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Residual-limb skin temperature in transtibial sockets

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Abstract—The insulated environment of the lower-limb prosthesis can result in elevated residual-limb skin temperatures that may contribute to skin irritation, blistering, and a reduced quality of life. The design and materials of the prosthetic socket, suspension system, and liner can potentially alleviate these conditions, but the thermal load may vary with activity and location within the socket. To characterize the thermal environment at the skin-prosthesis interface, we made temperature measurements on five transtibial amputees at 14 locations on the residual limbs. After the participants donned their prosthesis and rested in the seated position for 15 min, the mean skin temperatures of their residual limbs increased by 0.8 degrees Celcius. Subsequent walking for 10 min resulted in a 1.7 degrees Celsius total increase in mean skin temperature. Thermal contour maps revealed the skin was coolest at the anterior proximal location and warmest across the posterior section, correlating with areas of low and high perfusion. From the results, we determined that residual-limb skin temperature depends on activity and locality. This information may aid in understanding where and why skin problems develop on lower-limb residual limbs and may provide design requirements for new prosthetic socket systems intended to alleviate temperature-related discomfort.

Key words: amputation, artificial limbs, biomechanics, heat transfer, prosthetics, rehabilitation, residual limb, skin temperature, transtibial sockets, veterans.

INTRODUCTION

Within the last two decades, engineering advances in materials, design, and manufacturing have improved the performance and stability of prosthetic limbs for lower-limb amputees. Prosthetic innovations include knees that incorporate microprocessors allowing adaptation to changes in gait, shock-absorbing pylons that attenuate injury-causing foot-ground impacts, and feet that store and return energy during the gait cycle. Prosthetists routinely use engineering tools to manufacture prosthetic sockets custom-fit to the contours of an amputee's residual limb. These advances have helped reduce occurrence of injuries while maximizing fit and function. However, little has been done to reduce heat and skin temperatures at the interface between the residual limb and the prosthetic socket system.

Elevated skin temperatures can affect the amputees' perception of comfort and may be related to the incidence of residual-limb skin injuries. In a survey of lower-limb amputees (N = 90), Hagberg and Brånemark found that heat and perspiration inside the prosthetic socket were the

Abbreviations: LDPE = low-density polyethylene, SS = steady state, VAPSHCS = Department of Veterans Affairs Puget Sound Health Care System.

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most common causes for reporting a reduced quality of life (72%) [1]. Based on evidence that suggests blisters form more quickly under warm and moist conditions, heat buildup and an accompanying rise in skin temperature may increase the potential for skin problems [2–4]. Unfortunately for amputees, the closed environment of the residual limb and socket system creates both warm and moist conditions.

For amputees who experience temperature-related discomfort and increased risk for skin problems, understanding the thermal environment is the first step in developing new approaches to prosthetic socket systems that could resolve these problems. For this study, we measured residual-limb skin temperatures at the prosthesis interface and explored the influences of activity and sensor location.

METHODS

Five transtibial, unilateral amputees (body mass = 86 ± 9 kg; age = 44 ± 14 yr) with varying prosthetic prescriptions (**Table 1**) were recruited from the Department of Veterans Affairs Puget Sound Health Care System (VAPSHCS) patient population. All subjects were in average physical condition, wore their prostheses at least 8 hours a day, were at least 2 years postamputation of traumatic etiology, and did not have vascular problems, tumors, or a history of tumors. Each subject provided informed consent to an institutional review board-approved protocol prior to participating.

The experimental setup we devised to measure residual-limb skin temperatures consisted of 15 interchangeable thermistors (0.8 mm diameter, 9.5 mm length, 38-gauge wire, model MA100; Thermometrics, Edison, NJ), in series with one 10 kΩ 0.025 percent precision resistor, and one 16-to-1 channel multiplexor (model MPC506A, Texas Instruments, Dallas, TX). The precision resistor increased the series resistance of the multiplexor and thermistor circuit to keep thermistor power at or below 0.0055 mW. This low thermistor power prevented self-heating errors from affecting temperature output by no more than 0.01 °C. The multiplexor, switched at a rate of 1 Hz, provided a single output channel for data recording from the 16 input channels. We paired 14 of these input channels with thermistors to measure skin temperature on the residual limb. We used one channel with a thermistor to calculate a reference temperature (ice-point temperature [5]) to ensure the system was operating properly. We designated the sixteenth channel to gauge the multiplexor on-resistance (temperature dependent) necessary to convert the voltage drop output across the thermistor circuit to temperature. Each multiplexor channel had an identical on-resistance value. We sampled the data at 4 Hz with MATLAB software (MathWorks, Natick, MA) and a data acquisition board (DS-1102, dSpace, Paderborn, Germany). Absolute error propagation did not exceed 0.5 °C.

