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Modeling and Experimental Validation of Microbial Transfer via Surface Touch

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Modeling and Experimental Validation of Microbial Transfer via Surface Touch

Abstract

Surface touch spreads disease-causing microbes, but the measured rates of microbial transfer vary significantly.Additionally, the mechanisms underlying microbial transfer via surface touch are unknown. In this study, a new physical model was proposed to accurately evaluate the microbial transfer rate in a finger-surface touch, based on the mechanistic effects of important physical factors, including surface roughness, surface wetness, touch force, and microbial transfer direction. Four surface-touch modes were distinguished, namely, a single touch, sequential touches (by different recipients), repeated touches (by the same recipient), and a touch with rubbing. The tested transfer rates collated from 26 prior studies were compared with the model predictions based on their experimental parameters, and studies in which the transfer rates were more consistent with our model predictions were identified. New validation experiments were performed by accurately controlling the parameters involved in the model. Four types of microbes were used to transfer between the naked finger and metal surface with the assistance of a purpose-made touch machine. The measured microbial transfer rate data in our new experiments had a smaller standard deviation than those reported from prior studies and were closer to the model prediction. Our novel predictive model sheds light on possible future studies.

(200 words)

Key words

Effective contact area, Fomite, Microbial transfer rate, Model, Surface touch, Touching behaviors

1. INTRODUCTION

Environmental surfaces (i.e., fomites) can be contaminated with pathogens by hand contact and thus contribute to disease spread.1−3 Various pathogens have been detected on a broad range of high-touch surfaces in indoor environments,4−8 and the roles of surface contamination have been revealed in many outbreak reports9−11 and field studies.12−15 For example, approximately 20%−40% of nosocomial infections were reported to have been transmitted via the hands of healthcare workers.16 Infectious microbes are deposited on environmental surfaces chiefly through human activities.17 They can survive for days or even months on surfaces,18,19 upon which they may also form biofilms.20,21 The long-term survival of microbes on fomites or skin is a precondition for direct microbial transfer via touching behaviors such as kissing,22 handshaking,23 and hand-to-mouth contact24 and for indirect microbial transfer via high-touch surfaces in indoor environments.25−27 These high-touch surfaces are therefore reservoirs of pathogens, exposure to which may not be negated solely by frequent handwashing.28 Microbial transfer via surface touch belongs to the general phenomenon of particle transfer between surfaces in contact, which also includes the transfer of mites between fabrics,29 the transfer of deposited particles

between shoes and floors,30 the transfer of chemical residues from surfaces to hands,31 and the transfer of cosmetic powders while applying makeup.32 The microbial transfer rate via touch events has been evaluated as a parameter in various analyses of infection.10,33−35 Numerous efforts have been made to quantify the transfer rates of various microbes via surface touches, using different surfaces,36 touching behaviors,37 and environmental conditions.38 These measured transfer rates usually exhibit significant variations,38−44 partly due to the failure to identify and control significant influencing factors.45 Meanwhile, recent studies investigate microbial transfer due to multiple touching behaviors within groups of surfaces,46−48 which requires a higher accuracy of evaluated transfer rate. In addition, researchers have not identified any microbial species or surface material properties that have significant effects on the transfer rate.36,38,39 Thus, a mechanism-based model would help to explicate the basic rules of microbial transfer during touching behaviors and provide guidance for future studies. In this study, we developed a simple physical model for predicting the microbial transfer rate via surface touch based on the mechanisms of surface contact and surface−particle adhesion. Important factors, such as surface roughness, surface wetness, and rubbing action, were included in the model.45 The predictions generated by the new model were compared to experimental data from the literature and further validated by our experiments in which the conditions and touching behaviors were controlled more accurately. The new model explains the mechanism by which important physical factors act on microbial transfer and proposes some important concepts that will illuminate further studies.

2. METHODS

2.1. Mechanisms and Concepts. In a touch event between a finger pad and a normally flat surface, a microbial particle (i.e.,individual microbe or microbial aggregate) can transfer from one surface, the particle donor, to another surface, the particle recipient. We hypothesize that this transfer occurs in two steps: First, a microbial particle on the donor is effectively contacted by the recipient; second, the recipient provides a sufficiently large adhesive force to remove the microbial particle from the donor (Figure 1). A microbial particle can be transferred only if both of these steps occur, and each step corresponds to the touch probability (P_T) or adhesive probability (P_A), which are elaborated in Figure 1. Each step involves various influencing factors (Figure 2).

<Figure 1>

<Figure 2>

P_T refers to the probability that a microbial particle on the donor will be effectively contacted by the recipient. When two surfaces touch, only the microbial particles in the effective contact area (A_e) are able to transfer between surfaces (Figure 1). The probability density function [$\mathbf{h_D}(\eta)$ and $\mathbf{h_R}(\eta)$ for the donor and recipient surfaces, respectively] describes the variance in the normal position of points around an average plane on a rough surface; here, η is the normal position of surface points, assuming that the average plane has a normal position of η (Figure 1). For a surface as either a microbial donor or recipient, its average roughness, specified as RD or RR,

respectively, can be calculated by the corresponding h(η). Assume that a microbial particle is randomly situated on the donor. To calculate the probability that the particle will be effectively contacted by the recipient, we need to confirm the compactness of the two surfaces, which is quantified by calculating the average distance between them, $\eta_R - \eta_D$. Here, $\eta_R - \eta_D$ is calculated using an implicit function (eq 1) according to Hertzian contact theory.Detailed derivations are in the Supporting Information (SI) A.

$$F = \frac{\pi A}{4\lambda}\int_{-\infty}^{+\infty}\mathbf{h_D}(\eta_D)\left[\int_{-\infty}^{\eta_D}\mathbf{h_R}(\eta_R)(\eta_D-\eta_R)E^*\mathbf{d}\eta_R\right]\mathbf{d}\eta_D \qquad (1)$$

where F is the touch force, A is the nominal contact area, and E* is the effective Young's modulus.

The thickness of the microbial layer (as either a microbial suspension or dried microbial particles) on the donor also influences the touch probability. On the donor, an inoculated microbial suspension thins as it dries, and the thickness of the surface liquid (d_s) is thus determined using an empirical function involving the inoculation volume (V), inoculation area (A_i), surface drying time (t), environmental relative humidity (RH), and temperature (θ),51 as shown in eq 2. Detailed derivations are given in SI A.

$$d_s \approx \frac{V}{A} - \left(\frac{1}{7} - \frac{RH}{700}\right) \times \left(\frac{\theta}{10} + 1\right) t \qquad (2)$$

Thus, the thickness of microbial layer (Δ) on a surface equals the maximum of the two values, d_s, and the diameter of the target microbes (d_p), i.e., Δ = max (d_s,d_p). Then, for a microbial particle randomly situated on the donor, P_T can be calculated by eq 3 as the probability that the normal position of a point on the donor (η_D) plus the thickness of microbial layer (Δ) is higher than the normal position of the corresponding point on the recipient (η_R), i.e., $\eta_R < \eta_D + \Delta$ (Figure 1).

$$P_T = \mathbf{P}(\eta_R < \eta_D + \Delta)$$

$$= \frac{a}{a'} \times \int_{-\infty}^{+\infty}\mathbf{h}_D(\eta_D)\left[\int_{-\infty}^{\eta_D+\Delta}\mathbf{h_R}(\eta_R)\mathbf{d}\eta_R\right]\mathbf{d}\eta_D \qquad (3)$$

$$= \frac{\sqrt{2}}{2}\int_{-\infty}^{+\infty}\mathbf{h}_D(\eta)\mathbf{h}_R(\eta+\Delta)\mathbf{d}\eta$$

where a/a′ = 2−0.5 (see SI A).

