

HAND SKIN TEMPERATURE VARIATIONS FOR WORK IN MODERATELY COLD ENVIRONMENTS AND THE EFFECTIVENESS OF PERIODIC REWARMING

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An investigation of skin surface temperature variations under actual work conditions for four locations on the hand studied the utility of hot water immersion sinks for restoring heat to the hands during exposure to moderately cold temperatures in a food processing plant. Hand skin temperature was recorded for 15 subjects in 2 jobs with an ambient temperature of 13.3°C (56°F) and 1 job with an ambient temperature of 23.9°C (75°F). Averaged over all jobs, the mean temperature for the dorsal and palmar third finger was 17.7°C (63.9°F), which was significantly ($p < 0.01$) cooler than the mean dorsal and palmar hand temperature of 28.9°C (84.0°F). There was no significant difference between dorsal and palmar temperatures for either the finger or the hand ($p > 0.05$). In the warm environment there were no significant differences in skin temperature for any of the four hand locations ($p > 0.05$). An exponential model of digital warming and cooling was empirically derived using 12 subjects for predicting finger skin temperature when periodically rewarming the hands using a hot water immersion sink. The dorsal and palmar finger had a mean time constant of 151 sec for warming during immersion, 640 sec for initial cooling after a 15- to 30-min rest break at room temperature, and 198 sec for cooling after rewarming in the hot sink. The sink did not appreciably raise minimum finger skin temperature after subjects rewarmed the hands for as long as 2 min and then worked for more than 10 min without a rewarming session.

Cooling of the hands when working in moderately cold environments is a concern for worker health, safety, and manual work performance. Local peripheral cooling inhibits biomechanical,⁽¹⁾ physiological,⁽²⁾ and neurological⁽³⁾ functions of the hand. Exposure to localized cooling has been

correlated with decrements in manual performance and dexterity,⁽⁴⁻¹⁵⁾ tactility and sensibility,⁽¹⁶⁻²³⁾ and strength.^(1,24-28) These effects are attributable to various physiological mechanisms. The extent of the deficits depends on the amount of heat loss and relative location of the cold stimulus.⁽¹²⁾ Although these effects have been investigated thoroughly for extremely cold environments^(4-6,16,17,29-33) with temperatures between -23°C (-41°F) and +5°C (41°F), there is insufficient corresponding data with regard to the moderately cold environments between 10°C (50°F) and 20°C (68°F) often found in food processing industries.

Hand anatomy varies in size and density of vasculature, amount of insulating fat, surface area, and skin composition. The differentiation of physiological responses within the areas of the hand should be acknowledged. Numerous investigations of hand skin temperature have used a single location as a representation of the whole hand.^(7,9-11,14) Enander⁽²⁰⁾ pointed out that a single surface monitoring device is a poor indicator of hand cooling. Although recent studies have recognized temperature location differences in the hands,^(34,35) much of the previous research has considered the hand as a single body, which has led to variations in results and conclusions.

The poultry, meat, and food industries expose workers daily to moderately cold temperatures. The temperature of the product handled also contributes to the dissipation of heat in the extremities due to conduction. Gloves traditionally have been used to control this problem. The trade-off, however, between gained warmth for decreased finger sensitivity, strength, and dexterity with gloves is quite evident. Similarly, auxiliary heating⁽¹²⁾ (i.e., heating lamps) or radio frequency energy,⁽³⁶⁾ although beneficial to the worker, may be harmful to products such as frozen or chilled foods. External heating mechanisms, such as hot water immersion sinks that heat the hands while submerged under a flow of water at approximately 54°C (130°F), have been used to mitigate these effects. Their actual effectiveness has yet to be proven.

This article addresses the problem of how skin surface temperature varies in an occupational setting, under actual work conditions, for different locations on the hand. The study also investigates the use of hot water immersion sinks for restoring heat to the hands during exposure to moderately cold temperatures.

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Modeling digital warming and cooling assesses appropriate schedules for periodic hot water immersion sink usage.

METHODS

This investigation was conducted in the boning and evisceration departments of a turkey processing plant. All internal environments were controlled for ambient temperature. Hand skin temperature monitoring was conducted for jobs that had extensive meat handling requirements.

Sensor Placement

Individual temperatures were measured for four locations on the hand. The locations monitored included the palmar and dorsal sides of the proximal hand and the middle finger. Thermistors were placed on the palmar and dorsal sides over the middle phalanx of the third digit, and between the third and fourth metacarpal bones, 5.1 cm from the wrist. Microfoam tape (3M Company) was used for attaching the probes to the hand. To ensure that blood occlusion did not occur, overlapping and tape tension were kept to a minimum. The hand studied depended on the task. Hand locations were identified using DF for dorsal finger, PF for palmar finger, DH for dorsal hand, and PH for palmar hand.

Apparatus

Omega ON-409-PP (Omega Engineering, Stamford, Conn.) thermistor temperature probes (1.1 sec time constant) were used for all skin temperature measurements. These thermistors were encased in a 1.1 cm diameter, and 0.3 cm deep round stainless steel cups, with an epoxy backing. Wires ran underneath the outer garments in order to reduce their obtrusiveness.

Workers carried an Omega four channel analog-digital converter and data logger on a belt so they could move without interference from the attached equipment. Recording time was set between 90 and 120 min unless otherwise specified. Temperature data was sampled at a rate of four samples per min and was later downloaded from the data logger to a Toshiba T3200 microcomputer.

Experiment 1. Skin Temperature: Hand Location and Job Effects

The goal of this experiment was to determine if there were significant temperature differences among the four locations on the hand for various jobs at the turkey processing plant. Hand temperature was recorded for several jobs having distinct thermal conditions. Wing meat checking and shoulder cutting were performed in a moderately cold environment, and drawing was done in a warm environment.

Wing meat checking was conducted at an ambient temperature of 13.3°C (56°F). Thermistors were attached to subjects' hands in a room adjacent to the wing meat department that had an ambient temperature between 21.1°C (70°F) and 23.3°C (74°F). Turkey meat was kept at a mean temperature of 7.2°C

(45°F). The wing meat checker inspected the meat for bone fragments that remained after processing in automatic de-boners. Every checker inspected the incoming meat by squeezing, feeling, and manipulating the meat in a variety of ways. Each piece of meat was checked for approximately three seconds, unless it was especially large. The job required the checker to stand by a table while inspecting. An individual piece of meat weighed approximately 0.5 kg (1.1 lbs). Cycle time depended on the proficiency of the checker and on the rate of accumulation of meat on the workstation table.