To calculate skin temperature, we placed sensors (thermistors) at 14 locations on each subject's residual limb where significant skin temperature differences were expected. These locations were near large muscle groups and on the anterior tibia. To begin the experiment, we asked subjects to sit in a chair and doff their prostheses. We arranged thermistors in vertical sections, where sensors 1 through 4 composed the anterior section, sensors 5 through 8 composed the lateral section, sensors 9 through 11 composed the posterior section, and sensors 12

Table 1.
Subject demographics and prosthetic prescription.

Subject	Body Mass (kg)	Age (yr)	Amputation Level	Socket	Liner	Suspension	Socks
1	79	57	Midtibia	Thermoplastic*	Silicone†	Locking Pin	Cotton‡
2	92	36	Midtibia	Thermoplastic*	Leather-Lined Closed-Cell Low-Density Polyethylene‡	Cuff Strap and Muscle Grasp Suspension	Cotton†
3	98	56	3/4-Tibia	Thermoplastic*	None	Muscle Grasp Suspension	Wool†
4	77	48	Midtibia	Thermoplastic*	Thermoplastic Elastomer†	Locking Pin	Cotton‡
5	83	24	Midtibia	Carbon Fiber Laminate*	Thermoplastic Elastomer†	Locking Pin	Cotton‡

Layering order of each subject's prosthesis: *outermost layer, †layer adjacent to the skin, and ‡intermediate layer.

through 14 composed the medial section (**Figure 1**). Within each section, the sensor identification numbers increased distally. We evenly spaced the sensors across each vertical section from the height of the tibial tuberosity to the distal end of the limb. We held each sensor in place with a small piece of adhesive tape.

Subjects then donned their prostheses over the sensors. We recorded temperature measurements for the next 28 min. Subjects began the test while resting comfortably in the seated position for 15 min. We allotted 3 min to transition the subject onto the treadmill. The subjects then walked at a slow pace (0.27 m/s) for 10 min to complete the test.

To explore how the residual-limb skin temperature changed with time during the test, we analyzed the data in four distinct time periods: donning, steady-state (SS) resting, initial walking, and SS walking. The donning period included all observations within 1 min after subjects donned their prostheses (the first minute of the test). We defined SS resting as all observations within the last minute of the 15 min resting period (minute 15 of the test). Initial walking included all measurements within 1 min of beginning the treadmill walk (minute 19 of the test). SS walking included all measurements within the last minute of the 10 min walk (minute 28 of the test). To explore how residual-limb skin temperature varied around the limb, we also analyzed the data by section: anterior, lateral, posterior, and medial.

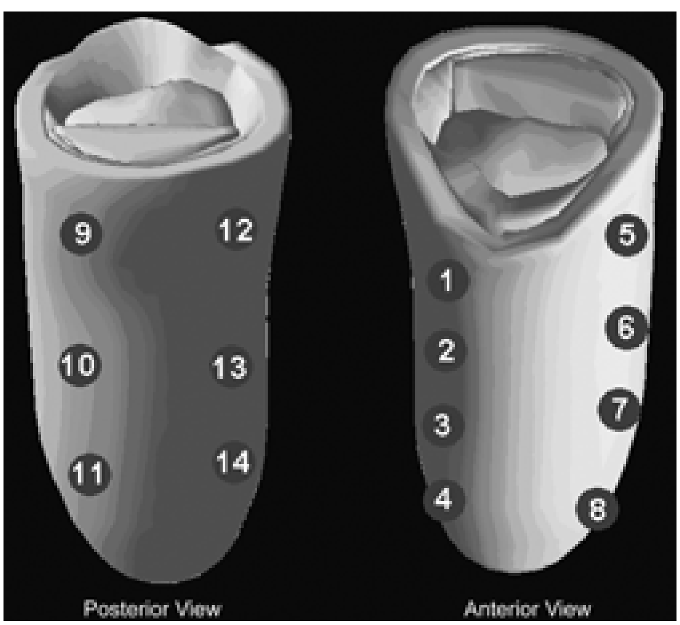

Figure 1.
Sensor placement on a left residual limb from posterior and anterior views. Sensor locations are indicated by circles and sensor identification numbers.

