Influence of isometric exercise on blood flow and sweating in glabrous and nonglabrous human skin

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Saad, Adham R., Dan P. Stephens, Lee Ann T. Bennett, Nisha Charkoudian, Wojciech A. Kosiba, and John M. Johnson. Influence of isometric exercise on blood flow and sweating in glabrous and nonglabrous human skin. J Appl Physiol 91: 2487–2492, 2001.—The distribution of the reflex effects of isometric exercise on cutaneous vasomotor and sudomotor function is not clear. We examined the effects of isometric exercise by different muscle masses on skin blood flow (SkBF) and sweat rate (SR) in nonglabrous skin and in glabrous skin. The latter contains arteriovenous anastomoses (AVAs), which cause large fluctuations in SkBF. SkBF was measured by laser-Doppler flowmetry (LDF) and reported as cutaneous vascular conductance (CVC; LDF/mean arterial pressure). SR was measured by capacitance hygrometry. LDF and SR were measured at the sole, palm, forearm, and ventral leg during separate bouts of isometric handgrip (IHG) and isometric leg extension (ILE). CVC and its standard deviation decreased significantly during IHG and ILE in the palm and sole (P < 0.05) but not in the forearm or leg (P > 0.05). Only palmar SR increased significantly during IHG and ILE (P < 0.05). We conclude that the major reflex influences of isometric exercise on the skin include AVAs and palmar sweat glands and that this is true for both arm and leg exercise.

arteriovenous anastomoses; muscle mass

REFLEX THERMOREGULATORY CHANGES in skin blood flow (SkBF) are controlled by two arms of the sympathetic nervous system: an active vasodilator system and a noradrenergic vasoconstrictor system (7, 11, 13, 23). It is generally agreed that glabrous skin lacks influence from active vasodilator nerves (12); therefore, reflex control of SkBF in those regions is thought to be controlled entirely by the noradrenergic vasoconstrictor system. Glabrous skin is characterized by an absence of hair and includes the palms, soles, and lips. SkBF in glabrous skin is also characterized by large spontaneous fluctuations, which are a manifestation of changes in blood flow through arteriovenous anastomoses (AVAs) (2, 3, 5, 16). Neither these fluctuations in blood flow through the AVAs nor the AVA architecture is present to any significant degree in nonglabrous skin (11).

It is well documented that isometric exercise elicits physiological responses such as increases in heart rate (HR), mean arterial pressure (MAP), cardiac output (CO), and sympathetic nerve activity directed to skeletal muscle (9, 14, 17–22, 30). It has also been reported that isometric exercise leads to an increase in skin sympathetic nerve activity (SSNA) (4, 19, 21, 29–30). However, in normothermia, forearm SkBF does not appear to be influenced by isometric exercise (7, 14, 19, 26). Although most measurements of SkBF during isometric exercise have concentrated on the forearm, the vasomotor control in glabrous skin, rich in AVAs, may differ from that in the forearm skin. Indeed, glabrous skin is considered to be much more responsive to environmental stimuli than nonglabrous skin (5, 6, 23).

Therefore, we sought to test whether the site of measurement was an important consideration in the cutaneous vasomotor responses to isometric exercise. Specifically, we tested the hypothesis that glabrous skin would show a more marked reflex response than nonglabrous skin to isometric exercise. We made measurements of SkBF from both glabrous and nonglabrous skin of the upper and lower extremities to establish whether there may be regional differences in the responses to isometric exercise. Included in the analysis were measures of the variation in SkBF in glabrous skin as an index of AVA function. We also measured sweat rate (SR) to include another potential site of reflex effects (15). Because other reflex responses to isometric exercise are dependent on the active muscle mass (10, 20, 22, 24), we hypothesized that any cutaneous vasomotor or sudomotor responses would show a similar dependence. Hence, we used both isometric handgrip (IHG) and isometric leg extension (ILE) to involve different muscle masses as another possible factor in the cutaneous vasomotor and sudomotor responses.

METHODS

Eight healthy, moderately active men (aged 20–31 yr, 24.8 ± 0.6 yr) participated in this institutionally approved study. Each subject provided voluntary written informed consent before his participation. Subjects refrained from the...
consumption of alcohol, tobacco, or caffeine for at least 12 h before the experiment. No subject was taking medication at the time of the study. Measurements of maximal voluntary contractions (MVCs) for both IHG and ILE were taken at least 1 h preceding experimentation. All experiments were performed at the same time of day to avoid any diurnal effects (1).

