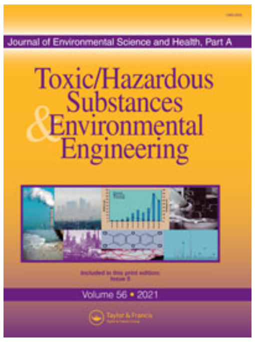

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Particle transfer and adherence to human skin compared with cotton glove and pre-moistened polyvinyl alcohol exposure sampling substrates

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ABSTRACT

Measurement of skin exposure to particles using interception (e.g., cotton gloves) and removal (e.g., wiping) sampling techniques could be inaccurate because these substrates do not have the same topography and adhesion characteristics as skin. The objective of this study was to compare particle transfer and adherence to cotton gloves, cotton gloves with artificial sebum, and a pre-moistened polyvinyl alcohol (PVA) material with bare human skin (fingertip, palm). Experiments were performed with aluminum oxide powder under standardized conditions for three types of surfaces touched, applied loads, contact times, and powder mass levels. In the final mixed model, the fixed effects of substrate, surface type, applied load, and powder mass and their significant two-way interaction terms explained 71% (transfer) and 74% (adherence) of the observed total variance in measurements. For particle mass transfer, compared with bare skin, bias was −77% (cotton glove with sebum) to +197% (PVA material) and for adherence bias ranged from −40% (cotton glove) to +428% (PVA material), which indicated under- and over-sampling by these substrates, respectively. Dermal exposure assessment would benefit from sampling substrates that better reflect human skin characteristics and more accurately estimate exposures. Mischaracterization of dermal exposure has important implications for exposure and risk assessment.

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Dermal; sampling; metals; particulate; sebum; exposure assessment

Introduction

During work, everyday life, and play, skin may be exposed to chemicals via deposition of airborne vapors and dusts, direct immersion, and unintentional spills, splashes, sprays, or contact with contaminated materials (e.g., soils) and surfaces. Skin exposure to metal particles is especially important because some metals have the capacity to oxidize in sweat, which releases ions that permeate the skin and could lead to development of allergic sensitization.[1,2] Once a person becomes sensitized, only avoidance of further exposure to the offending agent can prevent elicitation of an allergic reaction.[3–5] For children and the general population, avoidance may mean changes in daily activities and play to prevent exposure. Additional changes may include avoidance of certain consumer products, cosmetics, and jewelry, all of which can alter quality of life.[6] For adults, avoidance may also mean days away from work and even change of employment, the latter of which could include retraining, reduced income and benefits, and decreased quality of life, all of which are serious and costly problems for employees and employers alike.[7–11]

Once particles contact a substrate (e.g., skin or an exposure assessment sampling material), several types of interactions will influence whether they adhere or detach. Some of the main interactions between particles and surfaces are molecular interactions, electrostatic forces, and capillary condensation.[12,13] Molecular interactions are based on weak van der Waals interactions. Attractive van der Waals forces are proportional to particle diameter to the first power (d^1). Electrostatic forces between charged particles and a substrate surface may cause increased adhesion. Capillary condensation occurs when water vapor from ambient humidity (above 65% relative humidity) condenses in the gap between particles and a substrate surface. A water meniscus forms that draws the bodies together because of surface tension and reduces the pressure of the liquid, which results in an attractive force. Ambient humidity also influences the ability of a particle or substrate surface to acquire and maintain electrostatic charge, which makes it influential for adhesion of hydrophilic particles.[14] Mechanical removal forces depend on particle diameter to the third power (d^3), which means that once attached, very large forces are needed to remove small particles from substrate surfaces.

Table 1 summarizes several factors that have been investigated in previous studies to assess their impact on particle transfer and adherence to skin. Herein, the term transfer refers to the mass of particles transferred from a surface to a substrate and adherence refers to the amount transferred normalized to contact area with a substrate.[15] Relevant task-related factors included activity, contact time, contact frequency, contact type (e.g., press or smudge), applied load

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Table 1. Factors affecting particle mass transfer and adherence to skin.

Factor	Influence[a]	Reference
Task related		
Activity	+	Cit.[26, 42–44]
Time	+/-	Cit.[15, 26, 30, 34, 35, 45]
Contact frequency	+/-	Cit.[14, 30, 31, 34]
Type of contact	+	Cit.[14]
Load or pressure	+/-	Cit.[15, 34–36]
Contact surface	+/-	Cit.[14, 15, 31, 32, 34, 37, 45]
Powder mass	+	Cit. [30]
Temperature	+	Cit.[34]
Skin properties		
Area exposed	+	Cit.[26, 30]
Anatomical region	+	Cit.[26, 42–44, 46, 47]
Skin moisture	+/-	Cit.[14, 27, 30, 33, 37]
Particle properties		
Type	+/-	Cit.[15, 36, 37, 44, 48, 49]
Organic content	+/-	Cit.[48, 49]
Petroleum content	+	Cit.[50]
Size	+/-	Cit.[15, 25, 27, 33, 35, 36, 48, 49, 51]
Moisture content	+	Cit.[25, 26, 36, 45, 48, 50, 51]
Dustiness	+	Cit.[37]

a+ = positive influence, - = no influence, +/- = conflicting data

(or force or pressure) on a surface, topographical properties of contacted surfaces, mass of powder available for contact, and ambient temperature.

Given that development of allergic sensitization may have significant negative impacts on the health and quality of life of people of all ages[6] and that particle interactions with skin are complex[14] and may be influenced by several factors (Table 1), it is critical to accurately measure dermal exposures to particles for understanding risk of disease (e.g., dose modeling, risk assessment). Existing tools for dermal exposure assessment to particulate contaminants include removal and interception sampling.[16] Examples of removal sampling are wiping and washing. Skin wiping and washing have been reported to underestimate the mass of contaminant on skin and are highly variable.[17,18,25,29,33,36] Surface wiping is used to assess contamination levels, which are sometimes used as an indicator of exposure potential (assuming the wipe substrate removes particles from surfaces in a manner that mimics human skin). Interception sampling uses substrates such as cotton gloves or cloth patches to capture a contaminant before it contacts skin. Cotton gloves have been used as an index of skin loading for toxic and allergenic metals such as beryllium, cobalt, nickel and chromium.[19,20]

The stratum corneum is the outer surface of the skin and has microtopography (ridges and contours) that imparts a rough and random surface that consists of crisscross furrows, which can trap and retain adhered particles. A major assumption of existing dermal exposure assessment techniques is that sampling substrates such as cotton gloves or wipe materials, which possess markedly different topography and adhesion properties compared with skin (see Figure 1), capture and retain particles in a manner that mimics skin. However, the current understanding of particle transfer and adherence for sampling substrates compared with bare skin is very limited. The primary purpose of this study was to investigate particle transfer and adherence to common removal (pre-moistened wipe material) and interception (cotton gloves) sampling substrates compared with bare skin