P_A refers to the probability that an effectively contacted microbial particle between two surfaces is subject to a sufficiently large adhesive force from the recipient to remove it from the donor (Figure 1).47 The adhesive force exerted on a microbial particle by a surface varies by its position on the surface, which is mainly due to surface roughness. A new theory of van der Waals adhesion between a surface and a particle, based on Hamaker theory, has recently been proposed, in which the variation of the adhesive force (φ) on a rough surface is given as a function of η, i.e., φ =f (η), as shown in eq 4

$$\varphi = \frac{A_H d_p}{12 H_0} \times \frac{1}{b(\eta + a)} \quad (4)$$

where AH is the Hamaker constant related to the surface material; H0 is the smallest distance between the surface and the microbial particle and is fixed as 0.3 nm; and a and b are two parameters related to surface roughness. Detailed derivations are in SI B. The probability density function of the adhesive force between a microbial particle and a rough surface is obtained as f D(φ) and f R(φ) for the donor and recipient surfaces, respectively. Then, P_A can be calculated using eq 5 as the probability that the adhesive force exerted on a microbial particle by the recipient is greater than the adhesive force exerted by the donor, i.e., $\varphi_D < \varphi_R$ (Figure 1).

$$P_A = \mathbf{P}(\varphi_D < \varphi_R)$$

$$= \int_0^{+\infty} \left[\int_0^{\varphi_R} \mathbf{f_D}(\varphi_D) \mathbf{d}\varphi_D \right] \mathbf{f_R}(\varphi_R) \mathbf{d}\varphi_R \quad (5)$$

$$= \int_0^{+\infty} \mathbf{F_D}(\varphi) \mathbf{f_R}(\varphi) \mathbf{d}\varphi$$

In this study, we prefer to evaluate the P_A directly via experimentation as introduced below, instead of using eq 5 to calculate the value, because A_H varies among surfaces and is difficult to determine. Note that ϕ is proportional to d_p, 55 and thus, there is a zero-correlation between P_A and d_p (see SI B).Transfer probability (P), the probability of a microbial particle transferring from one surface to another, is calculated using eq 6. It is equal to the probability that the two events, touch and adhesion, occur simultaneously, as illustrated in Figure 1.

$$P = P_T \times P_A \quad (6)$$

onsider the microbial transfer rate in a single touch and define the four concepts of sequential touches, repeated touches, rubbing, and a hypothetical full touch. For C identical microbial particles spread randomly on a surface, the transfer rate (τ), defined as the proportion of particles within the nominal contact area that are transferred by a single touch, is equal to the transfer probability of each single particle, as in eq 7.

$$\tau = \frac{C \times P}{C} = P \quad (7)$$

“Sequential touches” refers to consecutive touches of a donor by a series of identical clean recipients, resulting in microbial transfer from the donor to these recipients. Assuming that there are constant physical parameters across the touches, the number of microbial particles remaining on the donor after N touches ($C - \sum_{i=1}^{N} \Delta C_i$), and the number transferred during the Nth touch (ΔC_N) can be calculated using eqs 8a and 8b. As the touchescontinue, $C - \sum_{i=1}^{N} \Delta C_i$ decreases exponentially and approaches zero.

$$\frac{C-\sum_{i=1}^{N}\Delta C_i}{C} \approx (1-P)^N \quad (8a)$$

$$\frac{\Delta C_N}{C} \approx P(1-P)^{N-1} \quad (8b)$$

"Repeated touches" refers to repeated touches of a donor by an initially clean recipient, resulting in a continuous transfer of microbial particles to the recipient and the return of some transferred particles back to the donor. Assuming constant physical parameters across the touches, eqs 9a and 9b are obtained.

$$\frac{C-\sum_{i=1}^{N}\Delta C_i}{C} \approx 1 - P_A + P_A(1-P_T)^N \quad (9a)$$

$$\frac{\Delta C_N}{C} \approx P(1-P_T)^{N-1} \quad (9b)$$

Similar to eq 8a, $C-\sum_{i=1}^{N}\Delta C_i$ in eq 9a also decreases exponentially as the touches proceed, but it approaches ($1 - P_A$) instead of zero (as in eq 8a). This means that as touching is repeated infinitely, the numbers of microbial particles on the two surfaces reach an equilibrium. Thus, the number of microbial particles transferred to the recipient in each subsequent touch equals the number of particles returned to the donor, and the ratio of microbial particles on the donor/recipient = $(1 - P_A)/P_A$. The complete forms of eqs 8 and 9, which consider surface roughness, are given in SI C. During repeated touches, the cumulative number of microbial particles transferred to the recipient ($\sum_{i=1}^{N}\Delta C_i$) is proportional to the total area on the donor that has been effectively touched by the recipient (see Table S2 in SI C).

The performance of a rubbing action during a touch event increases the effective contact area between the two surfaces and has a similar effect to repeated touches. Ignoring the effect of shear stress, we consider rubbing with a relative sliding distance (S) between a finger and a surface to be equivalent to N repeated touches. We assume a single touch between a surface asperity and a fingerprint ridge (assumed width S0 = 0.04 cm). Then, we use S0 as a coefficient to transform the sliding distance (S) during rubbing into the number of touches (N) during repeated touching, as in eq 10.

$$N = \frac{S}{S_0} \quad (10)$$

For the rubbing action assumed in this study (i.e., a touch with a 90°-twist rubbing action), an asperity on the surface slides an average of ≈1 cm while theoretically

crossing 2−25 fingerprint ridges. This is theoretically equivalent to N = 2−25 repeated touches (N_{min} = 2; N_{max} = S/S0 = 1 cm/0.04 cm = 25). Thus, an average of the cumulative transfer rates in two groups of repeated touches (N = 2 and N = 25) was evaluated as the predicted cumulative transfer rate in a touch with a 90°-twist rubbing action. A stricter relationship between N and S should be examined in future studies.

P_A is related only to the original properties of surfaces and microbial particles and is unaffected by touching behaviors.47 Thus, a full touch, as a useful concept, is defined as an ideal touch with sufficient rubbing (or an infinite number of single touches) and sufficient touch force such that P_T in eq 9a approaches 100%, in which the cumulative transfer rate is only determined by P_A, i.e., $\frac{\sum_{i=1}^{N} \Delta C_i}{C} = P_A$. In this study, P_A for each type of microbe and each transfer direction was pretested by measuring the cumulative transfer rate in a full touch.

2.2. New Validation Experiments.

New experiments were performed using our previously described methods,45 with accurate control and a complete set of experimental parameters. Four reference microbial strains, Staphylococcus aureus ATCC 25923, Escherichia coli ATCC 25922, Saccharomyces cerevisiae ATCC 9763, and enterobacteria phage P22 ATCC 97540, were cultured as the microbes to be transferred (see SI D). A target microbial suspension was inoculated on a washed naked finger (or a sterile metal surface) to create the donor, which was then touched to one or multiple sterile metal surfaces (or washed naked fingers). A purpose-made touch machine operated by a computer via an Arduino board was used to assist the surface touch by providing more accurate control of the touch force, duration, and rubbing action (see SI E). The experimental protocol was approved by the Human Research Ethics Committee, University of Hong Kong (ethical approval number: EA1603004).

