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Variability in coefficient of restitution in human facial skin

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Abstract

Background—If particles rebound on human facial skin, they can be re-entrained into the airflow and subsequently inhaled, increasing aspiration efficiency estimates. A realistic estimate of facial skin coefficient of restitution (CoR) is necessary to accurately model particle bounce. This study investigated the effects of sampling location, temperature, humidity levels, age, gender, and BMI on facial skin CoR.

Methods—A torsional ballistometer was used to measure facial CoR for 30 participants divided into three age groups (18–30, 31–40, and 41–65 years), at three temperatures and three humidity levels. The study was repeated twice: once in the late winter and once in the early summer to capture the seasonal variability.

Results—The CoR significantly varied across five facial locations, with values ranging from 0.55 to 0.75. Gender, sampling season and the interaction between sampling location and age were found to be significant, but changes in values were relatively small (0.05 at most) and are not considered practically significant.

Conclusion—CoR was non-uniform across the face. The use of uniform CoR value as modeling input parameters or for mannequin facial surfaces in experimental wind tunnel studies may not be accurate due to the high variability in CoR between facial sampling locations.

Keywords

CoR; coefficient of restitution; facial skin; ballistometer

Introduction

Accurately evaluating particle deposition and inhalation requires an understanding of whether particles will deposit or rebound from skin. Human inhalability is measured using surrogate methods, such as an inhaling mannequin in a wind tunnel or computational models. In wind tunnel testing, an inhaling mannequin is placed in a wind tunnel and a uniform concentration of particles in generated upstream of the mannequin. As particles flow past the surface of the mannequin, they can strike the surface of the mannequin and deposit there, or rebound off and re-enter the airstream and then subsequently be inhaled. The surface of these mannequins has included fiberglass [1] and hard plastic or latex stretched over hard plastic [2]. If the surface of mannequin differs dramatically from human skin, this could have an impact on particle interaction with the surface and affect inhaled particle concentrations. Wind tunnel studies using mannequins have tried to eliminate bounce by greasing the surface of the mannequin, whereas others have not reported controlling for particle bounce [1, 3].

To determine if mannequins' surfaces are appropriate surrogates for human exposure and to examine particle transport following impaction on skin, an understanding of human facial skin coefficient of restitution (CoR) is necessary. The coefficient of restitution (CoR) is defined as the ratio of the rebound velocity to the impacting velocity during a collision between two objects. In aerosol science, the value is related to characteristics of both the surface material and the particle striking the surface. A CoR of 1.0 represents a perfectly elastic collision, where 100% of the velocity at impact is retained by the colliding particle, whereas a CoR of 0 represents an inelastic collision, where the particle retains zero velocity on impact and, therefore, does not bounce. The CoR is used as a measure of skin elasticity in skin research, where a high measurement (near 1) indicates a highly elastic site. The CoR of skin is important to assess skin aging [4], skin substitutes [5], scars [6, 7], dermal diseases [8], and the effectiveness of topical agents on the skin [9], although little research has explicitly examined the uniformity of human facial skin CoR.

Agreement between particle inhalability studies using mannequins to estimate human aspiration is poor. This discrepancy could be due to different surface treatments of mannequins that yield dissimilar particle–surface interactions. However, CoR of the mannequin surface–particle interaction is not typically reported. Computer models can incorporate the complex surface of the human head, where the angle of the incident particle can be accurately simulated. However, simulations require a realistic estimate of the CoR to determine how much energy results in a particle rebound vs. deposition. Previous computational studies have assumed 0 and 100% bounce (CoR = 0, 1.0) when examining particle motion into an inhaling mouth [10, 11], but realistic values lie somewhere in between.

Research has shown the coefficient of restitution for human skin to be highly variable. Tosti, et al. [12] identified variations in the CoR due to age and the area of skin being tested for 46 subjects, ranging from 8 to 80 years old. They found a progressive linear decrease in CoR with increasing age for 12 skin areas, including the left frontal eminence (forehead), and identified prominent differences in CoR between sampling sites, although the amount the CoR decreased with increasing age depended on the area of skin sampled.

