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In-clothing Climate Sensing to Predict Comfort in Each Wearing Situation

Takayuki Hiwatari[1], Fumiko Harada[1,2], Hiromitsu Shimakawa[1,2]

[1] Graduate School of Information Science and Engineering, Ritsumeikan University, Osaka, Japan

[2] College of Information Science and Engineering, Ritsumeikan University, Osaka, Japan

Correspondence: Takayuki Hiwatari, Graduate School of Information Science and Engineering, Ritsumeikan University, Osaka, Japan.

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Abstract

In order to improve the quality of life, people wear comfortable clothing according to the time and occasion. However, some TPOs may sacrifice some comfort. In this study, we propose a method to estimate comfort for each TPO in order to realize clothing recommendation that recommends enough or acceptable comfortable clothing for the most important TPO of the day.

In this study, we hypothesize the following from the relationship between the outside temperature, the climate inside the clothes, and comfort. We hypothesized that the degree of comfort in a certain TPO is estimated from the following variables: temperature and humidity inside clothing and outside-air, their first-order and second-order differentiation, difference between inside-clothing and outside-air temperatures and humidities, and activity level in the TPO.

The proposed method collects temperature and humidity inside and outside clothing, and heart rate and activity levels through wearable sensors as well as comfort in each TPO through questionnaire for building prediction models. As a result of the experiment, the accuracy rate was better for XGBoost in 4 out of 5 subjects than RandomForest model. It is possible to use it for clothing recommendation considering the comfort of each TPO based on temperature and humidity in clothing, outside climate, the sensor data, and activity level in TPO.

Keywords: In-clothing climate, TPO, PMV, RandomForest, XGBoost, temperature, humidity, comfort

1. Introduction

In order to improve the quality of life, people wear comfortable clothing according to the time and occasion. However, some TPOs may sacrifice some comfort. Cheng et al. proposed a method to more accurately model the user's preference for the item for each user-item pair (Zhiyong, C et al., 2019)(Wen, C et al., 2019). Yu et al. proposed to introduce aesthetic information that is highly relevant to the user's preferences into the clothing recommendation system (Wenhui, Y et al., 2018) (Wenhui, Y et al., 2021). This study focuses on aesthetics. However, these studies do not take into account the comfort of clothing. In this method, the first temperature and humidity sensor is attached between the clothes and the skin as if hanging from the neck with a strap to obtain temperature and humidity data inside the clothes. The second temperature and humidity sensor is attached to the outside of the cooler bag like a strap to obtain temperature and humidity data of the outside air. As a result of the experiment, it was found that XGBoost had a higher accuracy rate than RandomForest for all subjects, and it was found that the outside temperature was an important variable for both learners and all subjects.

2. Climate inside Clothing and Comfort Metrics

2.1 Relationship between Outside Temperature, Climate inside Clothing and Comfort

Clothing has two functions (Hiroko K et al., 1990): The first is the health and hygienic function, which assists in regulating body temperature, protects the body, and adapts to daily activities (Shigeo K, 2003) (Katsuhiro H et al., 2007). In order to maintain a constant body temperature, the body sweats in a high-temperature environment and shivers in a low-temperature environment. In a high-temperature environment, high humidity makes it difficult for sweat to evaporate, which increases discomfort. On the other hand, if the environmental humidity is too low, a person may feel dry. In a low-temperature environment, he/she may feel cold and discomfort. Therefore, there is an effect on comfort of changes in temperature and humidity (de Dear, R., & Brager, G., 1998) (Fanger, P. O, 1970) (L. Fang et al., 1998) (Olli