The workers wore thin cotton liners inside latex gloves on both hands. Employees were dressed in clothing that was typical for work within the plant. The task required equivalent utility of both hands, so temperature sensors were placed arbitrarily on the nondominant hand.

Shoulder cutting occurred in a similar environment as wing meat checking, except that the meat handled was at the slightly cooler temperature of 6.1°C (43°F). Thermistors were attached to workers' hands in the same room as for wing meat checking. Shoulder cutters partially cut the breast meat from a turkey and removed the shoulder from the body cavity. The turkeys were hooked on a hanging conveyor system that transported birds across various jobs at an average rate of 27 birds per minute. Approximately 20 seconds of a 1-min cycle were spent in actual contact with the meat. A knife was held in the dominant hand and therefore that hand did not come in direct contact with the meat. The worker grasped the wing with the nondominant hand using a power grip. Hand protection on the nonknife hand consisted of a cotton liner inserted in a latex glove, all underneath a steel mesh glove. Skin sensors were placed on this hand for monitoring. As the nondominant hand pulled downward, the dominant hand made an incision at the top of the shoulder girdle. After the cut was complete the employee pulled down on the upper shoulder with the dominant hand, while the nondominant hand continuously pulled on the lower wing. After the shoulder was dislocated the worker cut off the wing chub and placed it on a conveyor.

The drawing task was performed in a warm environment within the evisceration department. The department and the room where temperature sensors were attached were maintained at 23.9°C (75°F). The monitoring period for this job lasted only 45 min due to job rotation constraints. Here, turkeys traversed the department via a hanging transport system. Once the turkey was in position, the worker leaned over slightly and placed the nondominant hand on the back of the turkey. The drawer pulled and removed the viscera from the body cavity using the dominant hand and placed it to the side of the bird. Temperature sensors were attached to the dominant hand. The viscera were typically at a temperature of 41.1°C (106°F). This process took approximately three to four seconds to complete. The hands were washed in 31.1°C (88°F) running water after every drawing. The line ran at approximately 30 birds per minute. Each worker drew the viscera from every fourth bird. The viscera weighed approximately 1.0 kg (2.2 lbs.). Each subject wore a single latex glove on each hand.

Experiment 1 included five workers from shoulder cutting, seven from wing meat checking, and three from drawing. Eleven were female and four were male, ranging in age from 21 to 51,

with an average of 6.7 years of experience. None of the subjects reported any previous conditions of rheumatic, arthritic, or Raynaud's syndromes. All subjects were selected arbitrarily by management to participate.

Gloves issued by this company were the same in all departments. Level of muscle exertions and the use of any combinations of a cotton liner, latex glove, and steel mesh glove was job dependent. Although glove combinations were different for all three jobs, all subjects within each job wore the same glove combination. Gloves were made available in different sizes, and therefore it was assumed that differences in glove fit in relation to individual hand size had a negligible effect.

Temperature effects for hand location and job were tested for statistical significance using a mixed model ANOVA, with subjects treated as a random effects blocking variable and nested within the job effect. Consequently the error term for the main effect of job was subject (job), the error term for the main effect of location was location \times subject (job), and the error term for the interaction effect of job \times location was location \times subject (job).

Experiment 2. Periodic Rewarming

This experiment was conducted in the moderately cold environment of the wing meat checking task, as described in Experiment 1. A hot water immersion sink (Figure 1) with running water between 52.2°C (126°F) and 55.6°C (132°F) served as the intermittent heat source. The sink allowed workers at predetermined periodic intervals to rewarm their hands under the running water. Although workers controlled the flow rate of water, its temperature was kept constant.

Digital cooling was measured for a subject pool that was required to work under two different conditions. The first condition required that seven subjects (six females and one male) perform the wing meat checking task without rearming their hands. The time period without rearming was 90 min. This served as an indicator of minimum hand skin temperature without rearming in the hot water immersion sink. The second condition required that the same subjects work without rearming their hands until after an initial 35 min, and then periodically every 20 min. Subjects were instructed to keep their hands under the running water in the hot sink for a self-selected time period. During breaks, which occurred intermittently and lasted 4 min, subjects were instructed not to attempt to warm their hands. Preliminary testing revealed that 35 min was more than enough time for hand skin temperature to asymptote to its lowest temperature. The subjects participating were the same as those in the wing meat checking task from Experiment 1. The two conditions provided an analysis of digital cooling at the commencement of work after entering from a room with an ambient temperature between 21.1°C (70°F) and 23.3°C (74°F), and also after rearming at the hot sink.

Another group of subjects performed the wing meat checking task for 35 min without any rearming. They were then instructed to rearm their hands in the hot water immersion sink for 8 min. The rate of digital warming was monitored during this period. Pilot measurements revealed that the skin temperature increase asymptotes after immersing the hands for less than 8