Fthenakis et al. [9] found age-related and site-related differences in measured CoR using a suction cup. They reported substantial differences in temple CoR between old [mean age = 59, CoR = 0.57 (SD < 0.001)] and young [mean age = 22, CoR = 0.7 (SD = 0.01)] subjects. Decreasing elasticity with increasing age was also found for subjects 21–31 years old for skin on the cheek, temple, and wrist. The temple and the cheek within each group were found to have similar coefficients of restitution, with the authors postulating that there may be similar skin structure throughout the face.

Jemec et al. [13] found the CoR for the palm to be 0.792 (SD = 0.025), dorsal forearm to be 0.876 (SD = 0.014), and the ventral forearm to be 0.883 (SD = 0.014). This study differed from other studies in that it identified age-related changes in the palm, but not in either forearm region.

For research looking at skin properties, CoR can be measured with several different instruments, including a ballistometer or a suction cup. The ballistometer used in this study is an instrument with a rigid arm with a probe at its tip, which is elevated to a preset height and then released. The bounce amplitude and number of bounces are determined by the physical properties of the test surface, given the ballistometer settings. The literature examining the CoR for human skin is conflicting and shows a high degree of variability, which may be attributed to setting variation, including release height, of the ballistometer.

To better understand the interaction between particles and their ability to bounce on skin and possibly be inhaled, the CoRs at specific facial regions are needed, but data are limited. In addition, the effects of environmental conditions (relative humidity, temperature) on measured CoR have not been reported, which may also be important in understanding particle–skin reaction, along with factors such as age and gender.

The objectives of this study were to:

- Determine realistic CoR values across the face and evaluate whether CoR varies for different locations on the human face (cheek, forehead, nose tip, and forearm)
- Determine the effect of temperature, humidity, BMI, age, and gender on the CoR of human skin

Accurate determinations of the CoR for human skin in the facial region will not only allow the incorporation of realistic parameters into models, but will also allow for the examination of appropriate surface materials for experimental mannequins in previous and future studies investigating particle bounce. A reasonable CoR for human skin must be determined to unify both experimental and computational studies.

Methods

Sampling strategy

As shown in Fig. 1, the CoR for five locations on the human face, where previous computational studies have shown that particle bounce is most likely to occur prior to inhalation, was determined experimentally for 30 human subjects at nine different environmental conditions. The effect of age, gender, temperature, and humidity on the CoR was determined. Three equidistant measurements along the volar forearm were also taken to determine whether the forearm could be used as an acceptable surrogate for facial skin in experimental studies. Nine environmental conditions were evaluated: temperatures of 20, 25, and 30°C, and humidity levels of <25, 25–40, >40%.

The CoR values for the same five facial sampling locations used for the human subjects were measured on a resuscitation mannequin (Resusci Anne, Laerdal, Stavanger, Norway) with standard latex (2.46 mm thick) stretched over the face. Five CoR measurements were taken at each location and averaged. Only baseline environmental conditions were assessed for the mannequin.

Changes in measured CoR as a function of the release height of the ballistometer probe were also assessed. CoR was determined for one location (the wrist) at the highest release setting and lowest release setting. Five replications per each release setting were made. All measurements were made at only the baseline environmental conditions.

Study participants

Participants aged 18–65 years were recruited for this study. Subjects were stratified into three age groups: 18–29, 30–40, 41–65 years, with 10 subjects per age group (five males and five females). Subjects with a history of collagen injections, dermal disorders, or scars on the face were excluded from the study. For this sample size, we anticipated 80% probability of determining a difference of 0.3 in CoR.

Equipment

A torsional ballistometer (Dia-stron Limited, Andover, UK) was used to measure the CoR. The release height for the ballistometer was set at 2.24 mm, which corresponds to the velocity particles impact at the surface of the human face from preliminary computational fluid dynamics data. Throughout the study, measurements were made in one room, which had sealed windows and two in-room heating/cooling units (no central ventilation).

Procedure

Eligible participants were given an informed consent prior to the first testing session and completed a screening questionnaire that assessed daily skin care routines, average hydration, sunscreen use, or sun protection.