Seppänen et al., 2006) (Ken, P, 2014) (Hitomi T et al., 2007). In addition, comfort/discomfort is affected by the climate inside clothing (Teruko T, 1995). The climate inside clothes is affected by the environment of insensible perspiration and sweating, which are considered to be a physiological phenomenon of human physiology, which is particularly involved in pleasure and discomfort, and the climate in clothing affects the comfort of the skin (Akiko M, 2008) (Hiromi T, 1984). If the temperature inside clothes is high, it will be difficult to regulate the body temperature and it tends to give the person a feeling of discomfort. If the temperature inside the clothes is low, the body temperature will be taken away by the outside air, by which the person feels cold. If the humidity inside the clothes is high, the heat and humidity inside the clothes will increase, and the person will feel discomfort. If the humidity inside the clothes is low, the skin will dry out easily, and rough skin and itching may occur. When the outside temperature is high, the temperature inside the clothes is also likely to rise. If the outside temperature is low, the temperature inside the clothes is also likely to decrease. If the humidity of the outside air is high, the evaporation of sweat is hindered and the humidity inside the clothes increases. Therefore, there is an effect on comfort due to the difference in temperature and humidity between the inside and outside of clothing (Ryuji H, 1999). Fabric refers to fabrics and materials, except in special circumstances such as clothing restrictions. Clothing fabrics are roughly divided into natural fibers and chemical fibers, which differ in thermal conductivity, breathability, moisture absorption, and moisture release (Md Rashedul Islam et al., 2023). The shape of garments affects the heat exchange with the outside air and the breathability. The presence or absence of openings and vents of garments also affect the intake and moisture release of outside air, contributing to comfort. The temperature and humidity inside clothes varies depending on its shape. If a clothing is highly sealed, moisture from sweat is easily trapped and the humidity tends to rise. On the other hand, if the clothing is breathable, the moisture is effectively released and the humidity inside the garment is kept appropriate. Therefore, the comfort of the outside air and the climate inside clothing vary greatly depending on the shape of the clothing.

2.2 PMV

PMV~ (Predicted Mean Vote) (Fanger, P. O, 1970), also known as the Predicted Average Mean Vote ~ is an index of the warmth and coldness felt by humans. PMV integrates the four elements of the environment (air temperature[℃], humidity [%], wind speed[m/s], and thermal radiation[℃]) that determine the feeling of warmth and coldness as well as two elements on the human body side (metabolic rate[met] and clothing volume[clo]). The metabolic rate is the amount of heat generated by the human body due to activity, which is expressed by the unit 1(Met) = 58.2 (W/m^2). The clothing volume is expressed by the unit 1(clo)=0.155(m^2K/W) which is determined by mainly the shapes of the clothing. In PMV, the state of PMV=0 means thermally neutral. The thermal comfort of humans is expressed between -3 and 3. In addition, PPD~ (Predicted Percentage of Dissatisfied) (Fanger, P. O, 1970) refers to the rate of people who feel dissatisfied or uncomfortable under a thermal environment.

According to the standards of the International Organization for Standardization, the range of $-0.5<PMV<0.5$(PPD is 10% or less) is recommended as the comfort range.

3. Materials and Method

3.1 The Relationship between TPOs and Clothing Comfort

In this study, the word TPO refers to Time, Place, and Occasion of a person’s daily activities. Time is defined as the time of the day, the Place is defined as the location, and the Occasion is defined as what the TPO is doing in the day. There exists plural TPOs in a person’s life in a day and there is difference of importance between the TPOs. For example, suppose that an exam is scheduled one day and a person goes to the examination site by bus or train, which are public transportation. The exam TPO has higher importance than riding the bus or train for him/her in this situation. Different TPOs allow or restrain a person’s wearing with different manners. For example, a person has to wear a certain set of clothing such as a suit for an interview. When he/she is relaxing at home, he/she can choose clothes freely. The former emphasizes formality, so the importance of comfort decreases (Kinji H et al., 1998) (Sanae N, 1997). On the other hand, he/she cannot tolerate even a little discomfort because he/she can wear as he/she likes. Therefore, the degrees of comfort/discomfort that a person can accept is different between TPOs. This indicates that the range of climates and garments that he/she can accept are different between TPOs. For these reasons, humans choose clothes that are suitable for TPO which is the most important in daily life.

3.2 Estimation of Comfort for TPOs

The goal of this study is to estimate comfort in wearing certain clothing in each TPO in order to realize a clothing recommendation that recommends comfortable clothing for the most important TPO of the day. In this study, we hypothesize the following from the relationship between the outside temperature, the climate inside the clothes, and comfort. Hypothesis: The degree of comfort in a certain TPO is estimated from the following variables: temperature and humidity inside clothing and outside-air, their first-order and second-order differentiation, difference between inside-clothing and outside-air temperatures and humidities, and activity level in the TPO. Figure 1 shows the method for testing the hypothesis. The method firstly collects the temperature and humidity inside the daily garments, the temperature and humidity of the outside air, the amount of activity and comfort for each TPO for each day. The collected data is divided into the 70% of the training data and 30% of the test data. Secondly, we train a RandomForest and XGBoost models to predict comfort with the training data, respectively. The difference of calculation of the degree of comfort between our models and PMV is as follows. Originally, PMV is an index used to evaluate indoor comfort, and there are only five types of metabolic rate: "resting, sleeping", "sitting", "office work", "normal walking", and "exercise". On the other hand, this study treats TPOs not only indoors but also outdoors, and the metabolic rate is expressed numerically in various situations.

