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MACHINE LEARNING FOR HAIR VOLUME ANALYSIS: ADVANCING METHODOLOGIES IN COSMETIC SCIENCE

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1. Introduction

The demand for personalized hair cosmetics necessitates accurate and objective assessment methods. Traditional hair analysis relies on sensory evaluations and manual measurements, which are subject to variability [1]. Supervised learning models, particularly deep neural networks, have revolutionized hair analysis, enabling the evaluation of volume and tress structure with high precision in detecting hair pores and counting strands (over 95% accuracy) [2]. Image-based methods further empower the creation of accurate 3D models of hair geometry [3]. These advancements highlight the potential of machine learning (ML) and Artificial Intelligence (AI) to transform hair analysis, driving innovation in the cosmetics and personal care industry.

Recent studies have explored AI's potential to automate and enhance hair analysis. Daniels et al. [1] demonstrated computer vision and ML algorithms identifying and classifying hair assembly features (volume, alignment) from treated/untreated tress images. Kim et al. [2] focused on automated hair density measurement using deep neural networks, achieving promising results in follicle detection and strand count classification. Furthermore, 3D hair structure reconstruction from single images has gained prominence, with Zhang & Zheng's Hair-GAN [3] recovering 3D hair structure via generative adversarial networks (GANs), paving the way for realistic modeling and simulation.

This work aims to compare the performance of a supervised machine learning model with conventional calculation methods in the analysis of hair volume for natural hair with different curvatures, as well as dyed and bleached hair.

2. Materials and Methods

A supervised machine learning approach was employed to develop a model capable of analyzing the volume of digital images of hair tresses.

Hair tresses measuring 25 cm in length and weighing 5.0 g were used in the experiments. For the training phase, four hair tresses were selected to build and optimize the machine learning model , as shown in Figure 1. The dataset of digital images was processed to extract volume-related parameters, ensuring accurate quantification across diverse hair types and conditions.

Figure 1. Training group images and the segmented images of the volume analysed by the machine learning model.

The validation phase included 200 natural tresses representing different curl types to enhance the robustness of the analysis. Additionally, 50 dyed tresses (red 6.66) and 50 bleached tresses were incorporated to assess the model's performance across different hair structures and chemical treatment conditions.

All hair tresses were additionally evaluated to determine their volume through conventional image analysis with the aim of serving as a reference for comparison with the volume calculated by the model proposed in this study.

Statistical Analysis

The significance of the difference between the calculations (conventional vs. model) was assessed using the paired, two-tailed Student's t-test, considering a 95% confidence interval.

Note: The Kolmogorov-Smirnov test normality test was applied, The data for Natural and Dyed hair followed a normal distribution. Therefore, the Student's t-test was used as the statistical method to compare the models.

The data for Bleached hair did not follow a normal distribution. Therefore, the Wilcoxon signed-rank test was used as the statistical method compare the models.

To assess the agreement between the conventional and model-based calculations, the Bland-Altman analysis was used, which allows for the verification of systematic bias and the limits of agreement between the methods.

3. Results

Natural hair

The volume calculations performed using the supervised machine learning model were compared to conventional calculations for different hair types.

The statistical analyses showed no significant differences between the volume values calculated by the conventional and model methods. Figure 2A shows the regression analysis of both methods. The Bland-Altman plot was constructed to visualize the differences between the methods in relation to the mean of the measurements, enabling the identification of bias and potential discrepancies Figure 2B.

Figure 3 presents representative images of natural hair curvature types, which were used to establish the validation group.

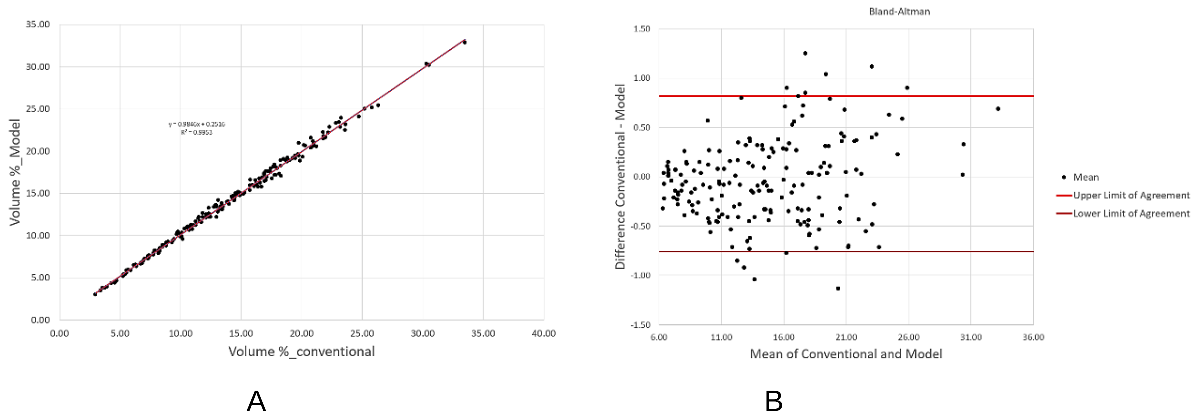


Figure 2. Natural hair: A) Method comparisons the two methods of Volume measurements presented as regression analysis; B), Bland and Altman plot.