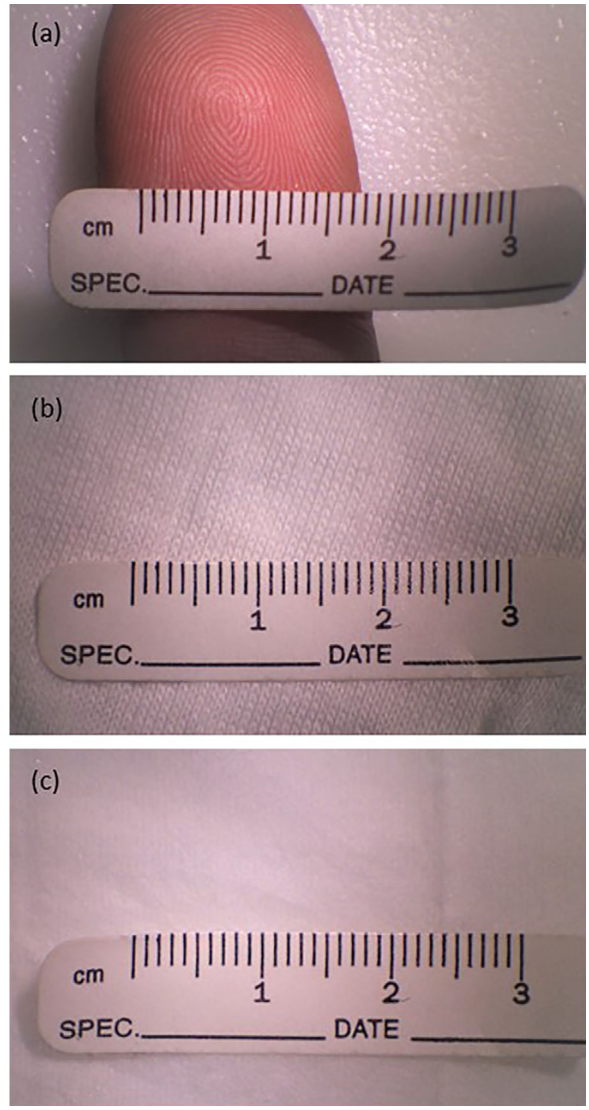

Figure 1. Photographs of (a) bare fingertip skin, (b) cotton glove sampling substrate, and (c) pre-moistened PVA material sampling substrate. All images at 2.5x magnification.

and understand factors that affect particle transfer and adherence. The secondary purpose was to investigate whether application of artificial sebum (the oily component of skin surface film liquids) to cotton gloves would more accurately mimic particle transfer and adherence observed for skin.

Materials and methods

Aluminum oxide (Al_2O_3) powder (Chromatography grade, Brockman I, 50-200 µm, Acros Organics, Fair Lawn, NJ, USA) was used as an inert test material and surrogate for a sensitizing metal. Existing data on ethnic variability in skin structure and function is conflicting.[21] As such, for this study, we recruited only one volunteer (white/non-Hispanic) to minimize variation in experimental results. The volunteer's skin was free of any visible dermatitis, scarring, or other noticeable abnormalities that could impact particle adhesion. Informed consent by the participant was obtained under a protocol approved by the NIOSH Institutional

Review Board. Bare fingertip (pad of index finger) and palm (at base of thumb) skin on the participant's right hand was exposed to Al_2O_3 powder. Sampling substrates were cotton gloves,[19] cotton gloves with artificial sebum prepared as described previously,[22] and a polyvinyl alcohol (PVA) material pre-moistened with deionized water equivalent to that used for wipe sampling of beryllium and skin sampling of cobalt, nickel, and chromium (GhostWipes™, Environmental Express, Charleston, SC, USA).[20,23] Additionally, we explored an artificial skin material composed of gelatin, glycerol, polysaccharides, and lipids that was purported to have similar adhesion and wetting characteristics to human skin[24] as a sampling substrate that replicated a person's actual skin topography. As shown in Appendix Figure A1, the silicone cast of human palm skin captured the skin topography in detail; however, the mold made of this artificial skin material did not reproduce that same detail, so it was excluded from testing.

Test apparatus

Figure 2 is a schematic of the custom-built apparatus used to evaluate particle transfer and adherence. The apparatus consisted of a rectangular steel plate with welded upright posts on either end. Each post had an adjustable cylinder with a hand screw that acted as a brake. Applied load is an important variable for assessment of particle adherence[15]; however, it is difficult to reproducibly control in human simulations of real-world activities.[25–27] To standardize applied load, a calibrated platen balance (Model XS2002S, Mettler Toledo, Greifensee, Switzerland) capable of reading to 10 mg was positioned at the center of the base of the custom-built apparatus. The hand bracket was lowered on the upright posts until the participant's bare palm or fingertip skin (or the laboratory technician's hand for cotton glove substrate) contacted a powder-free blank sample surface on the tared balance. A separate bracket was used for the PVA removal sampling substrate. The post and bracket brakes were iteratively adjusted until the desired applied load reading was observed on the balance (0.5, 1.0, or 1.5 kg). Once the brakes were locked in position, a bracket could not be moved further. In addition, the contact plate with openings for skin on the hand bracket was made of rigid steel so it would not deflect when pressed down on by the participant or laboratory technician. The exact applied load for each contact with powder was logged and transferred to a laptop computer using the balance manufacturer's software (BalanceLink, Mettler Toledo).

Exposed skin area is defined as the area available for particle contact. Deformation of the skin at the point of contact with particles is an important consideration because it results in an increased area of contact, which in turn can increase particle transfer.[14] Measurement of skin area is complicated by irregular shape of appendages such as fingers. In the current study, the area of bare or gloved skin available for contact with Al_2O_3 powder was standardized at 1.5 cm^2 (fingertip) and 4 cm^2 (palm) using holes of known dimension in the contact plate of the hand bracket. For the

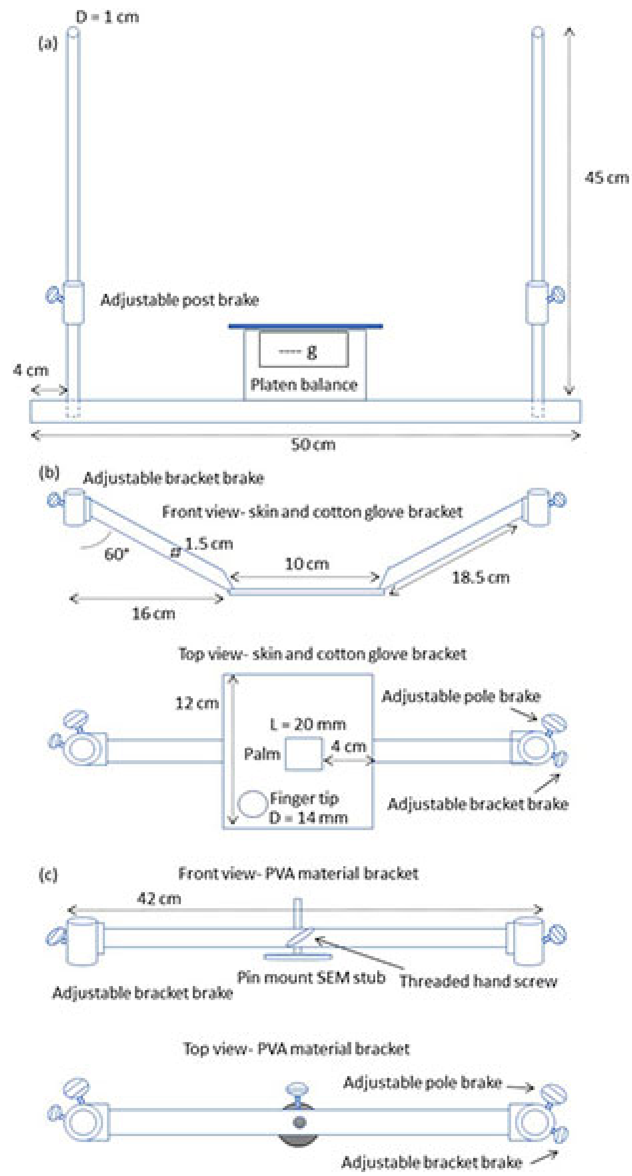

Figure 2. Custom-built apparatus to measure particle transfer and adherence: (a) base and weighing balance, (b) front and top view of bracket for bare skin, cotton glove, and cotton glove with artificial sebum, and (c) front and top view of bracket for PVA sampling substrate.