The temperature of the testing chamber was chosen to cover the range of thermal comfort standards from ASRAE 55, which recommends temperatures in the range of 20–23.3°C in the winter and 22.8–26.1°C in the summer. Temperature was controlled in the room by adjusting the room heating/cooling unit and using a space heater. Humidity levels were adjusted to targeted levels (<20, 20–40, and >40%) by running a humidifier (Vicks vaporizer, Proctor and Gamble, Cincinnati, OH, USA) or a SoleusAir Dehumidifier (Gree USA, City of Industry, CA, USA). Temperature and humidity levels were monitored using a Velocicalc (TSI, Shoreview, MN, USA). Target environmental conditions for a given test were randomly selected for each test and were set approximately 10–15 min prior to the subject entering the test room, which was sufficient time for conditions to stabilize. Subjects were placed in the test room for 5 min prior to testing.

After the subject reached equilibrium in the chamber, measurements of CoR were collected at eight areas, five areas on the face (randomly selected order) and three on the arm, with five replications per area. One temperature and humidity combination was tested each testing session. The study was repeated twice: once in the late winter/early spring and once in the late spring/early summer to capture the seasonal variability in skin moisturizing condition. Over each 5-week seasonal testing session, baseline conditions (T = 25°C, RH = 30%) were tested twice to assess variability between days.

Statistical analysis

Descriptive statistics (mean, standard deviation, and range) were computed overall test conditions by skin site and by age group, gender, temperature, and humidity combination. A general linear mixed model was developed to analyze significant covariates in predicting CoR. The mixed model was used to account for correlated measurements arising from multiple measurements on the same person including sampling location, temperature, and humidity. A compound symmetry correlation structure was used, which assumes that every observation collected from a subject is equally correlated with every other observation from that subject. More complicated correlation structures led to substantial loss of power or were not able to be fit. SAS Version 9.3 (SAS Institute, Inc., 2004) was used to perform the analyses. An alpha of 0.05 was used to determine significance.

Results

Thirty subjects were enrolled in this study. One subject dropped out after the first 5-week testing session, but all other subjects completed both 5-week testing sessions. Due to limitations with the test room, not all environmental conditions were measured for all participants. When an environmental condition could not be achieved, the actual conditions of the test room were recorded and CoR measurements were categorized using the measured environmental conditions.

Variables included in the analysis were sampling location, age group, gender, BMI, session, temperature, relative humidity, and the interaction between sampling location and age. The interaction between sampling location and age was included in the model due to results from previous studies showing that CoR decreased with increasing age differently depending on the location sampled. Participant was treated as a random effect to account for within-subject variability because the same participant was measured at multiple times.

Of the eight predictor variables, five were significant at an alpha of 0.05: sampling location, age, gender, session, and the interaction between age and sampling location. Using compound symmetry, the model had an estimated correlation near zero for the approximately 160 measurements per participant. The large number of repeated measurements per participant could account for the low correlation, but would still have a significant impact on the model.

Facial sampling location was found to be significant ($P < 0.001$). Table 1 displays the CoR by sampling location when averaged over all test conditions. The forehead, cheeks, and nose had significantly different CoR values when compared with each other using post hoc Tukey’s multiple comparisons. The cheeks, forehead, and nose had average CoR values of 0.74, 0.55, and 0.61, respectively. Although the middle forearm had similar CoR values to the cheek, the wrist and upper forearm were significantly different from any other sampling location. Symmetrical locations (i.e., left and right cheeks and forehead) did not have significant different CoR values. Overall CoR values ranged from 0.39 to 0.87, with the upper forearm having the highest values and the forehead having the lowest (Table 2).

The main effect for age was not found to be a significant predictor of CoR (P = 0.70), but the interaction between age and sampling location was statistically significant (P < 0.001). This implies that the relationship between age and CoR differed depending on sampling location, verified by plotting the CoR for each sampling location by age group (Fig. 2). Therefore, the final model included age, sampling location, and their interaction. From Fig. 2, it is apparent that CoR remains relatively constant or shows a very slight decrease with increasing age group for cheeks (left and right), nose, and arm. The CoR for the forehead (both left and right), however, shows an increase in CoR as age group increases, which was the opposite trend compared with other sampling locations. If all sampling locations showed the same trend across age groups, then the interaction would not be needed in the model. As the trend differs with sampling location, the interaction term is necessary.