Following our above-defined new concept of full touch, PA was initially evaluated for each type of microbe and transfer direction, as a series of pretests. For each type of microbe, a metal surface with an average roughness of 1.6 μm was repeatedly touched (N = 10) by an index finger, with each touch comprising a force greater than 30 N and a 90°-twist rubbing action to achieve a full touch. After a full touch, the numbers of microbes on the donor and recipient surfaces were considered to have reached equilibrium, i.e., $\frac{\sum_{i=1}^{N} \Delta C_i}{C} = P_A$. Thus,$P_A$ was obtained from the current cumulative transfer rate. For each type of microbe, P_A was tested separately for each transfer direction to obtain $P_{A(\text{metal-to-finger})}$ and $P_{A(\text{finger-to-metal})}$, which respectively, corresponded to the use

of the metal surface or the index finger as a donor, after inoculation with the target microbial suspension and air-drying to visible dryness.

In the main tests, we validated the new model by investigating six parameters selected in reference to our previous study,45 including the average roughness of the surface of either the microbial donor or recipient (R_D and R_R = 1.6−100 μm), the touch force (F = 2−30 N), the inoculation volume after drying (V = 20−0 μL), the touch mode (i.e., with/without a 90°-twist rubbing action), and number of touches during sequential touching (N = 1−5) and repeated touching (N = 1, 2, 4, and 8). A baseline experimental condition was defined as follows: a 20- μL aliquot of S. aureus in broth was inoculated onto a metal surface with an average roughness of 1.6 μm. The microbial suspension was air-dried to visible dryness (residue < 0.5 mg; considered as V = 0 μL). Subsequently, the contaminated surface was touched with a finger pad under a load of F = 8 N and without rubbing. In the main tests, each parameter was varied separately while the others remained constant, unless mentioned otherwise.

Microbes on each touched surface or finger pad were sampled by swabbing (sampling efficiency ≈ 70%, see SI F) followed by DNA extraction using our previously described procedure,45 which is convenient and yields relatively accurate microbial quantification (vs other methods). The number of microbes on each surface was quantified using a quantitative polymerase chain reaction (qPCR), and the microbial transfer rate of a touch was determined as the ratio of the DNA content on the recipient to the sum of the contents on the donor and recipient, based on the assumption that the DNA content of a surface sample is proportional to the microbial particle number (see eq11).

$$\tau = \frac{1}{(1+e)^{|C_{q(R)} - C_{q(D)}|} + 1} \qquad (11)$$

where $C_{q(D)}$ and $C_{q(R)}$ are the Cq values of the donor and recipient samples obtained via qPCR, respectively, and e is the PCR efficiency. For each pair of primers, the e value was calibrated as shown in SI F.

The transfer rate experiments were performed in triplicate.The index, middle, and ring fingers were each used as a replicate,and the mean and standard deviation (SD) of the three measured transfer rates were reported. The air temperature in the laboratory was maintained at 22 ± 1 °C with a relative humidity of 65%−75%.

A total of 103 test sets were generated by our new experiments(42 sets) and previous

study (61 sets; no. 29 in Table 1)45 (listed in SI H). To validate the new model, a predicted transfer rate was calculated for each of the 103 measured transfer rates by using the new model with the stated parameter values. The Pearson correlation coefficient (r) was determined for the pair of data sets from the experimental measurements and model predictions. The Cohen's d values of the measured transfer rates were calculated to evaluate the effect sizes of the investigated parameters (SI H).

2.3. Comparison between Model Prediction and Prior Measurement. Twenty-nine prior studies on microbial transfer from 1975 to 2019 were identified by searching Google Scholar using the terms "surface/fomite", "contact", and "virus/ bacteria transfer rate/efficiency". The results are collected in Table 1 [28 by others, one by us (no. 29)]. A key study selection criterion was that a paper has a clear description about the surface touching behaviors. We collated the reported data of 390 tests from 26 of the first 28 studies in Table 1 (except nos. 19 and 28, which did not report transfer rates directly). For each test, the values of 11 parameters (R_D, R_R, d_p, p, Rub, V, A_i, t, RH, θ, and N) and a resultant microbial transfer rate (τ) were collected from the reported texts and summarized as a 1 × 12 array, resulting in a data set in the form of a 390 × 12 matrix (see SI H). In addition, a predicted transfer rate was evaluated for each test, using our new model and the 11 parameters. Our model predictions and the 390 measured transfer rates were compared to determine the level of agreement.

3. RESULTS

3.1. Pretests of Evaluating PA. The measured PA varied by microbial type in both transfer directions (metal-to-finger and finger-to-metal), as shown by the gray columns in Figure 3a. For each microbial type, $P_{A(\text{metal-to-finger})}$ + $PA_{(\text{finger-to-metal})}$ was less than 100% (mean = 85.0%), despite full touches being performed. This may have been due to an increase in adhesive force between the microbial particles and the donor as the microbial suspension dried, given the shorter drying duration on a finger pad (≈20 min) than on a metal surface (≈2 h) and a higher $P_{A(\text{finger-to-metal})}$ on three-quarters of the microbial types.

3.2. Factors Affecting the Predicted Microbial Transfer Rate. The effects of four parameters (i.e., surface roughness, touch force, inoculation volume, and touch number) on the transfer rate of S. aureus were predicted for different transfer directions and touch modes (with and without rubbing) and are shown as the red lines and points in Figure 3a−f.

As shown in Figure 3b, the metal-to-finger transfer rate decreased as the metal roughness increased. Interestingly, the transfer rate decreased rapidly when the metal

roughness was similar to the finger pad roughness (average roughness = 10−20 μm83−85). Repeated touches amplified the effect of the metal roughness. Tests with a smaller touch force (Figure 3c) showed a similar trend in the transfer rate as a function of metal roughness but yielded slightly smaller average transfer rates. The finger-to-metal transfer rate (Figure 3d) did not vary monotonically with the metal roughness. With repeated touches, the transfer rate reached a maximum when the metal surface roughness was within 1 order of magnitude greater than that of the finger pad. As the number of touches increased, the maximum transfer rate tended to increase with greater metal roughness.

The transfer rate was positively correlated with the touch force but varied only within a small range (10%−15% for single touching) as the force increased from 2 to 30 N (Figure 3e). This variation was negligible for repeated touching. The microbial transfer rate decreased significantly (by 60%) as the inoculated suspension varied from no surface drying (V = 20 μL) to visible dryness (Figure 3f). Under the baseline condition, the transfer rate decreased rapidly at V = 6−7 μL with an inoculation area of Ai = 1 cm2

<Table 1>

SS, stainless steel; App., approximately; temp., temperature; (ND), not defined; (D), only used as the microbial donor; (R), only used as the microbial recipient. Not rigorously controlled. Wring out the dishcloth for 10 s; wring out the sponge for 10 s; turned the faucet handle on and off twice; cut the carrot into pieces; prepare four hamburger patties; hold the receiver for 30 s if answering the dTarget surfaces were immersed with the microbial suspension with the specified volume, but the inoculation volume is not identified.

We also predicted the effects of the touch number in both sequential and repeated touching modes. With sequential touches (Figure 3g), the cumulative number of microbial particles transferred from the contaminated finger ($\sum_{i=1}^{N} \Delta C_i$) increased with an increasing number of touched metal surfaces (N). As touching proceeded, however, the number of microbes transferred to each metal surface (ΔC_N) decreased. With repeated touches (Figure 3h), an increased number of microbial particles accumulated on the recipient finger. The microbial numbers on the metal and finger surfaces gradually approached a metal/finger equilibrium.