PVA substrate, a 12.7-mm diameter circle of material was cut out using a hole punch and attached to a 12.7-mm diameter aluminum scanning electron microscopy (SEM) pin stub (Cat. No. 16111, Ted Pella, Inc., Redding, CA, USA) using a 12-mm diameter circle of double-sided carbon tape (Cat. No. 16084-1, Ted Pella, Inc.) and mounted in the bracket. To mitigate electrostatic interactions and the influence of capillary condensation during testing, all measurements were made at 23.2 ± 0.8 °C and 44 ± 8% relative humidity.

Study protocol

The protocol to determine particle transfer and adherence to bare skin and sampling substrates involved 1) preparation of Al_2O_3 powder samples, and 2) contact with powder.

Preparation of Al_2O_3 powder samples

A microbalance (Model XS205 Dualrange, Mettler Toledo) capable of reading to 10 µg was used to prepare all powder samples. The microbalance was calibrated using its internal standard at the start of each sampling day and immediately verified using an independent ASTM Class 1 calibration weight (Denver Instrument, Bohemia, NY, USA). To ensure reproducible powder sample masses and levels for each contact, metal hardware washers (17 mm inner diameter, 2 mm thickness) were used to limit the spread of powder across a substrate. Briefly, a clean dry washer was glued (Gorilla Glue, The Gorilla Glue Company, Sharonsville, OH, USA) to a test surface, the glued assembly weighed on the calibrated microbalance, and the appropriate mass of Al_2O_3 powder added to the well created by the washer on the surface. Note that this well ensured reproducible experimental conditions; however, it effectively reduced the area for palm skin contact from 4 cm^2 (area of hole in contact plate of the hand bracket) to 2.26 cm^2 (area of the well). Three types of surfaces were evaluated: glass as a smooth surface (Cat. No. 12-544-4, 75 mm x 25 mm microscope slides, Fisher Scientific, Pittsburgh, PA, USA), sanded wood as a semi-rough surface (Cat. No. 10049505, 1.5-inch diameter woodcraft disks, ArtMinds®, The Michaels Companies, Irving, TX, USA), and coarse-grit sandpaper as a rough surface (60 grit, Ace Hardware, Oak Brook, IL, USA). Three masses of Al_2O_3 powder were evaluated, nominally 0.1, 0.2, and 0.4 g. These masses correspond to simulated surface contamination levels of 44, 88, and 177 mg/cm^2, respectively. The contamination level that corresponded to the 0.1 g applied load approximated levels of metal contamination observed in a hard metal production facility;[20] the higher masses were chosen as a factor of two progression to test the influence of this variable.

Contact with powder

The mass of powder transferred (M_T) from a surface to a substrate (bare skin, gloved skin, or PVA sampling media) was determined as follows: 1) a sample with known mass (M_0) of Al_2O_3 powder (prepared as described in the preceding section) was placed in the center of the calibrated platen balance, 2) the platen balance tared, 3) bare skin or a substrate was contacted with the powder at the specified applied load using the appropriate pre-adjusted bracket system for a specified time (nominally 10, 20, and 45 seconds), 4) the participant's hand (bare skin), laboratory technician's hand (cotton gloves), or bracket with PVA sampling media was carefully raised and a piece of paper inserted between the hand or PVA media and the powder sample to prevent any loosely adhered powder from falling back onto the powder sample, and 5) the sample with remaining powder was carefully transferred to the adjacent microbalance and reweighed (M_f). The mass of powder transferred to skin or a substrate was calculated from the gravimetric measurements. For the trials with bare skin, prior to each contact with a powder sample, the participant gently washed their fingertip or palm with warm water and a mild hand soap, rinsed their skin with warm clean water, dried their skin with a paper towel, then blotted their skin using a lint-free towel to ensure complete dryness. This procedure was repeated between all powder contact measurements. Their skin was visually inspected for cleanliness prior to contact with a powder sample. An alcohol wipe was used to clean the bottom and top of the contact plate and the hole for skin between contact measurements and allowed to dry prior to a measurement. The study design was a single contact with the Al_2O_3 powder. A single contact scenario was chosen to mimic the common practice of a worker briefly placing their hand on a contaminated surface. The mass transferred to skin or a substrate was calculated using Equation 1 and the corresponding particle adherence value was calculated using Equation 2.

$$M_T = M_0 - M_f \tag{1}$$

$$Adherence = \frac{M_T}{Area\ of\ skin\ or\ substrate} \tag{2}$$

Statistical analyses

A fully factorial study design was used to evaluate particle transfer and adherence for seven substrates (bare skin fingertip, bare skin palm, cotton glove fingertip, cotton glove palm, cotton glove fingertip with artificial sebum, cotton glove palm with artificial sebum, PVA media), three surfaces (glass = smooth, sanded wood = semi-rough, coarse grit sandpaper = rough), three applied loads (0.5, 1.0, and 1.5 kg), three contact times (10, 20, and 45 seconds), and three powder mass levels (0.1, 0.2, and 0.4 g). Duplicate measurements were made for each combination of the experimental factors on each substrate. The experimental design with 567 cells ($7 \times 3 \times 3 \times 3 \times 3$) and duplicate measures (n = 1134) provided adequate sample size to detect differences of at least 60% between cells (experimental conditions) with 80% power and alpha (α) of 0.05, assuming a coefficient of variation as high as 90% for particle transfer and adherence to bare skin or a sampling substrate. Inspection of normal-probability plots indicated that the transfer and adherence values were more normally distributed when log-transformed. All statistics were calculated using log-transformed values in JMP® (version 13.0.0, SAS Institute Inc. Cary, NC). To summarize mass transfer and adherence to a substrate (bare skin, cotton gloves, PVA material), mixed models were fit with no fixed effect, duplicate measurements as the random effect, and stratified by substrate to obtain the overall geometric mean (GM) and geometric standard deviation (GSD) values. These models were further stratified by a second factor of either surface type, applied load, contact time, or powder mass to obtain substrate- and factor-specific GM and GSD values. Single- and multi-factor mixed models were used to determine the impact of the fixed effects of the five experimental factors (substrate, surface type, applied load, contact time, and powder mass) on particle mass transfer and adherence with the duplicate measurements as the random effect. Two-, three-, four-, and five-factor models with two-way interaction terms of the main effects were used to identify the most important factors and interaction terms to be presented in the final model. The total variance explained by the models for mass transfer and adherence were calculated as the percent difference between the total variance of the model and the total variance of the null model (only the random effect). Percent bias was calculated from the means of the mass transfer and adherence values using Equation 3.

$$Bias\ (\%) = \frac{Substrate - Bare\ skin}{Bare\ skin}\ x\ 100 \quad (3)$$

Results

Particle transfer and adherence differed among bare skin, cotton gloves, and a pre-moistened PVA material. For both transfer and adherence, the final model included the factors substrate, surface type, applied load, powder mass, and their significant interaction terms.

Particle mass transfer

For PVA material, particle mass transfer was similar to bare skin fingertip and higher compared with bare skin palm. Transfer to cotton gloves with or without artificial sebum was lower compared with bare skin at both the fingertip and palm. Specifically, for the fingertip, the rank order of GM and GSD particle mass transfer values (highest to lowest) were: PVA (2.93 mg, GSD = 2.4) ≈ bare skin (2.40 mg, GSD = 1.6) > cotton glove with artificial sebum (1.29 mg, GSD = 1.5) > cotton glove (0.55 mg, GSD = 3.1); $p < 0.05$. For the palm, the rank order of values (highest to lowest) were: PVA (2.93 mg, GSD = 2.4) > bare skin (0.90 mg, GSD = 3.0) > cotton glove with artificial sebum (0.23 mg, GSD = 3.2) ≈ cotton glove (0.21 mg, GSD = 3.1); $p < 0.05$.

