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ABSTRACT

Space physiologists have an interest in upper body exercise since in the weightless state astronauts do a substantial amount of work with their arms and hands. Upper body exercise elicits a peak oxygen uptake approximately 70% of that obtained during lower body exercise; in addition, upper body exercise requires a greater oxygen uptake at a given power output than lower body exercise. Therefore, when performing exercise at a given power output, both the absolute and relative (% of peak $\dot{V}o_2$) exercise intensity is greater during upper body exercise. Although cardiac output responses for a given oxygen uptake are similar, the heart rate, blood pressure and total peripheral resistance responses are greater, and the stroke volume responses are lower at a given oxygen uptake during upper than lower body exercise. Body temperature responses to both exercise types are similar, but the temperatures are achieved by different heat exchange mechanisms. During upper body exercise, there is a greater reliance on torso dry heat loss for temperature regulation. Exercise training programs can improve aerobic exercise capabilities for the upper body, but there are minimal cross-training benefits between the arms and legs. Space physiologists and engineers in the manned space program should consider the unique physiology associated with upper body exercise for: (a) assuring that astronauts are prepared to perform mission related tasks; (b) developing effective exercise countermeasures programs; and (c) engineering of adequate life support systems.

INTRODUCTION

Upper body exercise provides many work performance and physiological problems that are not evident during physical exercise performed with the legs (1)*. Space physiologists have an interest in upper body exercise, since in the weightless state astronauts do a substantial amount of work with their arms and hands and often use their lower body only for stabilization (2,3,4). When aboard the spacecraft and during extravehicular activities (EVA), astronauts perform mission related tasks that require upper body exercise for periods of three to six hours at mean metabolic rates of 260 watts and peak metabolic rates of 625 watts (3,4). Shuttle astronauts have reported that local fatigue of the upper body skeletal muscles has limited their ability to perform EVA (3). As noted by Convertino (3), excessive muscular fatigue should not be surprising at these modest metabolic rates as they likely represent "heavy" relative intensities for the upper body muscle groups where they only represent "light" relative intensities for the lower body muscle groups.

The purposes of this paper are to discuss the physiological responses and control mechanisms for upper body exercise, and to briefly discuss their application to the manned space program. Upper body exercise has direct application to achieving a sustained human presence in space because: (a) astronauts must have sufficient physical fitness to perform mission related tasks of

*Numbers in parentheses designate references at end of paper.

which require use of the upper body muscle groups; (b) exercise countermeasures for microgravity environments must focus on maintenance of upper body work capabilities; and (c) the engineering of astronaut life support systems, such as microclimate cooling systems for EVA, must accommodate the unique physiological adjustments associated with upper body exercise.

PHYSIOLOGICAL RESPONSES

AEROBIC METABOLISM - Figure 1 presents a comparison of submaximal and peak oxygen uptake responses for arm-crank and leg-cycle exercise (5). A greater oxygen uptake is elicited by arm-crank than leg-cycle exercise performed at the same submaximal power output (5-13). Increased requirements for muscular stabilization of the torso (9,10,14,15), a greater isometric exercise component (1,5,6,16), as well as differences in skeletal muscle recruitment patterns (1) have been suggested as responsible for the relatively high oxygen uptake during submaximal arm-crank exercise.

Toner *et al.* (10) conducted experiments which provide insight into the physiological factors responsible for the relatively high oxygen uptake elicited by submaximal arm-crank exercise. Combined arm and leg exercise was performed where the distribution of a given power output (PO) was varied between arms and legs (20,40 and 60% arm PO/total PO), and these results were contrasted with exercise performed with only arm-crank and only leg cycle. Figure 2 presents the results from experiments performed at 76 W and 109 W (10). During the 76 W experiments, oxygen uptake increased linearly with increasing percent arm values; but during the 109 W experiments, oxygen uptake response could best be described by a power function. These investigators speculated that muscular stabilization of the torso accounted for the linear increase in oxygen uptake with increased arm participation during the 76 W experiments. A second unmeasured exercise component, believed to be excessive body movement, was suggested to account for the curvilinear increase in oxygen uptake at the higher power output experiments.

