Article:

Jiang, L, Wang, H, Zhang, X et al. (4 more authors) (2021) Characterizing skin color before and after 100-m sprinting. Color Research and Application, 46 (6). pp. 1255-1264. ISSN 0361-2317

https://doi.org/10.1002/col.22679

Characterizing Skin Color before and after 100-Meter Sprinting

Li Jiang[1], Han Wang[2], Xiaohui Zhang[2], Cheng Gao[2], Kaida Xiao[3], Manuel Melgosa[4], Changjun Li[2]

[1]School of Physical Education, University of Science and Technology Liaoning, Anshan, China
[2]School of Computer and Software Engineering, University of Science and Technology Liaoning, Anshan, China
[3]School of Design, University of Leeds, Leeds, UK
[4]Department of Optics, University of Granada, Granada, Spain

Correspondence
Changjun Li, School of Computer and Software Engineering, University of Science and Technology Liaoning, Anshan, 114051, China. Email: cjliustl@sina.com

Abstract
We studied skin color in participants before and after a 100-meter sprint using a Konica Minolta CM-2600d spectrophotometer. Four body positions (forehead, cheek, neck, and inner forearm) were measured for the approximately 30 students (non-professional runners) who participated in the experiment. Skin reflectance was measured three times at each position before running and again soon afterwards. Analysis of the data showed that average measurement repeatability (mean color difference from the mean) was 0.5, 0.4, 0.3, and 0.2 CIELAB units for forehead, cheek, neck, and inner forearm, respectively. However, average skin color differences produced by running were 1.8, 2.2, 2.0, and 1.7 CIELAB units for forehead, cheek, neck, and inner forearm positions, respectively, which are considerably higher than repeatability before or after running. Furthermore, appearance variation was analyzed in the CIELAB space, and it was found that sprinting for 100 meters considerably changes the values of the red-green a^* coordinate, while the lightness L^* and yellow-blue b^* coordinates remain almost constant. More specifically, on average, a^* decreases after running for the forehead, cheek, and neck positions, while the opposite is true for the inner forearm position. The findings in this paper may be useful to test previous physical models, achieve more realistic images of human skin after sprinting, and contribute to work of CIE TC 1-92 on skin spectra database.

KEYWORDS
skin reflectance, hemoglobin oxygen saturation, CIELAB color space

1. INTRODUCTION

Human skin color has been the subject of numerous studies[1-5], focusing on skin color measurement for the diagnosis of cutaneous related disease[6,7], skin color segmentation for face detection and recognition[8-11], skin color reproduction for the graphic arts, and skin color matching for body and maxillofacial soft tissue prostheses[12,13]. For such applications, a comprehensive knowledge of the range of skin shades in a representative sample of individuals, as well as an understanding of how skin color varies across different body locations and how these differences are perceived under a wide range of viewing conditions, is of vital importance[2].

In 2012, Xiao et al.[1] accumulated a large set of reflectance data measured using the Konica-Minolta CM-2600d for Chinese individuals, and skin appearance was examined in both the CIELAB and CIECAM02 spaces. In 2017, Xiao et al.[2] reported accurate skin color measurements from four different ethnic groups (Caucasian, Chinese, Kurdish, Thai) at four different body locations (forehead, cheek, inner arm, back of the hand) with the goal of creating a new skin color database for medical and cosmetic applications and for studying the color gamut in different ethnic groups. In 2018, Wang et al.[3] researched the variability of skin color measurements using non-contact and contact technologies with a PR-650 spectroradiometer and a CM-700d spectrophotometer, respectively.

The CIE has now set up its Technical Committee 1-92 to create a skin color database for industrial applications by collecting skin reflectance measurements for different ethnicities, genders, ages, and body locations. We have been developing a project in connection with CIE TC 1-92 by collecting spectral skin data before and after aerobic and anaerobic sports activities. The aim of this project is to study the change in skin color appearance before and after sports activities, and its dependency on body location.

In this paper, we report spectral skin reflectance measurements taken with a Konica Minolta CM-2600d spectrophotometer before and after a 100-meter sprint. During this short distance, runners normally exert much effort and hold their breath in order to run faster. Hence, it may be expected that oxygenation saturation in skin hemoglobin would be modified by running[14,15]. According to the hypothesis of Changizi et al.[16,17], modulations in hemoglobin oxygen saturation indeed change skin color. In a few words, the goal of the current paper is to provide a colorimetric characterization of skin color before and after 100-meter sprinting, as stated in its title. We focused on the 100-meter sprint because it is considered the queen of athletics, as it rewards the fastest man and woman in the world, and has been part of each of the 28 editions of the Olympic Games in the Modern Era. In addition, 100-meter sprinting is not a too long distance, and a popular sport exercise for which it is easier to find volunteers.

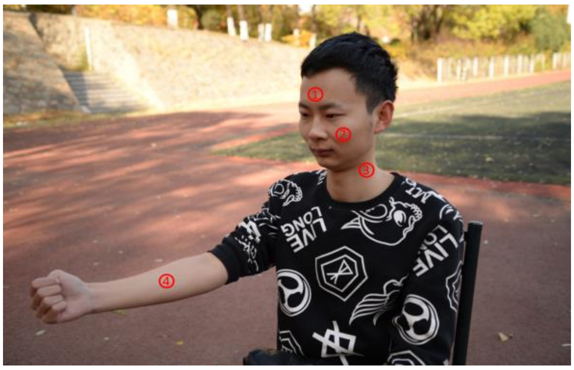

FIGURE 1 Illustration of measurements made at forehead (1), cheek (2), neck (3), and inner forearm (4) positions.

2. EXPERIMENT DESIGN

Skin measurements were made using a Konica Minolta CM-2600d spectrophotometer with an 8 mm diameter aperture size. We used the largest aperture available in our instrument, trying to average potential non-uniformity of color of the skin. Spectral reflectance factors were measured in a range of 360-740 nm (10 nm steps) at four positions (forehead, cheek, neck, and inner forearm, see Figure 1). These four positions are consistent with those considered in other works within CIE TC 1-92. Two of these four positions are in the subject's face, as most important part of the body in many applications.

Students from the University of Science and Technology Liaoning were recruited for these measurements. Table 1 lists the number of students (NS) participating in the experiment for each of the four measured body positions. For each position, we performed three measurements before running without moving the instrument. Each student was then allocated a number and all gathered at the starting point for the sprint. An experimenter with the CM-2600d spectrophotometer was waiting at the termination point. When the experimenter was ready for the measurement, a coordinator at the termination point sent a signal for the *j*-th participant to run. As soon as the *j*-th runner arrived at the termination point, the experimenter performed 3 quick measurements at each of the four body positions mentioned above. When these measurements were completed, the next participant started to run, and this sequence was repeated for all of the students.