To aid in understanding how the temperature varied temporally and spatially, we created thermal contour maps from the two most proximal sensors in each of the four sections (anterior sensors 1 and 2, lateral sensors 5 and 6, posterior sensors 9 and 10, and medial sensors 12 and 13) for each time period of interest (donning, SS resting, initial walking, and SS walking). The resulting data array of sensors we used to create the contour plot was 2×4 (2 most proximal sensors × 4 circumferential sensors). To produce smooth contour maps, we used a cubic spline algorithm to fit the data array to a higher resolution output array (20 × 40). A larger data array was thwarted by the consistent failure of the 38-gauge wire of sensor 11 (distal posterior).

RESULTS

Once the subjects donned their prostheses, their residual-limb skin temperatures typically increased monotonically for the duration of the test (**Figures 2** and **3**). The mean skin temperature of all subjects at the start of the test was 31.4 ± 1.3 °C in the first minute after donning their prostheses. The temperature rose by 0.8 °C to reach 32.2 ± 1.7 °C at the end of the 15 min resting period (**Table 2**). Skin temperatures were still increasing, albeit slightly, indicating the residual-limb skin now insulated by the prosthesis had not reached a well-defined SS thermal condition (e.g., within 1% of final value for several minutes). The skin temperature escalation during the 15 min resting period was somewhat variable across the five subjects. At the end of the resting period, the skin temperatures had climbed by 0.7 percent (Subject 1), 2.9 percent (Subject 2), 1.8 percent (Subject 3), 4.0 percent (Subject 4), and 2.3 percent (Subject 5), when compared with the skin temperatures upon donning the prostheses.

During the transition period, skin temperatures of all subjects increased by 0.1 °C to reach 32.3 ± 1.7 °C during the first minute of treadmill walking. Walking caused a further rise in the measured residual-limb skin temperatures. The 10 min walk resulted in a temperature escalation of 0.8 °C from the start of walking (1.7 °C from donning) to reach 33.1 ± 1.8 °C. Skin temperatures were still climbing at the end of the test and had not reached a well-defined SS. The skin temperature increase during the 10 min walking period was also variable across the