Table 2 summarizes the calculated GM and GSD particle mass transfer values for all levels of experimental factors. Based on linear regression models, particle mass transfer from smooth (0.71 mg, GSD = 4.2) and rough (0.76 mg, GSD = 3.9) surfaces were similar, though both were lower compared with the semi-rough surface (1.03 mg, GSD = 3.4); $p < 0.05$. Particle transfer for the 1.5-kg applied load (0.86 mg, GSD = 3.3) did not differ from 1.0-kg load (0.94 mg, GSD = 3.8), though both were significantly higher compared with the 0.5-kg load (0.68 mg, GSD = 4.4); $p < 0.05$. Particle transfer was not affected by contact time with powder (10 sec: 0.85 mg, GSD = 4.0; 20 sec: 0.83 mg, GSD = 3.8; 45 sec: 0.79 mg, GSD = 3.8). There was no statistical difference in particle transfer from 0.1 g powder mass (0.63 mg, GSD = 4.1) compared with 0.2 g powder mass (0.73 mg, GSD = 3.8), though both were significantly lower than transfer from 0.4 g powder mass (1.18 mg, GSD = 3.4); $p < 0.05$.

Particle adherence

Al_2O_3 adherence to the PVA material was significantly higher than any other substrate in our regression models of substrate ($p < 0.05$). Particle adherence to cotton gloves with or without artificial sebum under-sampled compared with

Table 2. Geometric mean (geometric standard deviation) particle mass transfer (mg) to bare skin, cotton glove (CG), and PVA substrates[a].

Factor:	Surface			Applied load (kg)			Contact time (sec)			Powder mass (g)		
Level:	Smooth[A]	Semi-rough[B]	Rough[A]	0.5[A]	1.0[B]	1.5[B]	10[A]	20 [A]	45 [A]	0.1[A]	0.2[A]	0.4[B]
Bare fingertip skin	2.32 (1.7)	2.79 (1.5)	2.11 (1.4)	2.20 (1.5)	2.74 (1.7)	2.28 (1.4)	2.67 (1.4)	2.18 (1.9)	2.34 (1.4)	2.63 (1.4)	2.12 (1.4)	2.47 (1.8)
CG fingertip	0.46 (3.1)	0.66 (2.5)	0.53 (3.8)	0.18 (2.7)	0.67 (2.5)	1.16 (1.7)	0.53 (3.3)	0.54 (3.5)	0.59 (2.6)	0.42 (2.6)	0.56 (3.5)	0.69 (3.1)
CG w/ sebum fingertip	1.27 (1.4)	1.48 (1.6)	1.15 (1.5)	1.21 (1.5)	1.46 (1.5)	1.22 (1.6)	1.32 (1.5)	1.36 (1.5)	1.21 (1.5)	0.97 (1.4)	1.27 (1.5)	1.76 (1.3)
Bare palm skin	0.92 (3.3)	1.08 (2.8)	0.77 (2.9)	1.16 (2.5)	0.80 (3.4)	0.86 (3.1)	1.09 (2.7)	0.83 (3.0)	0.86 (3.3)	0.40 (2.9)	0.73 (2.1)	2.35 (1.8)
CG palm	0.17 (3.4)	0.29 (3.0)	0.19 (2.8)	0.11 (2.6)	0.35 (2.3)	0.23 (3.5)	0.21 (2.8)	0.24 (3.0)	0.19 (3.7)	0.15 (2.6)	0.16 (3.5)	0.36 (2.6)
CG w/ sebum palm	0.14 (3.1)	0.47 (2.6)	0.19 (2.8)	0.22 (3.1)	0.20 (3.4)	0.29 (3.0)	0.21 (3.0)	0.25 (3.3)	0.62 (3.4)	0.17 (3.6)	0.22 (2.8)	0.33 (3.0)
PVA material	2.43 (1.9)	3.18 (3.3)	3.26 (1.8)	3.08 (2.2)	4.27 (2.2)	1.92 (2.3)	3.35 (2.6)	3.05 (2.0)	2.48 (2.5)	2.73 (2.1)	2.35 (2.5)	3.92 (2.3)

[a]Levels not connected by the same letter within each factor are significantly different

bare skin. For the fingertip, the GM adherence values followed the rank order (highest to lowest): PVA material (2.44 mg/cm^2, GSD = 2.4) > bare skin (1.59 mg/cm^2, GSD = 1.6) > cotton glove with artificial sebum (0.86 mg/cm^2, GSD = 1.5) > cotton glove (0.37 mg/cm^2, GSD = 3.1); $p < 0.05$. For the palm, the rank order of adherence values (highest to lowest) were: PVA material (2.44 mg/cm^2, GSD = 2.4) > bare skin (0.41 mg/cm^2, GSD = 3.0) > cotton glove (0.17 mg/cm^2, GSD = 3.1) > cotton glove with artificial sebum (0.10 mg/cm^2, GSD = 3.2); $p < 0.05$.

As summarized in Table 3, linear regression models indicated that the effect of surface type on particle adherence was: semi-rough surface (0.64 mg/cm^2, GSD = 3.6) > smooth surface (0.44 mg/cm^2, GSD = 4.5) ≈ rough surface (0.47 mg/cm^2, GSD = 4.2). For applied load, 1.5 kg (0.54 mg/cm^2, GSD = 3.5) ≈ 1.0 kg (0.59 mg/cm^2, GSD = 4.3) > 0.5 kg (0.42 mg/cm^2, GSD = 4.6). Contact time was not significant ($p = 0.76$). Particle adherence was influenced by powder mass, i.e., 0.4 g powder (0.74 mg/cm^2, GSD = 3.6) > 0.2 g powder (0.45 mg/cm^2, GSD = 4.0) ≈ 0.1 g powder (0.39 mg/cm^2, GSD = 4.5). All noted differences were statistically significant; $p < 0.05$.

Multiple regression modeling

First, single variable mixed models were fit for each factor. For both particle mass transfer and adherence, individually, the factors substrate, surface, applied load, and powder mass were significant (Appendix Table A1). Next, two-, three-, four-, and five-factor mixed models with two-way interaction terms (denoted by × symbol) of the main effects were fit. For particle mass transfer and adherence, the main effects of substrate, surface, applied load, and powder mass (but not contact time) were significant in all mixed models (Appendix Table A2). Based on these results, for particle mass transfer and adherence, the most important factors to enter the final model were the four main effects of substrate, surface, applied load, and powder mass and their significant two-way interaction terms, but excluding the non-significant interaction term of applied load × powder mass (Table 4). In the table, parameter estimates with a positive value indicate that the outcome variable was higher for this level of the variable compared with its reference and the converse is true for negative parameter estimates. The main effects of substrate, surface, applied load, and powder mass explained 71% (particle mass transfer) and 74% (particle adherence) of the total variance in the measurements. From Tables A1 and A2, the main effect variables contributing the most to the explained variance were (from most to least): substrate > applied load ≈ powder mass > surface for both particle mass transfer and adherence.

Differences between bare skin and sampling substrates

For particle transfer, compared with bare fingertip skin, bias calculated according to Equation 3 was −64% (cotton glove), −40% (cotton glove with sebum), and +76% (PVA material). For bare palm skin, bias was −77%, −70%, and

Table 3. Geometric mean (geometric standard deviation) particle adherence (mg/cm^2) to bare skin, cotton glove (CG), and PVA substrates[a].