TABLE 1 Numbers of students (NS) recruited for skin color measurements at the four body positions, and numbers of students after removing outlier data.

	Forehead	**Cheek**	**Neck**	**Inner Forearm**
NS	32	31	33	32
NS after removing outliers	29	31	27	30

The experimenter used paper napkins to clean the measured positions of the skin of each participant before and after the sprint. In this way we tried to avoid potential surface effects, in particular the effect on our measurements of small perspiration which may be produced by the sprint. All results reported in this paper correspond to measurements performed using the specular component excluded (SCE) mode of CM-2600d. We can assume that our measured surfaces had negligible gloss. As indicate above, for each of the four body positions, we measured 3 consecutive times in only one place, in such a way that color variability within a body position was not considered. However, the experimenter tried to measure approximately at the same place before and after the sprinting, applying the instrument on the skin with the same pressure.

Table 1 shows that an average of 32 students participated the experiment and measurements were performed at four body positions. We therefore performed a total of 768 spectrophotometric measurements (32 students x 4 body positions x 2 situations (before and after running) x 3 replications of measurement. Note that the bottom row in Table 1 lists the numbers of students (NS) for each of the four body positions after removing the outlier measurement data, as will be discussed in the next section.

3. RESULTS

First, the repeatability of the measurements made with the CM-2600d was studied. For each body position, spectral reflectance was measured three times and the corresponding results designated as $r_{j,k,1}$, $r_{j,k,2}$, and $r_{j,k,3}$, where the subindices *j* and *k* indicate the student (runner) and the position on the body, respectively. We designate as $Lab_{j,k,1}$, $Lab_{j,k,2}$, and $Lab_{j,k,3}$ the CIELAB coordinates calculated from $r_{j,k,1}$, $r_{j,k,2}$, and $r_{j,k,3}$ under the CIE illuminant D65 and the CIE 1931 standard colorimetric observer. We will let $Lab_{j,k}$ be the average of the three computed colors: $Lab_{j,k,1}$, $Lab_{j,k,2}$, and $Lab_{j,k,3}$. Meanwhile, $\Delta E_{j,k,1}$ will designate the CIELAB color difference between $Lab_{j,k}$ and $Lab_{j,k,1}$, and similarly for $\Delta E_{j,k,2}$ and $\Delta E_{j,k,3}$. The mean of the three differences, $\Delta E_{j,k,1}$, $\Delta E_{j,k,2}$, and $\Delta E_{j,k,3}$, denoted by $\Delta E_{j,k}$, represents measurement repeatability in CIELAB units for the *j*-th runner at the *k*-th position. Note that $\Delta E_{j,k}$ is the mean color difference from the mean (MCDM), which also shows the precision of these color measurements[18]. Measurement repeatability for the *k*-th body position is given by Equation 1, where NS is the total number of runners:

$$\Delta E_k = \frac{1}{NS}\sum_{j=1}^{NS} \Delta E_{j,k} \tag{1}$$

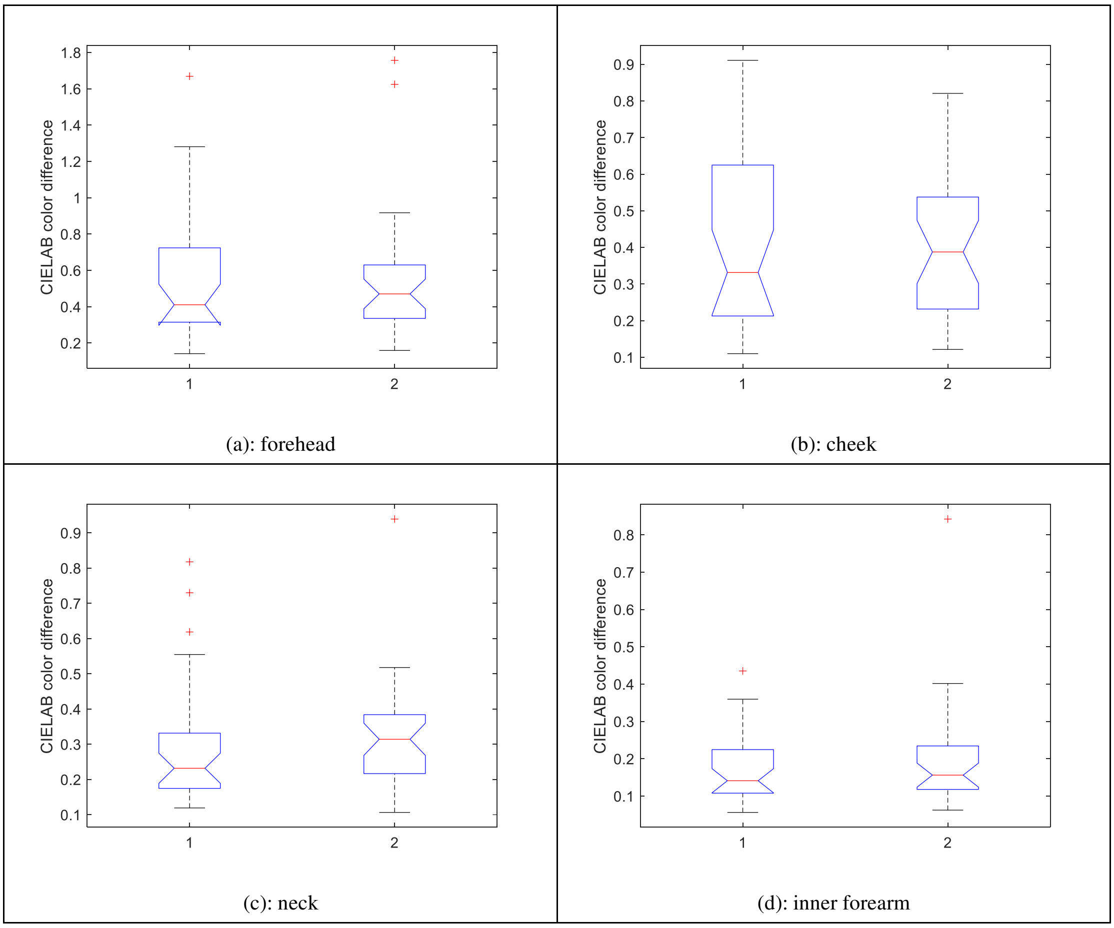

FIGURE 2 Box-plots with notches in which the horizontal axes 1 and 2 mean before and after running, respectively. The central mark in each notch indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentile CIELAB color differences, respectively. The whiskers (short segments above and below the box) extend to extreme data points not considered to be outliers, while the outliers are plotted individually using the "+" symbol. Plots (a), (b), (c), and (d) correspond to measurements at the forehead, cheek, neck and inner forearm, respectively.