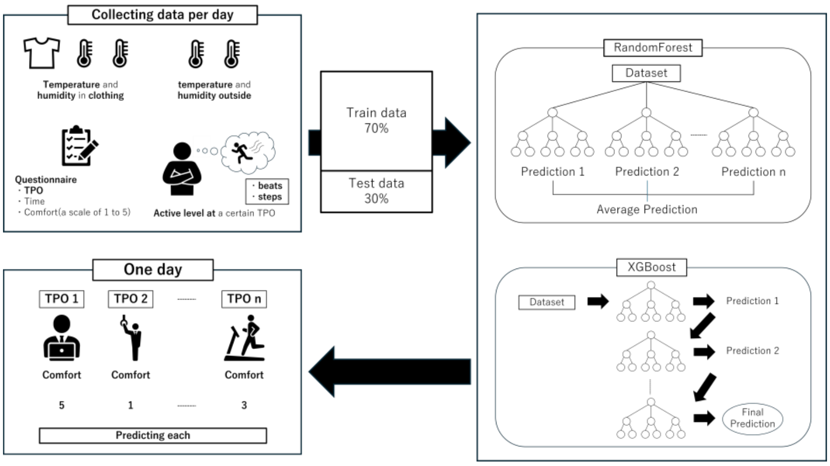

Figure 1. Outline diagram of the method

3.3 Features and Their Collection

Subjects daily attach a wireless temperature and humidity sensor to the inside of the garment and measure the temperature and humidity inside the garment at each point in time. In the same way, a wireless temperature and humidity sensor is carried to measure the temperature and humidity of the outside air at each point in time. The sensor data is aggregated on the mobile device. In addition, a wristwatch-type wearable sensor is attached to the opposite arm to the dominant arm, and the heart rate and walking amount at each point in time are measured and obtained as the amount of activity. It can be obtained as time-series data because it changes from moment to moment. The first-order differentiation of the temperatures inside clothes and outside air are calculated from the collected data, respectively. The humidity data is processed similarly. The second-order differentiations also are calculated. We also calculate the difference of temperatures between inside clothing and outside air and that of humidities. Through a questionnaire, we ask the subjects to answer each time about the time duration and comfort they were doing for each TPO. Comfort is obtained on a five-point scale according to the questionnaire: when it is much more comfortable (just right), when it is basically comfortable, but sometimes in the middle or uncomfortable, when it is much in the middle (warm or cool or comfortable and uncomfortable equally), when it is basically uncomfortable but sometimes comfortable or in between, and when it is uncomfortable (hot or cold) all the time.

3.4 Estimating Comfort from Features

Comfort is estimated by aggregating data on temperature and humidity inside clothing, temperature and humidity of outside air, activity level, and comfort for each day. Comfort at each point in time is coded as follows: when it is much more comfortable (just right) = 5, when it is basically comfortable but sometimes in the middle or uncomfortable = 4, when it is much in the middle (warm or cool or comfortable and uncomfortable equally) = 3, when it is basically uncomfortable but sometimes comfortable or in the middle = 2, when it is uncomfortable (hot or cold) all the time =1. In this study, comfort is defined as related to the feeling of hod and cold. The collected data except the coded comfort is set as the explanatory variables while the coded comfort is done as the target variable. The variable except the coded comfort is set as explanatory variables, and comfort is set as the objective variable. Finally, we train RandomForest and XGBoost models to estimate comfort degree for each model, and compare which model is better based on the results. If comfort can be estimated to some extent, it is possible to find clothes that are suitable for the most important TPO of a given day, and clothes that can guarantee some comfort in other TPOs of the day. Here, in this study, a certain level of comfort is defined as "comfort that is not completely comfortable but can be tolerated" and a reference value is set. Therefore, there is a possibility that clothing recommendations for the most important TPO of a given day will be realized in the future.