3.3. Experimental Validation. Figure 3 compares our measured transfer rates with the predicted results. Generally, the variation in the measured transfer rates under each of the varied parameters was consistent with the model prediction. In Figure 3a, no correlations were observed between the measured transfer rates and any microbial properties (including individual microbial size). In Figure 3a−h, it can be seen that the measured transfer rates for single touches are slightly higher than the predicted rates (average absolute difference = 3.25%). In Figure 3b−e, most measured transfer rates for touches performed with a rubbing action are clustered around the violet lines (mean of N = 2 and 25) with an average absolute underestimation of only 0.474%. Each measured transfer rate yielded a substantial SD, despite our best efforts to accurately

control the surface touching parameters. Nevertheless, the average relative SD (RSD = SD/τ) of 35.3% was significantly lower than those reported in previous studies (mostly greater than 100%).38−44 A strong correlation was observed between the predicted transfer rates and our measured values (Figure 4a, Pearson's r = 0.857; both data sets follow a normal distribution). No obvious difference in the accuracy of the model prediction was observed between the data categorized by different touching behaviors (Figure 4b−e) and the examined parameters (Figure 4f−i).

3.4. Comparison between Model Prediction and Prior Measurement. Figure 5 compares our predicted transfer rates with those measured in 26 prior studies. The prediction residuals are indicated by squares and categorized by study. Generally, an average absolute residual of 1.489% indicates an accurate prediction from the new model. Specifically, measurements in the studies show various degrees of consistency with the model prediction, in view of the different means and SDs of the residuals (the black and red lines in Figure 5). Studies that completely controlled the investigated parameters (nos. 5, 8, and 12) exhibit better agreement with the model predictions, as indicated by their small SDs. Other studies in which most investigated parameters were well controlled (nos. 18 and 21− 25) had large means or SDs of prediction residuals, mostly due to a lack of control of the rubbing action (stacked columns in Figure 5).

4. DISCUSSION

4.1. First Mechanism-Based Prediction Model of Microbial Transfer. The above data enabled us to develop the first mechanism-based model for predicting the rate of microbial transfer via surface touch. The new model, which was based on several of our previous studies,45,47,55,88 introduces new definitions of transferring events and embodies new concepts, such as "equilibrium" and "full touch". This model successfully captures the effects of some important physical factors on the transfer rate, as summarized in Table 2. The model can be used to estimate the pathogenic transfer rates in various situations, such as when pressing a button or grasping a handle,by evaluating the related parameters. The model may be further combined with more empirical functions to introduce more commonly concerned factors, such as age and sex with their effects on the finger's hardness and adhesiveness to pathogens.

<Figure 3>

<Figure 4>

Our model produced several new insights into the effects of various factors on microbial transfer events. In repeated touches, the surface roughness of the microbial donor had a different effect to that of the microbial recipient. The cumulative transfer rate did not vary monotonically as the recipient surface roughness varied (Figure 3d), which might explain why this parameter was not identified as a significant factor in our previous linear regression-based analysis.45 The measured Young's modulus of the

researcher's finger pad (E_{finger}) was ≈0.25 MPa at F = 8 N and exhibited a near-linear increase from 0.17 to 0.7 MPa as F increased from 2 to 30 N (SI A), which is a similar magnitude to the results of previous studies.57,90,91 From Oprisan et al., E_{finger} was ≈0.2 MPa at F = 8 N and had an increase of ≈0.018 MPa with the increase per Newton in the touch force.90 Thus, the finger pad underwent little deformation under a commonly encountered touch force (over 2 N45), and the transfer rate during a touch did not significantly change as a function of force (Figure 3e). However, the absolute transfer rate under a given touch force may differ between individuals, as E_{finger} also varies by age and sex.

Our experiment did not find a significant effect of individual microbial size on the transfer rate (Figure 3a). This was partly due to the regular wavy structure of the finger surface, based on the contact mechanism in eq 3 (please also refer to Section 7.1 in Popov's book50). According to eq 3, if points at both touching surfaces are distributed randomly in the normal direction (e.g., $h_D(\eta)$ and $h_R(\eta)$ follow Gaussian distribution), the microbial size would have a significant effect on PT under dry conditions. Additionally, viruses and bacteria could remain discrete or form aggregates of various sizes.92 In this situation, little difference in the transfer rate was observed between different microbial types.

In future studies, we will further demonstrate the insignificant effect of the microbial type on the transfer rate.

We modeled the effect of surface wetness (quantified by inoculation volume) for the first time. Surprisingly, this factor had a significant effect on the transfer rate in both the modeling and validation experiments. Microbes in suspension may be distributed evenly throughout the liquid phase or clustered at the liquid−air interface as a monolayer.93 A future study of the importance of hand-drying after handwashing may be warranted, as we believe this has not been widely recognized.94 There were no obvious differences in the measured PA values between the different microbial types (Figure 3a), possibly because the microbes were either suspended in liquid or surrounded by culture medium precipitate after drying, thus preventing specific microbe−surface binding.

We also investigated microbial transfer during defined sequential touches and repeated touches. In previous studies,47,88 we used the sequential-touch method to calculate the transfer rate more accurately, without needing to evaluate the donor microbial concentration.88 For repeated touches, the concept of equilibrium is not novel.30,47,95 However, eq 9a reveals that the equilibrium depends only on PA, whereas the speed of reaching the equilibrium is determined by both PA and PT. In addition, the equilibrium was theoretically proven to be not strictly transitive,47,96 which illustrates the difficulty of accurately evaluating the spread and distribution of pathogens among surfaces.14,86,97

4.2. Iimproved Data Set of Measured Transfer Rates. We generated a data set of microbial transfer rates. As summarized in Table 1, prior studies of surface touching and evaluations of transfer rates used different methods, and some did not completely control the parameters (Figure 5). It is therefore unsurprising that the measured transfer rates contain large errors and vary significantly between the studies. Studies that reported SD values had average RSDs exceeding 40%,38−44 and most had values near 100%.38,39,42−44 Although most of those studies investigated various surface types and microbial species, neither factor was found to have a significant effect on the microbial transfer rate.45 According to our analyses, the significance of the results from those studies was undermined by unsystematic experimental protocols and poorly controlled influencing factors. In contrast, our model accurately predicted the measured transfer rates in our new validation experiments, in which the influencing factors were accurately controlled. The high value of the Pearson's r shown in Figure 4 indicates the high predictive accuracy of the new model. We conclude that (a) the new model can accurately evaluate the transfer rate and its variations in response to different factors, and (b) deviations in the transfer rate between ideally identical touching behaviors can be significantly reduced by accurately controlling the important factors.

<Table 2>

However, despite our ability to control important parameters during the measurement of microbial transfer, the deviations in our experimental results remained significant (average RSD ≈ 35.3%), albeit much smaller than those in prior studies.38−44 Such deviations are partly attributed to errors in subsequent microbial quantification methods, such as surface swabbing98 and qPCR.99 Significant uncertainty also exists in the transfer process itself, which is sensitive to several potential influencing factors, such as finger temperature, roughness structure, surface wettability, and chemical bonding between the microbes and surfaces.48 It would be extremely difficult to consider all of these complex factors. In our model, therefore, we included parameters that had displayed clear mechanisms of action and had been previously reported to exert significant effects on the transfer event.

4.3. Limitations of the New Model. The new model mainly focuses on widely addressed physical factors but does not study the biological characteristics of microbes in depth. Other aspects, including temperature, humidity, pH, and surface properties and detailed parameters such as the microbial shape and status (e.g., isolated, grouped or within a biofilm) might also influence microbial survival.48 Effects of surface material and microbial species on the microbial attachment on fingers or surfaces are not involved in the new model because we do not find any key parameters that dominate the strength of microbe− surface combination.100−102 A more detailed understanding of these aspects will require the coupling of biological mechanisms with our physics-based model.