Figure 2 shows box-plots with notches illustrating the repeatability of our measurements before (box-plot 1) and after (box-plot 2) 100-meter sprinting for the four body positions: forehead (a), cheek (b), neck (c) and inner forearm (d). In each of these box-plots, the red mark in the middle of the notch indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentile CIELAB color differences, respectively, while whiskers (segments above and below the box) extend to the extreme data points not considered to be outliers, the outliers being plotted individually using the '+' symbol. Figure 2 was drawn using the MATLAB function 'boxplot', which draws points as outliers if they are greater than $q_3 + 1.57 \times (q_3 - q_1) / \mathrm{sqrt}(n)$ or less than $q_1 - 1.57 \times (q_3 - q_1) / \mathrm{sqrt}(n)$, where q_1 and q_3 are the 25th and 75th percentiles of the sample data, respectively, and n is the number of data points.

Since there are some outliers in box-plots (a), (c), and (d) in Figure 2, these data were removed for later analysis. The last row in Table 1 lists the number of students for each body position after removing the outliers (2 outliers are not shown in box-plot (c) in Figure 2 to maintain a reasonable scale in its *y*-axis). Table 2 lists average color differences, representing measurement repeatability before (row 1) and after (row 2) the 100-meter sprint, as well as total averages (last row) for each of the four body positions. It can be observed that repeatability varies for different positions. The inner forearm shows the greatest repeatability (i.e. the lowest CIELAB color difference: 0.2 units), which is understandable as this part of the body is characterized by high color uniformity and the CM-2600d spectrophotometer is more easily applied. The lowest repeatability was found for the forehead measurements (0.5 CIELAB units). The manufacturer of CM-2600d indicates that the colorimetric repeatability of this instrument is a standard deviation within 0.04 CIELAB units, for a white calibration plate measured 30 times at 10-second intervals, after white calibration was performed.

TABLE 2 Measurements repeatability in terms of CIELAB color difference.

	Forehead	Cheek	Neck	Inner Forearm
Before	0.5	0.4	0.2	0.2
After	0.5	0.4	0.3	0.2
Average	0.5	0.4	0.3	0.2

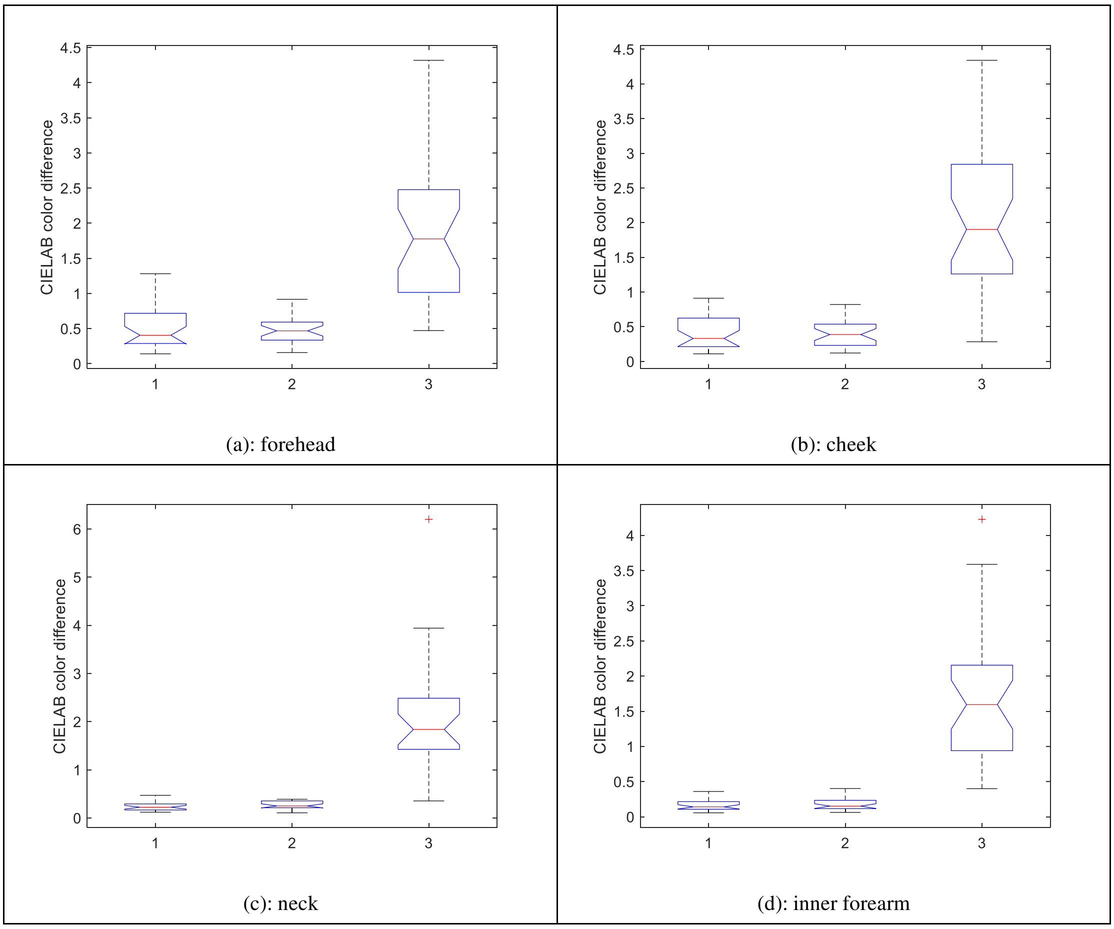

FIGURE 3 Idem to Fig. 2, but with outliers removed from the repeatability results (1 and 2 on the *x*-axis), and the addition of results for skin color differences produced by running (3 on the *x*-axis).

Figure 3 shows repeatability results after removing outliers (1 and 2 on the *x*-axis), as well as color differences generated by running (3 on the *x*-axis). The box-plot 3 in Figure 3 shows skin color differences between $Lab_{j,k}$ before and after 100-meter sprinting for the four body positions measured. It can be seen that the values in box-plot 3 are higher than in box-plot 1 and box-plot 2, which means that a significant skin color variation was produced by the 100-meter sprint. In Figure 3 (c) and (d), the lowest point in box-plot 3 is roughly coincident with the highest point in box-plots 1 and 2, while in Figure 3 (a) and (b), the 25th percentile in box-plot 3 is higher than the highest points in both box-plots 1 and 2. In fact, in each of the plots in Figure 3, the notch for box-plot 3 does not overlap with the notches in box-plots 1 and 2, and, following the MATLAB help document for the function ‘boxplot’, we can conclude with 95% confidence that the color differences in box-plot 3 (i.e. CIELAB color differences produced by running) are significantly different from those in box-plots 1 and 2 (i.e. CIELAB color differences representing measurement repeatability both before and after running).