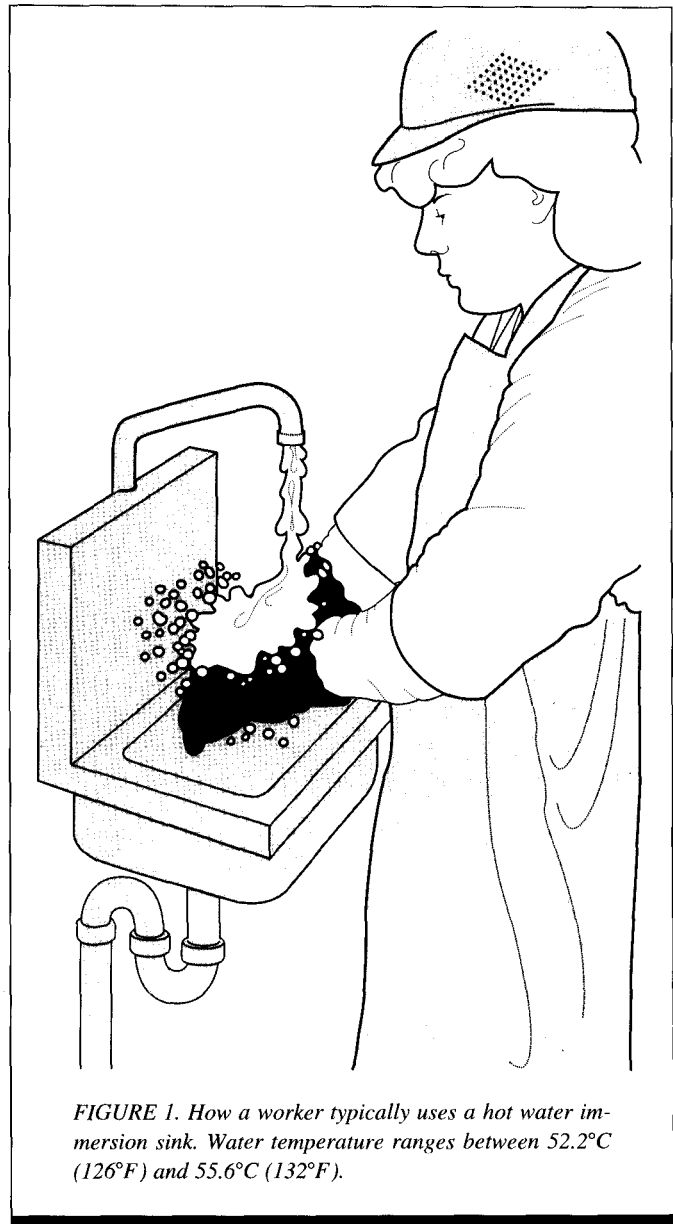


FIGURE 1. How a worker typically uses a hot water immersion sink. Water temperature ranges between 52.2°C (126°F) and 55.6°C (132°F).

min, which was the longest immersion time practical from a production standpoint. This group included one female and four males ranging in age from 23 to 38, with an average of 3.7 years of experience.

Testing was performed for all subjects after a 15 or 30 min work break. All subjects wore latex gloves with thin cotton liners inside. The experiment was conducted in two successive days. Only one condition was tested for a subject on a given day. The experimental conditions were counter-balanced so that half the subjects worked without rearming, and the other half periodically rearmed their hands on the first day. The alternate condition was used on the second day.

Analysis

Newtonian cooling curves were used for modeling hand skin cooling.⁽³⁷⁾ Digital warming and cooling for all subjects were

TABLE I. Comparison Between Average Minimum Temperatures at Four Hand Locations for Three Jobs^A (°C)

Job	Hand Location			
	Dorsal Finger	Palmar Finger	Dorsal Hand	Palmar Hand
Shoulder Cutting	14.8 (3.1)	14.9 (2.5)	27.6 (1.3)	30.0 (2.2)
Wing Meat Checking	13.5 (1.7)	14.0 (2.1)	26.1 (2.6)	27.5 (4.6)
Drawing	31.4 (0.5)	31.7 (1.1)	33.2 (0.3)	34.7 (0.3)

^A One standard deviation is listed in parenthesis.

evaluated by nonlinear regression using the method of least squares approximation. The first order exponential model for digit heating was described by:

$$T(t) = T_o + (T_{max} - T_o)(1 - e^{-t/\tau_A}) \quad (1)$$

where $T(t)$ is the skin temperature (°C) for a particular location on the finger at time t , T_{max} is the maximum temperature reached during rewarming, T_o is the initial or starting temperature, and τ_A is the time constant.

Initial digit cooling occurred after entering the work area at the onset of a working period. The fingers also cooled after rewarming at the hot water immersion sink. The first order exponential models for these two cooling effects were described by:

$$T(t) = T_{min} + (T_o - T_{min})e^{-t/\tau_B}, \text{ for initial cooling,} \quad (2)$$

and

$$T(t) = T_{min} + (T_o - T_{min})e^{-t/\tau_C}, \text{ for after rewarming,} \quad (3)$$

where T_{min} is the minimum temperature reached during cooling (within the first 35 min time interval), T_o is the maximum or starting temperature of the cooling curve, τ_B is the time constant for initial cooling, and τ_C is the time constant after rewarming at the hot water immersion sink.

A repeated measures ANOVA was performed using the mean hand location temperatures measured both without and with the use of a hot water immersion sink. The mean temperature for both conditions was derived from the 55- to 60-min time intervals commencing after the initial 35-min cooling period.

To identify feasible scheduling patterns for minimizing the descent of finger skin temperatures, an empirical model for work and intermittent rewarming intervals to address minimum finger skin temperatures was based on initial finger cooling, cooling after rewarming, and rewarming data. Time periods modeled for work between rewarming ranged from 1 to 60 min. Minimum finger temperatures were calculated for each work interval corresponding to several time periods for warming. Warming periods modeled ranged from 0 to 2 min. The start and end temperatures used for determining the time constants were the highest temperatures attained during the rewarming portion of the experiment and lowest temperature reached during the cooling experiment. All parameters in the model were taken from the average finger temperatures observed, which were representative of the work environment studied.

RESULTS

Experiment 1

The mean minimum temperature for each hand location is contained in Table I. The main effect for hand location was statistically significant ($p < 0.001$). Tukey pairwise multiple contrasts indicated that the mean tempera-

ture for both the DF (Mean = 17.5°C [63.5°F], SD = 7.4°C [13.3°F]) and PF (Mean = 17.9°C [64.2°F], SD = 7.5°C [13.5°F]) were significantly cooler than either the DH (Mean = 28.0°C [82.4°F], SD = 3.3°F [5.9°F]), or PH (Mean = 29.8°C [85.6°F], SD = 4.3°C [7.7°F]) ($p < 0.01$). There was no statistical significance between mean dorsal and palmar temperatures for either the finger or the hand ($p > 0.05$).

The main effect for job was statistically significant ($p < 0.001$). Post-hoc tests using Tukey pairwise multiple contrasts indicated that the drawing job (Mean = 32.7°C [90.0°F], SD = 7.4°C [13.3°F]) resulted in significantly warmer mean minimum hand skin temperatures than either the shoulder cutting task (Mean = 21.8°C [71.2°F], SD = 7.5°C [13.5°F]) or wing meat checking (Mean = 20.3°C [68.5°F], SD = 7.2°C [13.0°F], [$p < 0.01$]). The mean skin temperature for the two jobs in the moderately cold environment, shoulder cutting and wing meat checking, were not statistically different ($p > 0.05$).

