

# Relationships between Solar Ultraviolet Exposure Levels at Different Sites around the Body

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## ABSTRACT

**Introduction:** Ultraviolet light (UV) has both beneficial and detrimental effects on the human body. To identify the optimal UV exposure levels, we would ideally need to know the actual levels of UV exposure at all body sites. However, attaching sensors to every site is not feasible, so a means of estimating the exposure levels on the basis of measurements made at a representative site is necessary. This study had two aims: to clarify the convertibility of UV exposure level measurements between several skin sites and to examine the effects of behavior and weather on the applicability of conversion factors among the sites.

**Methods:** UV exposure level measurements at skin sites (face, chest, wrists, legs, and shoulders) were made in 17 participants during the autumn and winter of 2016. The correlations ( $\beta$ -coefficients) between the UV exposure energy at each site were analyzed, and the influence of behavior and weather on the relationships between the UV exposure readings among the exposed skin sites was separately examined.

**Results:** We found a fairly strong relationship between the UV exposure measurements among the exposed body sites, and the  $\beta$ -coefficients for two conditions (restricted and unrestricted behaviors) were statistically significant in all sites. By contrast, the influence of weather conditions on the conversion factors was small and statistically insignificant.

**Conclusions:** It is possible to accurately estimate the UV exposure levels at various body sites on the basis of exposure measurements made at a representative site. This finding should be of great help in identifying the optimal UV exposure level.

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**KEYWORDS:** exposure assessment, solar ultraviolet exposure level, body sites, conversion factors, optimal UV exposure level

## Introduction

We are all exposed daily to ultraviolet (UV) light, which has both beneficial and detrimental effects on the human body.<sup>1–3)</sup> Excessive exposure can lead to conditions such as skin cancer,<sup>4)</sup> cataracts, and pterygium,<sup>5)</sup> whereas under-

exposure (or insufficient exposure) adversely affects vitamin D production,<sup>6,7)</sup> which can lead to problems such as rickets, osteoporosis, and decreased immunity.<sup>2)</sup> However, the optimal level of UV exposure remains unknown.

To elucidate the pathology of diseases caused by UV exposure, measurements of the actual levels of exposure at

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the sites where the diseases develop would be very useful.<sup>8)</sup> Likewise, precise measurements of the exposure levels at all exposed skin sites would greatly aid investigations into the association between UV exposure and vitamin D production.<sup>9)</sup> However, attaching sensors to all exposed skin sites is not a realistic option in epidemiologic studies,<sup>10)</sup> so sensors attached to representative sites are used to estimate the exposure levels at other sites.

Humans show no major geometric differences according to characteristics such as age and sex, so the ratios of illuminance between illuminated surfaces (or between the coronal plane (anatomical plane, known as the frontal plane, which divides the body into belly and back sections), sagittal plane (or longitudinal plane that divides the body into right and left parts), and horizontal plane) are similar from person to person. If this relationship can be clarified, conversion factors can be applied to the UV exposure levels measured at a representative site (e.g., the wrist) to estimate the exposure levels at other sites. However, the influence of several factors needs to be considered in determining these conversion factors: first, different people move in different ways and to varying degrees and second, optical properties, such as the intensity and scattering of UV light, vary according to the weather.

Thus, the present study had two aims: to determine whether conversion factors can be used to estimate the UV exposure levels in various human skin sites and to examine whether individual behavior and weather affect the conversion factors. Determination of appropriate conversion factors would allow the UV exposure levels over the entire human body to be estimated with a high degree of accuracy based on values obtained by sensors attached to a representative site; this would greatly contribute to the determination of an optimal UV exposure level.

## Methods

### Participants

Measurements of the UV exposure levels were conducted in 17 participants (3 men and 14 women with a mean age of  $22.2 \pm 0.5$  years [SD]). Sensors were attached to all sites where UV exposure could be expected (face, chest, wrists, legs, and shoulders), and the exposure levels were measured. However, because of the limited number of devices (25), sensors were primarily attached to the face (which is always widely exposed to UV) and to the wrists and chest (sites that have been frequently used in earlier studies). The study protocol was approved by the Tokai

University Institutional Review Board for Human Research (16089), and informed consent was obtained from all participants.

### Measurement devices

We used a custom-made visible light/UV light measurement system (Ray Sensing Glass System, RaySeG, Fig. 1A [a]). This measurement system comprises a UV light sensor (G5842, Hamamatsu Photonics K.K.) sensitive to UV-A (400-315 nm) and UV-B (315-280 nm) and a visible light sensor (S9706, Hamamatsu Photonics K.K.). The light energy ( $W/cm^2$ ) irradiated to the sensor was measured at a sampling frequency of 1 kHz (recording frequency of 1 s) under conditions synchronized with human behavior; data were recorded on a micro SD card. We have previously reported the accuracy and validity of this system, as well as its applicability to epidemiological investigations.<sup>11, 12)</sup>

UV energy irradiated to the face was measured using eyeglass sensors (Fig. 1A[a, b]) in participants who did not regularly wear eyeglasses, whereas in those who did, a sensor was attached to the frame of their eyeglasses (Fig. 1A[c]). Flat sensors were directly attached to the skin or clothing to measure UV energy irradiated to the other attachment sites (Fig. 1A[d], 1B). Data were recorded under multiple synchronized conditions by the synchronous terminals in the RaySeG device (Fig. 1A[a]).

### Measurement location

Measurements were conducted in an open park (35.4 N, 139.3 E) with a circular concrete walkway and an outer circumference of approximately 250 m (Fig. 1C). The walkway was approximately 3-m wide. The area within the walkway was laid out to grass, and the area outside it was also mainly grass with some cobblestones. There were a few benches and trees at the outer edges of the park, but no significant shadows were cast on the participants when the measurements were made.