Additionally, some factors addressed in previous studies, such as the touch duration and porous/nonporous surface structure,38,67,81 are not included in the new model because these have unidentified effects on the microbial transfer rate, and their

mechanisms of action are not well understood. Although some studies found that microbe adhesive forces on surfaces increased with prolonged contact times,103−107 variations of the touch duration within a common range (generally 5−20 s)45 had little effect on microbe−surface adhesion. In Figure 5, 60 data points were measured under the condition of hand-to-poroussurface transmission, with a mean τ of 21.9%; another 118 data points were derived from porous-surface-to-hand transmission, with a mean τ of 5.11% (see SI H). These statistical results are consistent with our modeling results, in which we only differentiated the porous structure from the perspective of surface roughness.

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Figure 1. Schematic illustration of the two-step microbial-transfer process. PT and PA are the touch probability and adhesive probability, respectively.
ηD and ηR are the respective average normal positions of the points on the donor and recipient surfaces, respectively. Δ is the thickness of the microbial
layer on the donor. The blue, purple, and red circles represent the uncontacted, effectively contacted, and transferred microbial particles (individual
microbes or microbial aggregates), respectively.

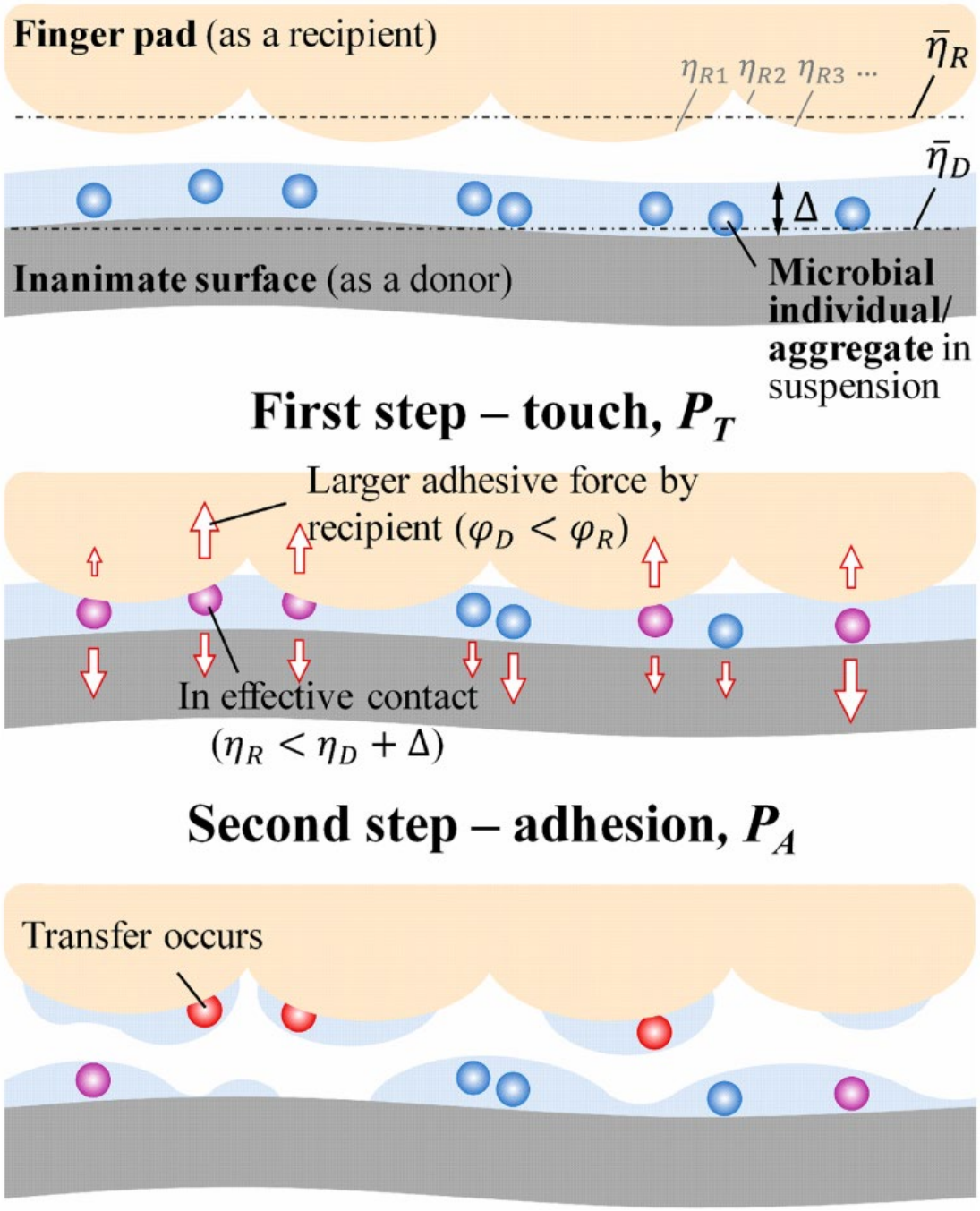

Figure 2. Flowchart of the new model for evaluating the microbial transfer rate. The influencing factors included in the model are specified as parameters acting on different steps.

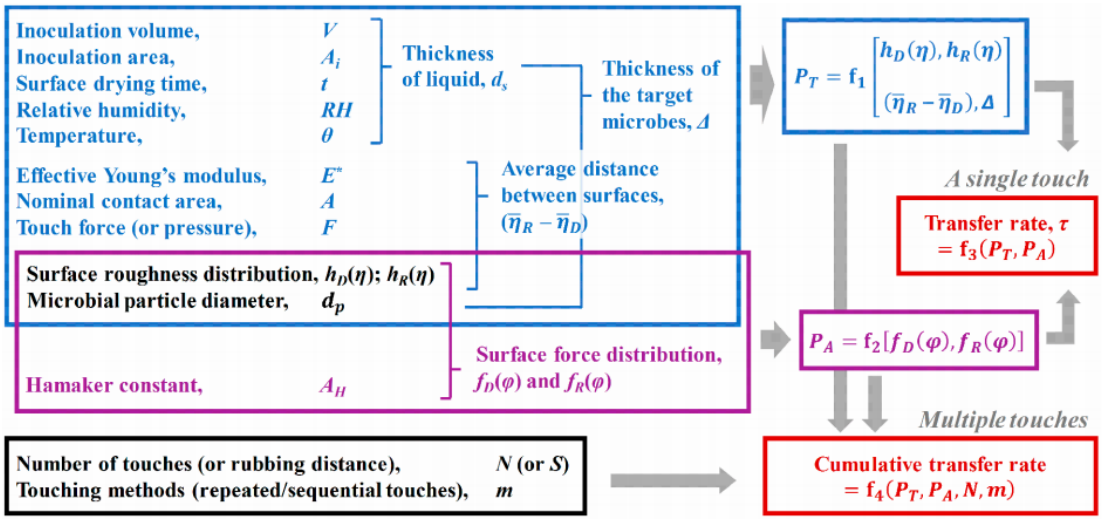

Figure 3. Comparisons of transfer rates (τ) between the model predictions (red) and our experimental measurements (black), with variations indifferent parameters. (a) Transfer of four types of microbe in two directions. Gray columns indicate the evaluated PA values. A typical individualdiameter (dp) is presented for each microbial type, and the values are from SI D. (b) Transfer of S. aureus from metal surfaces of various roughness (RD)to a finger pad. (c) Transfer of S. aureus transfer from metal surfaces of various roughness (RD) to a finger pad at a light touch force (F) = 2 N. (d)Transfer of S. aureus from a finger pad to metal surfaces of various roughness (RR). (e) Transfer of S. aureus from a metal surface to a finger pad under various touch forces (F). (f) Transfer of S. aureus from a metal surface to a finger pad with various inoculation volumes (V). (g) Transfer of S. aureus via sequential touches between a finger pad and N metal surfaces. (h) Transfer of S. aureus transfer from a metal surface to a clean finger pad via N repeated touches. The transfer rate was measured for a single touch (□) and a touch with rubbing (■). The error bars represent the standard deviations of three replicates. In plots b−e, the cumulative transfer rate for modeling repeated touches is shown as 11 red curves; the number of touches for curves from the bottom upward are set as N = 1, 2, . . ., 10 and 25. The thick violet curves represent the means of N = 2 and 25, as the predicted transfer rates in the touch
with the rubbing action.