The interaction between hand location \times job also was significant ($p < 0.001$). Tukey pairwise multiple contrasts indicated that the DF temperature for drawing was 16.3°C (29.4°F) warmer than shoulder cutting ($p < 0.05$) and 17.6°C (31.7°F) warmer than wing meat checking ($p < 0.01$); however, there was no statistical difference between shoulder cutting and wing meat checking ($p > 0.05$). An analysis for the PF location produced similar results as the DF. The mean minimum temperatures recorded among jobs were not statistically significant for either the DH or PH ($p > 0.05$).

The temperature differences at each hand location for the shoulder cutting and wing meat checking jobs paralleled the main effect for hand location. Within the shoulder cutting job the mean minimum temperature for both the DF and PF was at least 14.1°C (25.4°F) cooler than either the DH or PH ($p < 0.05$). There was no statistical significance between dorsal and palmar locations for either the finger or the hand ($p > 0.05$). Similar results were obtained for the wing meat checking job. There were no significant ($p > 0.05$) differences for the hand locations within the drawing job (see Table I).

Experiment 2

Palm temperatures did not deviate more than $\pm 5^\circ\text{C}$ (9°F). An example of a typical subject's hand temperature when working is shown in Figure 2. A comparison of hand temperatures when using and not using a hot water immersion sink are included to illustrate digital cooling after intermittent rewarming, and how it minimally induces a change in mean temperature throughout the hand. As a result of this, heating and cooling were modeled for just the dorsal and palmar sides of the digits.

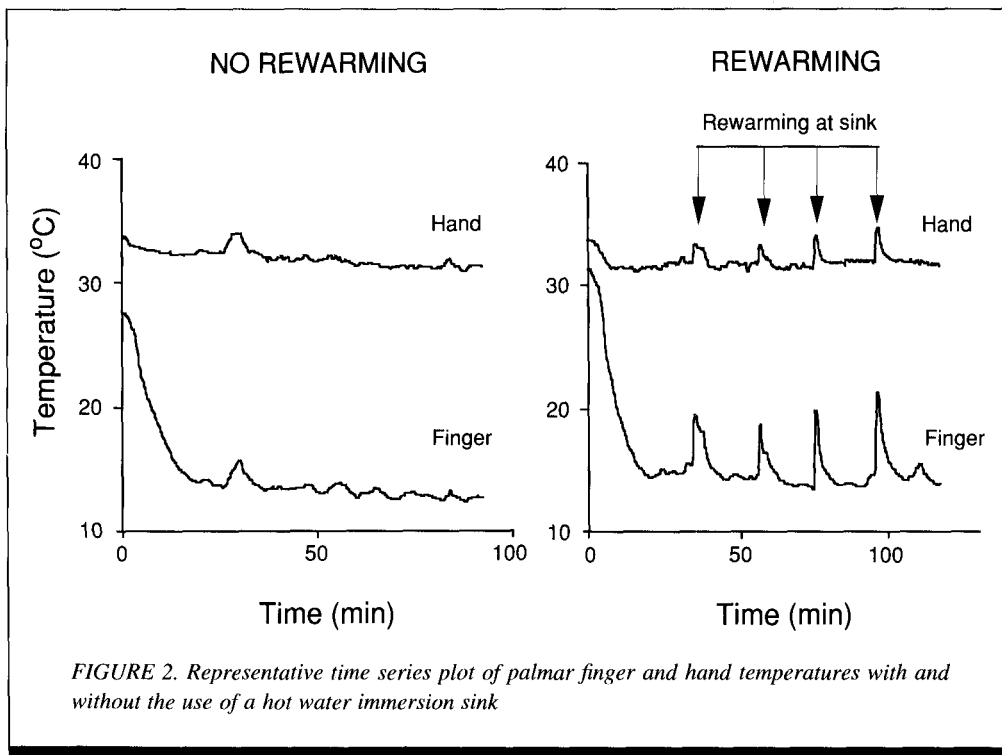


FIGURE 2. Representative time series plot of palmar finger and hand temperatures with and without the use of a hot water immersion sink

Average digital heating and cooling curves are shown in Figure 3. Time constants for the DF and PF locations are contained in Table II. The PF had a smaller time constant for warming than the DF; however, this difference was not statistically

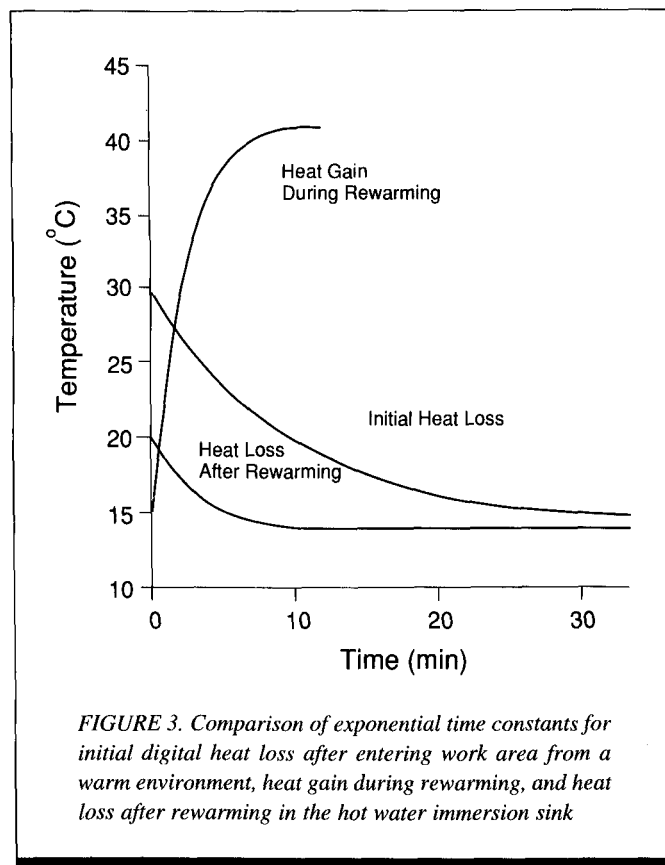


FIGURE 3. Comparison of exponential time constants for initial digital heat loss after entering work area from a warm environment, heat gain during rewarming, and heat loss after rewarming in the hot water immersion sink

significant ($p > 0.05$). Differences in time constants for the finger during initial cooling and cooling following rewarming were statistically significant for both DF ($p < 0.001$) and PF ($p < 0.001$). Tukey multiple pairwise comparisons indicated there were no significant ($p > 0.05$) differences among the time constants for intermittent rewarming for the DF and PF. Consequently, both sides of the finger (dorsal and palmar) during cooling after external heat application lost internal stored heat approximately three times faster than after the commencement of work.