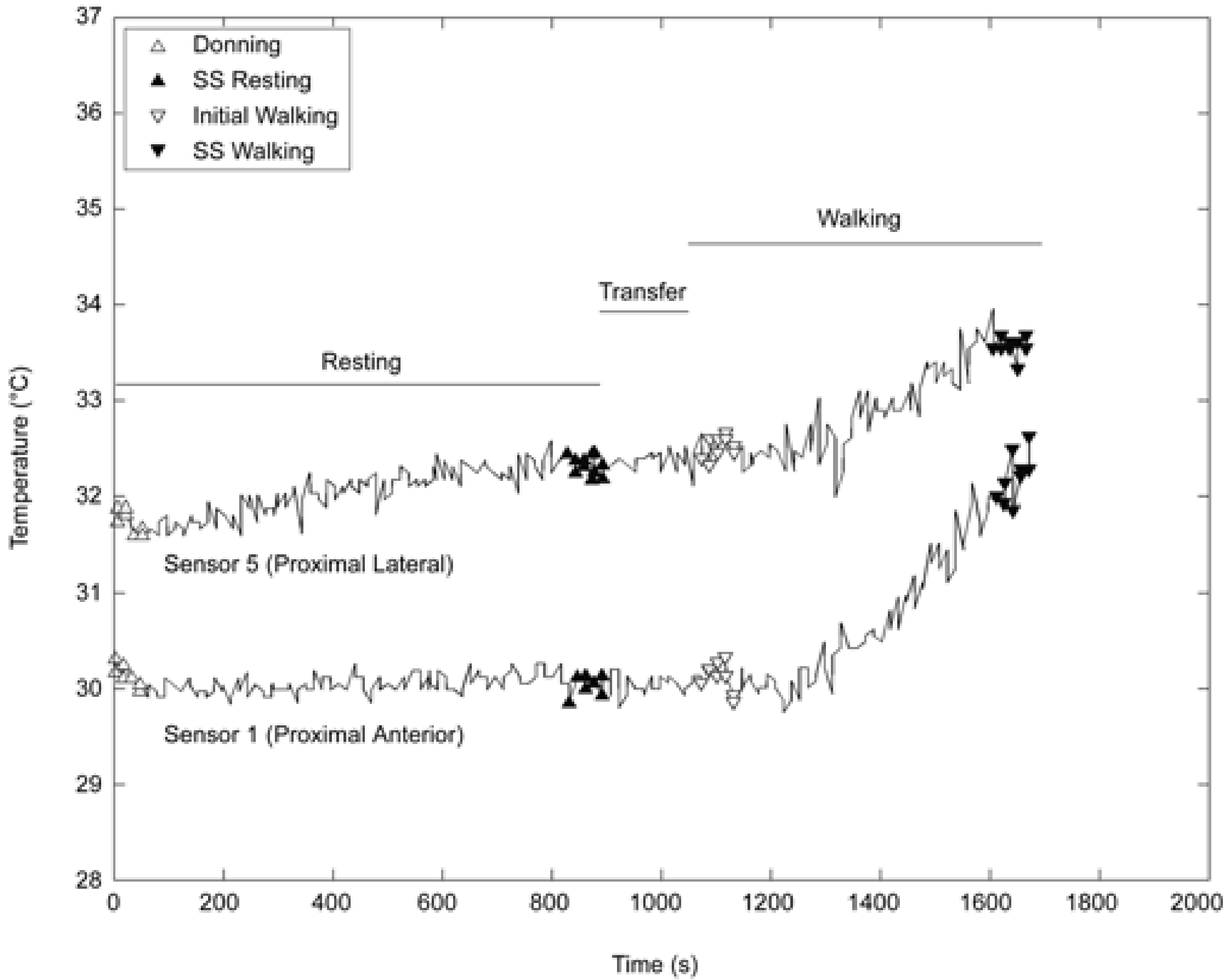

Figure 2.
Residual-limb skin temperature (Subject 5) versus time for proximal anterior and proximal lateral sensors over duration of test. SS = steady state.

five subjects. Compared with the skin temperature after donning the prosthesis, the temperatures had escalated by 4.9 percent (Subject 1), 4.8 percent (Subject 2), 3.4 percent (Subject 3), 9.5 percent (Subject 4), and 4.3 percent (Subject 5) by the end of the 10 min walking period.

Residual-limb skin temperatures also varied by location over the duration of the test (**Table 3**). The temperature across the anterior section for all subjects was coolest at 31.7 ± 1.6 °C. In order of increasing temperature, the medial section was 32.1 ± 1.9 °C, the lateral section was 32.6 ± 1.5 °C, and the posterior section was warmest at 32.9 ± 1.7 °C.

We observed that the spatial and temporal distribution of skin temperature varied greatly in the thermal contour plots (**Figure 4**). The skin temperature from all five subjects was coolest in the proximal anterior location during donning and warmest in the posterior section during the last minute of the 10 min walk.

DISCUSSION

Researchers have known that many lower-limb amputees find their prosthetic sockets uncomfortably warm. In addition to being uncomfortable, this warm and moist environment may result in the increased occurrence of residual limb skin problems. To better understand the thermal environment at the skin-prosthesis interface, we measured the skin temperatures at distributed locations on the residual limbs of five transtibial amputees under resting and walking conditions.