### Measurement conditions

We separately examined the effects of the participants' behavior and the weather, the two factors we believed might affect the relationships between the UV exposure levels at different sites. To examine the effects of behavior, we compared measurements taken under two behavioral conditions: (1) restricted behavior and (2) unrestricted behavior.

Under condition (1), participants were asked to walk around the circular walkway at normal walking speed (4-5 km/h) for 15 min. They walked in groups, with enough distance between them to avoid casting shadows over each

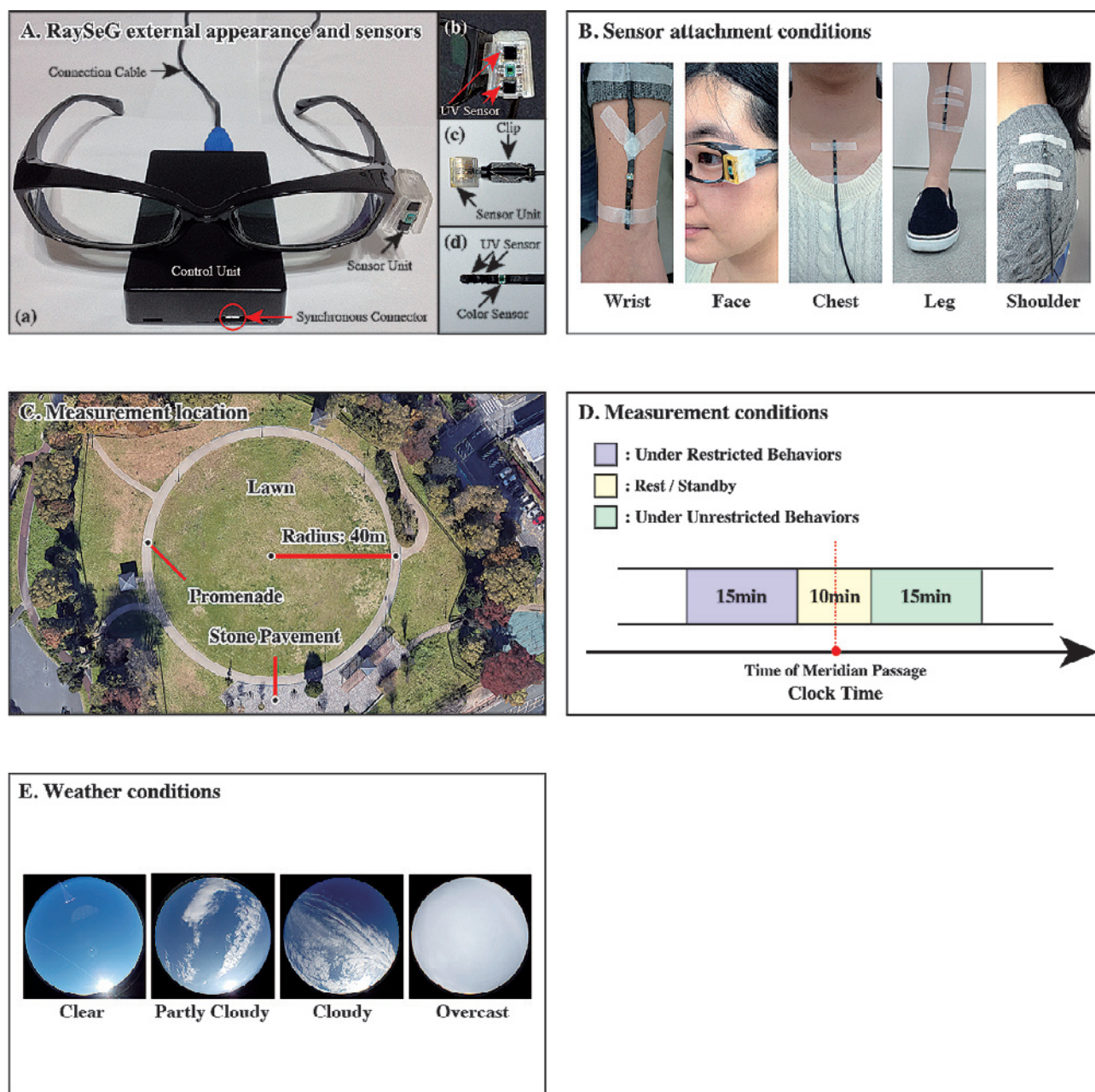


Fig. 1 Measuring device and measurement conditions

- A RaySeG external appearance and sensors
- B Sensor attachment conditions
- C Measurement location
- D Measurement conditions
- E Weather conditions

other, and were instructed to look straight ahead and walk straight. They were allowed to engage freely in conversation as measurements were taken.

Under condition (2) (unrestricted behavior), participants were allowed to roam freely around the park for 15 min. Although free to do whatever they liked in other respects, the participants were, however, restricted from leaving

the experiment site (i.e., the park) or entering any shaded areas.

To avoid differences in the UV exposure levels due to changes in solar altitude, all measurements were taken for 20 min before and 5 min after solar culmination (when the sun is at its highest point) (Fig. 1D). In addition, UV sensors were placed on the ground to confirm that there were no

changes in environmental UV levels due to changes in the weather before and after solar culmination.

To examine the effects of the weather on the relationships between the UV exposure levels at different skin sites, we qualitatively classified the level of cloudiness using all-sky photographic images taken on a smartphone (iPhone, Apple Inc.) equipped with a fisheye lens (angle of view: 230°, NELOMO) in the center of the circular walkway (Fig. 1E). First, the weather was classified into four types according to the level of cloud cover: clear (no clouds at all), partly cloudy (clouds were present, but the sun was not hidden), cloudy (the sun was visible but covered by clouds), and overcast (the sun could not be seen through the clouds). Because of the small sample size, the categories were then reduced to two, based on whether the sun was covered by clouds or not: fine (clear or partly cloudy) and cloudy (cloudy or overcast).