The nonlinear regression model for digital heat gain and heat loss served as an apt representation of warming and cooling at the DF and PF locations. The coefficients of determination for the model are summarized in Table III.

Average temperature for hand location and immersion are contained in Table IV. The mean temperature for all four hand locations for immersion (Mean = 21.8°C [71.2°F], SD = 7.6°C [13.6°F]) was slightly warmer than those for nonimmersion in the hot sink (Mean = 21.1°C [70.0°F], SD = 8.5°C [15.3°F]), but was not statistically significant ($p > 0.05$). The effect for hand location was significant ($p < 0.001$). Tukey multiple pairwise comparisons for hand location, averaged over immersion and nonimmersion conditions, indicated that the mean temperatures for both the DF (Mean = 14.3°C [57.8°F], SD = 1.0°C [1.7°F]) and PF (Mean = 14.9°C [58.9°F], SD = 1.0°C [1.8°F]) were significantly ($p < 0.01$) cooler than either the DH (Mean = 27.3°C [81.1°F], SD = 1.2°C [2.2°F]) or PH (Mean = 29.4°C [85.0°F], SD = 1.3°C [2.3°F]). The DF did not differ from the PF ($p > 0.05$); however, the DH was 2.1°C (3.9°F) cooler than the PH ($p < 0.05$). The interaction between hand location \times immersion was not statistically significant ($p < 0.05$).

Initial finger temperatures for the DF and PF were compared with the mean peak temperature reached during the rewarming sessions. Results are contained in Table V. Differences between initial temperatures and peak temperatures were significant for

TABLE II. Comparison of Finger Warming and Cooling Time Constants (sec)^A

Condition	Hand Location	
	Dorsal Finger	Palmar Finger
Initial Heat Loss	676 (216)	603 (170)
Heat Loss After Rewarming	217 (140)	179 (130)
Heat Gain During Rewarming	165 (32)	137 (34)

^A One standard deviation is listed in parenthesis.

TABLE III. Average Coefficients of Determination for Heat Gain and Heat Loss Nonlinear Regression Models^A

Hand Location	Coefficient of Determination (R^2)		
	Heating N = 5 subjects	Initial Cooling N = 7 subjects	Cooling After Rewarming
Finger Dorsal	.999 (.001)	.942 (.039)	.861 (.178)
Finger Palmar	.999 (.001)	.937 (.033)	.849 (.189)

^A One standard deviation is listed in parenthesis.

the DF ($p < 0.001$) and the PF ($p < 0.001$). Tukey pairwise comparisons indicated that significant differences were observed for the DF and PF between initial temperatures and each of the four average peak temperatures reached during rewarming ($p < 0.001$). There were no significant differences among the average peak temperatures reached during the rewarming sessions for either the DF or PF ($p > 0.05$).

The mean initial temperatures for the four hand locations were significantly different ($p < 0.001$). The temperature ranges were bounded by a lower limit for the DF (Mean = 27.4°C [81.3°F], SD = 2.9°C [5.4°F]) to an upper limit of the PH (Mean = 31.7°C [89.0°F], SD = 1.7°C [3.1°F]). Tukey pairwise multiple contrasts indicated that the only significant differences existed between the DF and PH ($p < 0.001$) and between the PF and PH ($p < 0.01$). There were no significant differences among the dorsal and palmar sides of the finger or the hand ($p > 0.05$).

An example of the model for a work-rewarming cycle of 1 min of warming for 20 min of work is illustrated in Figure 4. Coefficients for the exponential equations in the model were estimated as a function of observed data in this study. An initial finger temperature of 28.6°C (83.5°F) was used, since it was the average initial finger temperature for eight subjects (see Table V). The minimum baseline temperature for cooling was set at 13°C (55.4°F), which was based on typical mean working temperatures without rewarming (see Table IV). The peak temperature for rewarming was limited to 40.9°C, which was the average peak temperature reached during the rewarming measurements. Time constants were based on averages from Table II. The time constant for initial cooling was 640 sec, and 198 sec was used for cooling after rewarming. The heating time constant was set at 151 sec. Minimum finger temperatures predicted for various work-rewarming cycles for up to 15 min using the resulting model are shown in Figure 5.

TABLE IV. Mean Working Temperatures at Four Hand Locations During a One-Hour Period for Hot Sink Rewarming and for No-Rewarming Conditions^A (°C)

Condition	Hand Location			
	Dorsal Finger	Palmar Finger	Dorsal Hand	Palmar Hand
No Rewarming	13.8 (1.6)	13.9 (1.7)	27.0 (1.9)	29.8 (1.5)
Rewarming at Sink	14.9 (1.2)	17.2 (1.9)	27.6 (2.5)	29.0 (3.2)

^A One standard deviation is listed in parenthesis.

DISCUSSION

Many industrial environments expose workers to moderately cold temperatures. The environment and elements within it may cause changes in hand skin temperatures. These effects are not uniform, as indicated by the decrease in the proximal hand temperature

accompanied by disproportionate temperature reduction in the fingers for the jobs performed in moderately cold environments. This difference indicates that during cumulative exposure proximal and distal areas of the hand respond differently, which may be due to their capacity to store heat and to the thermal sensitivity of the physiological mechanisms of the digits. The proximal areas of the hand were clearly more resistant to thermal fluctuations than the fingers.

Differences in hand temperature occurred not only in the distal and proximal hand locations, but also in the palmar and dorsal regions. Both jobs within the moderately cold environment exposed the palmar side of the hand to cold conduction from the meat products. The DH, however, was exposed only to ambient conditions and did not come into direct contact with the meat product due to the nature of the tasks. Despite this, the mean minimum hand temperatures for the DH were slightly cooler than the PH. Conduction from the meat product (6.1°C [43°F] to 7.2°C [45°F]) as compared with air convection (ambient temperature of 13.3°C [56°F]) seemingly contributed to a larger percentage of the heat loss from the hands, due to the magnitude of the difference in temperature and its higher heat transfer coefficient. This would account for differences in skin temperature for equivalent meat and ambient temperatures.