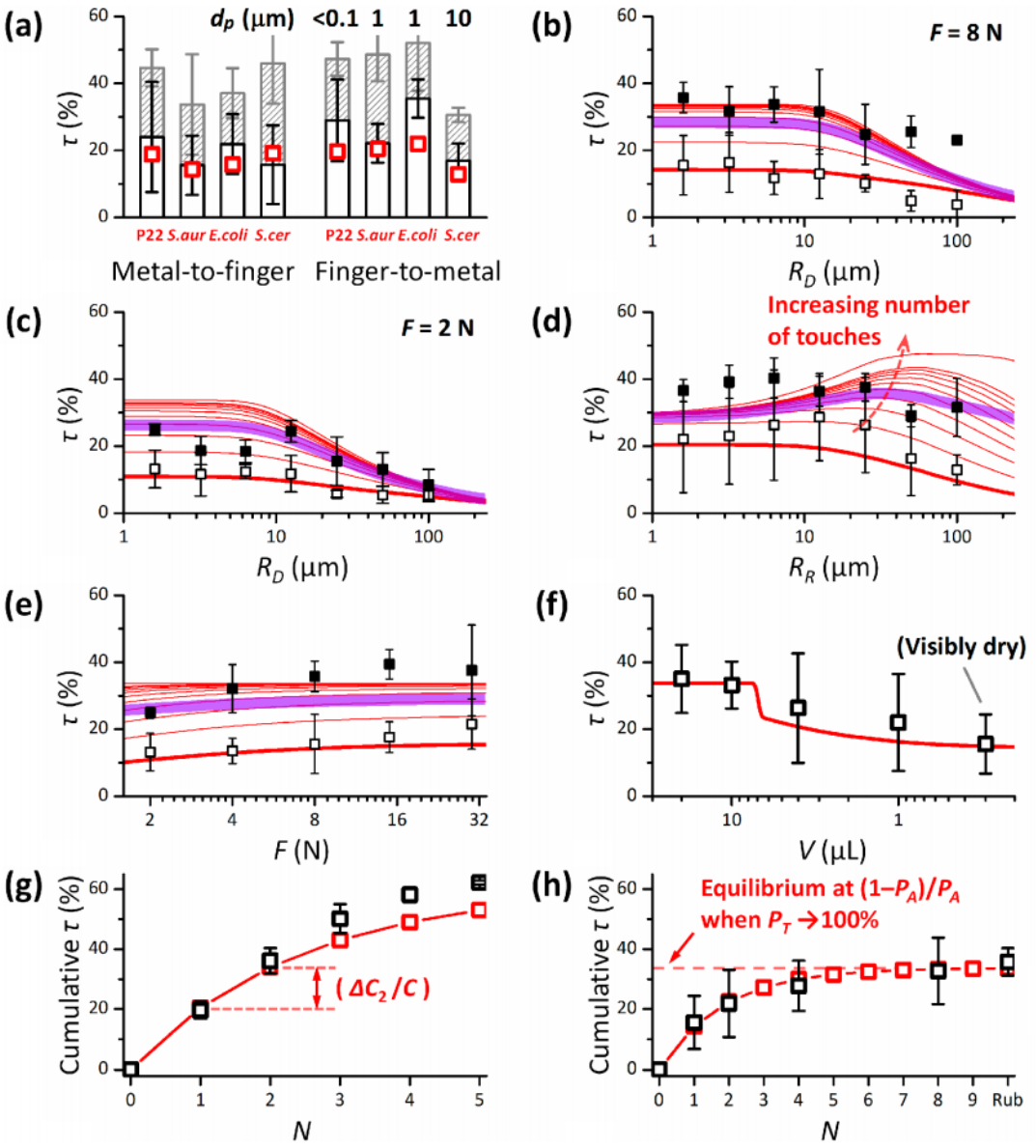

Figure 4. Validation of the new model against 103 sets of data measured in this and our previous studies (items marked with ∗ in the key).45 The model-predicted transfer rates were compared with the measured data by performing a linear regression (a). The data are categorized by different touching behaviors (b−e) or the examined parameters (f−i).

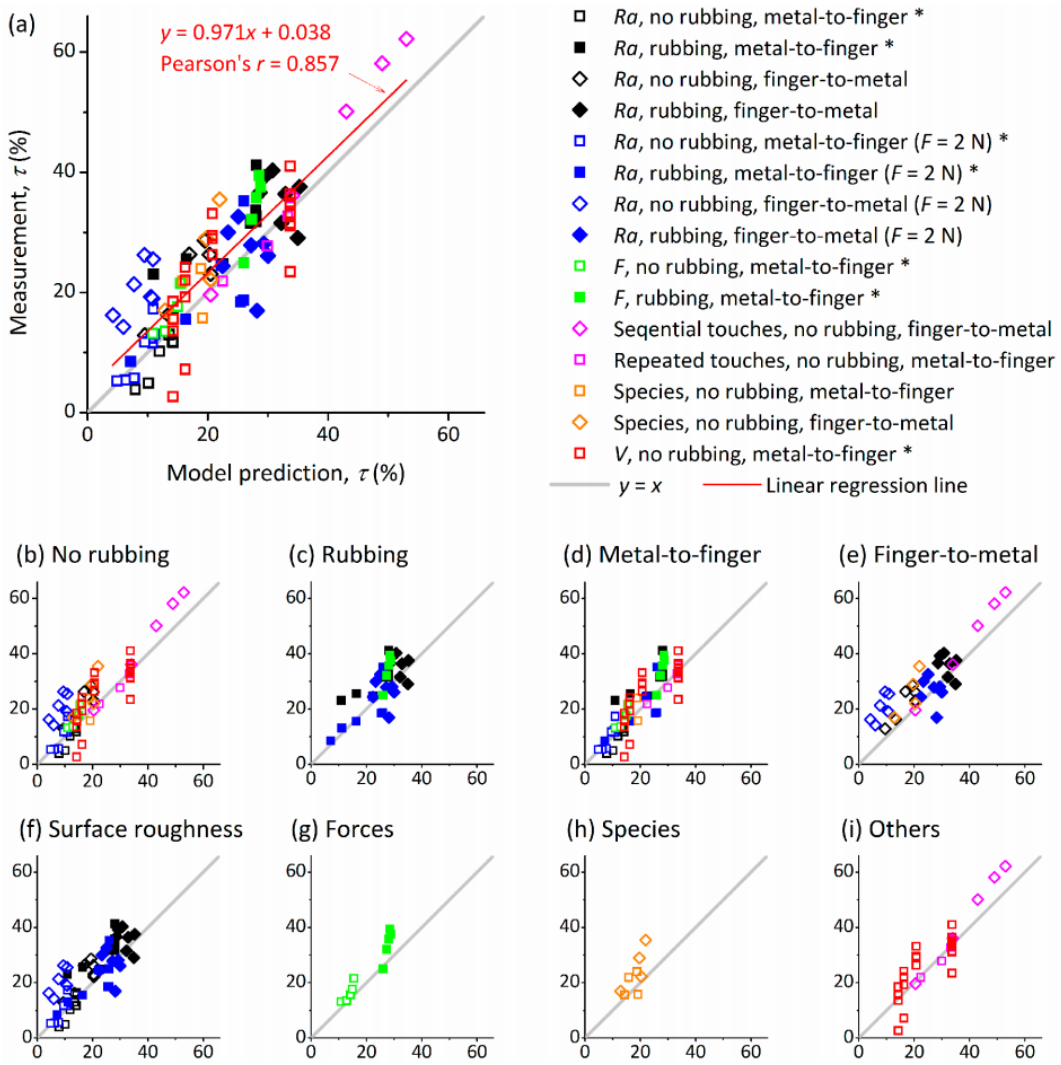

Figure 5. Comparison of the model predicted and measured values from 390 sets of experimental data from 26 prior studies (in Table 1). The model prediction residual for each set of experiment result is shown as the square point. Different colors indicate different studies. For each study, the mean and standard deviation (SD) of prediction residuals are shown as black and red lines, respectively, and uncontrolled parameters are indicated by stack columns.