#### Measurement period

Measurements were taken on a total of 21 days between October 7, 2016 (culmination time: 11:31, solar elevation at the time of culmination: 50.0°), and November 14, 2016 (culmination time: 11:27, solar elevation at the time of culmination: 36.3°) (no measurements were taken on rainy days). The weather was clear on 6 of the 21 days, partly cloudy on 4, cloudy on 4, and overcast on 7. The mean number of participants involved on each day was 4.0.

#### Data processing

UV exposure energy ( $\text{J}/\text{cm}^2$ ) at each sensor attachment site was calculated by integrating UV irradiance ( $\text{W}/\text{cm}^2$ ), as measured using the RaySeG devices, with time under each measurement condition (restricted behavior/unrestricted behavior, 15 min each); the devices were pre-calibrated to assure that the accuracy and detection limit of each one were equal. Exposure energies at the attachment sites (face, chest, wrists, legs, and shoulders) were compared, with the wrist site used as reference, because the wrist is a realistic sensor attachment site for epidemiological studies, and actually, many studies have used wristwatch-type sensors for UV exposure monitoring purposes. Correlations between the UV exposure energy levels in the various sites were analyzed on the assumption that the correlations between environmental UV light and exposure at all sites were linear (i.e., as environmental UV light decreased, exposure decreased in the same ratio at all sites). Linear regression analyses were performed with no constant terms to estimate the conversion factors ( $\beta$ -coefficients, inclination of linear regression formula) and

correlation coefficient for the face, chest, legs, and shoulders. Each model included UV exposure energy as measured at the wrist as a dependent variable and UV exposure energy at one of other sites as an independent variable. The influences of behavior and weather on the conversion factors for the exposed sites were separately examined by including each of them as an interaction term. A likelihood ratio test was performed to determine the significance of interaction. STATA Special Edition ver. 14.2 (StataCorp LLC, USA) was used for statistical analyzes. The statistical significance level was set at 5% (two-tailed test).

## Results

### Typical example of individual UV exposure levels over time

Fig. 2 shows the changes in the UV exposure levels in a selected participant who attached sensors to five body sites (wrists, face, chest, legs, and shoulders) during a 15-min period (under both restricted and unrestricted behaviors) before and after solar culmination (11:27, solar altitude: 43.1°) on a partly cloudy day.

Under restricted behavior (11:07-11:22), five characteristic peak UV exposure patterns were obtained when the representative participant walked on the circular walkway.

The sensor attachment surfaces can be categorized as coronal (face, chest, and legs), sagittal (wrists), and horizontal (shoulders). The peak pattern showed the same phase for each surface category. Specifically, the phases for the face, chest, and legs (with the sensors in the coronal plane) were similar, and a phase difference of approximately 90° was observed between these and the wrists (sagittal plane). Moreover, the peak pattern for the shoulder was recorded at a phase close to that of the wrists because of the solar altitude (close to 45°) on the measurement day.

The UV exposure patterns were obtained when the participant was under unrestricted behavior (11:32-11:47, subject playing badminton) and provided more detailed motion records than those obtained when the participant's behavior was restricted, but the phases of the waveform patterns on each surface were the same under both behavioral conditions.

The cumulative UV exposure energies (and powers) over 15 min when the representative participant was under restricted behavior (Fig. 2A) were as follows: wrist,  $1.0 \text{ J}/\text{cm}^2$  ( $1.1 \text{ mW}/\text{cm}^2$ ); face,  $0.68 \text{ J}/\text{cm}^2$  ( $0.76 \text{ mW}/\text{cm}^2$ ); chest,