However, the difference in skin temperature between the DH and PH was not significant. Havenith et al.⁽³⁷⁾ demonstrated that at equal thermal levels the back of the hand was approximately 3°C (5.4°F) cooler than the palmar side. That study, however, did not document whether there was statistical significance.

The physiological phenomenon of thermo-regulation causes vasoconstriction in the most peripheral locations of the body, where blood vessels are closest to the skin. This reduces the heat loss from the hands. The difference in soft tissue and vascular density is also undoubtedly a factor. The metabolic heat production from the muscle activity of the thenar eminence, at the base of the thumb, is a potential contributor to heat sustenance. Furthermore, there are no intrinsic muscles and there is less fat on the dorsal side of the hand. This experiment demonstrates that

TABLE V. Comparison of Average Initial and Peak Temperatures During Rewarming^A

Hand Location	Initial Temperature (°C) N = 8 subjects	Peak Temperature (°C) N = 8 subjects
Finger Dorsal	28.1 (3.1)	19.3 (2.2)
Finger Palmar	29.0 (3.5)	20.4 (2.2)

^A One standard deviation is listed in parenthesis.

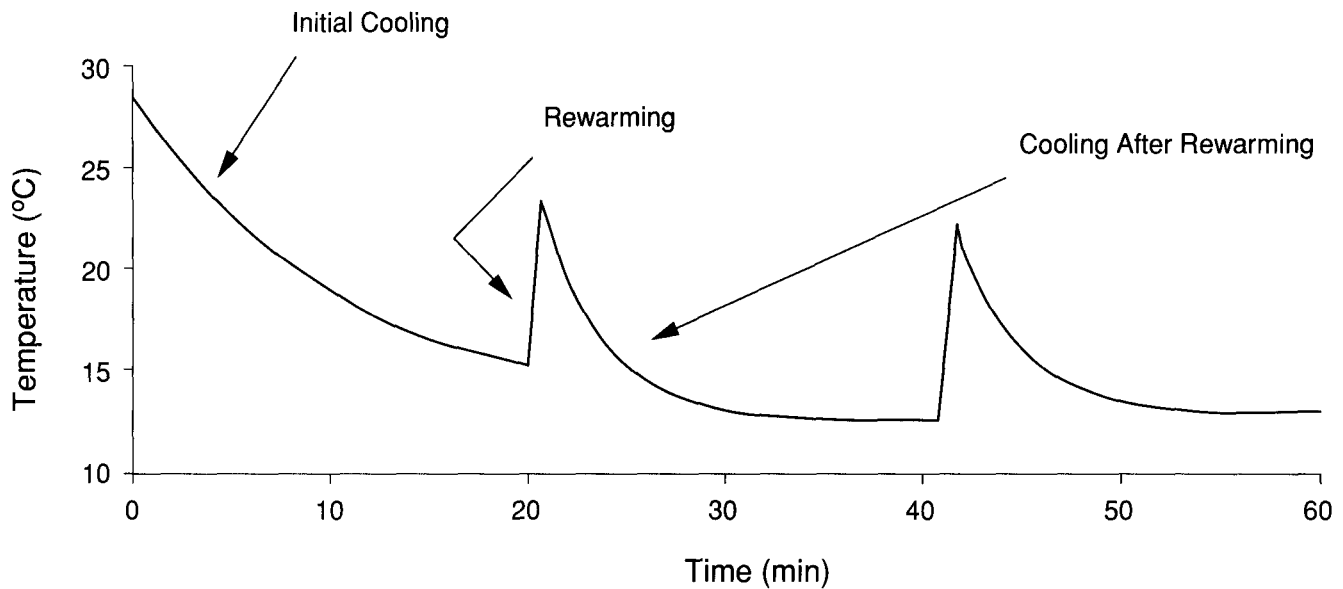


FIGURE 4. Modeled finger temperature response using derived time constants for a 1-min rewarming period after every 20 min of work. The resulting equation for initial cooling was $T(t) = 13 + 16.6 e^{(-t/6.40)}$. The rewarming equation was $T_R(t) = T_R(1200) + 25.6(1 - e^{-(t - 1200)/1511})$. The cooling after rewarming equation was $T_C(t) = 13 + [T_R(1260) - 13](1 - e^{-(t - 1260)/198})$.

hand skin temperatures should not be monitored at a single location even at moderately cold temperatures.

There is no uniform method for monitoring hand skin temperature. Effective and valid hand temperature monitoring should account for the natural differences in heat capacity and thermo-regulation among the distinct regions of the hands. Although surface probes such as thermistors or thermocouples are relatively small, their actual size in comparison to the hand and finger surface area poses a problem. This problem of sensor placement is compounded by the fact that sensors actively interfere with manual dexterity, forceful hand exertions, use of power tools or equipment, or even direct contact with highly conductive materials, such as metals or liquids. Therefore, it is desirable to use the least number of sensors.

The results of this study indicate that hand temperature depends on sensor location in moderately cold conditions. Based on the conditions of this experiment, routine placement of temperature sensors on the hand can be greatly simplified in the distal and proximal regions by locating sensors on the dorsal side of the hand. Monitoring hand temperature on the dorsal side also would be pragmatic. The problem of interference of sensors when monitoring skin temperature during tasks that require intensive hand work could be solved.