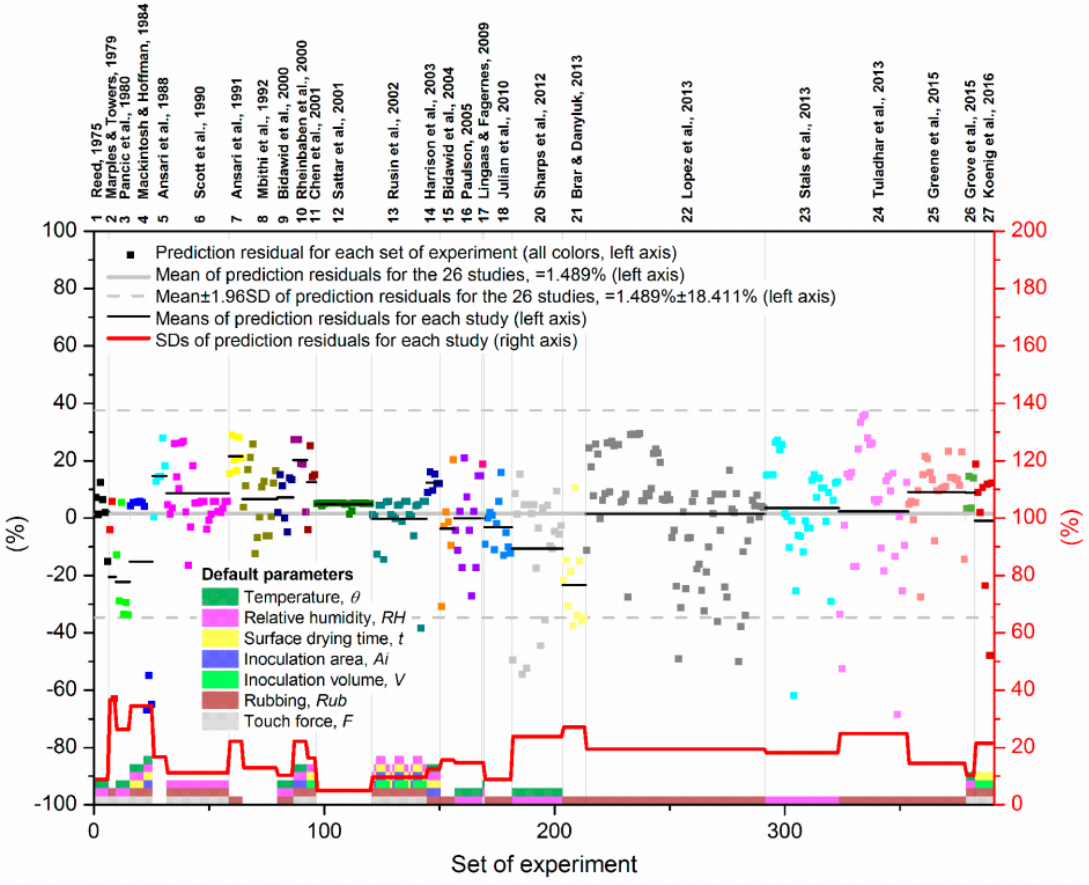
1 Reed, 1975
2 Marples & Towers, 1979
3 Pancic et al., 1980
4 Mackintosh & Hoffman, 1984
5 Ansari et al., 1988
6 Scott et al., 1990
7 Ansari et al., 1991
8 Mbithi et al., 1992
9 Bidawid et al., 2000
10 Rheinbaben et al., 2000
11 Chen et al., 2001
12 Sattar et al., 2001
13 Rusin et al., 2002
14 Harrison et al., 2003
15 Bidawid et al., 2004
16 Paulson, 2005
17 Lingaas & Fagernes, 2009
18 Julian et al., 2010
20 Sharps et al., 2012
21 Brar & Danyluk, 2013
22 Lopez et al., 2013
23 Stals et al., 2013
24 Tuladhar et al., 2013
25 Greene et al., 2015
26 Grove et al., 2015
27 Koenig et al., 2016
Prediction residual for each set of experiment (all colors, left axis)
Mean of prediction residuals for the 26 studies, =1.489% (left axis)
Mean±1.96SD of prediction residuals for the 26 studies, =1.489%±18.411% (left axis)
Means of prediction residuals for each study (left axis)
SDs of prediction residuals for each study (right axis)
Default parameters
Temperature, θ
Relative humidity, RH
Surface drying time, t
Inoculation area, Ai
Inoculation volume, V
Rubbing, Rub
Touch force, F
(%)
(%)
Set of experiment

Table 1. Summary of 29 Studies Investigating Microbial Transfer via Surface Touch