Factor:	Surface			Applied load (kg)			Contact time (sec)			Powder mass (g)		
Level:	Smooth[A]	Semi-rough[B]	Rough[A]	0.5[A]	1.0[B]	1.5[B]	10[A]	20 [A]	45 [A]	0.1[A]	0.2[A]	0.4[B]
Bare fingertip skin	1.55 (1.7)	1.86 (1.5)	1.40 (1.4)	1.46 (1.5)	1.83 (1.7)	1.52 (1.4)	1.78 (1.4)	1.45 (1.9)	1.56 (1.4)	1.75 (1.4)	1.42 (1.4)	1.65 (1.8)
CG fingertip	0.31 (3.1)	0.44 (2.5)	0.36 (3.8)	0.12 (2.7)	0.45 (2.5)	0.77 (1.7)	0.35 (3.3)	0.36 (3.5)	0.39 (2.6)	0.28 (2.6)	0.37 (3.5)	0.46 (3.1)
CG w/ sebum fingertip	0.85 (1.4)	0.99 (1.6)	0.76 (1.5)	0.81 (1.7)	0.97 (1.5)	0.81 (1.6)	0.88 (1.5)	0.91 (1.5)	0.80 (1.5)	0.64 (1.4)	0.84 (1.5)	1.17 (1.3)
Bare palm skin	0.41 (3.3)	0.48 (2.8)	0.34 (2.9)	0.51 (2.5)	0.35 (3.4)	0.38 (3.1)	0.48 (2.7)	0.37 (3.0)	0.38 (3.3)	0.18 (2.9)	0.32 (2.1)	0.96 (1.8)
CG palm	0.13 (3.3)	0.23 (3.0)	0.15 (2.8)	0.09 (2.6)	0.28 (2.3)	0.18 (3.5)	0.17 (2.8)	0.19 (3.0)	0.15 (3.7)	0.12 (2.6)	0.12 (3.5)	0.29 (2.6)
CG w/ sebum palm	0.06 (3.1)	0.21 (2.6)	0.06 (2.8)	0.10 (3.1)	0.09 (3.4)	0.13 (3.0)	0.09 (3.0)	0.11 (3.3)	0.11 (3.4)	0.08 (3.6)	0.10 (2.8)	0.14 (3.0)
PVA material	2.02 (1.9)	2.65 (3.3)	2.72 (1.8)	2.57 (2.2)	3.56 (2.2)	1.60 (2.3)	2.79 (2.6)	2.54 (2.0)	2.07 (2.5)	2.27 (2.1)	1.96 (2.5)	3.27 (2.3)

[a]Levels not connected by the same letter within each factor are significantly different

+197% for the cotton glove, cotton glove with artificial sebum, and PVA material, respectively. For particle adherence, compared with bare fingertip skin, bias was −64% (cotton glove), −40% (cotton glove with artificial sebum), and +108% (PVA material). For bare palm skin, bias was −59%, −70%, and +428% for the cotton glove, cotton glove with artificial sebum, and PVA material, respectively.

Discussion

Skin wiping has been used to assess exposure to systemic toxins such as lead particles and allergenic metal dusts such as cobalt and nickel.[18,20] Cotton gloves have been used to approximate exposures to highly toxic metal dusts such as beryllium, house dust, and pesticides.[19,52–55] We expected that based on their different topography and adhesion characteristics, a pre-moistened PVA material used for removal sampling and cotton gloves used for interception sampling would over-sample compared with bare skin. Results demonstrated that this expectation was true for the PVA substrate but not the cotton glove substrate. For particle mass transfer, the PVA material had a bias of +76% (fingertip) and +197% (palm) and for adherence the PVA material had a bias of +108% (fingertip) to +428% (palm). Cotton gloves consistently under-sampled particle transfer and adherence with bias of −64% (finger) and −59% to −77% (palm). Consistent with this latter observation, Edwards and Lioy[28] reported that cotton gloves had lower collection efficiency compared with bare skin for house dust, especially for particles with sizes greater than about 60 µm, which is within the range used in our study, 50-200 µm. Opposite to our findings for sampling substrate, Gorman Ng et al. reported that cotton gloves over-sampled a glycerol solution compared with a wipe material for a constant skin loading.[29] Other studies indicated that cotton gloves oversampled pesticide exposure levels on skin compared with rinsing techniques and oversampled petroleum oil levels on skin compared with skin wiping techniques.[52,53,56] Note that some caution is warranted in comparison of these cited study results to the current study because transfer and adherence of liquids and liquid droplets is also influenced by wicking effects of cotton, which does not occur with particles. Brouwer et al.[30] reported that particle mass transfer to cotton gloves after 12 sequential contacts was a factor of 70x higher compared with bare skin. A likely reason for the diverging results between our study and Brouwer et al. is that we used a single-contact design whereas they used a sequential contact design, which allowed for accumulation of particles on gloves over many contacts; in that study, contact frequency was the major determinant that contributed to particle mass transfer.

A secondary purpose of this work was to evaluate whether application of artificial sebum to cotton glove substrate would more accurately mimic particle transfer and adherence observed for bare skin by accounting for the oily component of skin film liquids. Artificial sebum on cotton gloves improved particle mass transfer for the fingertip location by over a factor of 2x (1.29 mg with sebum versus 0.55 mg without sebum) but did not improve mass transfer for the palm location. Similarly, artificial sebum on cotton gloves improved adherence for the fingertip location by over 2x (0.86 mg/cm^2 with sebum versus 0.37 mg/cm^2 without sebum), but not the palm location. The volume of artificial sebum solution applied to the glove palm and fingertip were believed to be proportional to account for differences in the area contacted with Al_2O_3 powder at each location; however, there is more fabric on the glove palm compared with the fingertip. As such, more sebum solution could have wicked beyond the palm area used for contact with the particles, which resulted in a thinner sebum layer than believed to have been applied and may explain why transfer and adherence results were lower at the palm with sebum compared to the fingertip with sebum. Van Dyke et al.[31] evaluated methamphetamine transfer to cotton gloves and cotton gloves moistened with artificial saliva and reported higher transfer efficiencies for the substrate moistened with a biofluid. Clausen et al.[32] reported that transfer of organic chemicals from glass or aluminum surfaces was similar for dry cotton wipes and cotton wipes moistened with artificial sweat, though removal of contamination from surfaces of consumer products was sometimes higher for cotton wipes with artificial sweat. In the only study to evaluate the influence of skin fluid properties *in situ*, Edwards and Lioy[33] examined the effect of skin surface sebum content on collection efficiency of pesticides and herbicides from hand skin. The authors reported negative correlations with sebum level and pesticide collection efficiencies, which suggested that the higher the sebum level, the lower the collection of contaminants. Collectively, our results and existing literature indicate that sebum and sweat, which are components of skin surface film liquids, may slightly improve mass transfer and adherence to cotton sampling substrate for some, but not all types of contaminants. Even with artificial sebum, in our study, the cotton glove substrate still under-sampled transfer and adherence compared with bare fingertip skin (bias of −40%) and bare palm skin (bias of −70%).

In this study, three factors related to exposure scenarios (surface type, applied load, and contact time), one factor related to contaminant properties (powder mass), and one factor related to the collection technique (substrate) were evaluated to understand their importance for particle transfer and adherence. Based on the final model, the most important main effects were substrate, surface, applied load, and powder mass and their significant two-way interaction terms, which explained 71% and 74% of the total variance for particle mass transfer and adherence, respectively. Statistically, substrate explained the most variance for particle transfer (52%) and adherence (56%), followed by applied load and powder mass, then surface. Although all four of these fixed effects were statistically important in the final model, from a practical viewpoint, applied load, powder mass and surface combined explained only 19% (transfer) and 18% (adherence) of the total variance, thus had much less impact compared with substrate. As summarized in Table 1, and explained in detail below, several studies have observed that applied load, powder mass and surface

Table 4. Final model for most important factors affecting particle mass transfer and adherence (CG = cotton glove)[a].