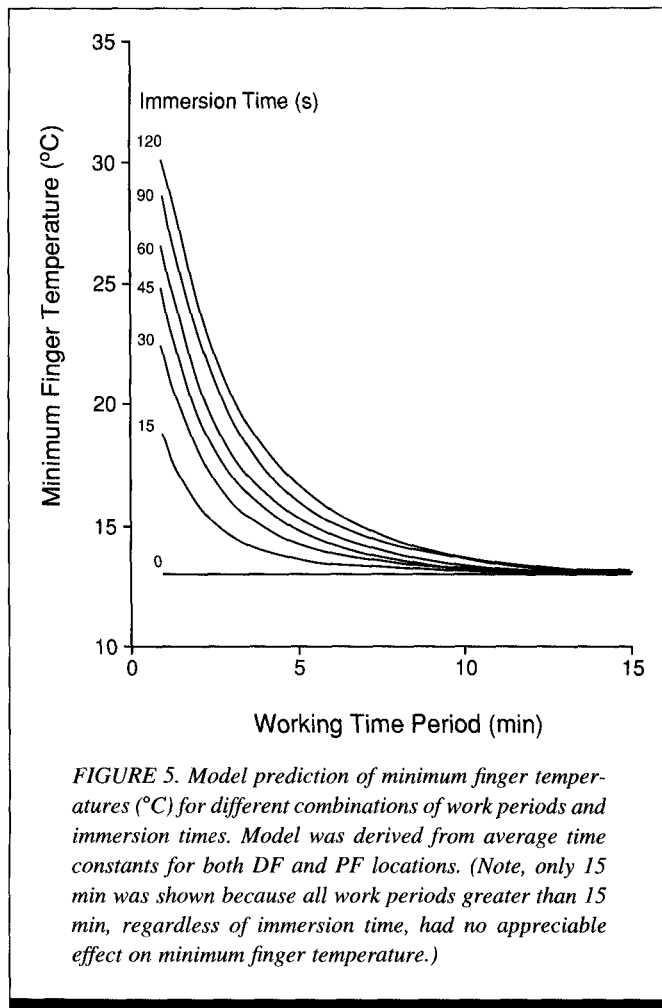
Duckro et al.⁽³⁴⁾ pointed out the need for a clear methodical guideline for placing temperature sensors on the hands. They acknowledged the need for additional studies to augment published data. Certain hand locations, such as the palmar surface of a finger's most distal phalanx, have been selected for clinical biofeedback studies for monitoring sympathetic nervous system activity. Due to the specificity of physiological responses to factors such as rate and locus of cooling, exposure time, task requirements, and other external environmental factors present in

industry, it follows that a monitoring procedure should record representative data indicative of the thermal reactions.

Sensor placement depends on the intensity of the cold stressor to which an individual is exposed. Duckro et al.⁽³⁴⁾ concluded that for digital skin temperatures above 26.7°C (80°F) there were negligible differences in temperatures between the web dorsum (dorsal side) and various locations among the digits. This experiment supports the conclusion that hand temperature is less dependent on location in warmer temperatures. It was shown statistically for the drawing job, where ambient temperatures were approximately 23.8°C (75°F) and there were no differences in skin temperatures for all hand locations monitored. Therefore, a high monitoring resolution (number of sensors) is probably not warranted in warm environments in which hand skin temperatures exceed 29.4°C (85°F).

Although the thermal magnitude of cold conduction due to product temperature was larger than ambient temperature effects in both shoulder cutting and wing meat checking, finger temperatures did not recede below ambient temperatures. It is unknown whether this would hold true for exposures to materials having greater thermal conductivity given similar ambient temperatures. Conversely, in the drawing job hand temperatures surpassed ambient temperatures. Therefore, sensor placement should account for the overall thermal responses of the hands, due to environmental factors as well as those aspects of the physical task that would have a locus effect, whether it be heat loss or heat gain.

Unfortunately, an in-plant field study does not permit complete control of the situation, and consequently recording time for each job varied. This plant provided breaks every 2 hours. Therefore, hand temperature recordings had to be made within these constraints. A 45-min time period was used, because workers in the drawing task rotated every 45 min. Since the comparison in



Experiment 1 was based on mean minimum temperatures, averages contained just one data point per subject. Therefore, it did not matter that drawing time was only 45 min compared with the other jobs. It was an accurate representation of the job.

The beneficial aspects of intermittent rewarming in regard to cold stressors in the environment greatly depends on the extent to which the deeper tissue layers are warmed. The time constants represented a quantifiable measurement that could be used to assess rates of heating and cooling. Due to the industrial setting and the use of workers in real working conditions, certain issues were evident. Control of testing conditions was quite limited because of the production pressures in such an environment. Special instances arose when workers went on rest breaks (3 to 4 min), which were part of the job. Although the subjects were instructed not to attempt to warm their hands, the effect of removing their hands from the cold product indirectly caused a disruption of the cooling process of the fingers. Apparently, skin cooling is highly sensitive to cold stressors that are conductive in nature. Due to these disruptions, on five occasions it was necessary to disregard data that may have been valid otherwise, resulting in fewer replicates.

Differences between dorsal and palmar finger time constants for heating were not statistically significant. Direct observation indicated that hot water exposure to the palmar and dorsal sides of the fingers was equivalent due to the systematic movement of

the hands under the running water. Although time constants for heating were expected to be much smaller than those for cooling, the effect was smaller than expected due to the gloves worn by the workers. The insulative properties of the gloves for cold elements may have served as an inhibitor of heat transference from the hot water immersion sink to the hands.

Due to the constraints inherent in field studies, a gender bias occurred resulting in a 1:6 male to female ratio for digital cooling compared to 4:1 for digital warming, which may have affected the outcome. This was a consequence of the wing meat checker job, which was primarily performed by females (90%). It is acknowledged that anatomical differences such as skin texture and insulating fat form the basis of an expected gender bias and should be considered; however, it is anticipated that these gender differences at the fingers have a minimal effect. Riley and Cochran⁽³⁸⁾ observed only 0.6° to 1.2°C differences in minimum finger temperature between males and females.

The time constants for both the dorsal and palmar sides of the fingers for cooling after rewarming were one-third of the time constant for initial cooling after entering the cold from room temperature. Gaydos⁽¹⁰⁾ suggested that local warming of a vasoconstricted hand has little effect on its blood flow if the rest of the body remains cool. Enander et al.⁽³⁹⁾ showed that workers in a packing department of a cold store (low intensity work similar to the present study) experienced nearly a 1°C (1.8°F) drop in body temperature in an ambient temperature of 10°C (50°F). Although not experimentally accounted for, it seems probable in an environment such as this that the whole body over time could become cooler. The sinks allowed for only a locus heating effect on a superficial level.

Another explanation is based on the presumption that the deeper tissues of the digits are warm at the initial stages of work. During work the underlying tissues decrease in temperature and do not recuperate to their initial thermal states because, as the hands are rewarmed, only the outer skin layers are heated. Thus only a small percentage of the digital mass actually absorbs heat, as compared to the mass of a fully warmed digit at the commencement of work. The rate of cooling may depend on the percentage of soft tissue mass that retains heat.

Another factor in the lower cooling time constants after intermittent rewarming may be evaporation from the gloves. In a study by Molnar et al.⁽³¹⁾ Newtonian cooling curves were faster for wet hands than for dry ones. Although the temperatures in that study were much colder, the difference between wet and dry conditions was due to excess heat loss from evaporation. The current study did not directly account for that factor, but it was observed that the gloves were constantly wet due to meat handling or to immersion in the hot sink. Rapid hand movements are prevalent throughout most tasks in the turkey processing plant. Because of the increased air velocity and the wet glove surfaces, evaporative heat loss from the gloves may have occurred.