SkBF was measured as laser-Doppler flow (LDF) (model MBF3D, Moor Instruments). Cutaneous vascular conductance (CVC) was calculated as the ratio of LDF to MAP. Each site was instrumented with an aluminum fitting that housed a LDF flow probe. The housing also served as a heating unit used to control local temperature at the site of blood flow measurement and allowed for the measurement of SR at that site. SR was measured by capacitance plethysmography. MAP and HR were measured noninvasively at the finger by photoplethysmography (Finapres, Ohmeda, Englewood, CO). Both SkBF and SR were always measured on the left extremity at each of four sites: palm at the thenar eminence, ventral forearm, arch of the sole, and ventral leg over the tibia. Whole body skin temperature (Tsk) was controlled at 34°C through the use of a water-perfused suit, with Tsk recorded as a weighted average of thermocouple measurements from six sites (26). A Tsk of 34°C was used because it is considered to be a thermoneutral skin temperature. The water-perfused suit covered the entire body with the exceptions of the head, feet, hands, and arm and leg areas of LDF measurement. Local skin temperatures at the sites of LDF and SR measurement were also controlled at 34°C throughout each study. All measurements were sampled once per second.

The subject was outfitted in the water-perfused suit 1 h after MVC measurement. Subjects were seated throughout all studies. Laboratory light level was dimmed and the sound level reduced during the study to minimize environmental influences, which can markedly change blood flow to glabrous skin (16). After an initial baseline period of at least 10 min, the subject performed a 2-min isometric exercise bout at 30% MVC. Every isometric exercise bout was preceded by at least 5 min of baseline and followed by at least 5 min of recovery. Each subject performed four bouts: two of IHG and two of ILE. ILE and IHG were always performed by the right extremity. The order of exercise type was randomized. The study was performed as a series of two experiments, which were identical except for the site of measurement of SkBF and SR. In one experiment, SkBF and SR on the sole and ventral leg were measured and, in the other, measurements were taken at each of four sites: palm at the thenar eminence, ventral forearm, arch of the sole, and ventral leg over the tibia. Whole body skin temperature (Tsk) was controlled at 34°C through the use of a water-perfused suit, with Tsk recorded as a weighted average of thermocouple measurements from six sites (26). A Tsk of 34°C was used because it is considered to be a thermoneutral skin temperature. The water-perfused suit covered the entire body with the exceptions of the head, feet, hands, and arm and leg areas of LDF measurement. Local skin temperatures at the sites of LDF and SR measurement were also controlled at 34°C throughout each study. All measurements were sampled once per second.

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Data analysis. CVC data are expressed as means ± SE. CVC was expressed as a percentage of the 5-min baseline period before each exercise bout. Both normalized CVC data and SR data were then summarized into 20-s averages. These 20-s averages were analyzed by repeated-measures ANOVA with a Dunnett’s multiple-comparison test. Two-way ANOVA compared responses in CVC at the palm, forearm, sole, and ventral leg during the same type of exercise. Furthermore, responses in CVC to IHG and ILE were compared by two-way ANOVA at all four sites.

Changes in MAP during IHG and ILE were compared to determine whether there was an effect of muscle mass. This was achieved by a paired t-test analysis comparing the increases from the last 20 s before exercise to the last 20 s of exercise. The same comparison was made for HR.

To examine whether fluctuations in CVC were affected by exercise, for each subject the standard deviations of the 1-s CVC data for each 20-s period were calculated. Standard deviations of the 20-s summaries of CVC data were then averaged over three 2-min periods: preceding, during, and after exercise. These values were then compared for the group by one-way ANOVA with repeated measures followed by a Student-Newman-Keuls multiple-comparison test. The level of significance was set at P < 0.05 for all analyses.

RESULTS

Figure 1 represents a typical response to the protocol from a single subject. On the average, MAP increased from 93.1 ± 1.3 to 107.7 ± 1.2 mmHg during IHG and from 94.0 ± 1.7 to 116.8 ± 1.0 mmHg during ILE. HR increased from 67.1 ± 2.6 to 78.3 ± 2.6 beats/min during IHG and from 68.6 ± 2.7 to 87.5 ± 2.3 beats/min during ILE. In each case, the response was greater during ILE than during IHG (P < 0.05). With each bout of exercise, there was a consistent, significant reduction in the average level of CVC at the palm. Note also that the temporal variation in CVC at that site was also markedly reduced during each of the exercise bouts. In contrast, CVC levels in the nonglabrous skin (forearm) showed no consistent response to isometric exercise.

Figure 2 depicts the average responses in CVC from all four skin sites to both IHG and ILE. During both IHG and ILE, there were significant decreases in CVC to both glabrous regions (palm and sole) (P < 0.05). In contrast, the nonglabrous regions (leg and forearm) showed no significant changes in CVC during either exercise type (P > 0.05). Therefore, regardless of the active muscle group, the only significant changes in blood flow occurred at the glabrous regions. There were no significant differences in responses in CVC between the palm and sole during the same type of exercise (P > 0.05). This was also true for the leg compared with the arm. There was a significant difference in the responses in CVC at the palm between IHG and ILE, with a greater vasoconstriction during ILE (P < 0.05) (Fig. 2). There was no significant difference in the responses in CVC between the two exercise types at the other three sites (P > 0.05).