TABLE 3 Average CIELAB skin color differences produced by the 100-meter sprinting at the four body positions.

Forehead	Cheek	Neck	Inner Forearm
1.8	2.2	2.0	1.7

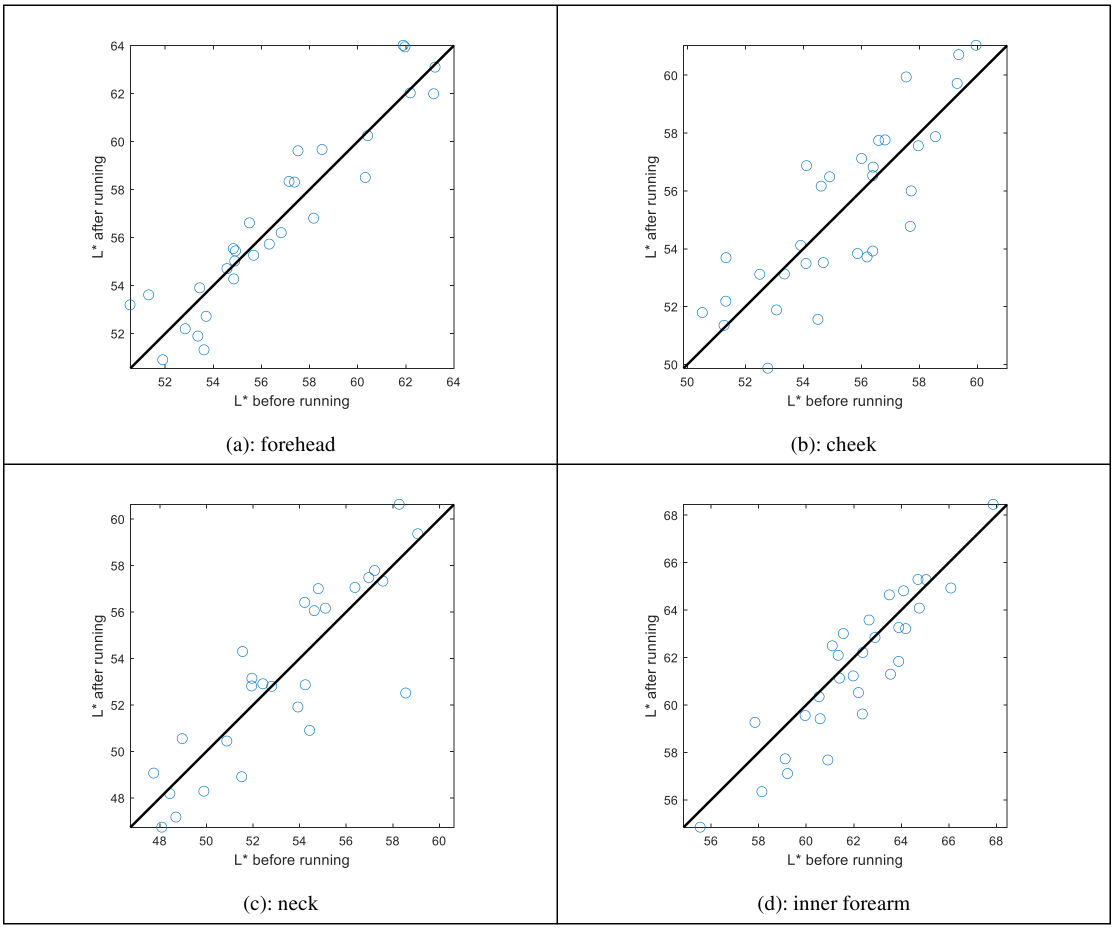

FIGURE 4 Comparison of CIELAB lightness L^* before and after running for different body positions: (a) forehead, (b) cheek, (c) neck, and (d) inner forearm.

Table 3 lists average skin color differences for measurements before and after the 100-meter sprint for each of the four body positions. When these results are compared with those in Table 2, it can be observed that the change in skin color produced by the 100-meter sprint at each body position is quite significant. For a better understanding of the magnitude of these color differences, we might point out that 0.6-1.1 CIELAB units was determined as the average human visual threshold in a previous paper by Huang et al.[19]. We feel that the large variation in skin appearance produced by the sprint may be caused mainly by a variation in the oxygenation saturation[14,15] of skin hemoglobin, but we didn't perform specific measurements of hemoglobin to test this point. Our findings also show that the CM-2600d spectrophotometer can indeed detect color variations, both before and after running. Note that the color differences shown in Table 3 correspond to non-professional runners. It can be expected that for professional runners skin color differences before and after a 100-meter sprint will be even greater.

As is well known[18,20], in the CIELAB space L^* represents lightness, a^* represents red-green, and b^* represents yellow-blue. Figure 4 shows lightness L^* before running (horizontal axis) versus lightness L^* after running (vertical axis) for forehead (diagram (a)), cheek (diagram (b)), neck (diagram (c)), and inner forearm (diagram (d)) positions. The solid lines in Figure 4 have a slope of 1, and all points on these lines represent no lightness change as a result of running. It can be seen from diagrams (a) to (c) that there is no clear trend for the forehead, cheek, and neck positions. However, for the inner forearm position (d), most points are located below the line with slope 1, meaning that lightness decreases (i.e. the skin has a darker appearance) after running.

