PREDICTION OF CLOTHING COMFORT DURING SWEATING USING MULTIMODAL EXPLAINABLE MACHINE LEARNING

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ABSTRACT

Clothing comfort during sweating is influenced by interactions among psychological perceptions, physiological responses, and textile material properties. This study investigated whether interpretable machine-learning models could predict subjective clothing comfort and identify the factors associated with it. Five polyester sportswear garments differing in knit structure, thickness, mass per unit area, and moisture-management finish were evaluated under controlled environment conditions (30 °C and 65%RH). Ten participants completed repeated exercise-rest cycles. Subjective and physiological responses were recorded at five time points for each garment, while fabric mechanical and water-absorption properties were measured separately. A total of 250 observations (10 participants x 5 garments x 5 time points) were analyzed as a single regression task using a generalized linear model, decision tree, random forest, and support vector machine. The support vector machine achieved the numerically lowest RMSE (0.560 ± 0.060). Ease of movement and perceived surface fineness were consistently identified as important predictors across models. These findings demonstrate the potential of multimodal machine learning for predicting clothing comfort during sweating and identifying the factors associated with subjective comfort.

Keywords: Clothing Comfort, Nonlinear Modeling, Sportswear, Physiological Measurement, Textile Material Properties

1 INTRODUCTION

Clothing comfort is a multidimensional perception that arises from interactions among the physical properties of clothing, the wearer's physiological responses, psychological perceptions, and the environmental conditions (Li, 2001). In sportswear and other functional clothing, these interactions change dynamically during physical activity and sweating, and sensations such as wetness, stickiness, thermal sensation, and tactile sensation become important determinants of comfort (Raccuglia et al., 2018). Because these factors interact in complex and potentially nonlinear ways, evaluations based solely on individual material properties or conventional linear analyses may be insufficient to explain overall clothing comfort.

Previous studies have demonstrated that overall perceived clothing comfort during exercise can be predicted from multiple subjective sensory evaluations using artificial neural network (ANN) models (Wong et al., 2003). Integrating psychological perceptions with physiological responses has also been shown to improve the prediction of clothing comfort compared with models based on either type of information alone (Karasawa et al., 2022). Collectively, these findings suggest that clothing comfort should be regarded as a multimodal and potentially nonlinear outcome. Machine-learning approaches are therefore well suited to integrating heterogeneous data and capturing complex relationships among variables that may not be adequately represented by conventional single-domain or linear analytical methods. However, previous studies have primarily focused on subjective evaluations or combinations of psychological and physiological responses, whereas the simultaneous integration of psychological, physiological, and textile material variables during sweating has received limited attention. Accordingly, this study compared four regression algorithms using multimodal data comprising psychological evaluations, physiological responses, and fabric material properties. The objectives were to evaluate the predictive performance of these models and to identify the variables consistently associated with perceived clothing comfort during repeated exercise-rest cycles.

2 EXPERIMENTS

A wear trial was conducted under controlled environment conditions (30 °C and 65% RH) using five 100% polyester knitted sportswear garments differing in knit structure, thickness, mass per unit area, and water-absorbing or water-repellent finish. Mechanical and surface properties were evaluated using the Kawabata Evaluation System (KES), and water absorbency was measured according to JIS L 1907 by the drop and Byreck methods.

Ten healthy male university students aged 22-24 years completed a protocol consisting of a 10-min seated rest followed by four cycles of 10-min cycling at 50 W and 60 rpm interspersed with 5-min rest periods. Subjective ratings and physiological responses were recorded at five predefined time points for each garment. Physiological measurements included skin and core temperatures, mean body temperature, clothing microclimate humidity, sweat rate, electrocardiographic (ECG) signals, and heart-rate-variability (HRV) indices. Semantic differential scales were used to assess perceived wetness, stickiness, slipperiness, stiffness, roughness, softness, ease of movement, and overall clothing comfort. Body mass and garment mass were measured before and after the experimental protocol.

Overall clothing comfort at each measurement point was used as the only target variable and ranged from -3 (uncomfortable) to +3 (comfortable); therefore, it was excluded from the predictor variables. Each measurement point was treated as a separate observation for predictive modeling. Time point and elapsed time were not included as predictors because the objective was to estimate comfort from the concurrent psychological, physiological, and material states at different stages of sweating rather than to model temporal transitions.

The dataset consisted of 250 observations (10 participants × 5 garments × 5 measurement points). Four regression models-- a generalized linear model (GLM), decision tree, random forest, and support vector machine (SVM)—were developed using the same standardized predictor set. The observations were randomly divided into training (60%) and validation (40%) sets. The

procedure was repeated using seven randam train – validation splits ; the highest and lowest RMSE values were discarded, and the mean ± SD of the remaining five runs was reported. Model-specific feature importance was interpreted within each algorithm, and the consistency of highly ranked variables across models was examined.