Table 1 presents a comparison of physiological responses to maximal effort arm crank and leg-cycle exercise (5,12-28). Peak oxygen uptake is consistently lower during arm-crank than leg-cycle exercise. Arm-crank exercise values range from 36% to 89% with a mean of 73% of leg-cycle exercise values. The investigations of Cerretelli *et al.* (18), Seals and Mullin (26), as well as Vrijens *et al.* (13) indicate that individuals who train their upper body muscle groups can achieve arm-crank values approaching 90% of their leg-cycle exercise peak oxygen uptake values, whereas, sedentary individuals may achieve only approximately 60%. Generally, strong correlation coefficients (r=0.70 to 0.94) have been reported (see Figure 3) for peak oxygen uptake responses between upper and lower body exercise (15,20,29,30). A few investigators, however, have reported weaker relationships (r=0.30 to 0.60) between these exercise types (31,32).

The relatively smaller skeletal muscle mass involved during upper body exercise likely contributes to the reduced peak oxygen uptake values compared to lower body exercise. Although the smaller skeletal muscle mass limits peak oxygen uptake by its smaller oxidative capacity and reduced ability to generate tension, the role of muscle mass in accounting for individual differences of peak oxygen uptake during arm-crank exercise remains unresolved (20,30,33). Arm volume measurements may (33) or may not (20,30) account for individual differences in peak oxygen uptake during arm-crank exercise. Nevertheless, arm volume measurements provide a poor estimate of the skeletal musculature employed during arm-crank exercise because the chest, back and shoulder muscle groups are not included.

Upper body muscle groups are relatively weaker than lower body muscle groups (34). In theory, muscular strength could influence upper body performance by enabling stronger individuals to achieve higher levels of cardiorespiratory stress prior to local fatigue and exercise termination. Sawka *et al.* (30) reported non-significant correlation coefficients between peak oxygen uptake for arm-crank exercise and grip strength or isokinetic elbow extension (30°/s) strength. Likewise, Falkel *et al.* (20) found grip strength as well as isokinetic (30 and 180°/s) elbow flexor and extensor strength values had nominal relationships with peak oxygen uptake and endurance time for arm-crank exercise.

CARDIOVASCULAR - Cardiac output respon-

TABLE 1. Comparison of oxygen uptake responses to maximal effort arm crank and cycle exercise.

Study	Year		Peak Oxygen Uptake ($l \cdot min^{-1}$) AC	CY	%
Åstrand et al.	1965		2.36	3.50	67
Bergh et al.	1976		3.01	4.12	73
Cerretelli et al.	1979		1.60	2.48	65
			2.60	2.98	87
Davies & Sargeant	1974		1.14	3.27	36
Davies et al.	1974		1.62	3.50	46
Davis et al.	1976		2.34	3.68	64
Falkel et al.	1985		3.07	3.88	79
			2.26	2.97	76
Fardy et al.	1977		2.26	3.17	71
Pendergast et al.	1979	Sedentary	1.90	3.20	59
		Trained	2.40	3.40	71
Reybrouck et al.	1975		2.41	3.75	64
Sawka et al.	1982		2.27	3.31	69
Sawka et al.	1983		2.95	3.59	82
Sawka et al.	1984		2.46	3.44	72
Seals & Mullin	1982	Crew	3.36	3.85	87
		Gymnasts	2.82	3.27	86
		Swimmers	3.22	3.94	82
		Wrestlers	3.10	3.49	89
		Sedentary	2.08	3.14	66
Secher et al.	1974		3.62	4.27	85
Vander et al.	1984		1.60	2.02	79
Vokac et al.	1975		------	------	78
Vrijens et al.	1975	Paddlers	3.92	4.42	89
		Control	3.67	4.52	81
Mean..			2.56	3.49	73

AC is arm crank; CY is cycle; % is AC%CY value.

ses at a given submaximal oxygen uptake are similar for arm-crank and leg-cycle exercise (6,11,14,16,23,35,36). Although upper and lower body exercise elicit a similar cardiac output, the hemodynamics are quite different. According to Poiseuille's equation, flow or $\dot{Q}$ is the quotient of driving pressure (P) divided by resistance to flow (R). By transposition, R equals P divided by $\dot{Q}$; and P equals the product of $\dot{Q}$ and R. Examination of Figure 4 indicates that blood pressure is higher during arm-crank than leg-cycle exercise at a given oxygen uptake. If P is higher, then R would be proportionally higher to elicit the same $\dot{Q}$ during upper than lower body exercise. Numerous investigators report higher systolic (9,16,37-39), diastolic (9,16,36,37) and aortic (6) blood pressures during arm-crank than leg-cycle exercise. Similarly, total peripheral resistance is generally reported to be higher during arm-crank exercise (6,9), although Miles *et al.* (36) reported no difference between the exercise types.