3.5 Experiment Outline

We conducted experiments to extract the relationship between comfort and features derived by sensor data for each TPO. We observed the temperature and humidity in clothes, the temperature and humidity of the outside air, and the activity level in real life. The duration of the experiment was 3 days, and 5 males in their 20s belonging to a university laboratory were selected as the subjects. In below, each subject was denoted as A, B, C, D, and E, respectively. The experimental days of Subject A were October 29, November 5, and December 3. Those of Subject B were designated as January 16~18. Those of Subject C were doneas January 16, 17, and 22. The experiment for Subject D was conducted on January 16, 17, and 19. Subject E was tested on January 16, 17, and 18. The subjects were asked to wear two small wireless tags, TWELITE ARIA (TWELITE ARIA, 2021) with a temperature and humidity sensor attached. They also wear a Fitbit Charge5 (Fitbit Charge5, 2021) which is a wristwatch-type exercise meter. Through these sensors, we collected data from the first TPO to the last TPO during the day. During the experiment, the subjects were not given any special instructions on clothing, and they were free to choose what to wear and to put on and take off outerwear such as coats and jackets. Here, we tried to include both outdoor and indoor TPOs to make the temperature and humidity in clothing as variable as possible.

3.6 Collecting Data

Each of the subjects worn two pieces of TWELITE ARIAs: the first TWELITE ARIA is attached to a strap and hung around the neck between clothing and his skin. The second TWELITE ARIA is attached like a strap to the outside of a cooler bag. The reason for using a cooling bag is to prevent the effects of heat from starting up the Raspi. The TWELITE ARIA sensors were set up to run as the TWELITE ARIA mode, to observe every seconds and send the sensor data every minutes. The TWELITE ARIA sensor can run with a coin-type battery CR2032. It automatically continues sensing as long as the battery lives. During the experiment, the mobile batteries were charged by the subjects after the last TPO of the day. In order to collect sensor data observed by the TWELITE ARIAs, the subjects were instructed to carry a mobile device, Raspberry Pi, with them during the experiment. In each of the Raspberry Pi (Raspi 4, 2019) device was installed a python-based application to aggregate the sensor data and write the data into a CSV file. The application starts automatically on starting the device. The device was equipped with an RTC module, DS3231 (DS3231, 2004), to adjust the system time without connecting to any NTP servers on the web. At the start of each experimental day, the subjects operated the device by the following manner: First, the subjects inserted a mobile battery into the Raspberry Pi and start it. Secondly, the subjects inserted a wireless PAN module called MONOSTICK (MONOSTICK, 2017) into its adapter. The Raspberry Pi aggregates the data by connecting it wirelessly to ARIA via USB. Data for each day were obtained from Raspi collected after the experiment. The Fitbit Charge 5 collects the subjects’ walking steps and heart rate every minute. The subjects connected their Charge 5s to the smartphones on which the Fitbit 5 application ran by Bluetooth. Its observed data was automatically aggregated to the application and uploaded to the cloud. In addition, at the end of each experimental day, we asked the subjects to answer all of the TPOs of the day, the time of each of the TPO, and the comfort of each TPO each time in an Excel-based questionnaire. Subjects arbitrarily categorize and name the day's activities. However, they were instructed to TPO even the smallest details, such as movement, but excluding during sleep. The subjects were asked to answer on a five-point scale for comfort for each TPO: when it is much more comfortable (just right) = 5, when it is basically comfortable but sometimes in the middle or uncomfortable = 4, when it is much in the middle (warm or cool or comfortable and uncomfortable equally) = 3, when it is basically uncomfortable but sometimes comfortable or in the middle = 2, when it is uncomfortable (hot or cold) all the time =1. In addition, the materials listed on the tags of the clothes of the day were also tabulated.

4. Results and Discussion

4.1 Recorded TPOs

From the questionnaire answer of Subject A, he had 7 TPOs obtained during the experiment period: 'Keihan bus', 'walking', 'Wheel lecture', 'laboratory', 'Keihan train', 'snack', and 'work'. The TPO 'Keihan bus' means riding the Keihan bus. 'laboratory' means to spend the time in the laboratory. Subject B had 8 TPOs: 'walking', 'Hankyu train', 'waiting for the train', 'part-time job', 'grandmother's house', 'Kyoto municipal bus', 'laboratory', and 'returning home'. Subject D has 6 items: 'Cooking dinner', 'Graduation thesis', 'Walking', 'Convenience store break', 'Cafe', and 'Ramen restaurant'. Subject E has 11 items: 'Subject', 'School cafeteria', 'Laboratory', 'Follow-up', 'Walking', 'Train', 'Bicycle', 'Cram school part-time job', 'Nibojiro', 'McDonald's', and 'Running'. 'Subject' is subjected to experiments other than this experiment.. 'Nibojiro' is a Ramen restaurant.