A striking feature of the responses in CVC at the palm (Fig. 1) and sole was a sudden marked reduction in the spontaneous temporal variations. To analyze this objectively, we compared the average standard deviations in CVC before, during, and after exercise (Fig. 3) and found that, for both the palm and the sole, the mean standard deviation during exercise was significantly less than that before or after exercise (P < 0.05). In contrast, in the forearm and leg, changes in variability were not consistent, increasing to a small but significant degree in the forearm during exercise (P < 0.05) but not changing significantly in the leg (P > 0.05).

Figure 4 shows the average responses in SR to IHG and ILE from the four skin sites. There was a significant increase in SR only at the palm, and this was true for both types of isometric exercise (both P <0.05). There was a trend for SR to increase at the sole, but this tendency did not achieve statistical significance (P = 0.15 during ILE and P = 0.20 during IHG). Palm
SR was significantly greater during ILE than during IHG ($P < 0.05$).

**DISCUSSION**

We sought to characterize the vasomotor and sudomotor responses to isometric exercise in both glabrous and nonglabrous human skin. Our primary finding was that there were significant vasoconstrictor responses in the glabrous skin of the palm and the sole to both ILE and IHG (Fig. 2). These reductions in the average level of CVC in glabrous skin were accompanied by decreases in the second-to-

![Fig. 1. Responses in cutaneous vascular conductance (CVC; in arbitrary units/mmHg) at the palm and forearm, mean arterial pressure (MAP), and heart rate (HR) to 2 periods each of isometric handgrip (bouts 1 and 3) and isometric leg extension (bouts 2 and 4). Exercise periods are denoted by the shaded areas. Note that palmar CVC is sharply reduced throughout each period of exercise and that the spontaneous variability in palmar CVC is also reduced. CVC from forearm skin did not show a consistent response to isometric exercise, falling slightly in some cases and rising or not changing in others.](image1)

![Fig. 2. Average responses (±SE) in CVC at the 4 sites [palm and forearm (A) and leg and sole (B)] during both isometric leg extension (ILE) and isometric handgrip exercise (IHG). ● and □, responses in nonglabrous skin (leg, forearm); ■ and △, responses in glabrous skin (palm, sole); ● and ●, responses to IHG; ○ and △, responses to ILE. Pre, preexercise; post, postexercise. *Significantly different from the 1-min control (preexercise) value, $P < 0.05$. †Significantly different from the palm IHG values, $P < 0.05$.](image2)
second variation of blood flow (Fig. 3). As in earlier studies, we found no consistent changes in CVC in nonglabrous skin to isometric exercise in normothermia (7, 8, 14, 19, 25, 26).

One consideration for the difference in response between the two skin types is the difference in the microvascular anatomy between glabrous and nonglabrous skin. It is well known that AVAs are found...
predominantly in glabrous skin regions (11–13). Additionally, it is assumed that the large variations in CVC observed in glabrous skin represent AVA function (2, 3, 5, 16, 27). These fluctuations are evident in measurements of CVC at the palm and sole (see Figs. 1 and 3). It is likely, therefore, that the differences in response in CVC between those regions relate directly to the presence or absence of AVAs.

In support of this conclusion, we examined the changes in the pattern of blood flow at the glabrous sites. The large blood flow fluctuations in glabrous skin were first characterized by Burton in 1939 (5), who described the parallel fluctuations in blood flow between the contralateral finger and toe. Thoreson and Walløe (27) characterized the fluctuations in more detail through ultrasonic Doppler methods. They also concluded that the fluctuations were caused by the opening and closing of the anastomotic vessels. In the present study, these fluctuations in CVC in glabrous skin decreased greatly during exercise (Figs. 1 and 3). In nonglabrous skin, the observed effects were not as consistent. In the leg, there were no significant changes in the variability of CVC during isometric exercise, whereas, in the arm, it increased slightly. The reduction in variability as well as in the mean levels of CVC in the palm and sole indicates that the AVAs have more sustained vasoconstrictor tone during isometric exercise than at rest. The absence of consistent changes in CVC at the nonglabrous sites is generally consistent with other studies in which blood flow was measured (7, 14, 25, 26). This supports the notion that decreased AVA blood flow caused the observed changes in CVC in glabrous skin and that there is little or no effect on blood flow through nutritional vessels.