Gender was also a significant factor (*P* = 0.02), although differences in CoR between genders ranged from −0.02 to 0.03, which may not be practically significant. On average, females had a higher CoR (0.69) compared with men (0.67) (Table 3).

There was almost no change in CoR values with increased temperature and humidity, and the effects were not significant (P = 0.34, 0.54, respectively) (Tables 4 and 5). Changes of 0.01–0.02 as temperature and relative humidity increased were observed, but there was no discernible pattern to the changes in CoR values. For example, the left cheek increased by 0.02 as temperature increased, but the right cheek showed no change as temperature increased. The changes in CoR value can be attributed to measurement variability and not an effect of temperature or humidity.

BMI ranged from 20 to 54 over all participants, but was not found to be a significant predictor of CoR (*P* = 0.23). CoR values differed significantly between the late winter/early spring testing session and the late spring/early summer testing session (*P* < 0.001).

CoR measurements for mannequin

The CoR averaged over all sampling locations for the mannequin's facial surface was 0.68. The CoR for the forehead was slightly lower (CoR = 0.67) compared with the cheeks (CoR = 0.68), but not significantly so (*P* = 0.35). The slight differences in CoR could be due to how tightly the latex was stretched over the plastic; the latex was looser over the cheeks compared with the forehead. The regionally averaged CoR for the human subjects across all sampling conditions was 0.64. This compares well to the mannequin's CoR of 0.68, indicating that the resuscitation mannequin may be a reasonable surrogate for human skin, if one regionally averaged CoR value can be used.

Effect of release height on CoR

The sensitivity of CoR to the release height was assessed for one location on the skin: the wrist. At the highest release setting for the probe, the CoR averaged 0.76. For the lowest release height setting, the CoR averaged 0.64.

Discussion

CoR was found to be non-uniform across the face. Differences in CoR between sampling locations on the face were as large as 0.25. Areas with less body fat, such as the forehead and nose, had lower CoRs (0.55 and 0.61, respectively) compared with the cheeks (0.74), which had more body fat. Fthenakis et al. [9]. reported CoRs for the forehead ranging from 0.57 to 0.7, for older (mean age = 59) and younger (mean age = 22) participants, respectively. CoRs for the forehead for the youngest age group in this study (18–30) were 0.535, which is much lower than those reported by Fthenakis et al. [9]. Subjects in the youngest age group were toward the upper end of the age bracket, although this is not enough to account for the difference of 0.165 in CoR observed between our results and Fthenakis et al.'s reported CoR. For the oldest age group (40–65), CoRs were 57.5, which compares well with Fthenakis et al.'s results.

Similar to other studies, CoR values were similar for symmetrical areas. This was expected as both symmetrical sides have the same underlying skin structure, thus CoR should not differ between symmetrical sampling locations. Slight differences in the CoR for symmetrical facial sampling locations, on the range of 0.03, were attributed to variability in angle of the ballistometer probe to the skin surface.

The wide range of CoR values for different sampling locations on the face, with differences as large as 0.25 between facial locations, would indicate that a uniform CoR of a mannequin's surface or uniformly applied CoR in CFD modeling may not be an appropriate assumption. To realistically estimate secondary aspiration, regionally averaged CoR values may be necessary. The effect of regionally averaged and uniform CoR values on aspiration efficiency estimates should be evaluated further.

In addition to facial sampling location, significant predictors of CoR in human facial skin were age, gender, season, and the interaction between age and site. Although these variables were found to be statistically significant predictors of human facial skin CoR, differences ranged from−0.04 to 0.07 and are not considered practically significant for assessing differences in particle bounce on human facial skin. The only factor found to be practically significant was sampling location with differences in CoR as large as 0.25 between sampling locations. The differences in CoR due to these factors would likely have a minimal effect on aspiration efficiency estimates, compared to the effect of different sampling locations.