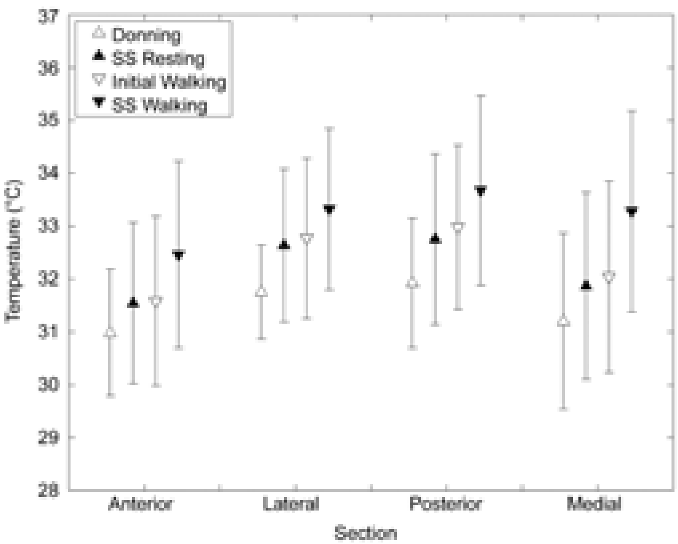

Figure 3.
Residual-limb skin temperature at anterior, lateral, posterior, and medial sections during donning, steady-state (SS) resting, initial walking, and SS walking. Error bars represent standard deviation.

To minimize the risk of residual-limb tissue injuries during the test, we measured temperature at the residual-limb-skin prosthesis interface with a network of sensors (thermistors), each no larger than a grain of rice. None of the five subjects found the sensors or wires uncomfortable. However, the fine 38-gauge wires used to complete the measurement circuit failed repeatedly at the distal posterior location (sensor 11). Larger gauge wire would likely prevent this failure, but may lead to skin irritation.

Insufficient testing time and a small population of amputees ($N = 5$) limited this study. A thermal SS response was not reached in either the resting or walking tests, so the results may represent a transient condition. However, the period of time amputees spend resting and walking while participating in their vocational and recreational activities is likely quite variable, suggesting that thermal SS conditions may not be as common as transient conditions. While most amputees could participate in a study with a longer resting period, not all would be able to complete the longer walking period necessary to obtain SS. The duration to achieve SS is unknown but is certainly longer than 15 min while resting and 10 min while walking. Longer periods would also reveal if skin temperatures oscillate while approaching SS, enabling use of additional metrics such as time and magnitude of peak overshoot and settling time.

Table 2.
Residual-limb skin temperatures (°C) for all subjects during donning, steady-state (SS) resting, initial walking, and SS walking time periods (mean ± standard deviation).

Subject	Donning	SS Resting	Initial Walking	SS Walking
1	30.5 ± 0.6	30.7 ± 0.8	30.7 ± 0.9	32.0 ± 0.9
2	31.1 ± 0.7	32.0 ± 0.7	32.1 ± 0.7	32.6 ± 1.0
3	32.6 ± 0.8	33.2 ± 1.1	33.2 ± 1.0	33.7 ± 1.0
4	32.6 ± 0.6	33.9 ± 1.0	34.2 ± 1.0	35.7 ± 0.6
5	30.0 ± 0.9	30.7 ± 1.4	30.6 ± 1.1	31.3 ± 0.9
All	31.4 ± 1.3	32.2 ± 1.7	32.3 ± 1.7	33.1 ± 1.8

Table 3.
Residual-limb skin temperatures (°C) for all subjects for anterior, lateral, posterior, and medial sections (mean ± standard deviation).

Subject	Anterior	Lateral	Posterior	Medial
1	30.3 ± 0.6	31.1 ± 0.6	32.3 ± 1.1	30.5 ± 0.5
2	31.6 ± 1.0	32.4 ± 0.8	32.1 ± 0.7	31.6 ± 0.9
3	32.3 ± 0.6	33.1 ± 0.7	33.9 ± 0.8	34.1 ± 1.2
4	33.8 ± 1.2	34.5 ± 1.4	34.6 ± 1.2	33.5 ± 1.3
5	30.1 ± 0.8	32.0 ± 0.9	30.8 ± 0.9	30.1 ± 1.1
All	31.7 ± 1.6	32.6 ± 1.5	32.9 ± 1.7	32.1 ± 1.9

