigid averaging can be unfair. While the results remain largely consistent with classical grading, the fuzzy approach provides deeper insight into performance by considering variations across subjects and competencies. Its transparent and adjustable structure enables instructors to adapt assessment criteria to specific educational goals, which is particularly valuable in competency-based biomedical education. Overall, the findings support the use of fuzzy logic as a modern, fair, and explainable assessment tool, with strong potential for application in other academic fields and for further enhancement through larger datasets and hybrid intelligent systems.

ACKNOWLEDGMENTS

The authors thank the Faculty of Rehabilitation Sciences, Sports University of Tirana, for providing institutional support, and the Polytechnic University of Tirana for financially supporting the publication of this article.

FUNDING INFORMATION

The publication of this article has been financially supported by the Scientific Research Fund of the Polytechnic University of Tirana.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Elda Maraj	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
Anila Peposhi		✓	✓	✓	✓	✓				✓	✓			✓
Aida Bendo	✓	✓			✓		✓	✓	✓	✓		✓	✓	

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

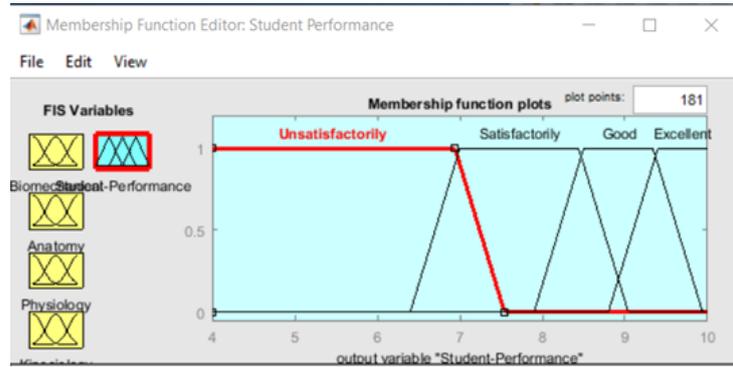
DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [EM], upon reasonable request.

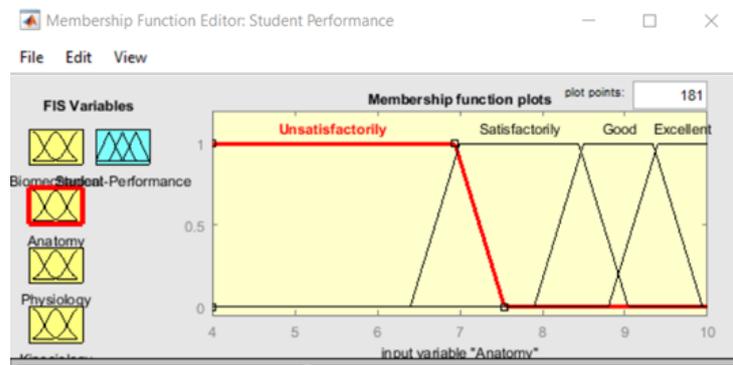
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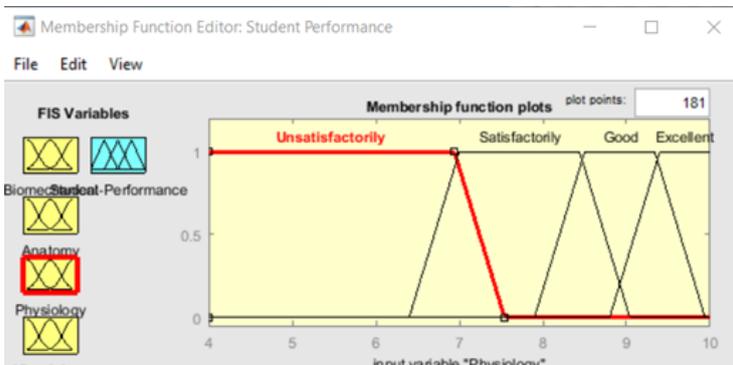
APPENDIX



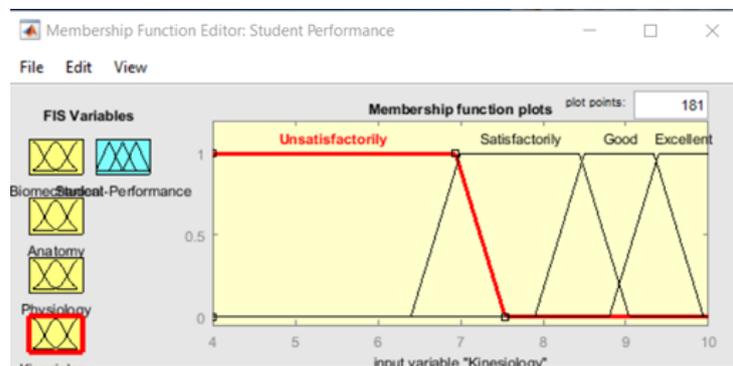
(a)



(b)



(c)



(d)

Figure 2. Membership function of the input variables from (a) biomechanics, (b) anatomy, (c) physiology, and (d) kinesiology

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