	Particle mass transfer			Particle adherence		
	Estimate	Standard Error	p-value	Estimate	Standard Error	p-value
Intercept	−0.245742	0.019763	**<0.05**	−0.720765	0.019763	**<0.05**
Substrate [bare fingertip skin]	1.118919	0.053319	**<0.05**	1.1884762	0.053319	**<0.05**
Substrate [CG fingertip]	−0.449432	0.055174	**<0.05**	−0.379874	0.055174	**<0.05**
Substrate [CG w/sebum fingertip]	0.501787	0.052883	**<0.05**	0.5713447	0.052883	**<0.05**
Substrate [CG palm]	−1.390948	0.055498	**<0.05**	−1.154943	0.055498	**<0.05**
Substrate [CG w/sebum palm]	−1.210943	0.052883	**<0.05**	−1.551285	0.052883	**<0.05**
Substrate [PVA material]	1.321939	0.053029	**<0.05**	1.5579452	0.053029	**<0.05**
Surface [smooth]	−0.172007	0.031247	**<0.05**	−0.172007	0.031247	**<0.05**
Surface [rough]	−0.101701	0.035889	**<0.05**	−0.101701	0.031335	**<0.05**
Applied load [0.5 kg]	−0.251341	0.031335	**<0.05**	−0.249525	0.031432	**<0.05**
Applied load [1.0 kg]	0.167533	0.035652	**<0.05**	0.1666634	0.031020	**<0.05**
Powder mass [0.1 g]	−0.295302	0.031447	**<0.05**	−0.295302	0.031447	**<0.05**
Powder mass [0.2 g]	−0.117860	0.031046	**<0.05**	−0.117860	0.031046	**<0.05**
Substrate × Surface	–[b]	–	**<0.05**	–	–	**<0.05**
Substrate × Applied load	–	–	**<0.05**	–	–	**<0.05**
Substrate × Powder mass	–	–	**<0.05**	–	–	**<0.05**
Surface × Applied load	–	–	**<0.05**	–	–	**<0.05**
Surface × Powder mass	–	–	**<0.05**	–	–	**<0.05**
Explained variance	71%			74%		

[a]References for fixed effect factors: Substrate = bare palm skin, Surface = semi-rough, Applied load = 1.5 kg, Powder mass = 0.4 g
[b]– = parameter estimates reported in Appendix Table A3

are important factors for skin exposure and their contribution varies with the study design.

Influence of applied load

Particle mass transfer and adherence were similar at the 1.5 and 1.0 kg applied loads but significantly higher compared with the 0.5 kg load. The equivalent applied pressures (load per unit area) for the experimental setup that corresponded to the 0.5, 1.0, and 1.5 kg applied loads were: 0.325, 0.650, and 0.975 kg/cm^2 (fingertip), 0.221, 0.442, and 0.664 kg/cm^2 (palm), and 0.407, 0.815, and 1.222 kg/cm^2 (PVA material). These pressures were higher than those used by Brouwer et al. (0.005 kg/cm^2) and Rodes et al. (0.008 kg/cm^2) but within the range studied by Ferguson et al. (0.1 to 0.6 kg/cm^2).[14,15,30,34,35] The higher particle mass transfer and adherence observed at higher pressures in this study was consistent with Ferguson et al.[15,34–36] who reported that adherence was generally independent of applied pressures less than 0.4 kg/cm^2 but significantly higher for applied pressures of 0.5 to 0.6 kg/cm^2. Hence, pressures below 0.4 kg/cm^2 could be insufficient to depress enough skin surface so that it is in full contact with the top layer of particles on a contaminated surface whereas forces above this level result in full contact, and therefore, higher transfer and adherence. This threshold effect of applied pressure also explains why for particle transfer and adherence, bias was higher at the palm location compared with the fingertip location for both cotton gloves and cotton gloves with artificial sebum.

Influence of powder mass

Particle mass transfer and adherence were significantly higher for the 0.4 g powder mass level compared with the lower powder mass levels. For most studies in Table 1, especially those that focused on soil (dirt, sediment, clay), the mass of powder available for skin contact was generally not known in the experimental design, which precluded inference on the effect of this factor on transfer and adherence. Consistent with our results, Brouwer et al.[30] observed that both particle mass transfer and adherence were increased at a higher average powder mass loading of about 180 µg/cm^2 compared with a loading of about 6 µg/cm^2. In our experimental design, powder mass was confined to the area bounded by the metal hardware washer (17 mm internal diameter x 2 mm thickness) attached to a substrate so at the 0.4 g level, the layer of powder in the well created by the washer was thicker compared with the 0.2 and 0.1 g powder mass levels. Potentially, this experimental configuration could limit transfer (and adherence) to the surface monolayer of powder; however, for both transfer and adherence, values were significantly higher for the 0.4 g powder mass load. Hence, the experimental configuration permitted powder deeper than the surface monolayer to transfer to a substrate. Additionally, as noted in the previous section, transfer and adherence were both significantly higher for the 1.5 kg applied load compared with the 0.5 and 1.0 kg applied loads, which indicated that more than monolayer transfer occurred at the highest applied load. We cannot rule out that with the 0.2 and 0.1 g powder mass levels, material on the inside perimeter of the washer (2.26 cm^2 area) was inaccessible for palm skin contact (4 cm^2 area hole in plate), thereby reducing transfer and adherence values.

Influence of surface type

Particle mass transfer and adherence were significantly higher for contact with a semi-rough surface (sanded wood) compared with rough (coarse sandpaper) or smooth (glass) surfaces. Sanded wood has surface irregularities, sandpaper consists of large grit particles embedded in a paper matrix that creates troughs and valleys, and glass is relatively smooth. At a microscopic level, all surfaces have roughness from asperities. If asperities are smaller than the particles (i.e., the particle is resting on top of the asperities), less particle mass is in contact with the surface, which translates to less adhesion force between the particle and surface. If asperities are larger than the particle (i.e., the particle is resting between asperities), more particle mass is in contact with the surface, which results in more adhesion force between the particle and surface.[12,13] In this study, particle mass transfer from a rough surface was lower compared with a semi-rough surface, consistent with the fact that more particles were in valleys created by grit particles on the sandpaper and were inaccessible to contact skin. At a microscopic level, Al_2O_3 particles smaller than asperities on sandpaper grit would have more adhesion forces that need to be overcome to remove the material. Particle mass transfer was also lower for a smooth surface compared with a semi-rough surface, which is inconsistent with the concept that particles larger than the topography of a surface are more easily removed. In general, most prior studies have reported higher transfer from smooth surfaces compared with rough surfaces because adhesive forces are lower for smooth surfaces.[14,32,37] For the semi-rough surface, it is possible that particles were present on closely packed surface irregularities of the sanded wood surface where they were readily available for contact with skin, rather than in valleys between irregularities. At a microscopic level, these irregularities have asperities much smaller than the particles, which enabled greater transfer to skin.

Study limitations

In this study, five factors relevant to particle transfer and adherence were examined; however, other factors not examined in this study may be important. Only one human volunteer was used to minimize inter-person variability so that the impact of these five factors on transfer and adherence could be eliminated; given that skin topography is unique to individuals this design limits the generalizability of the study results. In the current study, a press contact was evaluated for strictly defined skin areas (see Figure 2). During a press contact, most particles will be transferred to epidermal ridges; however, for a smudge contact, skin is moved laterally on a surface, which increases the size of the contact area and forces particles into skin troughs as well, resulting in order of magnitude variations in adherence.[13,14] This study found a disconnect between particle transfer and adherence on bare skin to cotton gloves and a pre-moistened wipe substrate. An alternative approach not evaluated in this study is tape stripping, which can remove contamination on the skin surface as well as contamination in the outer layer of the skin and might better mimic collection of bare skin. In the current study, skin hydration status of the volunteer was not assessed. Intuitively, it would make sense that increased skin hydration would yield increased particle adherence via capillary condensation effects. Consistent with this concept, Rodes et al.[14] reported that skin hydration significantly increased particle mass transfer. Brouwer et al. reported that increased skin moisture limited powder transfer to the hands.[30] Gorman Ng et al. observed that particle adherence was not influenced by skin moisture content and Edwards and Lioy reported that diazinon and chlorpyrifos pesticide collection efficiencies were negatively correlated with skin hydration[33,37].