In addition to comparisons of regional responses to exercise, we also compared the blood flow and SR responses between the two exercise types. During ILE, a much larger muscle mass is exercised than in IHG. Therefore, we examined whether active muscle mass would influence the degree of response. We found a significant difference in the response of CVC and SR in the palm between IHG and ILE (Fig. 2). CVC was more reduced and SR was greater during ILE than IHG, suggesting that the degree of response is dependent on the muscle mass exercised, which is consistent with past studies (10, 20, 22, 24). However, we did not see significant differences in blood flow responses between ILE and IHG at the remaining three sites. In fact, blood flow responses at the leg, sole, and forearm appear almost identical between the two exercise types (see Fig. 2). We also found that the increases in MAP and HR from rest to the peak of exercise were significantly greater during ILE than during IHG, which further supports a muscle mass effect (10, 20, 22, 24). At this point, it is not clear why such a role for muscle mass would exist in palmar skin but not in other regions.

Our results appear to differ from those of Saito et al. (19), who measured SkBFP and SR on the sole, as well as SSNA in the tibial nerve, which innervates the sole. Of particular interest is that those investigators found SR to increase significantly, whereas cutaneous vascular resistance was not significantly changed. Differences in methods, protocols, and thermal environments preclude a conclusive explanation for these differences. In our view, the likely case is that both AVAs and sweat glands in that region are targets for the reflex effects of isometric exercise. Environmental factors can influence the response of AVAs to nerve activity. For example, in preliminary work, we noted mild skin cooling abolished both the spontaneous fluctuations in blood flow to glabrous skin and the reduction in CVC with isometric exercise (A. R. Saad, D. P. Stephens, and J. M. Johnson, unpublished observation). We cannot say whether this explains the difference between our findings and those of Saito et al. (19) but consider the possibility worth further study.

An important role for the thermal background also applies to nonglabrous skin. Crandall et al. (7, 8) noted that there was no consistent or significant reduction in CVC in the forearm to IHG in normothermia. However, during hyperthermia, IHG provoked a significant reduction in forearm CVC. In that study, selective blockade of the adrenergic vasoconstrictor system led to the conclusion that the reduced CVC in response to IHG in hyperthermia was due to inhibition of the cutaneous active vasodilator system (7, 8). Of note is that the reflex origin of this inhibition is most likely the muscle metaboreceptor reflex because it was slow to develop and it was sustained by postexercise ischemia (8). Kondo et al. (15) made similar observations for sweating in both glabrous and nonglabrous skin when subjects were moderately warm. The vasocostriction noted in glabrous skin in the present study probably has its origin in central command (18). The response is rapid in onset and followed the same time course as previously described for the SSNA response to central command (28–30).

We observed an increase in SR on the palm during IHG and ILE (Fig. 4). Although SR did not increase significantly on the sole, there was a trend for SR to increase ($P = 0.15$ during ILE and $P = 0.20$ during IHG). Saito et al. (19) found a significant increase in SR at the sole during IHG. In an earlier study, Crandall et al. (7) found no response in SR of the forearm to IHG in normothermia, but they did note an increase in SR when IHG was performed during heat stress. These results and observations by Bini et al. (4) and Kondo et al. (15) indicate that our observation of a sudomotor response in the palm might extend to other areas, depending on thermal conditions. Another possibility is that the lack of consistency in the response of SR at the foot may reflect the amount of water that reaches the skin surface as opposed to the stimulation of the sweat glands. It is unlikely that the lack of sweating at the foot represents a difference in the neural control of sweating between the sole and the palm because some of our subjects did sweat at the sole during exercise, as in the study by Saito et al. (19). Others did not, however, which indicates that the sole has lower sensitivity for sweating than the palm. This
possibility might be tested in future studies by varying the exercise intensity or the length of the exercise bout.

Several investigators noted an increase in SSNA during isometric exercise (4, 19, 28–30). Saito et al. (19) reported increases in SSNA from the tibial nerve, which innervates the sole. Taking those findings and ours together, it is likely that these increases in SSNA to glabrous skin are targeting both AVAs and sweat glands. In other studies (4, 28–30), recordings taken from the nerves targeting nonglabrous regions also showed increases in SSNA in response to isometric exercise. However, we saw no changes in SkBF or SR in nonglabrous skin. At this point, it is not possible to make any firm conclusions about the targets of these increases in SSNA. A future direction would be a comparative study between tibial and peroneal nerve recordings during isometric exercise. In such a study, measurements of SkBF and SR on the sole and lower leg would be made along with nerve recordings from the tibial and peroneal nerves during isometric exercise.

Taken together, the findings show the primary cutaneous responses to isometric exercise in normothermia to be in the AVAs and sweat glands of glabrous skin. In the palm especially, these responses are graded with the active muscle mass.

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