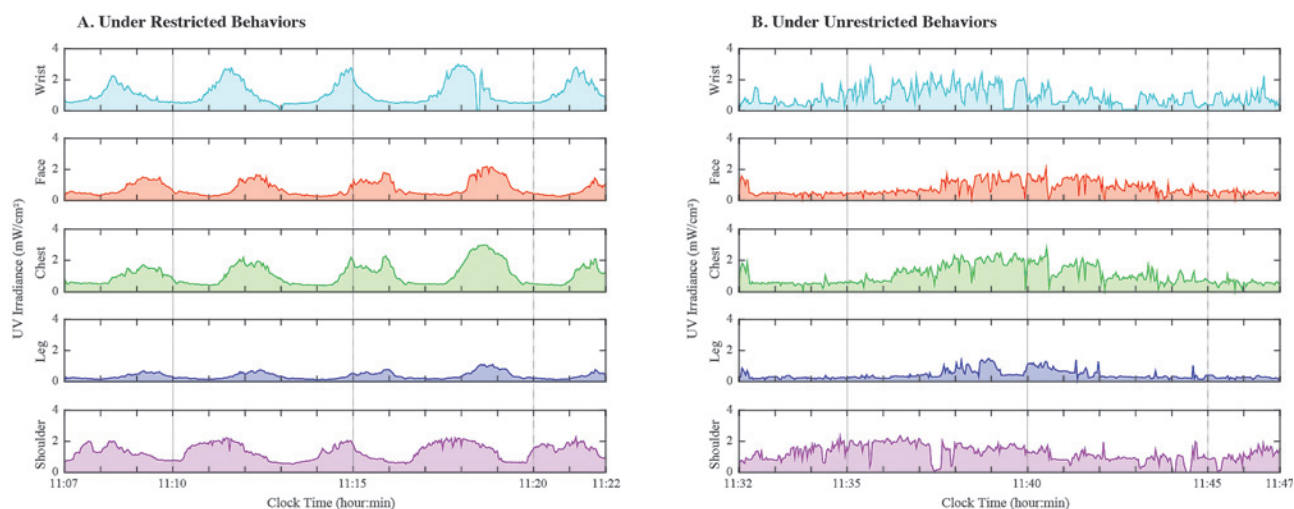


Fig. 2 Typical examples of changes in the UV exposure levels over time

0.98 J/cm<sup>2</sup> (1.1 mW/cm<sup>2</sup>); leg, 0.32 J/cm<sup>2</sup> (0.36 mW/cm<sup>2</sup>); and shoulder, 1.2 J/cm<sup>2</sup> (1.3 mW/cm<sup>2</sup>). In contrast, the cumulative energies when the participant was under unrestricted behavior (Fig. 2B) were wrist, 0.80 J/cm<sup>2</sup> (0.89 mW/cm<sup>2</sup>); face, 0.68 J/cm<sup>2</sup> (0.76 mW/cm<sup>2</sup>); chest, 0.96 J/cm<sup>2</sup> (1.1 mW/cm<sup>2</sup>); leg, 0.38 J/cm<sup>2</sup> (0.42 mW/cm<sup>2</sup>); and shoulder, 1.1 J/cm<sup>2</sup> (1.2 mW/cm<sup>2</sup>).

#### Effect of behavior on the conversion factors

Fig. 3 shows a scatter plot of UV exposure (J/cm<sup>2</sup>) at each attachment site against that at the wrist (reference), according to behavior category. The correlation coefficients were high at 0.91-0.99. The total exposure according to behavior category in the selected representative participant described above is highlighted in Fig. 3. Fig. 3 also shows the regression lines obtained in a linear regression analysis (no constant term) performed for each behavior category. The  $\beta$ -coefficients of each regression line (and confidence intervals) are shown in Table 1.

The  $\beta$ -coefficients for measurements made under unrestricted behavior were statistically significantly smaller than those for restricted behaviors in all sites. However, the differences in  $\beta$ -coefficients due to behavioral changes were small, with a decrease of approximately 9% at most noted.

#### Effect of weather on the conversion factors

Fig. 4 shows a scatter plot of UV exposure (J/cm<sup>2</sup>) at each attachment site (the wrist was again used as the reference) according to weather conditions (fine vs. cloudy). The correlation coefficients were high at 0.94-0.99. No constant term linear regression analysis was performed, and the regression lines obtained are shown in Fig. 4. The  $\beta$ -

coefficients (and confidence intervals) are shown in Table 2. There were no differences in the  $\beta$ -coefficients between fine and cloudy weather at all sites. Because different behaviors (restricted/unrestricted) affected the  $\beta$ -coefficients of the regression lines (as shown in Fig. 3 and Table 1), we repeated the analysis after stratifying for behavior (Fig. 5, 6, Table 2). The weather had no effect on the  $\beta$ -coefficients for any of the sites or either behavior.

## Discussion

Under the hypothesis that humans vary little in shape and size and that there must, therefore, be a relationship between the UV exposure levels at various sites on the body, we tried to identify correlations and establish a conversion factor that would allow us to estimate the UV exposure levels at various sites on the basis of measurements taken at a representative site. Our results showed a high level of correlation among the sites, suggesting that our hypothesis was correct. We found that although the conversion factor was mildly affected by behavior, it was not significantly influenced by the weather.

Taking the human body as a simple cube, we can categorize the skin surfaces selected for the present study as coronal (face, chest, and legs), sagittal (the wrists), and horizontal (the shoulders). Similar UV exposure patterns were obtained for the sites belonging to the same category. The phases of exposure patterns for the face, chest, and legs were similar, and a phase of 90° was noted between the wrist and shoulders with participants under restricted behavior (walking in a circular direction) (Fig. 2), supporting the existence of a relationship among the sites.