Our study design utilized a single press contact, which is not representative of exposure scenarios that involve multiple repeat contacts. Data on the importance of the number of skin contacts with contaminants on exposure are inconclusive. For example, a study of methamphetamine contaminated surfaces revealed no difference in collection efficiency from one to three contacts.[31] In another study, Brouwer et al.[30] observed that particle mass transfer increased as the number of contact events increased from one to 12, possibly via increased skin contact area; adherence increased non-linearly with increased number of contacts. Results of experiments by Ferguson et al.[34] suggested that the amount of material that adhered on second contact was less than that from the first contact. A decrease in adherence with subsequent contacts may be due to brush-off effects whereby once a layer of material adheres to all available skin area, additional contacts result in some fraction of adhered material being dislodged with the bulk powder or to the surface.

Only physical powder mass transfer and adherence were assessed in this study. For metal allergens, chemical dissolution on skin is an important consideration because particles can dissolve in skin surface film liquids and release ions that are capable of penetrating into the immunologically active layer of the stratum corneum, where they can induce sensitization or provoke an allergic response.[2,38–40] It is postulated that the fraction of metal that dissolves and penetrates through skin may be a more biologically relevant metric of exposure allergens than particle mass transferred to skin.[41] Powder properties such as dustiness have also been shown to influence particle transfer and exposure, with more dusty materials transferred to skin compared with less dusty materials.[37]

It is important to note that we used only one study participant to evaluate particle transfer and adherence to bare skin and one type of metal powder. Additional research is needed to render these results more generalizable, including a better understanding of the effects of sex, age, race and ethnicity, presence of common skin conditions (e.g., dermatitis), and anatomical site as well as powder characteristics on particle transfer and adherence.

Future research

As part of this study, we explored the idea of using an artificial skin replica of human skin[24] to cast a sampling substrate from a silicone mold of the participant's index fingertip and palm (Appendix Figure A1) but were unable to accurately mold the material. Edwards and Lioy[28] evaluated a material that they referred to as synthetic skin and reported that it under-sampled compared with bare skin. The synthetic skin material used in their study was a wound dressing composed of a thin, oxygen permeable polyurethane film (Bioclusive Transparent Dressing, Johnson and Johnson, New Brunswick, NJ), though whether it had topography and adhesion characteristics similar to skin is unknown. Another possible substrate is a moldable skin-like material intended for creating masks and other special effects (e.g., Dragon Skin^{TM}). Regardless of material, future research should include identification and evaluation of sampling substrates that possess the same topography and adhesion properties as bare skin.

Summary

A pre-moistened PVA material and cotton glove sampling substrates generally did not collect particles in a manner that mimicked human skin, which indicated that these dermal exposure sampling substrates over-sample (PVA material) or under-sample (cotton gloves). Mischaracterization of exposure has important implications for exposure and risk assessment. For example, over-estimation of exposure will shift a dose-response curve and falsely deflate a risk estimate in epidemiological analysis, whereas under-estimation of exposure will inflate the risk estimate. Sampling substrates that mimic human skin topography and adhesion characteristics are needed for more accurate exposure and risk assessment. One possibility for future dermal exposure assessment research is to evaluate the utility of artificial skin as a sampling substrate.

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Declaration of interest statement

The authors declare that they have no competing interests, financial or otherwise.

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Data availability statement

De-identified data set is available upon request from the corresponding author.

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Appendix

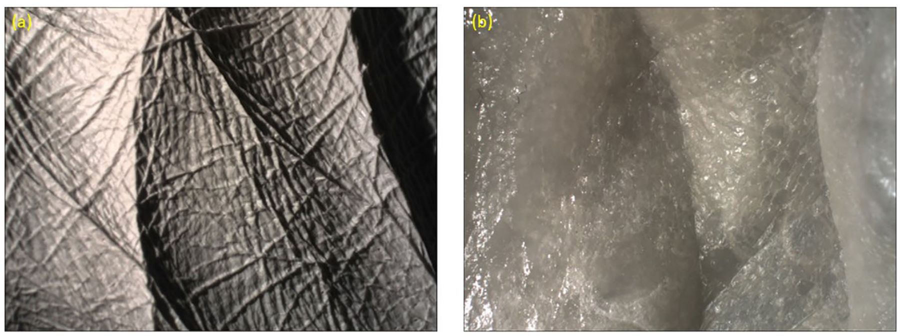

Figure A1. (a) Silicone cast of palm skin, (b) mold of human skin made from artificial skin material.

Table A1. Significance values for single factor models.

	Particle mass transfer		Particle adherence	
Effect[a]	p-value	Explained variance	p-value	Explained variance
Substrate	<0.05	52%	<0.05	56%
Surface	<0.05	1%	<0.05	1%
Applied load	<0.05	1%	<0.05	1%
Contact time	0.74	0%	0.76	0%
Powder mass	<0.05	4%	<0.05	3%

[a]Substrate (bare fingertip skin, bare palm skin, cotton glove index finger, cotton glove with sebum index finger, cotton glove palm, cotton glove with sebum palm, PVA material)
Surface (smooth, semi-rough, rough)
Contact time (10, 20, 45 sec)
Applied load (0.5, 1.0, 1.5 kg)
Powder mass (0.1, 0.2, 0.4 g)

Table A2. Significance values for two-, three-, four-, and five-factor models and their two-way interactions.

Effect[a]	Particle mass transfer p-value	Particle adherence p-value
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Substrate × Surface	<0.05	<0.05
Explained variance	54%	59%
Substrate	<0.05	<0.05
Applied load	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Explained variance	59%	63%
Substrate	<0.05	<0.05
Contact time	0.44	0.44
Substrate × Contact time	0.75	0.75
Explained variance	52%	56%
Substrate	<0.05	<0.05
Powder mass	<0.05	<0.05
Substrate × Powder mass	<0.05	<0.05
Explained variance	58%	62%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Applied load	<0.05	<0.05
Substrate × Surface	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Surface × Applied load	<0.05	<0.05
Explained variance	63%	67%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Contact time	0.39	0.39
Substrate × Surface	0.05	<0.05
Substrate × Contact time	0.71	0.71
Surface × Contact time	0.91	0.91
Explained variance	54%	59%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Powder mass	<0.05	<0.05
Substrate × Surface	<0.05	<0.05
Substrate × Powder mass	<0.05	<0.05
Surface × Powder mass	<0.05	<0.05
Explained variance	62%	65%
Substrate	<0.05	<0.05
Applied load	<0.05	<0.05
Contact time	0.25	0.25
Substrate × Applied load	<0.05	<0.05
Substrate × Contact time	0.75	0.75
Contact time × Applied load	0.16	0.17
Explained variance	59%	63%
Substrate	<0.05	<0.05
Applied load	<0.05	<0.05
Powder mass	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Substrate × Powder mass	<0.05	<0.05
Applied load × Powder mass	0.37	0.37
Explained variance	66%	69%
Substrate	<0.05	<0.05
Contact time	0.31	0.31
Powder mass	<0.05	<0.05
Substrate × Contact time	0.55	0.55
Substrate × Powder mass	<0.05	<0.05
Contact time × Powder mass	0.30	0.29
Explained variance	58%	62%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Applied load	<0.05	<0.05
Contact time	0.21	0.21
Substrate × Surface	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Substrate × Contact time	0.67	0.67
Surface × Applied load	<0.05	<0.05
Surface × Contact time	0.85	0.86
Applied load × Contact time	0.12	0.12
Explained variance	63%	67%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Applied load	<0.05	<0.05

(continued)

Table A2. Continued.