No significant change in CoR with increasing age was found, contrary to trends published in other studies. Tosti et al. [12] reported a large decrease with increasing age for all areas of skin sampled. Although results were presented graphically by sampling location (forehead, dorsum of the hand, and medial surface of the thigh), the authors did not statistically evaluate any results. Although not explicitly evaluated, Tosti et al. [12] did note that the decrease in CoR with increasing age depended on the sampling location, which might indicate significant interaction between sampling location and age, as seen in our study. The results presented in our study compared well with Tosti et al.'s study in that it found a significant interaction between age and sampling location, although for our study, the CoR for the forehead *increased* with increasing age, whereas the other sampling locations showed flat or slight downward trends. This would indicate that as age increases, skin becomes more elastic for the forehead, but for the cheeks, nose, and arm measurements, CoR remains relatively constant as age increases. The CoRs for the forehead reported in Tosti et al. [12] was lower (0.1–0.55) compared with the CoRs reported in our study (0.39–0.84), which could also be due, in part, to different measurement techniques. The ballistometer used in their study was balanced hammer with a metallic head (500 mg) in contact with an electromagnet. To release the hammer, the circuit was broken and the rebounds measured. Similar to our study, they reported that the forehead gave some of the lowest values compared with other locations sampled and did not see significant differences between symmetrical areas (i.e., left and right forehead).

Although temperature and humidity did not significantly affect CoR values, season did have a significant effect. This could be indicative that the acclimatization period for subjects was not long enough for the surface of skin to reach equilibrium. However, additional tests were conducted and CoR did not significantly change between acclimatization periods of 2, 15, or 30 min. The significant effect of season could indicate that long-term exposure to temperature is more important than the short-term acute temperature change.

The CoR measurements for the mannequin (0.68) with latex stretched over hard plastic were within the range of CoRs measured for human skin (0.55–0.74) indicating that latex over hard plastic may be a good approximation of human facial skin and the underlying skin structures. Mannequins made entirely of hard plastic or fiberglass may not be good surrogates, however, and the CoR for these mannequin types still needs to be investigated.

Measurements were taken from locations on the arm to determine if the arm had similar CoR values as facial skin to determine if it could be an acceptable surrogate for the human face for examining particle bounce in wind tunnel experiments. While the middle forearm had similar CoR values to the cheeks, CoR values for the rest of the arm did not match CoR values from locations on the face, which would indicate that the arm is not an appropriate surrogate for human facial skin.

The release height on the ballistometer is controlled by the researcher. Typically, the release height is set at one constant value for a study. Often the release height or energy setting for the ballistometer is not reported in studies and if different settings on the ballistometer are used, this could account for some of the discrepancies seen between reported CoRs. Changes in the ballistometer release height produced a 0.12 difference in the measured CoR, indicating that it is crucial to report the settings for the ballistometer for between-researcher comparisons to be made. A difference of 0.12 between reported CoR values could potentially have a substantial impact on aspiration efficiency estimates, so for purposes of evaluating inhalability, it may be vital to report the ballistometer settings.

One important limitation of this study was that the study participants were mostly office workers who spent 90% of their time indoors away from exposure to sun and the elements, which reduces the generalizability of the results from this study. Workers who spend part of their workday exposed to sun, adverse weather conditions, or contaminants on the factory floor could have less elastic skin due to exposure to elements and thus overall lower CoR values. Although not explicitly examined in this study, it is anticipated that such populations might have overall less elastic skin, with lower CoR values.

Conclusion

CoR for human facial skin was found to vary depending on the location sampled. Areas with less body fat, like the forehead and nose, were found to have lower CoRs compared with areas with higher body fat, such as the cheeks. Although gender and season had a significant effect on facial CoR, the effect was in the range of 0.05 and was not considered practically significant. Facial CoR did not significantly change within normal workplace temperatures or humidity levels. On average, CoR for human facial skin ranged from 0.55 to 0.74, with lower CoR values being associated with regions of lower body fat. This study indicates that the underlying skin structure in the human face is, for practical purposes of assessing particle bounce, non-uniform but unaffected by factors such as gender, temperature, and humidity. This would indicate that other differences between subjects, such as skin oil levels or pore sizes, would have minimal effect on the coefficient of restitution for facial skin. The resuscitation mannequin with latex stretched over hard plastic had comparable CoR to human facial skin and may be an appropriate surrogate for experimental wind tunnel studies.

