Thermal Model for Hand-Object Interactions

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ABSTRACT

A thermal model is proposed that predicts the temperature responses of the skin and material surface during hand-object interactions as well as the heat flux exchanged when the fingerpad makes contact with an object. The surface features of the fingerpad were measured in order to estimate the thermal contact resistance which is included in the model. A simulation based on the model was performed to calculate the thermal responses of the fingerpad as it made contact with a range of materials with varying thermal properties. A thermal measurement system based on an infrared camera has been designed and fabricated to overcome the limitations imposed by the contact thermal sensors. This system will be used to evaluate the validity of the model in predicting the changes in skin temperature during contact.


Keywords: Fingerpad surface roughness, hand-object interaction, haptic interface, thermal contact resistance, thermal display, thermal feedback, thermal model, virtual environment

1. INTRODUCTION

Modeling the thermal responses that occur when the hand makes contact with an object is essential for developing thermal feedback systems for haptic displays. Several thermal models have been proposed to describe the heat transfer process between the skin and a material during contact [1-6]. With the exception of the model proposed by Benali-Khoudja et al. [1], which was developed using an electrical analogy, all the other analytical models are based on the bio-heat equation formulated by Pennes [7], each with different assumptions and boundary conditions. Analyses of the changes in skin temperature during contact [6] suggest that thermal contact resistance is a significant factor influencing the change in skin temperature. Thermal contact resistance depends on a number of variables that are related to the thermal, surface and mechanical properties of the fingerpad [8, 9]. Information regarding some of these variables is available in the literature. However, the surface properties of the fingerpad, such as the average surface asperity slope and the root mean square surface roughness are not commonly specified. These properties were therefore measured in order to estimate the thermal contact resistance between the fingerpad and material surface during contact.

The changes in skin temperature during contact with different materials are generally measured with small thermal sensors, such as thermistors or thermocouples, that are affixed to the skin [3, 4, 6, 10]. In some studies, the sensors were placed directly on the contact area [6, 10], and so the sensor deformed with the fingerpad and affected the surface area between the fingerpad and material. In other studies [3, 4], the sensor was attached to the perimeter of the contact area. However, the localized nature of the change in skin temperature during contact with an object may mean that the sensor was not able to detect the full extent of the temperature change in these studies. In order to eliminate the limitations of contact thermal sensors, a non-contact thermal measurement system has been developed. Measurements obtained with this system will be used to examine the validity of the thermal model.

2. THERMAL MODEL

When the fingerpad makes contact with an object, the contact between the fingerpad and object surface is not ideal in the sense of heat transfer because of the thermal contact resistance that exists between them. None of the analytical thermal models that have been proposed to describe the heat transfer process during contact [2-6] takes thermal contact resistance into account. In this paper, the thermal model based on the semi-infinite body model [3, 4] is further developed to take into consideration the influence of thermal contact resistance. Using this model, the surface temperature responses of the skin and material during contact were then simulated under normal contact conditions.

2.1 Theory

The resting temperature of the skin on the hand ranges from 25 to 36 °C [11], and is typically higher than the temperature of materials encountered in the environment. The thermal interaction between the skin and a material in contact with the skin is a transient process and is dominated by heat conduction. Heat is transferred across the interface by conduction and flows through a thermal contact resistance. This process is shown in Figure 1 and the governing equations of the skin and material are:

\[
\frac{\partial^2 T_{\text{skin}}}{\partial x^2} = \frac{1}{\alpha_{\text{skin}}} \frac{\partial T_{\text{skin}}}{\partial t}, \quad \begin{cases} t = 0, & T_{\text{skin}} = T_{\text{skin, i}} \end{cases}, \quad x = \infty, & T_{\text{skin}} = T_{\text{skin, i}} \quad (1)
\]
The boundary conditions at the interface are given by:

$$\dot{q}_{\text{skin}}, \dot{q}_{\text{material}} = q''$$  

where $T$ is temperature, $\alpha$ is thermal diffusivity, $t$ is time, $q''$ is heat flux, and $R$ is thermal contact resistance. Subscripts $i$ and $s$ represent the initial and surface conditions, respectively.