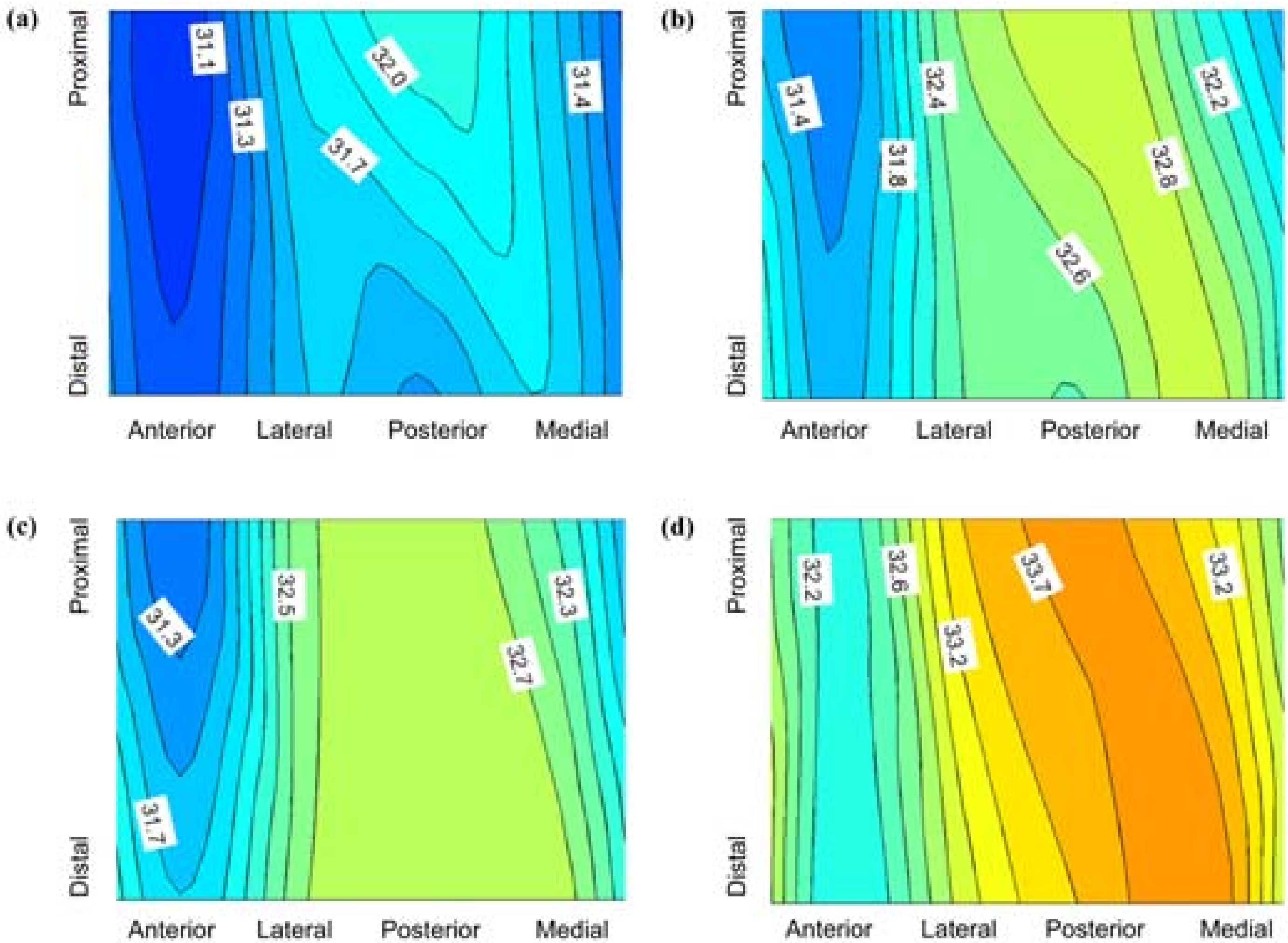

Figure 4.
Thermal contour map of proximal portion of residual limb during **(a)** donning, **(b)** steady-state (SS) resting, **(c)** initial walking, and **(d)** SS walking.

A small sample population (*N* = 5) with broad inclusion and exclusion criteria may also limit the overall results. Considering the diversity of socket, liner, and sock materials available commercially, we suggest an experimental design with a large subject population. The prosthetic prescriptions of the participating subjects were different, as were the lengths, sizes, and shapes of their residual limbs. Increasing the number of participating subjects with a more stringent inclusion and exclusion criteria may produce more robust results.