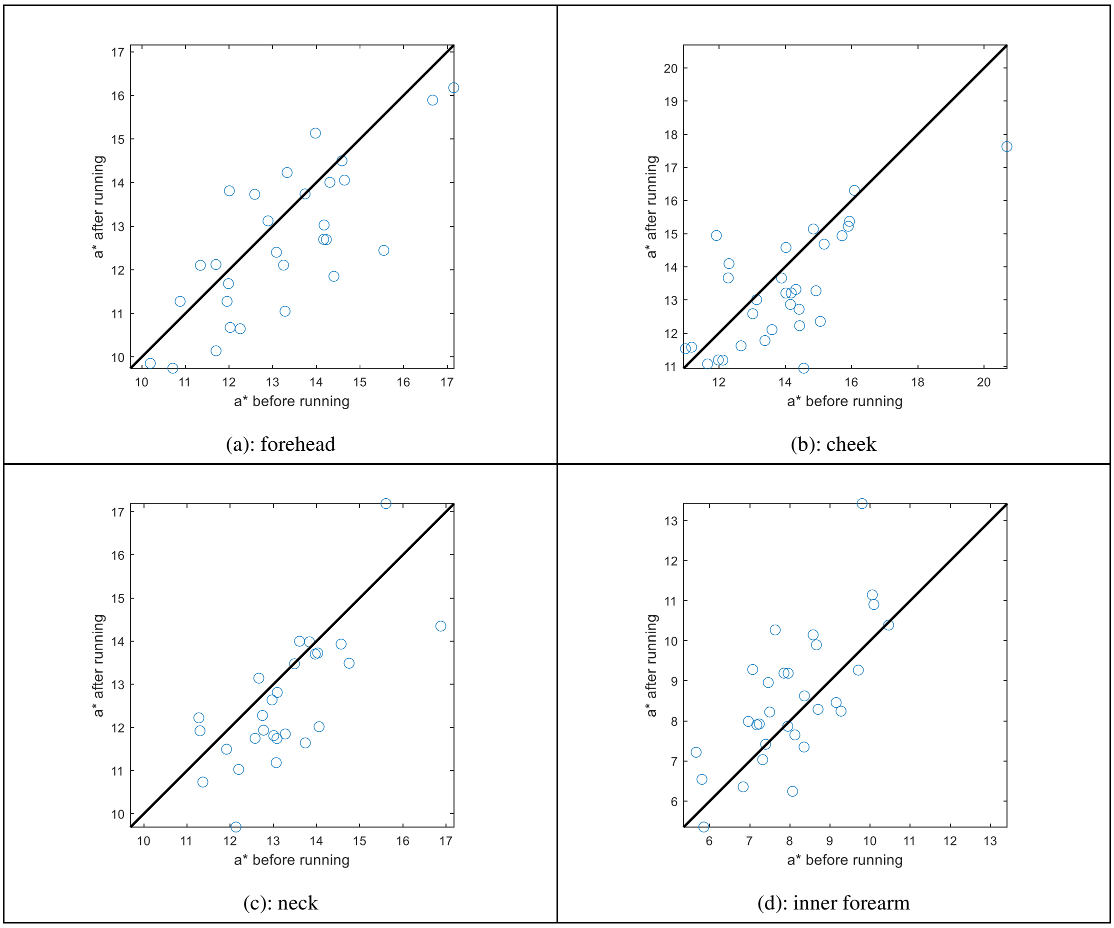

FIGURE 5 Comparison of CIELAB a^* before and after running for different body positions: (a) forehead, (b) cheek, (c) neck, and (d) inner forearm.

Figure 5 shows the CIELAB a^* coordinate before running (horizontal axis) versus a^* after running (vertical axis) for forehead (diagram (a)), cheek (diagram (b)), neck (diagram (c)), and inner forearm (diagram (d)). It can be seen in Figure 5 that there are more points located below the lines with slope 1 in diagrams (a) to (c), which means that a^* decreases with running. However, diagram (d) shows the opposite trend, as there are more points located above the line with slope 1, meaning that a^* increases with running.

Figure 6 shows the CIELAB b^* coordinate before running (horizontal axis) versus b^* after running (vertical axis) for forehead (diagram (a)), cheek (diagram (b)), neck (diagram (c)), and inner forearm (diagram (d)). It can be seen in Figure 6 that there is no clear trend for variation of the b^* coordinate with running. This is certainly the case for diagrams (c) and (d), while there are a few more points located below/above the line with slope 1 for diagrams (a) and (b), respectively.

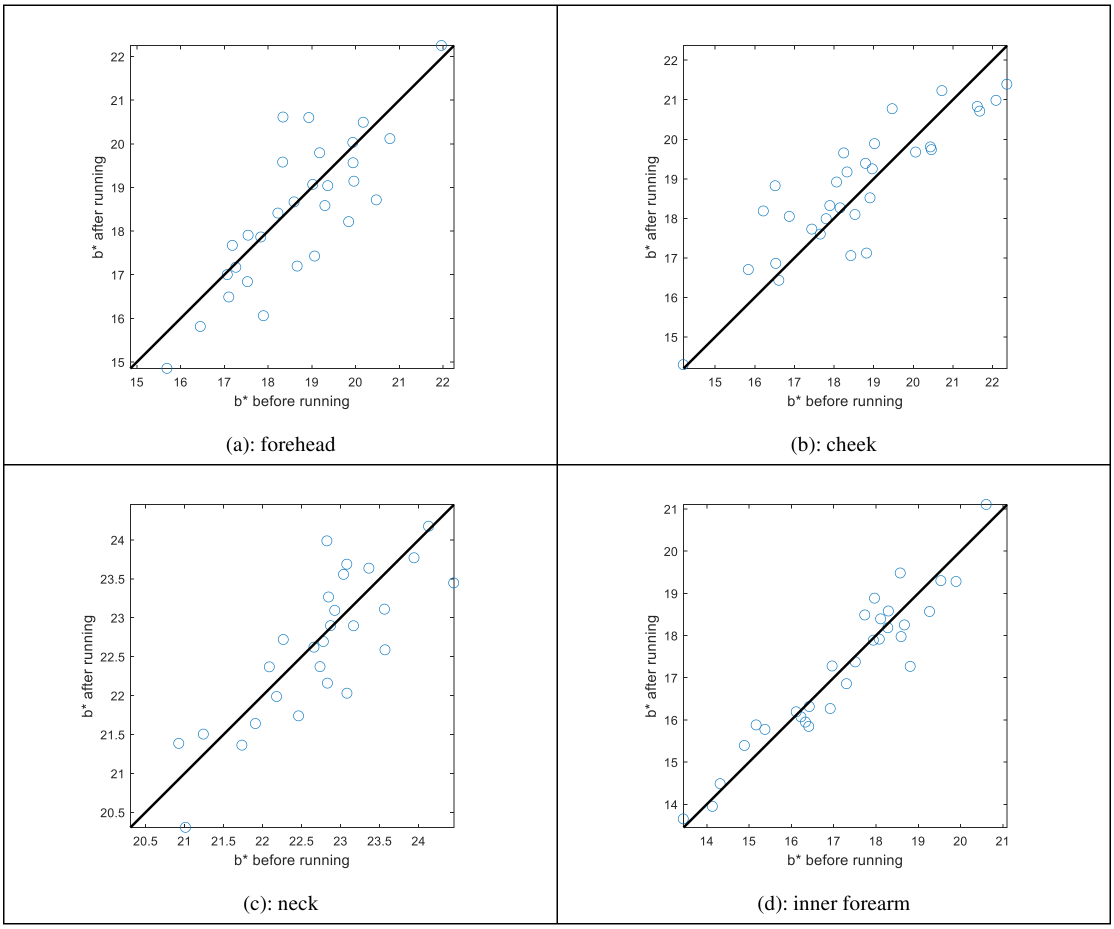

FIGURE 6 Comparison of CIELAB b^* before and after running for four body positions: (a) forehead, (b) cheek, (c) neck, and (d) inner forearm.