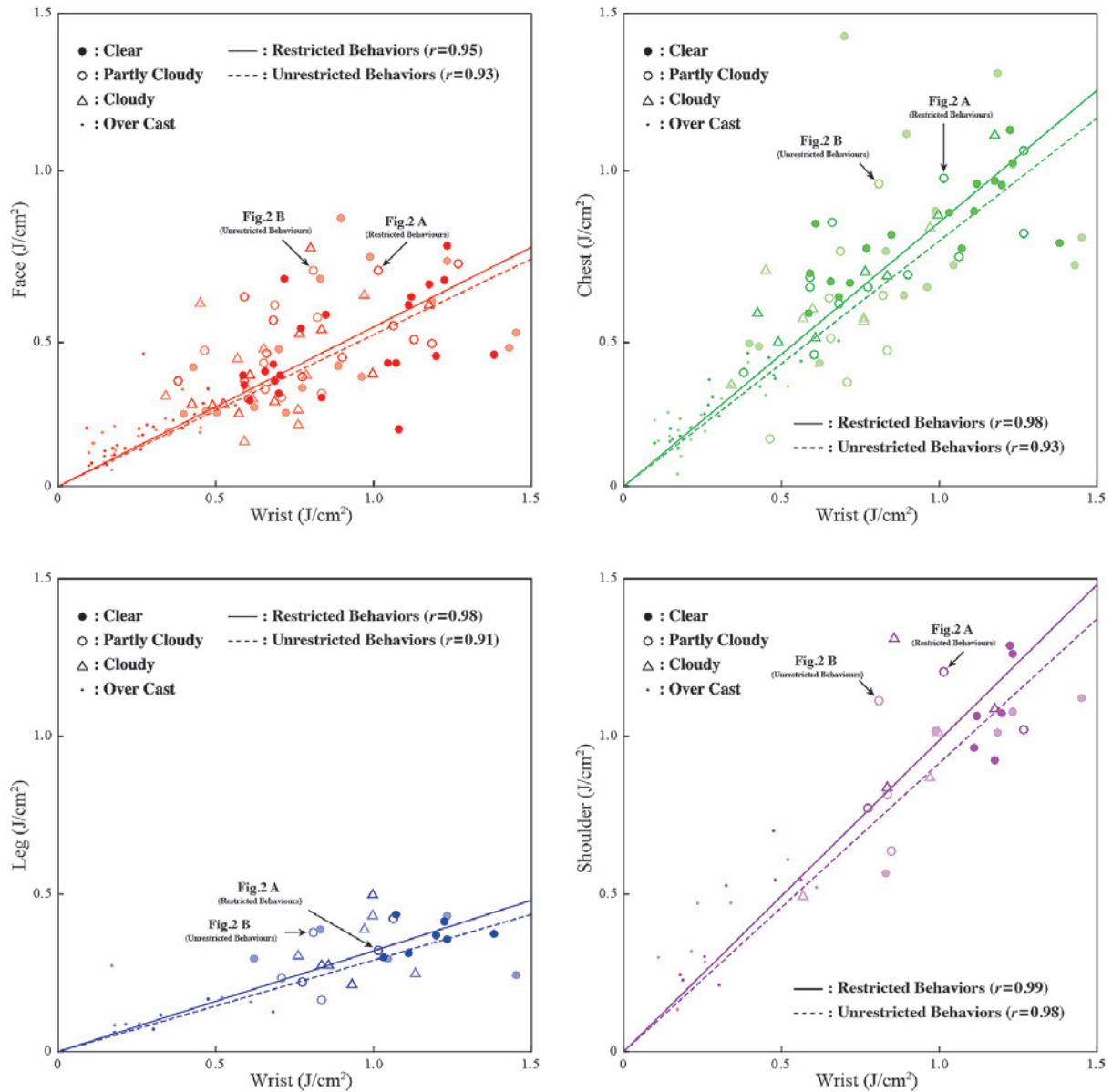


Fig. 3 Correlation among sensor attachment sites under different behavioral conditions

Table 1 Regression analysis of sensor attachment sites under different behavioral conditions

Independent Variable	Dependent Variable	Behavioral Conditions						<i>p</i> -values
		Under Restricted Behaviors			Under Unrestricted Behaviors			
		<i>n</i> (pairs)	β-coefficient	95% Conf. Interval	<i>n</i> (pairs)	β-coefficient	95% Conf. Interval	
Wrist	Face	69	0.51	(0.47-0.54)	61	0.48	(0.43-0.53)	0.003
	Chest	56	0.84	(0.80-0.88)	50	0.78	(0.69-0.87)	0.024
	Leg	20	0.32	(0.29-0.35)	19	0.29	(0.23-0.35)	0.001
	Shoulder	20	0.99	(0.90-1.07)	19	0.91	(0.82-1.01)	0.009

We defined the relationship between the ground and surface of each attachment site as a dihedral angle (at an angle of 180° (or 0°), the two planes were parallel, and at 90°,

the two surfaces were perpendicular). A dihedral angle decreased in the order of the wrist, chest, face and leg. Thus, the UV exposure level of the chest was smaller than the