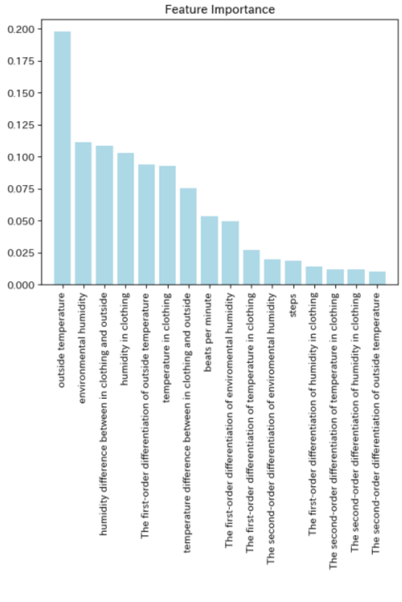

Figure 2. A's Feature Importance

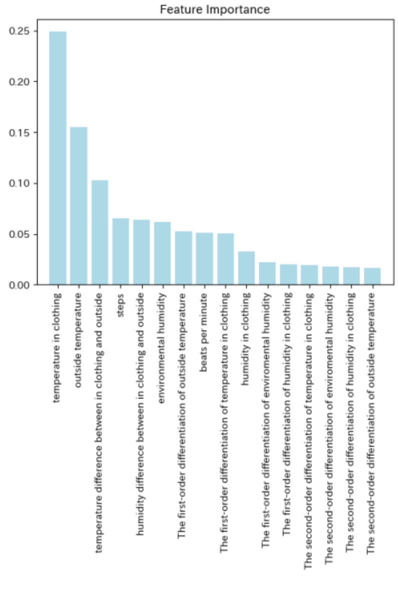

Figure 3. B's Feature Importance

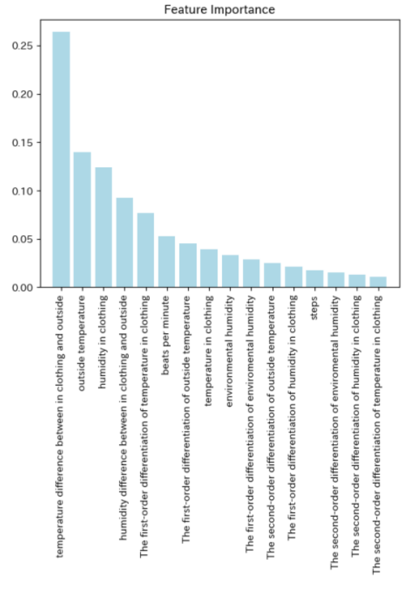

Figure 4. C's Feature Importance

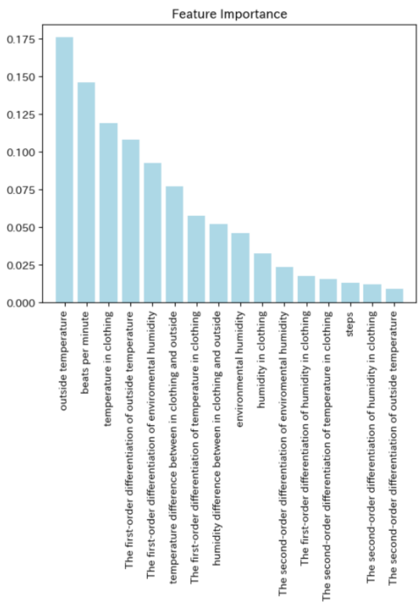

Figure 5. D's Feature Importance

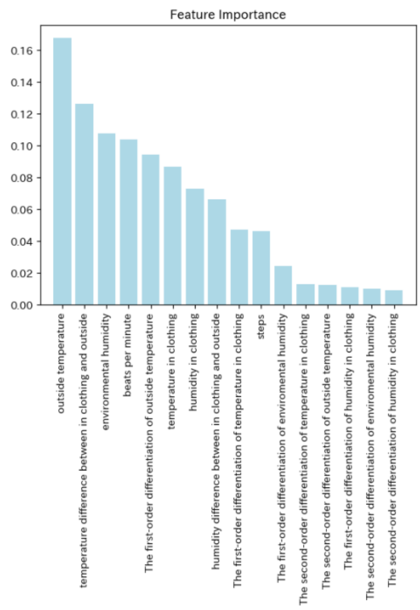

Figure 6. E's Feature Importance

4.2 Comfort Estimation with RandomForest

The comfort of each subject for each TPO was label-encoded by the digits from 1 to 5. The features were calculated from the collected sensor data according to described in Section 3. The features and comfort data was divided into the training data of 70% and the test data of 30%. A RandomForest model is trained by the training data to estimate the label-encoded comfort. In addition, each subject was individually model trained. In this study, it is used as a classification. As hyperparameters, n_estimators is set to 100, criterion to 'gini', max_depth to None. From these results, the correct answer rate of each subject was 0.95 for Subject A, 0.94 for subject B, 0.93 for subject C, 0.95 for subject D, and 0.97 for subject E. Figure 2, 3, 4, 5, 6 shows a graph plotting the importance of the feature variables that represent the contribution to the estimation of comfort for each subject. The three variables of the highest importance for each subject are shown in order: Those in Subject A are outside temperature, environmental humidity, and humidity difference between in clothing and outside. Those in Subject B are temperature in clothing, outside temperature, and temperature difference between in clothing and outside. Those in Subject C are temperature difference between in clothing and outside, outside temperature, and humidity in clothing. Those in Subject D are outside temperature, heart rate, and temperature in clothing,. Those in Subject E are outside temperature, temperature difference between in clothing and outside, and environmental humidity.