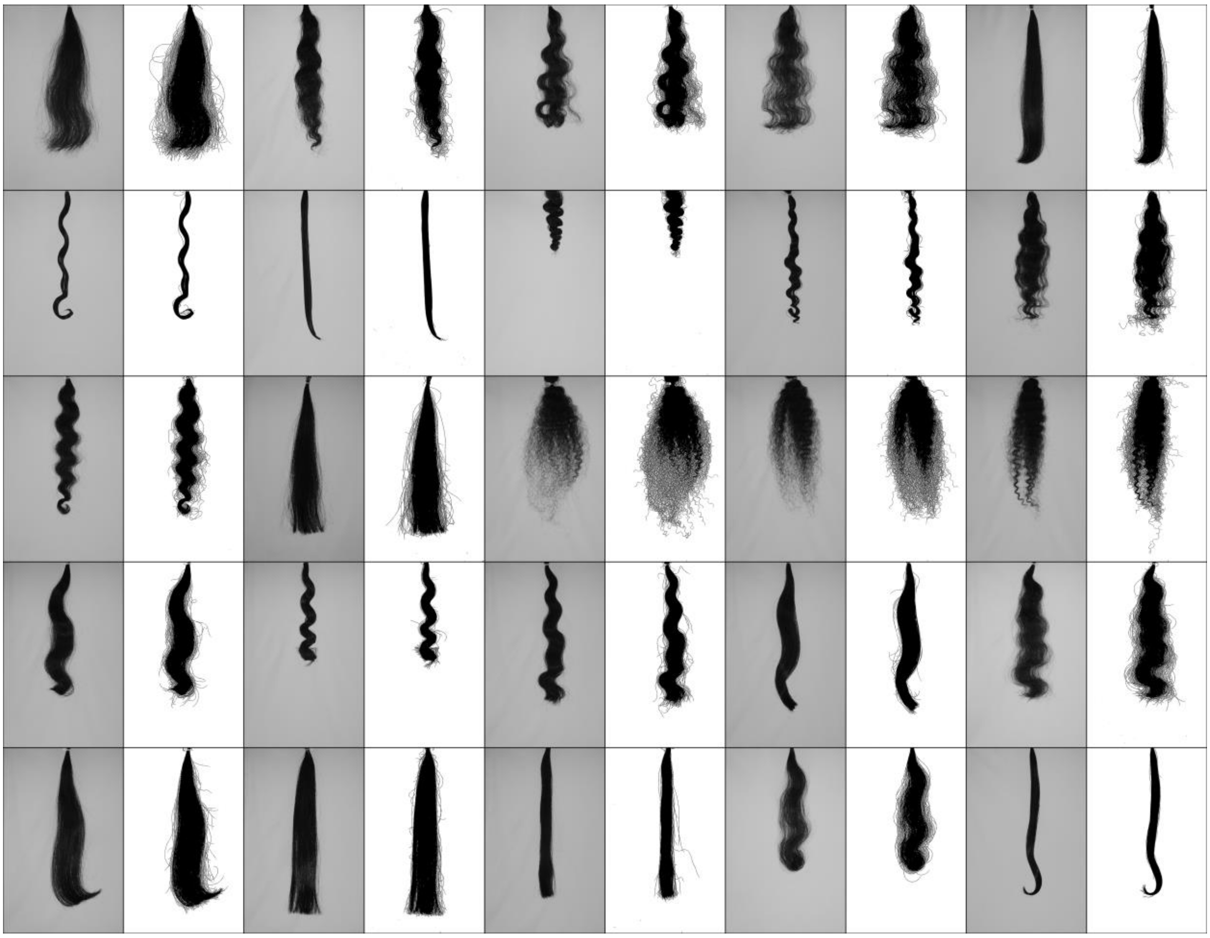
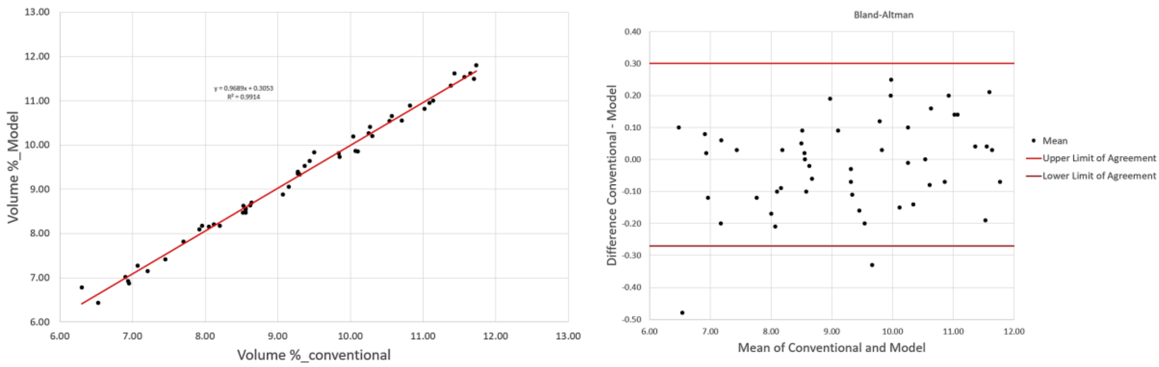