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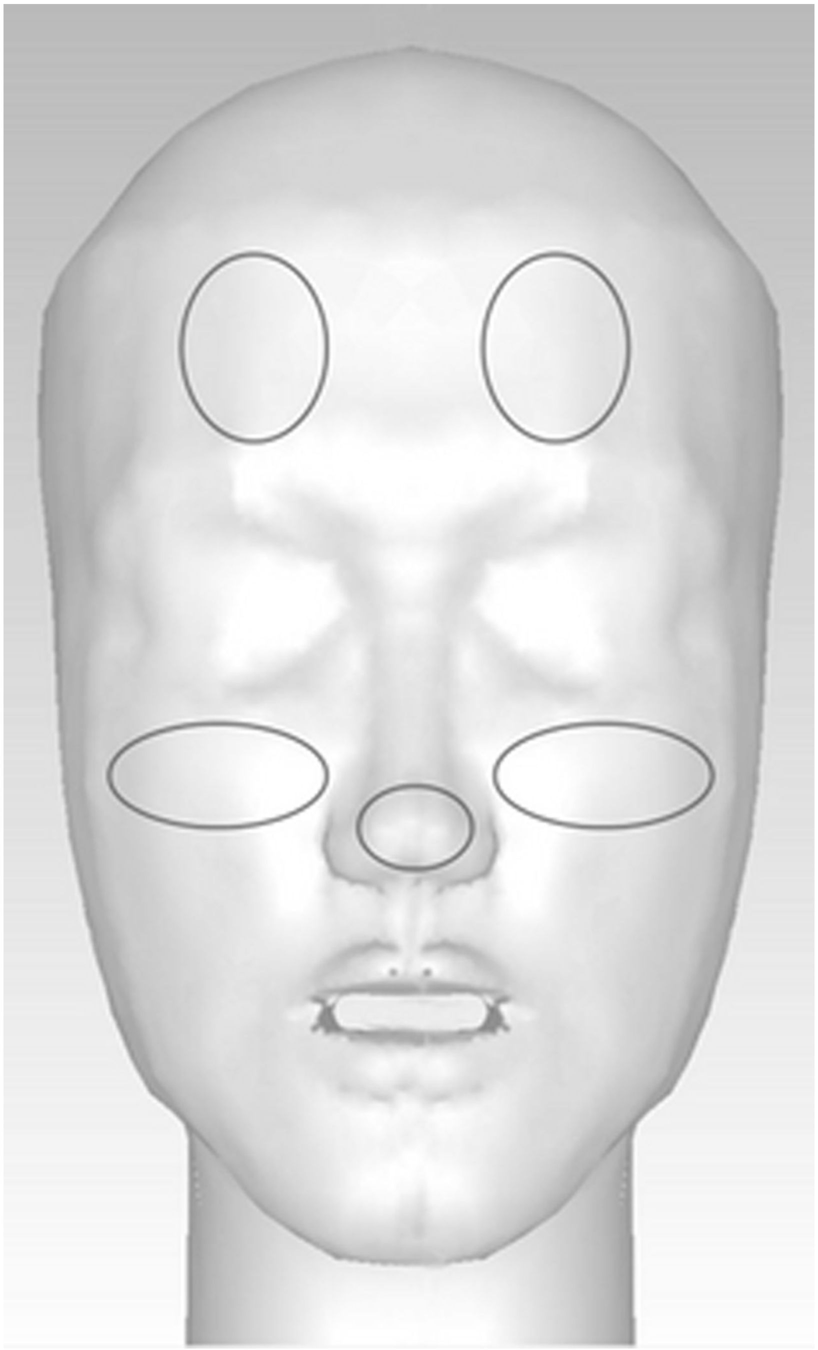