By determining the contact resistance, $R$, and initial temperatures of the skin, $T_{\text{skin},i}$, and material, $T_{\text{material},i}$, the skin surface temperature, $T_{\text{skin},s}$, material surface temperature, $T_{\text{material},s}$, and heat flux exchanged during contact, $q''$, can be solved as a function of $t$:

$$T_{\text{skin},i} = \frac{A}{B} \left[ 1 - e^{\alpha \sin^2 t} \operatorname{erf} \left( B \sqrt{\alpha t} \right) \right] + T_{\text{material},i}$$  

$$A = -\frac{(T_{\text{skin},i} - T_{\text{material},i})}{k_{\text{skin}} R}, \quad B = \frac{1}{k_{\text{skin}} R} \left[ 1 + \frac{(k \rho c)^{1/2}}{(k \rho c)^{1/2}_{\text{material}}} \right]$$  

$$T_{\text{material},s} = \frac{C}{D} \left[ 1 - e^{\alpha \sin^2 t} \operatorname{erf} \left( D \sqrt{\alpha t} \right) \right] + T_{\text{material},i}$$  

$$C = \frac{T_{\text{skin},i} - T_{\text{material},i}}{k_{\text{material}} R}, \quad D = \frac{1}{k_{\text{material}} R} \left[ 1 + \frac{(k \rho c)^{1/2}_{\text{material}}}{(k \rho c)^{1/2}_{\text{skin}}} \right]$$  

$$q'' = k_{\text{skin}} A \left[ 1 - e^{\alpha \sin^2 t} \operatorname{erf} \left( B \sqrt{\alpha t} \right) \right]$$  

where $k$ is thermal conductivity, $\rho$ is density and $c$ is specific heat. $(k \rho c)^{1/2}$ is the contact coefficient that characterizes the thermophysical properties of the skin and material during contact.

### 2.2 Contact resistance estimation

In order to calculate the surface temperatures of the skin and material during contact, the thermal contact resistance must be estimated. According to the model proposed by Yovanovich [9], the thermal contact resistance is a function of mechanical, thermophysical and surface properties. With no fluid in the interfacial gap, the thermal contact resistance is given by:

$$R = \left( 1.25k \frac{\Delta a}{R^8} \left( \frac{P}{H} \right)^{0.95} \right)^{-1} \text{(km}^2\text{W)}$$  

where $k_s$ is the harmonic mean thermal conductivity of the interface:

$$k_s = \frac{2k_{\text{skin}} k_{\text{material}}}{k_{\text{skin}} + k_{\text{material}}} \text{ (W/mK)}$$  

$R_q$ is the effective root mean square surface roughness:

$$R_q = \left[ R_{q_{\text{skin}}}^2 + R_{q_{\text{material}}}^2 \right]^{1/2} \text{ (m)}$$  

$\Delta a$ is the effective absolute average surface asperity slope:

$$\Delta a = \left[ \Delta a_{\text{skin}}^2 + \Delta a_{\text{material}}^2 \right]^{1/2}$$  

P is the contact pressure, and H is the microhardness of the softer material, which is the skin in this situation. Dellon et al. [12] reported that the hardness of the skin on the fingertip was 12.5 g/mm².

The surface properties of the skin did not appear to be available in the literature and so these had to be measured in order to estimate the thermal contact resistance. For this purpose, an experimental system was constructed to measure the surface roughness and asperity slope of the fingertip.

### 3. Fingerpad surface roughness measurement

#### 3.1 Procedures

**Subjects.** Ten normal healthy adults (five women and five men) aged between 20 and 30 years participated in this experiment. They had no known abnormalities of the tactile or thermal sensory systems and no history of peripheral vascular disease. There were no calluses on their right index fingerpads. This research was approved by the local ethics committee.

**Apparatus.** A surface roughness tester (SurfTest SV-3000S4, Mitutoyo) was used for the measurement. The detector of the tester has a 60 degree conical tip and a tip radius of 2 µm. The measuring force of the detector is 0.75 mN and the measuring speed is 1 mm/s. The vertical measurement range of the tester is 800 µm with a resolution of 0.01 µm.