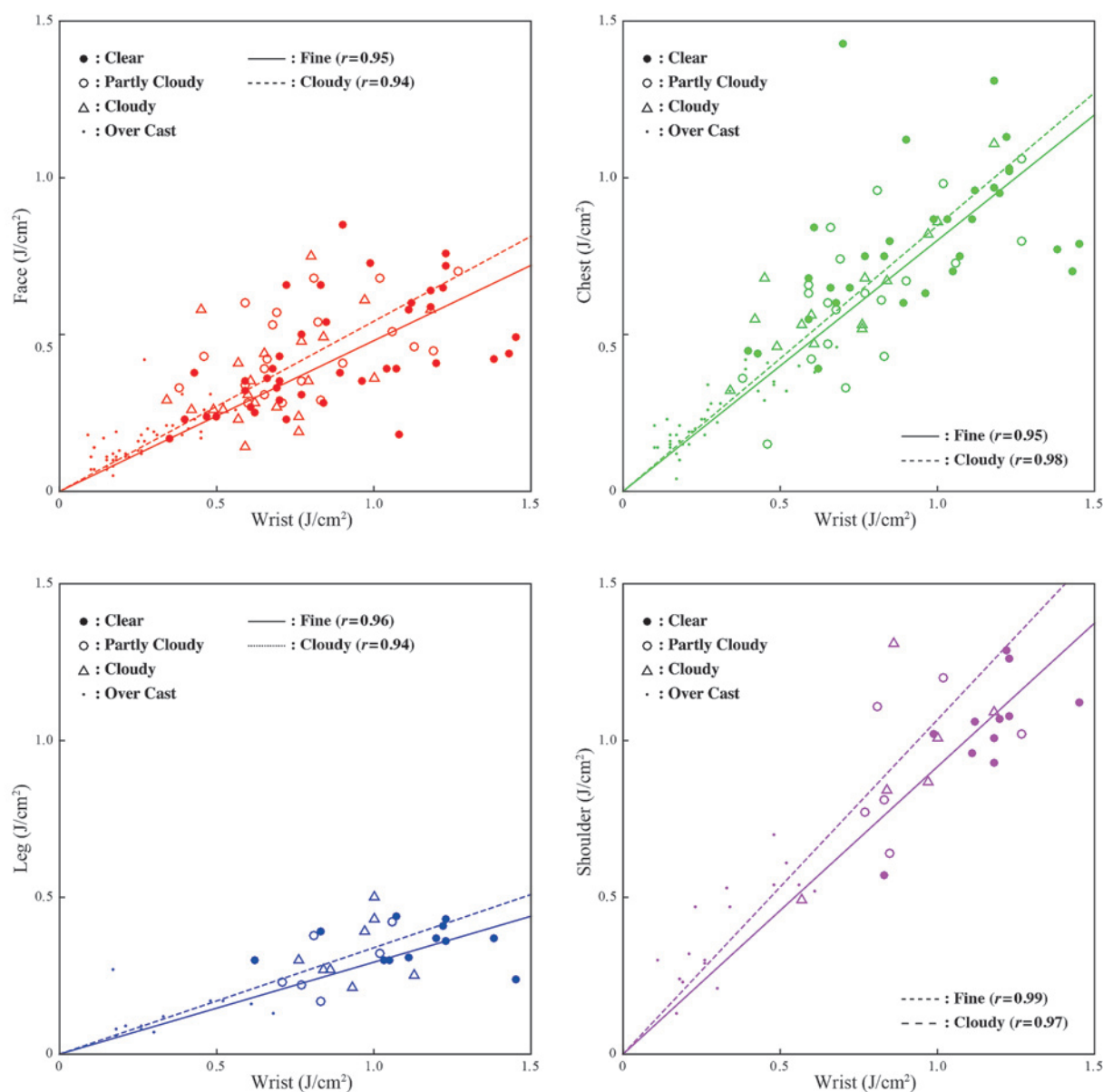


Fig. 4 Correlation among sensor attachment sites under different weather conditions

wrist, and the level of the face was smaller than the chest; furthermore, the exposure level of the leg was the lowest UV exposure value. With a dihedral angle of  $180^\circ$  between the shoulders and the ground, the shoulders might be expected to show the highest UV exposure level. However, because the measurements were made in late autumn/early winter and the solar altitude was relatively low (mean altitude:  $43.3^\circ$ ), the incident angles of the wrist and shoulders were almost equal, probably explaining why the exposure levels of the wrists and shoulders were comparable.

Similar to our study, others have shown that the shoulders and neck receive high doses of UV radiation, whereas

the legs receive low doses.<sup>10,13,14</sup> On the other hand, large variations in the exposure levels have been reported for the face and chest, and especially for the wrists<sup>10,13-20</sup>; in our study, the wrists showed the highest UV exposure, whereas several earlier studies found higher exposure in other sites (e.g., chest, face).<sup>10,13</sup> We believe that because wrist sensors are easily hidden by clothes, exposure levels were probably underestimated in these earlier studies.<sup>21</sup> In our study, all participants' sleeves were fixed to the upper arm with special bands, so there was little possibility of underestimation.

With the wrist used as a reference, the conversion factors for UV exposure found in various studies have varied

Table 2 Regression analysis of sensor attachment sites under different weather conditions

Behaviors	Independent Variable	Dependent Variable	Weather Conditions						<i>p</i> -value
			<i>n</i> (pairs)	Fine $\beta$ - coefficient	95% Conf. Interval	<i>n</i> (pairs)	Cloudy $\beta$ - coefficient	95% Conf. Interval	
All Behaviors	Wrist	Face	64	0.48	(0.44-0.52)	66	0.54	(0.49-0.59)	0.63
		Chest	53	0.80	(0.73-0.87)	53	0.85	(0.80-0.89)	0.91
		Leg	19	0.29	(0.25-0.34)	20	0.34	(0.28-0.40)	0.95
		Shoulder	17	0.92	(0.84-0.99)	22	1.1	(0.95-1.2)	0.95
Under Restricted Behaviors	Wrist	Face	35	0.49	(0.44-0.54)	34	0.55	(0.49-0.61)	0.83
		Chest	29	0.83	(0.77-0.89)	27	0.86	(0.81-0.92)	0.99
		Leg	10	0.32	(0.28-0.35)	10	0.33	(0.25-0.41)	0.49
		Shoulder	9	0.94	(0.84-1.0)	11	1.1	(0.94-1.3)	0.57
Under Unrestricted Behaviors	Wrist	Face	29	0.47	(0.40-0.54)	32	0.53	(0.45-0.61)	0.59
		Chest	24	0.77	(0.63-0.91)	26	0.82	(0.74-0.91)	0.82
		Leg	9	0.26	(0.17-0.36)	10	0.35	(0.25-0.45)	0.90
		Shoulder	8	0.89	(0.73-1.0)	11	1.0	(0.85-1.20)	0.44

widely: from 1.2 to 3.2 for the shoulders, from 0.8 to 1.4 for the face, from 0.9 to 2.3 for the chest, and from 0.3 to 1.7 for the legs.<sup>10, 13-20</sup> Such inconsistencies can probably be largely explained by variations in participants' personal behaviors. For instance, if a participant spent an extended period lying on the ground,<sup>10</sup> UV exposure in the legs would increase, with concomitant effects on the conversion factor. Thus, direct comparisons among conversion factors for UV exposure are difficult.

Differences in personal behavior and weather can influence the conversion factors between the exposed sites. For example, humans tend to unconsciously avoid direct exposure to bright light by looking down. Thus, the conversion factors will vary according to whether participants' behavior is restricted or unrestricted. And indeed, we found that the UV exposure levels in the face were smaller and the  $\beta$ -coefficients of the regression lines were significantly lower when the participants were under unrestricted behavior than when they were under restricted behavior (Fig. 3, Table 1). We can assume that actual daily exposure levels are closer to those measured in our study when the participants were under unrestricted behavior. However, the differences between the  $\beta$ -coefficients measured under the two behavior conditions in our study were quite small, with a maximum difference of only approximately 9%.

Weihls et al.<sup>10</sup> reported that the UV exposure levels in different sites on the human body depend on each site's relative position to the sun. Naturally, the UV exposure levels in surfaces facing the sun can be expected to be sev-

eral times higher than those in shadow. However, one characteristic of UV light is that it scatters, a characteristic that becomes more intense as cloud cover increases. To investigate the influence of this characteristic on the conversion factors, we analyzed our UV exposure findings under two types of weather (fine or cloudy) classified according to the level of cloud covering the sun. To our surprise, we found that the influence of weather conditions on the conversion factors was insignificant (Table 2), indicating that there is no need to use different conversion factors to compensate for different weather conditions.