Effect[a]	Particle mass transfer p-value	Particle adherence p-value
Powder mass	<0.05	<0.05
Substrate × Surface	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Substrate × Powder mass	<0.05	<0.05
Surface × Applied load	<0.05	<0.05
Surface × Powder mass	<0.05	<0.05
Applied load × Powder mass	0.37	0.37
Explained variance	71%	74%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Contact time	0.24	0.24
Powder mass	<0.05	<0.05
Substrate × Surface	<0.05	<0.05
Substrate × Contact time	0.47	0.47
Substrate × Powder mass	<0.05	<0.05
Surface × Contact time	0.88	0.88
Surface × Powder mass	<0.05	<0.05
Contact time × Powder mass	0.28	0.28
Explained variance	62%	65%
Substrate	<0.05	<0.05
Applied load	<0.05	<0.05
Contact time	0.12	0.12
Powder mass	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Substrate × Contact time	0.51	0.51
Substrate × Powder mass	<0.05	<0.05
Applied load × Contact time	0.11	0.11
Applied load × Powder mass	0.36	0.36
Contact time × Powder mass	0.25	0.25
Explained variance	66%	70%
Substrate	<0.05	<0.05
Surface	<0.05	<0.05
Applied load	<0.05	<0.05
Contact time	0.08	0.07
Powder mass	<0.05	<0.05
Substrate × Surface	<0.05	<0.05
Substrate × Applied load	<0.05	<0.05
Substrate × Contact time	0.35	0.35
Substrate × Powder mass	<0.05	<0.05
Surface × Applied load	<0.05	<0.05
Surface × Contact time	0.77	0.77
Surface × Powder mass	<0.05	<0.05
Applied load × Contact time	0.06	0.06
Applied load × Powder mass	0.34	0.34
Contact time × Powder mass	0.22	0.22
Explained variance	71%	74%

[a]Substrate (bare fingertip skin, bare palm skin, cotton glove index finger, cotton glove with sebum index finger, cotton glove palm, cotton glove with sebum palm, PVA material)
Surface (smooth, semi-rough, rough)
Time (10, 20, 45 sec)
Load (0.5, 1.0, 1.5 kg)
Powder mass (0.1, 0.2, 0.4 g)

Table A3. Parameter estimates for interaction terms for all levels of the most important factors in the final model affecting particle mass transfer and adherence (CG = cotton glove)[a].

	Particle mass transfer			Particle adherence		
	Estimate	Standard Error	p-value	Estimate	Standard Error	p-value
Bare fingertip skin × smooth	0.139015	0.075416	0.07	0.137659	0.074958	0.07
Bare fingertip skin × rough	−0.018167	0.075771	0.81	−0.018394	0.075311	0.81
CG fingertip × smooth	0.000189	0.078229	0.99	0.000189	0.078229	0.99
CG fingertip × rough	0.001123	0.078924	0.99	0.001123	0.078924	0.99
CG w/sebum fingertip × smooth	0.153589	0.074829	**<0.05**	0.153589	0.074829	**<0.05**
CG w/sebum fingertip × rough	−0.017057	0.074866	0.82	−0.017057	0.074866	0.82
CG palm × smooth	−0.172671	0.080369	**<0.05**	−0.172671	0.080369	**<0.05**
CG palm × rough	0.059171	0.078249	0.45	0.059171	0.078249	0.45
CG w/sebum palm × smooth	−0.340662	0.074829	**<0.05**	−0.340662	0.074829	**<0.05**
CG w/sebum palm × rough	−0.091031	0.074866	0.22	−0.091031	0.074866	0.22
PVA material × smooth	−0.016863	0.074932	0.82	−0.016863	0.074932	0.82
PVA material × rough	0.206993	0.074963	**<0.05**	0.206993	0.074963	**<0.05**
Bare fingertip skin × 0.5 kg	0.160153	0.075495	**<0.05**	0.160153	0.075495	**<0.05**
Bare fingertip skin × 1.0 kg	−0.028919	0.075665	0.70	−0.028919	0.075665	0.70
CG fingertip × 0.5 kg	−0.862690	0.080357	**<0.05**	−0.862690	0.080357	**<0.05**
CG fingertip × 1.0 kg	0.102775	0.077396	0.18	0.102775	0.077396	0.18
CG w/sebum fingertip × 0.5 kg	0.186654	0.074907	**<0.05**	0.186654	0.074907	**<0.05**
CG w/sebum fingertip × 1.0 kg	−0.043216	0.074735	0.56	−0.043216	0.074735	0.56
CG palm × 0.5 kg	−0.465729	0.080936	**<0.05**	−0.465729	0.080936	**<0.05**
CG palm × 1.0 kg	0.409493	0.077526	**<0.05**	0.409493	0.077526	**<0.05**
CG w/sebum palm × 0.5 kg	0.177717	0.074907	**<0.05**	0.177717	0.074907	**<0.05**
CG w/sebum palm × 1.0 kg	−0.326668	0.074735	**<0.05**	−0.326668	0.074735	**<0.05**
PVA material × 0.5 kg	0.300580	0.075318	**<0.05**	0.300580	0.075318	**<0.05**
PVA material × 1.0 kg	0.208236	0.074839	**<0.05**	0.208236	0.074839	**<0.05**
Bare fingertip skin × 0.1 g	0.384743	0.076140	**<0.05**	0.384743	0.076140	**<0.05**
Bare fingertip skin × 0.2 g	−0.002005	0.075056	0.97	−0.002052	0.075056	0.98
CG fingertip × 0.1 g	−0.023802	0.078347	0.76	−0.023803	0.078347	0.76
CG fingertip × 0.2 g	0.138853	0.078126	0.08	0.138853	0.078126	0.08
CG w/sebum fingertip × 0.1 g	0.004986	0.074913	0.95	0.004986	0.074913	0.95
CG w/sebum fingertip × 0.2 g	0.098791	0.074745	0.28	0.098791	0.074745	0.19
CG palm × 0.1 g	−0.059518	0.079618	0.45	−0.059518	0.079618	0.45
CG palm × 0.2 g	−0.152982	0.077091	**<0.05**	−0.152982	0.077905	0.05
CG w/sebum palm × 0.1 g	−0.007686	0.074913	0.92	−0.007686	0.074913	0.92
CG w/sebum palm × 0.2 g	0.080273	0.074745	0.28	0.080273	0.074745	0.28
PVA material × 0.1 g	0.222810	0.075011	**<0.05**	0.222810	0.075011	**<0.05**
PVA material × 0.2 g	−0.105130	0.074847	0.16	−0.105130	0.074847	0.16
Smooth × 0.5 kg	0.150137	0.044823	**<0.05**	0.150137	0.044823	**<0.05**
Smooth × 1.0 kg	−0.268205	0.043910	**<0.05**	−0.268205	0.043910	**<0.05**
Rough × 0.5 kg	−0.080233	0.044558	0.07	−0.080233	0.044558	0.07
Rough × 1.0 kg	0.050110	0.044162	0.26	0.05011	0.044162	0.26
Smooth × 0.1 g	−0.092016	0.044465	**<0.05**	−0.092016	0.044465	**<0.05**
Smooth × 0.2 g	−0.042937	0.044103	0.33	−0.042937	0.044103	0.33
Rough × 0.1 g	−0.029335	0.044939	0.51	−0.029335	0.044939	0.51
Rough × 0.2 g	0.013235	0.043992	0.76	0.013235	0.043992	0.76

aReferences for fixed effect factors: substrate = bare palm skin, surface = semi-rough, applied load = 1.5 kg, powder mass = 0.4 g