A fixture was constructed using splinting materials (Smith & Nephew Rolyan) as the fingertip and hand supports as shown in Figure 2. Elastic fabric strips and Velcro were also used to adjust and fix each subject’s hand and fingerpad position during the measurement.
Procedure. The procedure for selecting the cut-off wavelength, $\lambda_c$, for the surface roughness measurement followed the ISO standard 4288:1996 and was 2.5 mm. The short wavelength cut-off, $\lambda_s$, was 0.025 mm. The measurement was done in both the proximal-distal (PD) and medial-lateral (ML) directions on the right index fingerpad. The number of sampling intervals was three and two for the PD and ML directions, respectively.

Prior to the experiment, subjects washed their hands with soap. The width and length of each subject’s right index fingerpad were measured with digital calipers (Absolute digimatic, Mitutoyo). The average width and length was 16.56 and 25.12 mm, respectively.

Subjects were instructed to sit in a comfortable posture and place their right hand on the support with their palm facing up. Based on each subject’s fingerpad size, the starting point of the measurement was decided and marked. The subject’s right index fingerpad was then cleaned with alcohol. The position of the wrist and fingertip was adjusted in order to make the surface of the right index fingerpad level with respect to the roughness detector and the midline of the fingerpad aligned with the detector. The elastic strips and Velcro were then used to fix the position of the hand. The measurement was repeated five times for the PD and ML directions with the order (PD or ML) randomized. There was a rest period of 5 minutes between the two directions and the total measurement time was approximately 30 minutes.

3.2 Results

Following the ISO standard 4287:1997, the roughness parameters that are available are RMS surface roughness, $R_q$, RMS surface asperity slope, $R\Delta q$, and the mean spacing of profile irregularities, $RSm$. The surface asperity slope parameter, $\Delta a$, used in the thermal contact resistance calculation is not defined in this ISO standard. However, it can be estimated based on the relationship between the average and RMS values of the asperity slope, as proposed by Mikic and Rohsenow [13]:

$$\Delta a = \frac{R\Delta q}{1.25}$$  \hspace{1cm} (12)

The results of the surface asperity slope were therefore analyzed in terms of the average asperity slope, $\Delta a$.

The results for surface roughness, asperity slope and spacing of profile irregularities of the fingerpad skin are shown in Figures 3, 4, and 5, respectively. A repeated measures analysis of variance (ANOVA) of surface roughness with measurement direction and gender as within and between factors respectively, indicated that there was a significant difference between the two measurement directions ($F(1,8) = 7.409; p = 0.026$) but no significant effect of gender ($F(1,8) = 2.098; p = 0.186$). The analysis of the asperity slope indicated that there was no significant difference between the two measurement directions ($F(1,8) = 1.886; p = 0.207$) or gender ($F(1,8) = 4.280; p = 0.072$), although there was a trend for male subjects to have higher asperity slopes. A similar result was found for the spacing of profile irregularities with no significant difference between measurement directions ($F(1,8) = 1.399; p = 0.271$) or gender ($F(1,8) = 0.001; p = 0.978$). The mean and standard error for surface roughness, asperity slope and spacing of profile irregularities of the fingerpad skin are listed in Table 1.
Table 1. Surface roughness, asperity slope and spacing of profile irregularities of the fingerpad skin

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q_{\text{skin}}$ (µm)</td>
<td>ML 23.15</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>PD 20.23</td>
<td>2.21</td>
</tr>
<tr>
<td>$\Delta a_{\text{skin}}$ (radian)</td>
<td>ML 0.32</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>PD 0.28</td>
<td>0.03</td>
</tr>
<tr>
<td>$R_{Sm_{\text{skin}}}$ (mm)</td>
<td>ML 0.65</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>PD 0.73</td>
<td>0.04</td>
</tr>
</tbody>
</table>

3.3 Discussion

In this experiment, the roughness detector exerted an extremely small force of 0.75 mN as it traveled across the fingerpad, and this caused a slight displacement of the skin. As a result, the surface roughness of the fingerpad measured here is assumed to be influenced by the ridges and furrows on the fingerpad skin and by the pulp tissue underneath.