This study showed that UV exposure measurements taken at a representative skin site can be used together with estimated conversion factors ( $\beta$ -coefficients) to estimate the exposure levels at other sites. Furthermore, information on sun protection measures (e.g., the use of clothing, hats, parasols, and sunscreen) can be factored in to calculate the actual level of UV exposure.

The merits of this study include first the UV measuring system we used (RaySeG), which had a high sampling capacity of up to several kHz; it was also capable of measuring momentary changes in UV energy in the participants. This compares favorably with the sampling intervals used in previous studies, which were relatively long: mostly once per hour, and once every few minutes at best. Therefore, we were able to measure reflexive reactions to bright light with much higher accuracy than seen in previous studies. Second, although many studies have investigated UV exposure in participants undertaking various activities (walking, playing tennis, swimming, etc.), few have consid-



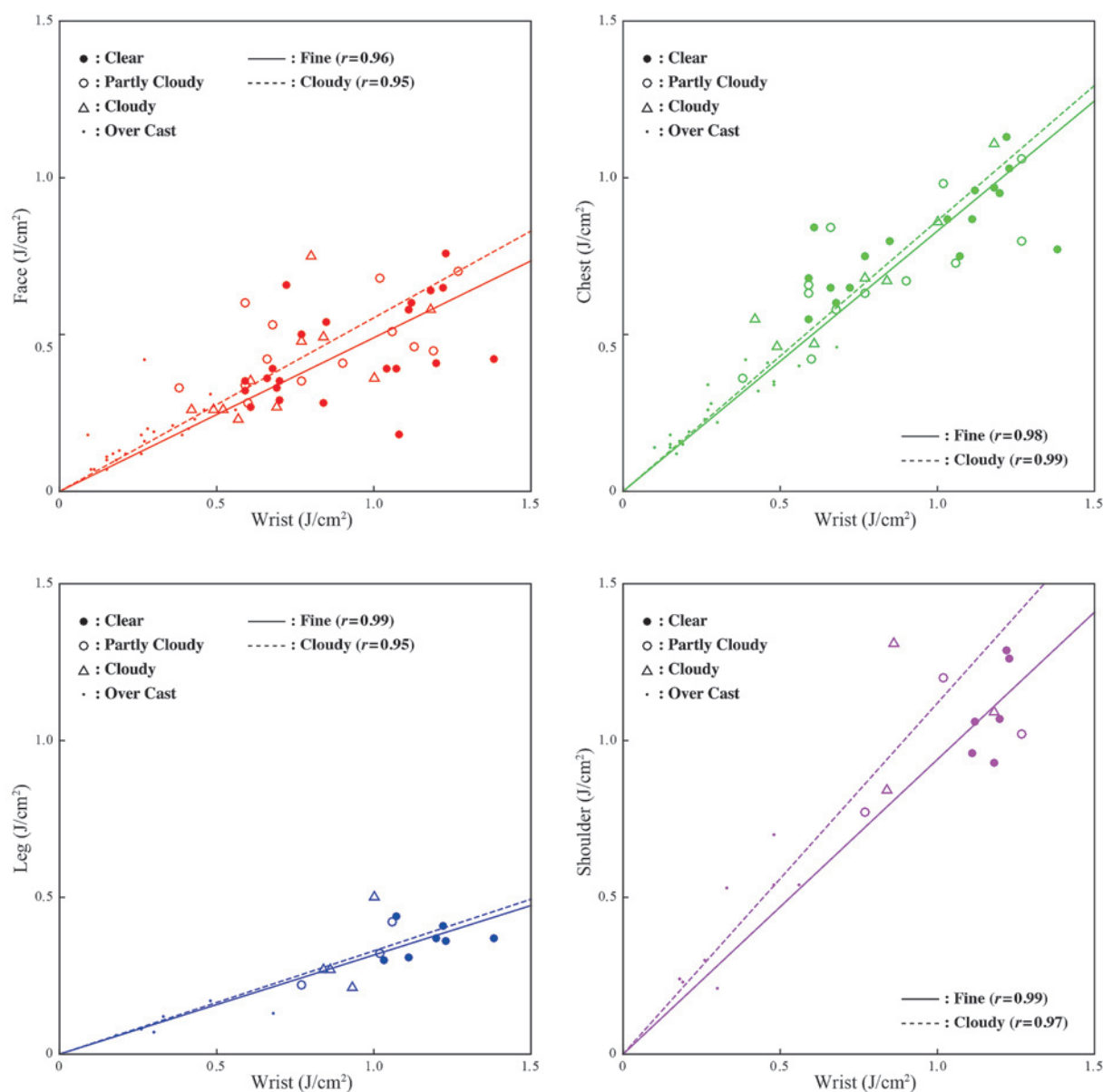


Fig. 5 Correlation among sensor attachment sites under different weather conditions under restricted behaviors

ered the effects of solar altitude. In the daytime, UV radiation intensity changes along with the sun's altitude. To avoid any influence on our results of changes in solar altitude, we took measurements for 20 min before and 5 min after solar culmination on every testing day. Therefore, because we were able to assume that the participants were receiving equal UV radiation doses under the two behavioral conditions we studied (restricted and unrestricted behaviors), we were able to investigate the differences in exposure characteristics in terms of these behavioral conditions alone.