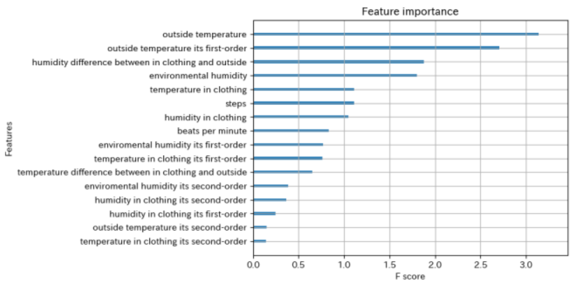

Figure 7. A’s Feature Importance

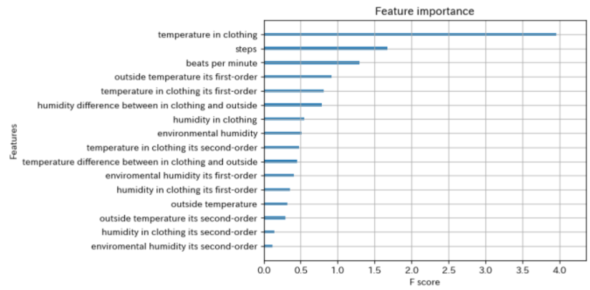

Figure 8. B’s Feature Importance

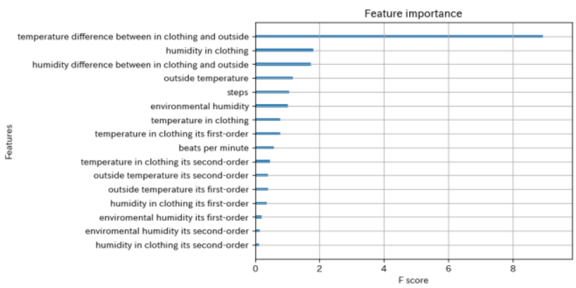

Figure 9. C’s Feature Importance

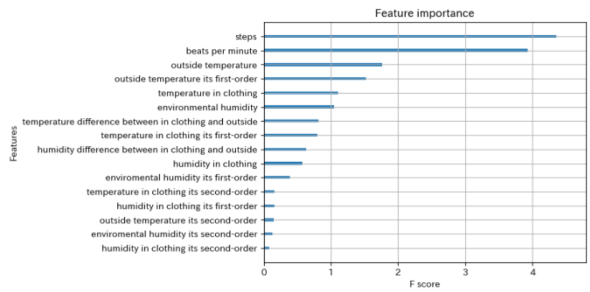

Figure 10. D’s Feature Importance

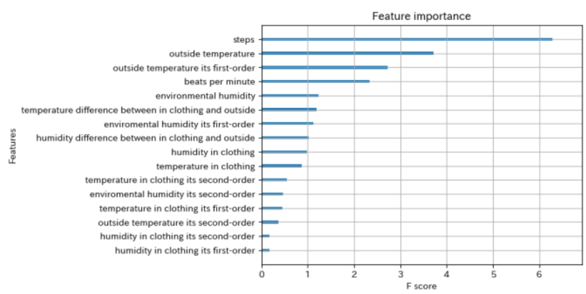

Figure 11. E’s Feature Importance

4.3 Comfort Estimation with XGBoost

The comfort of each subject for each TPO was label-encoded as '1 (much uncomfortable) ~ 5 (much more comfortable)', and the comfort was estimated using XGBoost. The features and comfort data was divided into the training data of 70% and the test data of 30%. A XGBoost model is trained by the training data to estimate the label-encoded comfort. In addition, each subject was individually model trained. In this study, it is used as a classification. As hyperparameters, n_estimators is set to 100，learning_rate to 0.3，max_depth to None. From these results, the correct answer rate of each subject was 0.95 for Subject A, 0.95 for subject B, 0.96 for subject C, 0.97 for subject D, and 0.94 for subject E. Figure 7, 8, 9, 10, 11 shows a graph plotting the importance of the variables that represent the contribution to the estimation of comfort for each subject. The three variables of the highest importance for each subject are shown in order: Those in Subject A are outside temperature, outside temperature its first-order, and humidity difference between in clothing and outside. Those in Subject B are the temperature in clothing, the amount of walking, and heart rate. Those in Subject C are temperature difference between in clothing and the outside, humidity in clothing, and temperature in clothing. Those in Subject D are the amount of walking, heart rate, and outside temperature. Those in Subject E are the amount of walking, the outside temperature, and the outside temperature its first-order.

4.4 Difference in Results between RandomForest and XGBoost

The accuracy rate was better for XGBoost in 4 out of 5 subjects. Here, in RandomForest, the variable importance of outdoor temperature is high for all subjects. On the other hand, in XGBoost, the importance variable is different for each subject. From this result, the reason why the XGBoost has a better rate of correct answers is that the variables that are important to each individual are different compared to RandomForest. In other words, the reason may be that XGBoost was able to estimate the comfort level with high accuracy at any comfort level