The number of cut-offs used to evaluate the surface roughness in the ML and PD directions were two and three respectively which is less than the value of five recommended by the ISO standard. The vertical range of the detector is only 800 µm and the curvature and dimensions of the fingerpad are too small to provide a flat area for measurement with 5 cut-offs across the distance covered.

Although the ridge lines on the fingerpad typically form a concentric pattern, they are not symmetric in the medial-lateral (ML) and proximal-distal (PD) directions. Therefore, the surface roughness of the fingerpad was measured in both directions. The results indicated that surface roughness is greater in the ML than the PD direction. Based on observations of the fingerprint, the surface roughness of the fingerpad would be expected to exhibit a periodic profile. Measurements of the spacing parameter, $R_{Sm_{\text{skin}}}$, indicated that the mean spacing of the ridges is consistent in both measurement directions and is similar for men and women.

The surface asperity slope parameter is not as commonly specified as the height parameter in the literature. Correlations between the surface asperity slope and RMS surface roughness have been reported [14]. However, the surface texture data used to establish these correlations were from solid materials which have a much lower surface roughness than the fingerpad ($0 < R_q < 2$ µm). The surface asperity slope was therefore measured directly in this study. The correlation between $R_q_{\text{skin}}$ and $\Delta a_{\text{kin}}$ was not significant for the fingerpad (Pearson’s $R = 0.139$, $p = 0.167$), and $\Delta a_{\text{kin}}$ was similar in both measurement directions.

In this small sample of subjects there was no significant difference between men and women with respect to any surface properties measured. This finding is consistent with other studies of the skin on the fingerpad and palm of the hand which have shown that there is no significant difference between men and women in skin thickness [15] or hardness [12].

4. Thermal Model Simulation

Several parameters need to be calculated before performing the simulation using the thermal model. The thermal contact resistance used in this simulation was estimated using the mean RMS surface roughness, $R_q_{\text{skin}}$, and the mean surface asperity slope, $\Delta a_{\text{kin}}$, averaged across the two directions. The contact pressure is calculated with a contact force of 2 N and contact area of 135 mm$^2$. The initial temperatures of the fingerpad and materials were set at 34 and 24 °C respectively. The materials selected in this simulation covered a broad range of thermal properties (see [3, 4]); they were copper, stainless steel, granite, plastic (ABS), and foam.

With these parameters determined, the skin surface temperature, material surface temperature, and heat flux exchanged were simulated for 10 s of contact. The results are shown in Figures 6, 7, and 8, respectively. As can be seen in Figures 6 and 7, the surface temperature of the skin and material change with time and reach a steady state by the end of the contact period. The earlier semi-infinite body model [3, 4] predicted that the skin and material surface temperature changed to the interface temperature at the moment of contact and remained constant during the contact period. With the addition of thermal contact resistance to the model, the temperature responses of the skin and materials become more realistic.
The thermal responses of the skin and material during contact primarily depend on the material's contact coefficient, \((kpc)^{1/2}\). As shown in Figure 6, the decrease in skin temperature during contact, \(T_{\text{skin,i}} - T_{\text{skin,s}}(10\ s)\), increases with the material's contact coefficient. However, the increase in material surface temperature, \(T_{\text{material,i}}(10\ s) - T_{\text{material,s}}\), is smaller for materials with higher contact coefficients. These results indicate that materials with high contact coefficients are able to maintain their own temperature while having a significant influence on the skin surface temperature during contact. As a result, the heat flux exchanged during contact is also higher for materials with higher contact coefficients.

A comparison between the results predicted by the present model and the semi-infinite body model indicates that for all materials the skin surface temperatures during contact are higher for the new model than those predicted by the semi-infinite body model. As a result, the present model predicts a smaller decrease in skin temperature than the semi-infinite body model \([4]\). The difference between the two models in terms of the changes in skin surface temperature increases with the contact coefficient of the material. For materials with extremely low contact coefficients, such as foam, there is almost no difference between the two skin surface temperature responses.

For the material surface temperatures during contact, the temperature changes predicted by the present model are smaller than those predicted by the semi-infinite body model. The difference between the models in their predictions of material surface temperature becomes smaller for materials with higher contact coefficients. For materials with extremely high contact coefficients, such as copper, there is almost no difference between the two material surface temperature responses.