Figure 3. Representative images of natural hair curvature types from validation group.

Dyed hair

The statistical analyses showed no significant differences between the volume values calculated by the conventional and model methods. Figure 4A shows the regression analysis of both methods and Figure 4 B showa the Bland-Altman plot.



A B

Figure 4. Dyed hair: A) Method comparisons the two methods of Volume measurements presented as regression analysis; B), Bland and Altman plot.

Figure 5 presents representative images of dyed hair tresses, which were used to establish the validation group.

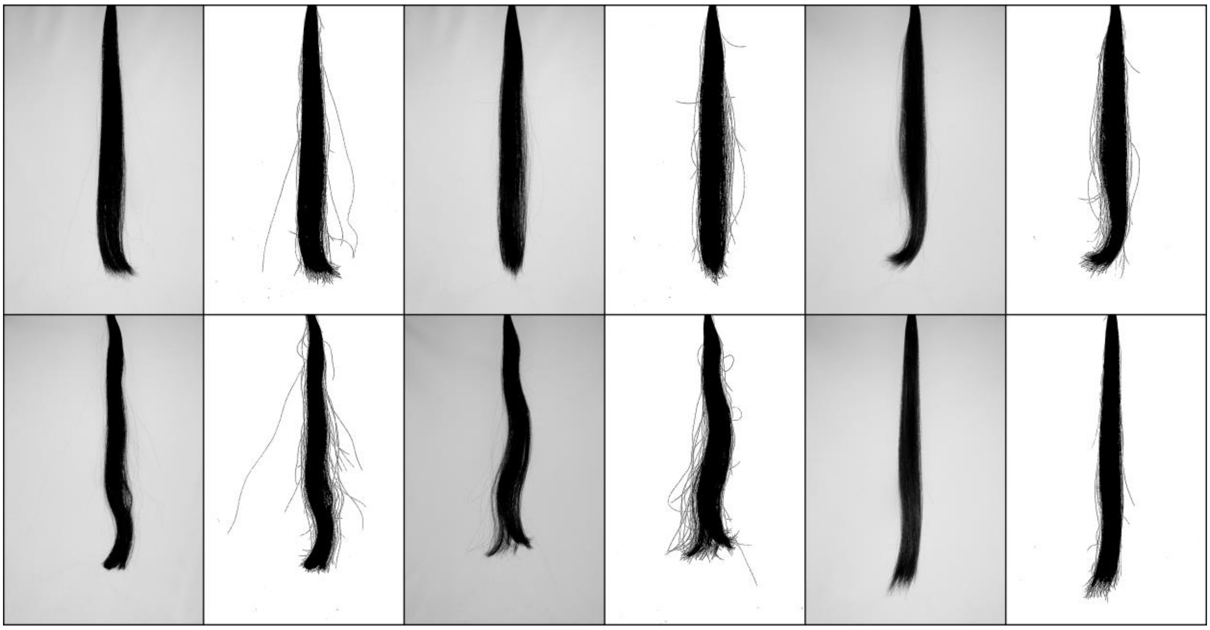


Figure 5. Representative images of dyed hair tresses from validation group.

Bleached hair

The statistical analyses showed significant differences between the volume values calculated by the conventional and model methods. Figure 6 shows the regression analysis of both methods.

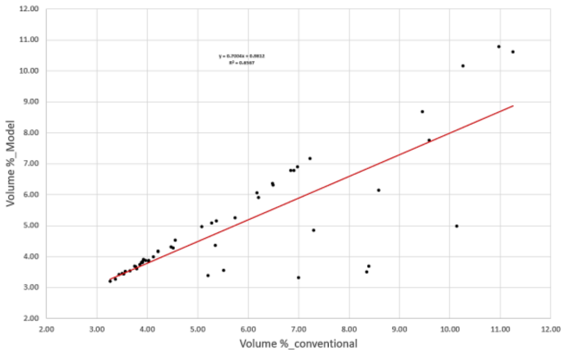


Figure 6. Bleached hair: Method comparisons the two methods of Volume measurements presented as regression analysis.