Recently Chen et al.⁽⁴⁰⁾ reported much lower time constants for finger cooling (36 sec) compared with those for initial cooling (603 sec for the palmar finger) or intermittent cooling (179 sec for palmar finger) measured in the current investigation. That study, however, investigated finger cooling while subjects applied 10 N finger force using bare hands against an 11 cm aluminum cube at ambient temperatures that were much colder (-1°C to

-14°C) than the current study. The large divergence in time constant magnitude between the two studies can be attributed to the use of insulative gloves and differences in the thermal conductivity of the materials, ambient temperatures, and acclimatization of the subject populations. The most important difference was that between the heat conductivity of aluminum ($202 \text{ Wm}^{-1} \text{ K}^{-1}$ at 0°C) in their study and that of the meat handled in the current study, which contained a high water content ($0.554 \text{ Wm}^{-1} \text{ K}^{-1}$).

Although there was a slight trend towards decreasing time constants after each rewarming session, there were no significant statistical differences. Therefore, it is reasonable to believe that over the two- to three-hour work period the physiological responses to the environment were constant and were not time dependent.

An issue that should be discussed is the workers' perception of thermal sensation, and more specifically, their ability to discriminate between perceived rewarmed skin temperatures reached during intermittent rewarming and those temperatures that would represent normal thermal states. Apparently, subjects rewarmed their hands to an average temperature of 19.8°C (67.6°F) deemed satisfactory to them, as compared with their average starting temperature of 29°C (84.2°F). The workers were usually allowed 4 min for each rewarming period at the sink. In analyzing the data it was apparent that the time for rewarming to a perceived level of thermal adequacy was less than 1 min. Thus an individual's perceptual recognition of skin temperature may in fact deviate from true thermal states. A structured work-rewarming schedule would solve this apparent problem objectively.

When analyzing the mean working hand temperatures in Experiment 2 it was apparent, as noted in Experiment 1, that there was a hand location effect. Both conditions induced temperature differences between the distal areas (dorsal and palmar sides of the finger) and the proximal areas of the hand. Workers tended to handle food products that were quite small and the process of detecting bone fragments in the meat was done most effectively with the use of their fingers. This limited the amount of contact exposure of the meat to the palm areas of the hand, thereby reducing any further heat loss through conduction. This gives further credence to the results obtained in Experiment 1.

The mean working temperatures with and without the use of a hot water immersion sink demonstrated that the sink did not induce statistically significant average temperature changes at any hand location. It is interesting to note that the experimental design was not indicative of a typical day at the turkey processing plant. The job rotation program allows for each employee to use a hot water immersion sink approximately two to three times per quarter (2- to 3-hour time period). The 1-hour time interval used for collecting the temperature data included two rewarming sessions, and it was still incapable of inducing a thermal difference.

To further explore the thermal effects of hot water immersion sinks on mean finger skin temperatures, a model for digital heating and cooling was used to theoretically develop a work-rewarming schedule. It was assumed that the ineffectiveness of the hot sink was due to suboptimal utilization. To verify this, various combinations of work intervals and rewarming periods at the hot water immersion sinks were analyzed. It was concluded that working for more than 10 min with the longest practical time period for rewarming (2 min) did not warm the hands

appreciably. An example of a work-rewarming cycle is shown in Figure 4. The illustration clearly indicates that finger skin temperatures would converge to the lowest feasible temperature (13°C, 55.4°F) that could be induced by the environmental conditions. Furthermore, these skin temperatures would be held constant for extended periods of time. It is apparent that periodic rewarming must occur within the interval of at most two to three time constants for digital cooling.

To induce warmer minimum skin temperatures (18°C, 64.5°F) different rewarming schedules can be used. If 18°C (64.5°F) was the goal for a minimum finger temperature, one of several possible schedules could be used (see Figure 5). All would be impractical, however, due to the fact that 25% to 50% of actual work time would be spent at the sink. It is quite apparent, according to the model, that hot water immersion sinks are ineffective in balancing worker time constraints with the needed frequency of rewarming in order to maintain a thermal state above a minimum temperature. Although the practical benefits of heating using a hot water immersion sink are limited, there are undoubtedly some psychological aspects that cannot be disregarded. It should be noted that the workers appear to believe in the system and would not work contentedly without it.

Currently there are few alternatives available aside from frequent hot sink immersions. Warming from increased muscular activity apparently is ineffective, since these jobs already involve highly repetitive motions. Furthermore, increased muscle exertions would have the adverse effect of increasing the risk of a musculoskeletal disorder. In light of these findings, and simply due to the lack of economically feasible solutions, it is suggested that future studies evaluate alternative types of insulative gloves. A caveat regarding any consideration of gloves is that it should also account for any properties of gloves that would adversely affect strength, tactility, and dexterity, especially given the nature of the work in this environment, which is highly hand intensive.

CONCLUSIONS

This investigation demonstrated that hand skin temperature for proximal and distal hand locations differed at room temperature and in moderately cold environments. Hand skin temperatures above 29.4°C (85°F) did not induce hand location effects. Consequently, effective hand temperature monitoring cannot be accomplished at one hand location below moderately cold temperatures. This procedure, however, can be greatly simplified in the distal and proximal regions of the hand by locating sensors on the dorsal side, since no difference between dorsal and palmar temperatures were observed. This mitigates any active interference with those tasks requiring intensive hand work, as commonly found in industry.

Hand skin temperature monitoring in the moderately cold environments within the turkey processing plant allowed for a relatively in-depth analysis of digital cooling. A clear distinction was noted for digital cooling at the commencement of a working period when the body was warm compared with cooling after periodic rewarming during work when the body was presumably cooler. The apparent difficulties in sustaining reasonable skin

temperatures during work under its current usage led to a development of an empirical model for digital heating and cooling.

The model used for analyzing digital heating and cooling proved to be an adequate representation of skin cooling. The efficacy of hot water immersion sinks for periodic work-rewarming was concluded to be of minimal value due to its ephemeral relief. The need for extraordinary modifications such as scheduling frequent rewarming further inhibited its practical utility in industry.

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