Based on Poiseuille's equation, a greater total peripheral resistance must account for the elevated blood pressure response during arm-crank exercise, since $\dot{Q}$ is equal to that obtained during leg-cycle exercise. Vessel radius and blood viscosity are the primary factors influencing R, and both factors probably contribute to the greater total peripheral resistance during arm-crank exercise. A smaller skeletal muscle mass is available for arm-crank than leg-cycle exercise; therefore, the vascular cross-sectional area is smaller even during maximal vasodilation. The smaller vascular cross-sectional areas being perfused by the same $\dot{Q}$ will result in a greater R. Also, an increased sympathetic response to arm-crank exercise will result in the non-exercising muscles having a greater vasoconstrictor tone and contribute to an increased R (40). Several investigators (19,41) reported that plasma catecholamine concentrations are inversely related to the active skeletal muscle mass during submaximal exercise at a given oxygen uptake. Therefore, vasoconstrictor drive is expected to be greater during arm-crank than leg-cycle exercise.

Total peripheral resistance may also increase because of greater mechanical compression of the vasculature during upper body exercise. Exercise performed with a smaller skeletal muscle mass must develop a greater percentage of its maximal tension to produce a given power output (24,42). This could result in intramuscular tension that exceeds perfusion pressure and thereby effectively decrease the vascular cross-sectional area perfused (43,44). In cat fast- and slow-twitch muscles, intramuscular pressure exceeds perfusion pressure at tensions above 50% of maximal (43). Since 15%-20% of the quadriceps muscles' maximal isometric tension is used during maximal effort leg-cycle exercise (40), it seems reasonable that upper body exercise might generate sufficient intramuscular tension to mechanically increase peripheral resistance within the exercising arms.

Although cardiac output is the same during submaximal arm-crank and leg-cycle exercise, it is achieved by marked differences in heart rate and stroke volume relationships (see Figure 4). Investigators consistently report a higher heart rate and lower stroke volume at a given submaximal oxygen uptake during arm-crank than leg-cycle exercise (6,9,11,14,16). The elevated heart rate probably reflects a greater sympathetic stimulation during arm-crank exercise (1). This increased sympathetic stimulation should improve myocardial contractility; however, similar values of contractility indices are reported during both exercise types (36). An increased myocardial contractility may not be detected during arm-crank exercise because of differences in cardiac filling or pre-load. During upper body exercise, reduced skeletal muscle pump activity might transiently fail to facilitate venous return and decrease the ventricular end-diastolic volume (40). Therefore, a reduced pre-load will have the myocardium contracting on a less efficient portion of the ventricular function curve. Under such conditions, an increased sympathetic stimulation (positive inotropic effect) would be needed to obtain similar contractility values during upper body as compared to lower body exercise. This reduced pre-load hypothesis may partially explain why stroke volume does not increase (unlike lower body exercise) markedly with arm-crank exercise intensity (6,9,11,35,45). Additionally, the increased afterload reported for upper body exercise would impede stroke volume.

TEMPERATURE REGULATION - There is debate as to whether upper body exercise results in different equilibrium levels of core temperature than those elicited by lower body exercise at the same metabolic rate (46). Several (47-49) investigators indicated that arm-crank exercise elicited different thermoregulatory responses and core temperature values than lower body exercise. Examination of those early studies, however, suggests that small sample size, technical problems and inconsistent results make any conclusions tenuous.

As previously discussed, maximal effort arm-crank exercise elicits an oxygen uptake that is approximately 70% of that obtained during maximal effort leg-cycle exercise. It can be argued that if core temperature elevations during exercise are determined by relative intensity (with respect to the musculature employed) then arm-crank exercise would be expected to elicit a higher core temperature for a given metabolic rate than would lower body exercise. There is also a different muscular source of metabolic heat during upper than lower body exercise; as a result, temperatures measured within a given body region may be different relative to other body regions. Therefore, different sites of core temperature, such as esophageal or rectal, might provide disparate values. For example, blood warmed from leg muscular exercise might influence the rectal temperature to a greater degree than the esophageal temperature. The surface area-to-mass ratio of the arms is greater than that of the legs. A greater surface area-to-mass ratio for the exercising arms or limb could facilitate heat loss and alter thermoregulatory responses during exercise.