Figure 1. Sampling locations on the face

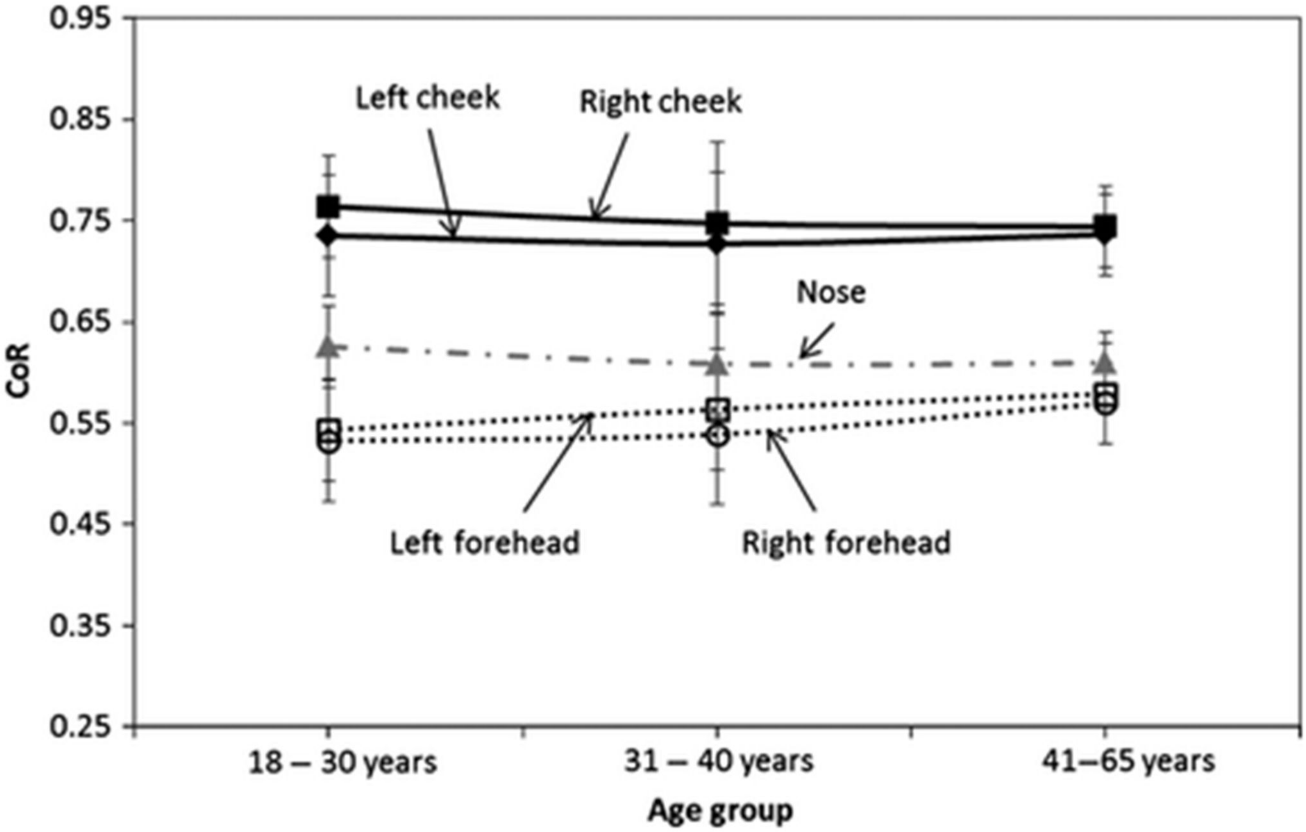

Figure 2.

CoR by age group and sampling location. CoR values are averaged over all environmental conditions (temperature and humidity levels). For clarity, only facial sampling locations are displayed. The wrist, middle forearm, and upper forearm showed CoR remaining flat as age group increased.