ref	Surfaces	Species	Touching behaviors	Inoculation, V (μL)	Inoculation area, A_i	Drying time, t (min)	RH (%)	θ (°C)
1. Reed, 1975[63]	Finger, pen, table, steel	Rhinovirus	Firmly rub	5.5	2−3 cm^2	10	(ND)	(ND)
2. Marples and Towers, 1979[64]	Fabric, index finger, hands	*S. saprophyticus*	Grasp a fabric-covered bottle firmly	1 mL[d]	10 cm × 20 cm for fabric; 360 cm^2 for hands	0, 60	26	Room temp.
3. Pancic et al., 1980[65][65]	Finger, faucet handle, door knob	Rhinovirus	Grasp firmly, slide back and forth twice	50, 100	Contaminate 5 fingers	10	(ND)	(ND)
4. Mackintosh and Hoffman, 1984[66]	Fabric, hand	*S. saprophyticus*, *E. coli*, *P. aeruginosa*, *K. aerogenes*, *S. pyogenes*, *S. marcescens*	Grasp firmly	1 mL[d]	10 × 20 cm	(ND)	(ND)	(ND)
5. Ansari et al., 1988[67]	Hand, SS disks	Human rotavirus	1 kg/cm^2, without any friction or rubbing motion	10	Vial, 8 mm inside diameter	20, 60	App. 50	App. 22 ± 2
6. Scott et al., 1990[68]	Laminate (D), cloth (D), fingertip (R)	*E. coli*, *K. aerogenes*, *S. aureus*	Place firmly	100, 3000[d]	2 cm^2 1260 cm^2	0, 60, 120, 1440	60	18−20
7. Ansari et al., 1991[69]	Hand, disk	Rhinovirus 14, Human Parainfluenza Virus 3	1 kg/cm^2	10	1 cm diameter	20	50 ± 5	22 ± 2
8. Mbithi et al., 1992[70]	SS disk, fingerpad	Hepatitis A virus	0.2 kg/cm^2, without any friction	10	8 mm inside diameter	20, 60, 120, 180, 240	45 ± 5	22 ± 2
9. Bidawid et al., 2000[71]	Fingerpad (with various disinfection procedures) (D), lettuce (R)	Hepatitis A virus	0.2−0.4 kg/cm^2[69]	10	App. 2 cm × 1 cm	in a hood for 20−30 min	(ND)	(ND)
10. Rheinbaben et al., 2000[72]	Door handle, washed/unwashed hand, finger tip	φ-X174	(ND)	400, 100	(ND)	15	(ND)	(ND)
11. Chen et al., 2001[73]	Chicken (D), gloved finger (R), spigot, clean hand (R), hand (D), lettuce (R)	*E. aerogenes*	(ND)	(ND)	1 cm × 1 cm	(ND)	(ND)	Room temp.
12. Sattar et al., 2001[37]	Fabric (100% cotton; 50:50 cotton/polyester) (D), fingerpad (moist or not) (R)	*S. aureus*	0.2 kg/cm^2 with/without friction[70,74]	10	8 mm inside diameter[70,74]	0 (moist/re-moist), 60	47−58	22−25
13. Rusin et al., 2002[36]	Dishcloth (D), sponge (D), faucet (D), carrot (D), hamburger (D), phone receiver (D), laundry (100% cotton; 50:50 cotton/polyester) (D), hand (R)	*M. luteus*, *S. rubidea*, PRD-1	Varied by surfaces[c]	(ND)	(ND)	(ND)	(ND)	Room temp.
14. Harrison et al., 2003[75]	Paper towel dispenser, hand	*M. luteus*, *S. marcescens*	0.1 kg/cm^2	100	(ND)	(ND)	(ND)	(ND)
15. Bidawid et al., 2004[76]	Fingerpad, ham, lettuce, metal disk	Feline calicivirus	0.2−0.4 kg/cm^2	10	1 cm diameter	20	45	24 ± 2
16. Paulson, 2005[77]	Spatula (D), lettuce (D), fork (D), cutting board (D), door knob (D), SS coupon (D), gloved fingertip (R)	(Norwalk virus) Feline calicivirus	0.2−0.4 kg/cm^2, without friction or rubbing	10	App. 0.25 cm^2	5, 15	(ND)	(ND)
17. Lingaas and Fagernes, 2009[78]	Hand	*E. coli*	Sliding movement	150	(ND)	2	(ND)	(ND)
18. Julian et al., 2010[39]	Unwashed/washed finger, glass	MS2, φ-X174, fr	Average of 25 kPa (range of 16−38 kPa)	5	1 cm diameter[69]	10	45−60	20−22
19. Hübner et al., 2011[79]	Index fingertips, paper	*E. coli*	(ND)	25	(ND)	(ND)	55 ± 5	23 ± 2
20. Sharps et al., 2012[40]	Latex-gloved fingertip, SS, blueberry (R), grape (R), raspberry (R)	GII.4 NoV, GI.3b NoV, MNV-1	50 ± 5 g, 1 cm^2 area	10	App. 1 cm^2 area	30	(ND)	(ND)
21. Brar and Danyluk, 2013[41]	Gloved finger (single use, clean reusable, dirty reusable), tomatoes	*Salmonella*	light pressure (no impression on the tomato surface)	100	Square piece (5 × 5 cm) on glove, circle (2−3 cm in diameter) on tomato	0, 60	37 ± 10	22 ± 3
22. Lopez et al., 2013[38]	Acrylic (D), glass (D), ceramic tile (D), laminate (D), SS (D), granite (D), cotton (D), polyester (D), paper currency, finger (R)	*E. coli*, *S. aureus*, *B. thuringiensis*, MS2 coliphage, Poliovirus 1	Average 1.0 kg/cm^2 (range, 700−1500 g/cm^2)[67,70]	10	App. 1 cm^2 area	30	15−32, 45−60	19−25
23. Stals et al., 2013[42]	Gloved finger, SS disc, boiled ham, sandwich bun, lettuce	NoV GII.4, MNV-1	Pressure of 0.2−0.4 kg/cm^2 and twist 90°	20	1 cm diameter, 0.785 cm^2	20	(ND)	Room temp.
24. Tuladhar et al., 2013[43]	Finger pads, SS, Trespa, whole tomato, cucumber slices	MNV1, NoV GI.4, NoV GII.4	0.8−1.9 kg/cm^2	10	2.2 cm ×2.2 cm	0, 10, 40	40−45	25−26

Table 1. continued

ref	Surfaces	Species	Touching behaviors	Inoculation, V (μL)	Inoculation area, A_i	Drying time, t (min)	RH (%)	θ (°C)
25. Greene et al., 2015[44]	Glass, SS, porcelain, polypropylene, polycarbonate, rubber, fingerpad, latex gloved fingerpad	*A. baumannii*	Average of 25 kPa (range of 16−38 kPa)[39]	20	1 cm in diameter	12.5	App. 40	App. 22
26. Grove et al., 2015[80]	SS tap, lettuce, hand	MNV-1	"turn on" and then "turn off" (for tap); pick up all diced pieces (for lettuce)	10, 20, 25	App. 10 cm^2 (for tap); 5 cm × 5 cm (for lettuce)	10, 30	(ND)	(ND)
27. Koenig et al., 2016[81]	Gloved hand, plastic cellular telephone back, SS rod	*S. aureus*	(ND)	(ND)	1 cm diameter and 5 cm in length (for rod)	(ND)	70	22 ± 2
28. Bellissimo-Rodrigues et al., 2017[82]	Hand	*E. coli*	Fingers interlock for 1 min	(ND)	Whole hands	(ND)	(ND)	(ND)
29. Zhao et al., 2019[45]	Metal (D), glass (D), quartz (D), fingerpad (R)	*S. aureus*, *E. coli*	200, 400, 800, 1500, 3000 g with/without 90°-twist	20	1 cm^2 area	App. 120 min	65−75	22 ± 1

Table 2. Effects of Parameters in New Model on Microbial Transfer Rates

Parameters[a]	In the model		In the validation experiment		
	Correlation to τ	Validated by our experiment	Parameter values	Cohen's d[b]	
Donor roughness	Negative	Yes	100 μm/0.4 μm	−2.12 (No rubbing)	−2.24 (Rubbing)
Recipient roughness	Nonmonotonic	Yes	100 μm/1.6 μm	−0.96 (No rubbing)	Not suitable[c] (Rubbing)
Touch force (or pressure)	Positive	Yes	32 N/2 N	0.89 (No rubbing)	0.92 (Rubbing)
Microbial diameter	Positive	No	*S. cerevisiae*/P22	−0.41 (No rubbing)	−0.91 (Rubbing)
Inoculation volume	Positive	Yes	0 μL/20 μL	−2.44	−2.44
Sequential touches	Negative	Yes	Fifth/First recipient	−5.30	−5.30
Repeated touches	Positive	Yes	Eight touches/One touch	2.02	2.02
Existence of rubbing	Positive	Yes	Rubbing/No rubbing	2.02	2.02
Surface hardness	Negative	Unmeasured	–	–	–
Relative humidity	Positive	Unmeasured	–	–	–
Temperature	Negative	Unmeasured	–	–	–
Surface inoculation area	Negative	Unmeasured	–	–	–
Surface touching area	Negative[d]	Unmeasured	–	–	–
Microbial species	(Not identified)	–	–	–	–
Surface material	(Not identified)	–	–	–	–

[a]For the two factors of microbial species and surface material, we found no correlations between relevant parameters and microbial transfer rates. [b]Cohen's d is evaluated between the measured transfer rates with the two parameter values. A positive value indicates a positive correlation with the transfer rate τ. [c]For repeated touches or rubbing actions, the transfer rate reaches a peak value as the recipient roughness increases (Figure 3d), and the Cohen's d is not calculated due to the nonmonotonic variation. [d]Touching area is assumed to have covered the entire inoculated area.