We also have to acknowledge some limitations. First, the number of data obtained for each sensor attachment site

differed, with few measurements obtained for the legs and shoulders (Table 1, 2). There were two reasons for this: we had a limited number of measuring devices (only 25 devices), and priority was given to the site with the greatest exposure (i.e., the face) and to sites used in many earlier studies (i.e., the chest and wrists); second, the sensors (Fig. 1B) were very thin to make them easily attachable to the skin and clothes, and they are easily damaged in highly mobile sites, such as the shoulders. In the future, we believe it would be a good idea to carry out verification experiments using smaller, cordless sensors. The second limitation was that we did not investigate the effects of seasonal differences. During this study, the solar culmination

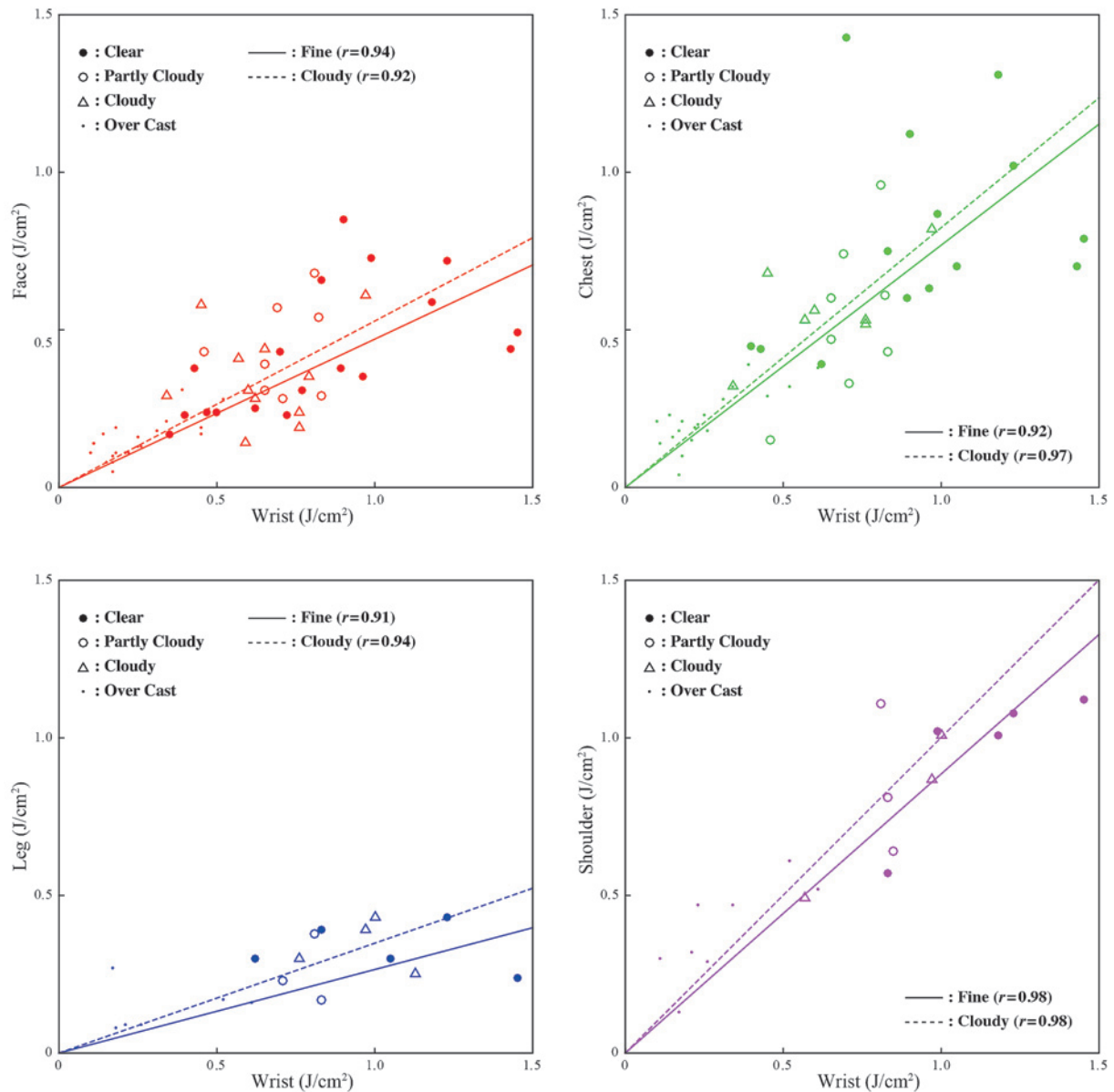


Fig. 6 Correlation among sensor attachment sites under different weather conditions under unrestricted behaviors

tion altitude was relatively low, because measurements were performed in late autumn/early winter. Solar altitude varies widely with the four seasons in Japan. For example, the culmination altitude in the park where our measurements were conducted was  $78.0^\circ$  on the summer solstice (June 21) in 2016, which was 2.5 times higher than it was on the winter solstice (December 21) in the same year:  $31.2^\circ$ . It is reasonable to assume that UV measurements taken in the shoulders (horizontal plane) are strongly influenced by the sun's altitude. Further studies in other seasons are necessary to take account of such differences.

Several studies on UV exposure and health have been

carried out, but the demarcation level that can be used to determine whether one's UV exposure is excessive or insufficient—the so-called optimal UV level—remains unknown.<sup>7,22)</sup> One reason for this is that the UV exposure levels at various exposed skin sites cannot be quantified simultaneously with constant precision and validity. The conversion factors among the various sites determined through the measurements made in the present study make it possible to estimate the UV exposure levels at individual sites more accurately, which should greatly contribute to efforts to determine the optimal UV exposure levels.

## Conclusion

It is possible to accurately estimate the UV exposure levels at various body sites on the basis of exposure measurements made at a representative site. This finding should be of great help in identifying the optimal UV exposure level.

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**Conflicts of interest:** None declared.

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