Simply donning their prostheses and resting for 15 min resulted in the amputees experiencing a mean residual-limb skin temperature increase of 0.8 °C (2.5%). After 10 min of walking, the mean residual-limb skin temperature climbed by 1.7 °C (5.4%) from the donning temperature. For this study, we demonstrated that the insulation properties of prosthetic socket systems can raise skin temperatures while subjects rested. Walking for even short periods of time can result in a greater increase in skin temperature. While the 10 min walking protocol did not allow the skin temperatures to reach a thermal SS condition, several subjects expressed that they do not frequently walk for periods that long. For amputees capable of walking 10 min or longer, their residual-limb skin is likely subjected to an increasing thermal load and may be more susceptible to blister and sore formation not only from a greater dose of gait-related forces but also from increased skin temperatures.

A common complaint of lower-limb amputees is that uncomfortably warm residual-limb skin temperatures reduce their quality of life [1]. A temperature increase of

1.7 °C may be of sufficient magnitude to produce this discomfort. While the duration of the test was not long enough to solicit comfort responses from the participants, we deduced from the broad selection of prosthetic components included in the study that a temperature increase of 1° or 2° is responsible for the reports of thermal discomfort in the literature.

From the individual subject data, we came up with several hypotheses about prosthesis effects on residual-limb skin temperature. One significant influence on skin temperature may be the liner material. Subjects 1 and 4 wore similar prostheses except for the liner (Subject 1: silicone, Subject 4: thermoplastic elastomer). At the end of the walking period, Subject 1 experienced a much smaller increase in temperature (1.5 °C) than Subject 4 (3.1 °C), in comparison with the temperature at the beginning of the test.

Estimates of thermal conductivity bolster the hypothesis that liner materials may have significant effects on skin temperature. A silicone liner manufactured by Ossur (Reykjavik, Iceland) has a conductivity of approximately 0.176 W/(m•K) [6] and a typical closed-cell foam, such as low-density polyethylene (LDPE), has a conductivity of approximately 0.040 W/(m•K) [7]. The greater thermal resistance (lower thermal conductivity) of the closed-cell foam may act as a more effective insulator and result in greater skin temperatures than the silicone liner.

Another significant influence on skin temperature may be the socket material. Subjects 4 and 5 wore similar prostheses except for the socket (Subject 4: thermoplastic, Subject 5: carbon fiber laminate). At the end of the 10 min walk, the skin temperature of Subject 5 increased by only 1.3 °C, compared to the increase of 3.1 °C of Subject 4.

We also noted locality differences in residual-limb skin temperatures. The anterior section revealed the coolest skin temperature (31.7 °C), while the posterior section was the warmest (32.9 °C). During basal states, perfusion and metabolism are the two dominant sources of thermal energy [8]. Perfusion does not chemically or mechanically generate thermal energy, but it does transfer thermal energy into the limb from the body's core by convection. Thermal energy generated by metabolism (during basal states) is insignificant compared with energy transferred by perfusion. Regardless, muscle has the highest rate of both metabolism and perfusion [9]. Consequently muscle tissues, such as the residual gastrocnemius and soleus, receive a relatively large amount of thermal energy, resulting in higher posterior section temperatures. Cooler temperatures may be expected where smaller muscle masses with low perfusion exist, such as the anterior section [9]. Future epidemiological studies exploring the locality of tissue injuries may reveal a correlation with the locations of higher skin temperatures.

Understanding thermal gradients and the effects of both prosthetic components and amputee activities may aid in the design of new prostheses that produce fewer blisters and sores and are more comfortable for the amputee.

CONCLUSION

We measured residual-limb skin temperatures at the skin-prosthesis interface of five transtibial amputees. After the participants comfortably rested in the seated position for 15 min, their overall mean skin temperatures increased by 0.8 °C. When the 15 min rest was followed by a 10 min walk, the overall mean skin temperature of the participants increased by a total of 1.7 °C, compared with the temperature immediately after donning the prosthesis. Thermal contour maps reveal the skin was coolest at the anterior proximal location and warmest across the posterior section, correlating with areas of low and high perfusion. From the results, we determined residual-limb skin temperature depends on activity and locality, and our findings may aid in understanding where and why skin problems develop on lower-limb residual limbs. Future studies on the effects of prosthesis design on residual-limb skin temperatures are warranted.

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