because it was able to take into account the individual's constitution. The reason why the RandomForest has a better accuracy rate is considered that there is less difference in variable importance than XGBoost, so it can be estimated with high accuracy at any comfort. When comfort was predicted for each TPO, a low percentage of correct answers was common for 'walking' for both study devices and for all subjects. In particular, the percentage of correct responses was low for TPOs related to the means of transportation. From these results, we believe that TPO can be divided into two categories: TPO in which one can create a convenient environment for oneself and TPO in which one cannot create a convenient environment for oneself, and TPO in which one cannot control comfort in the latter category. Therefore, TPOs related to means of transportation are the latter TPOs. We also considered that the accuracy of prediction for 'walking' would be lower than that for other TPOs because the amount of walking and the heart rate have a greater effect on walking than on other TPOs.

5. Conclusion

In this study, we proposed a method for estimating comfort predictions that take into account TPO based on the internal and external climates of clothing, focusing on the comfort of each TPO. In this method, subjects attach a wireless temperature and humidity sensor and a wristwatch-type wearable sensor to their clothes on a daily basis to collect sensor data. As a result of the experiment, it was found that XGBoost had a higher accuracy rate than RandomForest for all subjects, and it was found that the accuracy of the prediction was lower in TPO where it was not possible to create a favorable environment for the subject. The challenge for the future is to consider the use of cold-weather shirts such as Heattech and to adopt clothing materials as new features.

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Authors' contributions

All authors were responsible for study design and revising. Dr. Takayuki Hiwatari was responsible for data collection. Dr. Takayuki Hiwatari drafted the manuscript and Prof. Fumiko Harada and Prof. Hiromitsu Shimakawa revised it. All authors read and approved the final manuscript.

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Competing interests

The authors have no competing interests to disclose.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Redfame Publishing.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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