Bearing in mind that CIELAB is a tridimensional color space, the color changes produced by the sprinting may be better understood using plots of planes a^*b^*, a^*L^* and b^*L^* (see Figure 7). Specifically, Figure 7 shows the average color changes (or color shifts) produced by the sprinting for each of the four body positions. Figure 7 confirms the results previously indicated from Figures 4-6, and also shows that the highest color change corresponds to the a^* coordinate. The changes produced in the a^* coordinate mean that, as a consequence of the sprinting, the amount of redness decreases for forehead, cheek, and neck, the opposite happening for inner forearm. The reasons of these changes deserve future research. Table 4 shows the specific average values for the a^* coordinate before and after the sprinting.

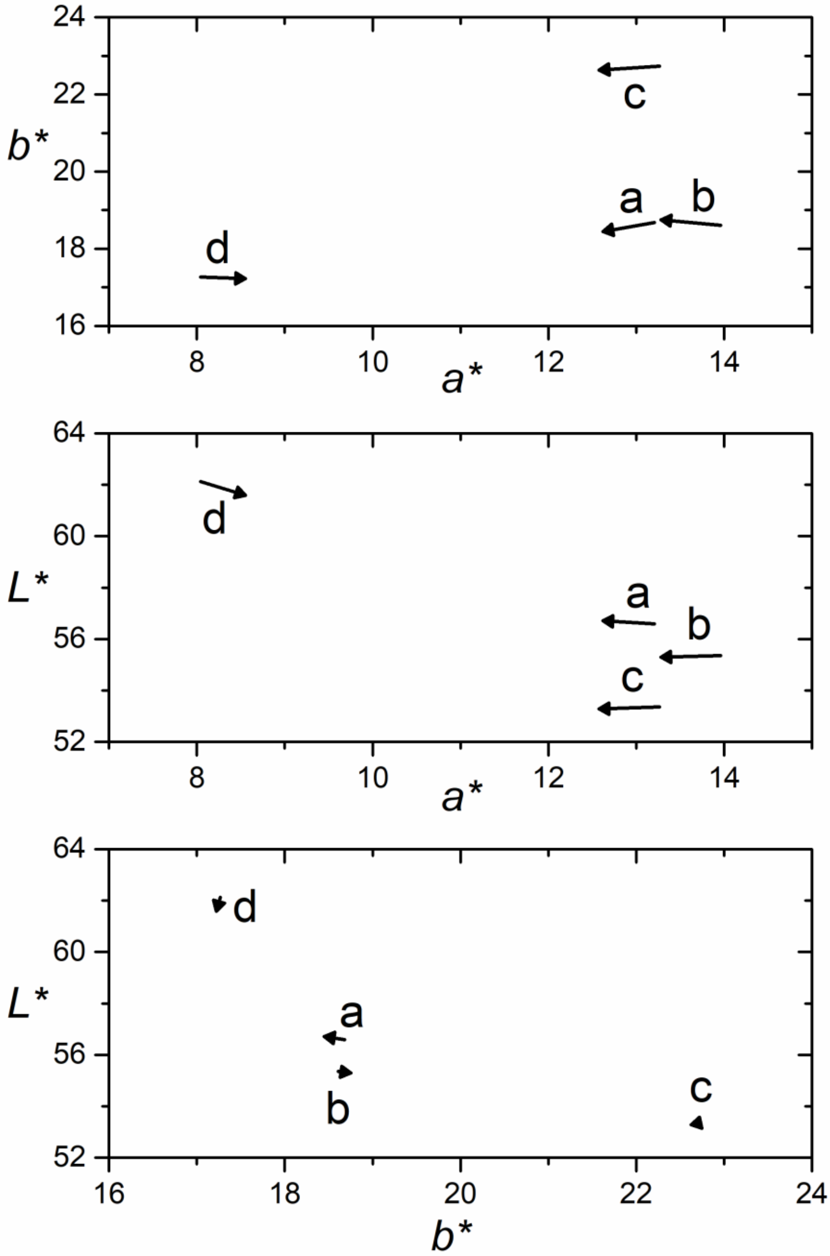

FIGURE 7 Average CIELAB color changes produced by the 100-meter sprinting in each of the four body positions (forehead (a), cheek (b), neck (c), and inner forearm (d)), distinguishing the *a*b**, *a*L** and *b*L** planes. The origins and ends of the arrows indicate the values before and after the sprinting, respectively.

We also studied CIELAB chroma variations with running, and found that C^*_{ab} also varies significantly, in a manner similar to that described earlier for the *a** coordinate. Table 4 lists average values of the *a** coordinate before ($(\overline{a^*})_B$, column 2) and after ($(\overline{a^*})_A$, column 3) running, as well as the differences between them (column 4). It can be seen that, for measurements at the forehead, cheek and neck positions, running causes the *a** coordinate to decrease by an average of 0.6, 0.7 and 0.7 units, respectively, while for the inner forearm position, the *a** coordinate increases by an average of 0.6 units. Keep in mind that the average human visual threshold is 0.6-1.1 CIELAB units[19]. As noted before, these results correspond to non-professional runners, greater color variations may be expected for professional runners.

TABLE 4 Means of the a* coordinate before ($(\overline{a^*})_B$, column 2) and after ($(\overline{a^*})_A$, column 3) running, and the differences (column 4) between $(\overline{a^*})_B$ and $(\overline{a^*})_A$ for each of the body positions (forehead, cheek, neck, and inner forearm).

	$(\overline{a^*})_B$	$(\overline{a^*})_A$	$(\overline{a^*})_B - (\overline{a^*})_A$
Forehead	13.2	12.6	0.6
Cheek	14.0	13.3	0.7
Neck	13.3	12.6	0.7
Inner Forearm	8.0	8.6	-0.6

We also studied variations in skin appearance after 100-meter sprinting using the CAM16-UCS[21] $J', a_{M'}, b_{M'}$ color space, obtaining results similar to those described earlier using the CIELAB analog coordinates L*, a* and b*, respectively.