Table 1

Average coefficient of restitution by sampling location

Sampling location	Mean	SD	Min	Max	*P*
Left cheek	0.73	0.05	0.44	0.84	0.001
Right cheek	0.75	0.06	0.42	0.86	0.001
Nose	0.61	0.04	0.43	0.79	0.001
Left forehead	0.56	0.05	0.39	0.83	0.37
Right forehead	0.55	0.06	0.40	0.84	–
Wrist	0.68	0.03	0.57	0.81	<0.001
Middle Forearm	0.74	0.03	0.59	0.83	<0.001
Upper forearm	0.80	0.02	0.62	0.87	<0.001

Table 2

Average coefficient of restitution by sampling location and age group

Age group	**18–30**				**30–40**				**40–65**			
Site	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Left cheek	0.74	0.06	0.45	0.84	0.73	0.07	0.44	0.83	0.74	0.04	0.51	0.83
Right cheek	0.76	0.05	0.51	0.86	0.75	0.08	0.42	0.84	0.74	0.04	0.53	0.83
Nose	0.63	0.04	0.50	0.79	0.61	0.05	0.43	0.76	0.61	0.03	0.51	0.77
Left forehead	0.54	0.05	0.39	0.73	0.56	0.06	0.43	0.78	0.58	0.05	0.48	0.83
Right forehead	0.53	0.06	0.40	0.82	0.54	0.07	0.40	0.82	0.57	0.04	0.49	0.84
Wrist	0.69	0.03	0.57	0.76	0.68	0.03	0.59	0.76	0.68	0.03	0.60	0.81
Middle forearm	0.75	0.03	0.63	0.83	0.73	0.03	0.59	0.78	0.74	0.02	0.66	0.79
Upper forearm	0.81	0.03	0.62	0.87	0.81	0.02	0.70	0.86	0.79	0.02	0.73	0.84

Table 3

Average coefficient of restitution by sampling location and gender

Sampling location	Female				Male			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Left cheek	0.74	0.05	0.45	0.84	0.72	0.06	0.44	0.84
Right cheek	0.76	0.05	0.51	0.86	0.75	0.06	0.42	0.84
Nose	0.61	0.04	0.51	0.79	0.62	0.04	0.43	0.78
Left forehead	0.57	0.05	0.39	0.73	0.55	0.06	0.43	0.83
Right forehead	0.55	0.06	0.41	0.84	0.54	0.06	0.40	0.75
Wrist	0.69	0.03	0.57	0.81	0.68	0.03	0.58	0.79
Middle forearm	0.75	0.02	0.66	0.83	0.73	0.02	0.59	0.77
Upper forearm	0.81	0.03	0.62	0.87	0.80	0.02	0.70	0.86

Table 4

Average coefficient of restitution by sampling location and temperature

Temperature	**<75**		**75–80**		**>80**	
Site	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Left cheek	0.73	0.07	0.73	0.05	0.75	0.05
Right cheek	0.76	0.06	0.76	0.05	0.76	0.05
Left forehead	0.57	0.06	0.56	0.06	0.56	0.05
Right forehead	0.56	0.07	0.54	0.07	0.56	0.06
Nose	0.62	0.04	0.61	0.04	0.61	0.04
Wrist	0.69	0.04	0.69	0.04	0.68	0.03
Middle forearm	0.75	0.02	0.74	0.03	0.75	0.03
Upper forearm	0.81	0.03	0.81	0.03	0.81	0.03

Table 5

Average coefficient of restitution by sampling location and relative humidity

Relative humidity	<20%		20–40%		>40%	
Site	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Left cheek	0.75	0.04	0.74	0.06	0.74	0.05
Right cheek	0.76	0.06	0.76	0.05	0.76	0.05
Left forehead	0.56	0.06	0.57	0.05	0.57	0.05
Right forehead	0.55	0.06	0.55	0.06	0.55	0.08
Nose	0.62	0.04	0.61	0.04	0.61	0.05
Wrist	0.69	0.04	0.68	0.03	0.68	0.04
Middle forearm	0.75	0.03	0.75	0.03	0.75	0.03
Upper forearm	0.81	0.02	0.81	0.03	0.81	0.03