Figure 7 presents representative images of bleached hair tresses, which were used to establish the validation group.

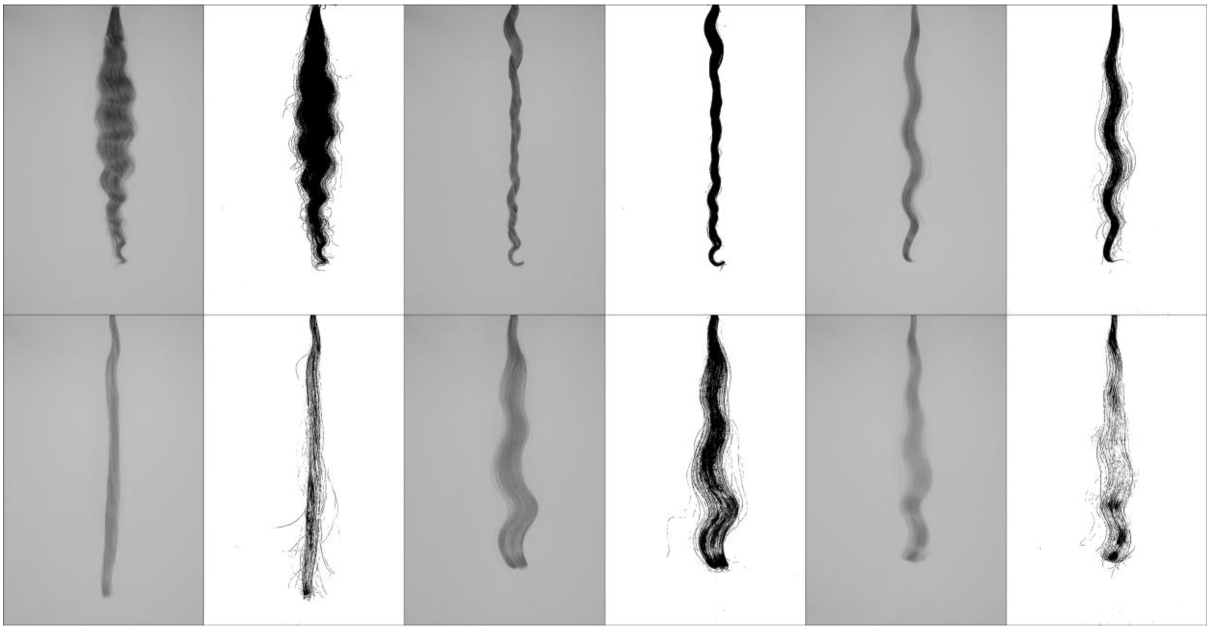


Figure 7. Representative images of bleached hair tresses from validation group.

4. Discussion

Natural Hair

The Bland-Altman plot demonstrates good agreement between the proposed model and the conventional method, with 95% of the differences falling within the limits of agreement (-0.76 to 0.92) [4]. The mean bias close to zero (0.028) indicates no significant systematic differences. Although a few outliers are present, they are minimal and statistically expected. These results highlight the model's reliability for practical applications, showing that it can serve as a valid alternative to the conventional method for volumetric hair analysis.

Dyed Hair

The Bland-Altman analysis revealed good agreement between the conventional method and the proposed model, with a mean bias of -0.015, indicating an insignificant systematic difference. The 95% limits of agreement ranged from -0.27 to 0.30, encompassing 96% of the data, which suggests that the discrepancies between the methods are small and acceptable for practical applications [4]. These results indicate that the model exhibits performance comparable to the conventional method, reinforcing its applicability in the proposed analysis.

Bleached Hair

In bleached tresses, particularly lighter ones, the model struggled to detect volume due to low definition of structural features, resulting in reduced contrast between the hair and the background, making segmentation difficult.

These results highlight the need for model optimization for bleached hair, particularly for cases with low visual contrast. Strategies such as image enhancement and more robust segmentation algorithms can be applied to improve accuracy.

5. Conclusion

The results highlight the effectiveness of the supervised machine learning model in accurately assessing hair volume for natural and colored tresses, demonstrating high agreement with conventional methods and strong correlation coefficients. These findings underscore the model's reliability and potential application in cosmetic science. However, some limitations were observed in bleached tresses, particularly in lighter tones, indicating areas for future optimization. Overall, this study reinforces the value of artificial intelligence in advancing methodologies for hair analysis, paving the way for more precise and innovative approaches in the evaluation of cosmetic products.

6. References

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