Next, we applied statistical tests to analyze the data shown in Figures 4-6. We will let X be any of the three CIELAB coordinates. The data plotted in Figures 4-6 can then be designated as $x_{B,j}$ versus $x_{A,j}$, where the subscripts A and B mean after and before running, respectively, and the subscript i means the i-th sample data. Let

$$y_j = x_{B,j} - x_{A,j}, \quad j = 1, 2, ..., \mathrm{NS} \tag{2}$$

Hence, the mean of y_j (denoted by $\bar{y}$) is the difference of the mean of $x_{B,j}$ (denoted by $\bar{x}_B$) and the mean of $x_{A,j}$ (denoted by $\bar{x}_A$); that is to say:

$$\bar{y} = \bar{x}_B - \bar{x}_A \tag{3}$$

The hypothesis of our statistical test is thus:

$$\bar{y} = 0 \tag{4}$$

with the alternative hypothesis being:

$$\bar{y} = \begin{cases} \neq 0 \text{ if } \ \mathrm{Tail} = \mathrm{both} \\ > 0 \text{ if } \ \mathrm{Tail} = \mathrm{right} \\ < 0 \text{ if } \ \mathrm{Tail} = \mathrm{left} \end{cases} \tag{5}$$

The MATLAB function “ttest” was also used, with a 5 percent significance level (default), and the results are listed in Table 5. Value 0 means that ttest does not reject the null hypothesis at the 5 percent significance level, which from Equations 3 and 4 means that $\bar{x}_B = \bar{x}_A$. However, the value 1 means that ttest rejects the null hypothesis at the 5 percent significance level, which from Equations 3 and 5 means:

$$\begin{cases} \bar{x}_B \neq \bar{x}_A \text{ if } \ \mathrm{Tail} = \mathrm{both} \\ \bar{x}_B > \bar{x}_A \text{ if } \ \mathrm{Tail} = \mathrm{right} \\ \bar{x}_B < \bar{x}_A \text{ if } \ \mathrm{Tail} = \mathrm{left} \end{cases} \tag{6}$$

First, it can be seen from columns 2-4 in Table 5 that the null hypothesis is true for the b* coordinate at the four body positions and for the L* coordinate at the forehead, cheek, and neck positions, which means that for all these cases $\bar{x}_B = \bar{x}_A$ (i.e. no statistically significant changes are produced by the 100-meter sprint). However, the alternative hypothesis $\bar{x}_B \neq \bar{x}_A$ is true for the a* coordinate at all body positions, and for the L* coordinate at the inner forearm position. Furthermore, from the results in columns 5-7 and 8-10 in Table 5 and Equation 6, we have $(\overline{a^*})_B > (\overline{a^*})_A$ for the forehead, cheek, and neck positions, while $(\overline{a^*})_B < (\overline{a^*})_A$ and $(\overline{L^*})_B > (\overline{L^*})_A$ for the inner forearm position.

The results in Table 5 indicate that skin appearance varies statistically along the red-green scale (a* coordinate). Changizi et al.[16,17] based their study on a physical skin reflectance model[22], claiming that modulations in hemoglobin oxygen saturation cause skin color variations along the red-green axis in a cone-opponent space. Our results here are thus consistent with Changizi et al.[16,17], since the 100-meter sprint is a kind of anaerobic sport exercise in which hemoglobin oxygen saturation changes soon after running[15,16]. However, our findings also indicate that skin appearance varies at different body locations.

TABLE 5 Results for paired-sample t-tests at 5 percent significance level with both right and left types of alternative hypothesis, respectively (see main text).

	Type of Alternative Hypothesis								
Tail	Both			Right			Left		
	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*
Forehead	0	1	0	0	1	0	0	0	0
Cheek	0	1	0	0	1	0	0	0	0
Neck	0	1	0	0	1	0	0	0	0
Forearm	1	1	0	1	0	0	0	1	0

4. CONCLUSIONS

We performed skin color measurements at four different positions of the body before and after a 100-meter sprint using a CM-2600d spectrophotometer. From about 30 young non-professional runners, a total of 768 skin spectra were measured. The repeatability of our measurements at the forehead was 0.5 CIELAB color difference units, with 0.4 for the cheek, 0.3 for the neck, and 0.2 for the inner forearm positions. However, skin appearance variation produced by the 100-meter sprint was 1.8 CIELAB color difference units for the forehead position, 2.2 for the cheek, 2.0 for the neck, and 1.7 for the inner forearm positions. These last values are significantly higher than repeatability and also greater than the 0.6-1.1 CIELAB units which is reported as the average human visual color threshold for normal observers[19]. Further analysis in the CIELAB (and CAM16-UCS) color space showed that skin appearance varies on the red-green axis, which is consistent with the results reported by Changizi et al.[16,17]: modulations in oxygenation change skin appearance along a red–green axis in the cone-opponent space. It was found for the forehead, cheek, and neck positions, the a^* coordinate tends to decrease after running, for the inner forearm position the opposite is true. However, we are unable to provide explanations about the reasons of the different variation trends at different body locations..

The accumulated skin spectra from this paper will complement the skin reflectance types that are currently being gathered by the CIE TC 1-92 skin colour database. Some data in this paper may be perhaps used for future evaluation of physical models like those given by Zonios et al.[23,24] We'd like that the results of this paper may also find applications in the fields of computer graphics, digital animation, and film production. For example, in digital animations of sports or running exercises, images with more realistic skin colour variations in different body locations are desirable. Anyway, it is known that skin color changes under various situations involving interpersonal and social contexts, such as excitement in public performance situations, work in the scorching sun, different sports, fever due to illness, etc.[25-27] It should be useful to clarify in future research the relationship and difference between changes in skin color before and after 100 meters sprint with other changes including various psychophysiological parameters.

Funding information

This study was supported by the National Natural Science Foundation of China (Grant numbers: 61575090, 61775169), the Ministry of Science and Innovation of the Government of Spain (PID2019-107816GB-I00/SRA/10.13039/501100011033), Liaoning Natural Science Foundation (2019-ZD-0267), and Scientific Research Project of Liaoning Educational Department (2020LNJC01)

ORCID

Changjun Li https://orcid.org/0000-0002-9942-7690

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request. The data are not publicly available due to privacy restrictions.

Acknowledgement:

English assistance from Mr. Donald J, Murphy Mcveigh is acknowledged.

REFERENCES

[1] Xiao KD, Liao NF, Zardawi F, Liu HX, Noort RV, Yang ZX, Huang M, Yates JM. Investigation of Chinese skin colour and appearance for skin colour reproduction. *Chinese Opt Lett*. 2012;10:083301.

[2] Xiao KD, Yates JM, Zardawi F, Sueeprasan S, Liao NF, Gill L, Li CJ, Wuerger S. Characterising the variations in ethnic skin colours: a new calibrated data base for human skin. *Skin Res Technol*. 2017;23:21–29.