In the present model the responses of the skin and material are determined by the thermophysical and surface properties of the skin and material and their initial temperatures. To simulate thermal contact in a virtual environment, the parameters in this model should be specified based on the contact condition. By simulating the temperature responses of the materials with this model, a haptic interface should be able to generate realistic thermal feedback for hand-object interactions.

5. NON-CONTACT THERMAL MEASUREMENT SYSTEM

5.1 System layout

In order to evaluate the validity of the thermal model, a non-contact thermal measurement system is being designed and built to measure the skin temperature response during contact, together with the contact area and contact force. A schematic diagram of the system is illustrated in Figure 9.

![Figure 9. Layout of the non-contact thermal measurement system](attachment:image9)

An infrared camera (A40M, FLIR Systems) is used to measure the change in temperature on the fingerpad. It can record a thermal image of the fingerpad during contact and eliminates the measurement limitations of contact thermal sensors, which can only record localized changes in skin temperature and can deform the skin during contact. In order to measure the contact area and temperature distribution on the fingerpad simultaneously, materials (zinc sulphide and barium fluoride) have been selected that can transmit wavelengths in both the visible and infrared spectrum. A beamsplitter is used to separate the infrared radiation and visible light from the contact area, and the skin temperature distribution and contact area is captured by the infrared camera and a digital camera, respectively. A 6-axis force transducer (Nano 43, ATI Industrial Automation) with a circular hole in the center is attached to the contact material and can measure the contact force without blocking the infrared and visible radiation from the fingerpad.

This non-contact measurement system is not designed to be integrated into a haptic interface but is to be used to assist in the development of the thermal model by obtaining better temperature measurements of the fingerpad during contact. With this system, a comparison between the empirical data and model predictions can be made to evaluate the validity of the thermal model.

5.2 Thermal image analysis for the fingerpad during contact

The change in skin temperature during contact is analyzed in terms of the difference between the thermal images prior to and during contact. A typical thermal difference image taken with a
lens with 50 µm spatial resolution is shown in Figure 10. This figure shows the change in skin temperature (white area) when making contact with a barium fluoride disk.

A spatial frequency analysis was performed on the image using a 2D fast Fourier transform in order to determine its frequency content. The power spectrum of the transform is shown in Figure 11. Most of the power in the thermal image lies in the low frequency range between 0 and 1.25 (1/mm). This suggests that the spatial frequency needed for capturing the essential thermal information from the fingerpad during contact should be at least 2.5 (1/mm), which equals a spatial resolution of 400 µm.

6. CONCLUSION

The thermal model proposed in the present study is able to predict the temperature responses of the skin and material surface and the heat flux exchanged during contact. The predicted changes in skin temperature can be compared to the measured changes in skin temperature during actual contact [3]. The predicted changes in skin temperature during contact are greater than those measured by a single thermistor attached to the perimeter of the contact area. It is anticipated that the non-contact thermal measurement system will provide a clearer picture of the changes in skin temperature during contact and that these data will be more similar to the model predictions.

When thermal contact resistance is included in the model, more realistic time constants for the thermal responses of the skin and material are obtained. The predicted decrease in skin surface temperature during contact is also more similar to the empirical data than that predicted by the semi-infinite body model.

Although the measurement of the fingerpad surface properties was required to estimate the thermal contact resistance, the results from this experiment also provide useful information about the surface features of the fingerpad. In particular, in this small sample of subjects, there was no significant difference between men and women in the various surface properties. Moreover, the surface roughness of the skin was found to be greater in the medial-lateral than in the proximal-distal direction.

The thermal measurement system that has been developed in this study not only eliminates the limitations of conventional contact thermal sensors but also provides an image of the temperature distribution across the fingerpad rather than a single point measurement from a thermal sensor. This system will enable more detailed analyses to be conducted on the changes in skin temperature during contact so that a realistic model of the change in temperature can be incorporated into a haptic display.

Figure 10. Distribution of the change in skin temperature during contact

Figure 11. Power spectrum of the difference thermal image for horizontal (a) and vertical (b) frequency

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REFERENCE