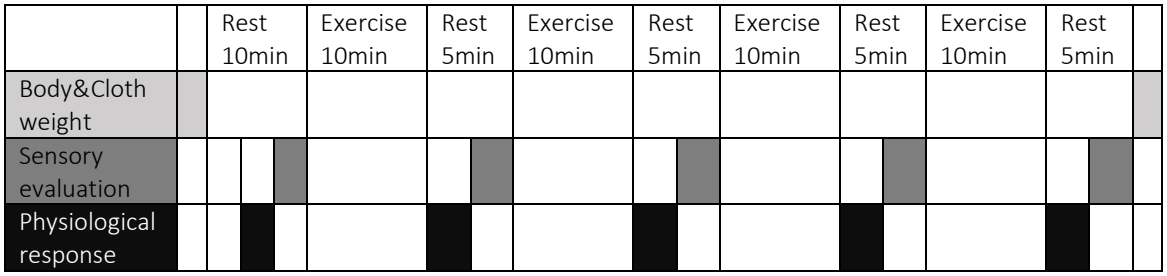


Figure 1. Experimental Procedure

3 RESULTS & DISCUSSION

Table 1 summarizes the prediction performance of models and the representative important predictors identified by each algorithm. The SVM achieved the lowest mean RMSE of 0.560 ± 0.060, followed by the GLM (0.586 ± 0.092) and random forest (0.598 ± 0.111). The decision tree exhibited the highest RMSE (0.690 ± 0.126). Given that the target variable was evaluated on a seven-point scale ranging from -3(uncomfortable) to +3(comfortable), these RMSE values correspond to an average prediction error of less than one scale point. The results indicate that subjective clothing comfort can be predicted with acceptable accuracy using multimodal psychological, physiological, and material information. However, the differences in prediction performance among the GLM, SVM, and random forest were relatively small, suggesting that all three approaches showed comparable predictive capabilities for this dataset.

Table 1. Prediction performance and representative important variables.

Model	RMSE	Representative high-ranked variables
GLM	0.586 ± 0.092	Hard to move - Easy to move; (Body) Cold - Hot; Coarse - Fine; Mean body temperature ; Top Absorption
Decision tree	0.690 ± 0.126	Coarse - Fine; Hard to move - Easy to move; Arm sweat rate; Rough - Smooth; Hard - Soft
Random forest	0.598 ± 0.111	Heavy - Light; Hard to move - Easy to move; Coarse - Fine; Hard - Soft; Compression
SVM	0.560 ± 0.060	Coarse - Fine; Hard to move - Easy to move; Heavy - Light; Loose - Tight; CVR-R

The variables identified as important predictors differed among models, and should not be interpreted as direct evidence of causality. Rather, they indicate that each model captured the associations between clothing comfort and the measured variables in different ways. Nevertheless, the semantic differential scales *Hard to move - Easy to move* and *Coarse - Fine* were

consistently ranked among the most important predictors across the models. These variables can therefore be considered robust indicators of clothing comfort under sweating conditions. Ease of movement is likely to reflect the combined effects of garment fit, fabric deformation, and mechanical resistance during body movement, whereas perceived surface fineness may be associated with skin-contact sensations, fabric surface characteristics, and adhesion between the skin and moisture-laden clothing.

Physiological and material variables were also identified as important predictors in several models. Mean body temperature, arm sweat rate, and CVR-R were among the variables associated with clothing comfort prediction, suggesting that thermal and autonomic responses may contribute to perceived comfort under hot and humid conditions. Top Absorption and Compression were likewise identified as important predictors, indicating that moisture absorption and mechanical properties may influence perceived comfort indirectly through their effects on the clothing microclimate and tactile sensation. These findings highlight the value of integrating psychological, physiological, and material information when predicting clothing comfort. However, because the dataset comprised repeated measurements from the same participants and garment samples, these findings should be interpreted as exploratory rather than conclusive. Future studies should evaluate generalizability of the models using participant-wise or sample-wise validation and investigate the temporal dynamics of clothing comfort perception during repeated exercise-rest cycles.

4 CONCLUSIONS

This study investigated whether subjective clothing comfort during sweating could be predicted using psychological evaluations, physiological responses, and fabric material properties. Among the evaluated models, the SVM achieved the lowest RMSE, whereas the GLM and random forest showed comparable predictive performance. Ease of movement and perceived surface fineness were consistently identified as important predictors, suggesting that these sensations are robust indicators of clothing comfort. Physiological and material variables were also identified as important predictors across several models, highlighting the value of multimodal machine learning for identifying factors associated with clothing comfort. Overall, the findings demonstrate the potential of interpretable multimodal machine learning as a framework for predicting clothing comfort while providing insight into the psychological, physiological, and material factors associated with comfort perception. Future studies should validate the proposed framework using independent participant- and sample-wise datasets.

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