[3] Wang YZ, Luo MR, Wang MM, Xiao KD, Pointer M. Spectrophotometric measurement of human skin colour. *Color Res Appl*. 2017;42:764–774.

[4] Rigal J, Abella ML, Giron F, Caisey L, Lefebvre MA. Development and validation of a new Skin Color Chart. *Skin Res Technol*, 2007;13(1):101-109.

[5] Han K, Choi T, Son D. Skin color of Koreans: statistical evaluation of affecting factors. *Skin Res Technol*. 2006;12(3):170-7.

[6] Paravina RD, Majkic G, Perez MDM, Kiat-Amnuay S. Color difference thresholds of maxillofacial skin replications. *J Prosthodont*. 2009;18(7):618-25.

[7] Milburn PB, Sian CS, Silvers DN. The color of the skin of the palms and soles as a possible clue to the pathogenesis of acral-lentiginous melanoma. *Am J Dermatopathol*. 1982;4(5):429-33.

[8] Chung DH, Sapiro G. Segmenting skin lesions with partial differential-equations-based image processing algorithms. IEEE Trans Med Imag. 2000;19:763–767.

[9] Bilal S, Akmeliawati R, Salami MJE, Shafie AA. Dynamic approach for real-time skin detection. *J Real Time Image Process*. 2015;10:371–385.

[10] Brancati N, Frucci MD, Pietro G, Gallo L. Dynamic clustering for skin detection in YCbCR colour space. *Pattern Recogn Inform Process*. 2016;49–53.

[11] Jones MJ, Rehg JM. Statistical color models with application to skin detection. *Int J Comput Vis*. 2002;46:81–96.

[12] Xiao K, Zardawi F, Noort RV, Yates JM. Color reproduction for advanced manufacture of soft tissue prostheses. *J Dent*. 2013;41(5):e15–e23.

[13] Xiao K, Zhu Y, Li CJ, Connah D, Yates JM, Wuerger S, Improved method for skin reflectance reconstruction from camera images. Opt Express. 2016; 24(13): 14934-14950.

[14] Wang RY, Su QS, editors, Exercise physiology, People's Physical Education Press, Beijing, 2012.

[15] Armstrong N, Welsman JR. Peak oxygen uptake in relation to growth and maturation in 11- to 17-year-old humans. *Eur J*

Appl Physiol. 2001;85(6):546-51.

[16] Changizi MA, Zhang Q, Shimojo S. Bare skin, blood and the evolution of primate colour vision. *Biol Lett*. 2006;2(2):217-221.

[17] Changizi MA, Rio K. Harnessing color vision for visual oximetry in central cyanosis. *Med Hypotheses*. 2010;74(1):87-91.

[18] Berns RS, Principles of Color Technology, 3rd Edition, page 97, John Wiley & Sons, Inc., 2000.

[19] Huang M, Cui GH, Melgosa M, Sánchez-Marañón M, Li CJ, Luo MR, Liu HX, Power functions improving the performance of color-difference formulas, *Opt Express*. 2015;23(1):597-610.

[20] CIE Publication 015:2018, Colorimetry, fourth edition, Vienna, CIE, 2018.

[21] Li CJ, Li ZQ, Wang ZF, XU Y, Luo MR, Cui GH, Melgosa M, H. Brill M, Pointer M. Comprehensive color solutions: CAM16, CAT16, and CAM16-UCS. *Color Res Appl*. 2017;42:703–718.

[22] Cabral MMS, Bos AJG, Amano H, Seino S, Shinkai S. Relationship between skin color, sun exposure, UV protection, fish intake and serum levels of vitamin D in Japanese older adults. *Nutrition and Food Science* 2017;47(3):409-442.

[23] Zonios G, Bykowski J, Kollias N. Skin melanin, hemoglobin, and light scattering properties can be quantitatively assessed in vivo using diffuse reflectance spectroscopy. *J Invest Dermatol*. 2001;117(6):1452-7.

[24] Zonios G, Perelman LT, Backman V, Manoharan R, and Feld MS. Diffuse reflectance spectroscopy of human adenomatous colon polyps in vivo. *Appl Opt*. 1999;38(31):6628-37.

[25] Chen HY, Robinson JK, Jablonski NG. A cross-cultural exploration on the psychological aspects of skin color aesthetics: implications for sun-related behavior. *Transl. Behav. Med.* 2020;10(1):234:243.

[26] Kim KH. Heat-related skin disease. *J. Korean Med. Assoc.* 2019;62(4):187-192.

[27] Amano K, Xiao K, Wuerger S, Meyer G- A colorimetric comparison of sunless with natural skin tan. *Plos One* 2020;15(12):e0233816.

AUTHOR BIOGRAPHIES

Li Jiang is an associate Professor in the School of Sports Education, University of Science and Technology Liaoning, Anshan, China. She received her B.Ed. in sports science in 1979 from Shenyang Sport University. Currently, she is interested in skin appearance variations before and after the sports exercises.

Han Wang is a graduate student in the Department of Computer Science, University of Science and Technology Liaoning, Anshan, China, where he received his BS in computer science in 2019. His current research interests are colour and imaging science.

Xiaohui Zhang is a research assistant in the Department of Software Engineering, University of Science and Technology Liaoning. He received BS (2017), and MS (2020) degrees respectively from this university. His current research interests are colour and imaging science.

Cheng Gao is a research assistant in the Department of Computer Science, University of Science and Technology Liaoning. He received BS (2015), and MS (2018) degrees in software engineering from this university. His current research interests are spectrum optimization of LED, color appearance modeling, and mesopic luminance computation.

Kaida Xiao is an Associate Professor in the Colour and Imaging Science in the School of Design, University of Leeds, UK. His research interests are 3D colour image reproduction, 3D colour printing, 3D printing facial prostheses, medical image capture and analysis, colour appearance modelling and image quality enhancement.

Manuel Melgosa is a full professor in optics and associate editor of this journal. He is the representative of Spain at CIE Divisions 1 and 8, serving also as member of CIE TCs 1-98, 8-14, 8-17 and JTC 10 (D1/D8). He is Vice-president of the Lighting Committee of Spain, and Secretary of the Color Vision and Psychophysics Study Group of the International Color Association (AIC). His main research interests are color-difference evaluation and applied colorimetry.

Changjun Li is Professor in the Department of Computer Science, University of Science and Technology. He received BS (1979), MS (1982), PhD (1989) degrees in computational mathematics from Peking University, China, Chinese Academy of Science, Beijing, China, and Loughborough University, United Kingdom, respectively. His current research interests are chromatic adaptation transform, colour appearance modeling, uniform colour spaces, and computational colour constancy. Currently he is the chair of CIE JTC 10 (D1/D8).