There are several neural factors that might modify thermoregulatory responses to upper body exercise. Robinson and colleagues (50) theorized that thermal receptors located in skeletal muscle and in associated veins may provide afferent inputs to the thermoregulatory centers in the brain. Likewise, mechanoreceptors and metaboreceptors within the skeletal muscles might provide afferent thermoregulatory information (48). Since upper body exercise employs a smaller skeletal muscle mass than lower body exercise, a greater metabolic rate and heat production per unit of muscle must occur in order to perform exercise at a given oxygen uptake. Thermoregulatory afferent information should therefore be somewhat quantitatively and qualitatively different using upper than lower body exercise. This logic has led several investigators to suggest that there is a different thermoregulatory setpoint (47,51) that results in higher equilibrium core temperature during upper than lower body exercise. Finally, plasma catecholamine concentrations are higher during submaximal exercise at a given oxygen uptake; therefore, vasoconstrictor drive would be expected to be greater during upper than lower body exercise (19,41).

The cardiovascular system may have greater difficulty in supporting the thermoregulatory system during upper than lower body exercise. For example, during upper body exercise the legs are inactive, so there is less skeletal muscle pump activity to facilitate venous return. If upper body exercise were performed in the heat, the large blood volume displaced in the cutaneous vasculature combined with minimal skeletal muscle pump activity could make it more difficult to maintain cardiac output. In addition, there is a greater total peripheral resistance and myocardial afterload during upper body exercise at a given oxygen uptake (52). Finally, there is a greater hemoconcentration at a given oxygen uptake during upper than lower body exercise (8,38). It is known that a reduced blood volume will result in less efficient thermoregulatory responses during leg exercise (53). As a result, the greater hemoconcentration might result in greater body heat storage during upper than lower body exercise.

Table 2 provides a summary of the investigations which have examined the core temperature and thermoregulatory responses to upper body exercise (25,47,48,54-57). During the following paragraphs, an attempt will be made to explain some of the discrepancies between these investigations.

In 1947, Asmussen and Nielsen (47) studied two subjects' core (rectal) temperature responses to arm-crank and leg-cycle exercise at the same metabolic rates. They found that after forty minutes of exercise, the elevation in rectal temperature was 0.28° C less during arm-crank than leg-cycle exercise. The authors noted that the subjects did not achieve steady-state rectal temperature levels by forty minutes, but were unable to exercise longer because of local fatigue. Asmussen and Nielsen (47) were concerned that rectal temperature values may have been spuriously high during leg-cycle exercise because of the warm venous blood returning from the leg muscles. They conducted additional experiments in which they measured stomach temperature. In agreement with their rectal temperature date, the stomach temperature values were consistently

TABLE 2. Comparison of thermoregulatory responses between upper and lower body exercise at a given metabolic rate.

Study	Year	n	Environ.	Ex. Mode	Core Temp.	Finding	Comment
1. Asmussen & Nielsen	1947	2	20-22°C db	AC vs CY	Rectal (20 cm)	$\downarrow T_{re}$	AC not steady-state
2. Nielsen	1968	2	27°C db 25-48% rh	AC vs CY	Rectal (12-27 cm) Esophageal	$\downarrow T_{re}$ $= T_{es}$ $= \dot{M}_{sw}$ $= K_{sk}$	
3. Davies et al.	1971	2	19°C db 75% rh	AC vs CY & TM	Tympanic	$= T_{ty}$ $= \dot{M}_{sw}$ $= K_{sk}$	
4. Sawka et al.	1984	9	24°C db 20% rh	AC vs CY	Rectal (10 cm)	$= T_{re}$ $= \dot{M}_{sw}$	$T_{re} = T_{es}$ for AC
5. Sawka et al.	1984	4	18 & 35°C db 78 & 28% rh	AC vs CY	Esophageal	$= T_{es}$	Avenues of Heat Loss Differ
6. Young et al.	1987	6	38°C db 30% rh	AC vs CY	Rectal (10 cm)	$= T_{re}$	Microclimate Cooling
7. Pivarnik et al.	1988	8	22 & 33°C db 75 & 57% rh	AC vs CY	Rectal (10 cm)	$= T_{re}$	

db is dry bulb temperature; rh is relative humidity; AC is arm-crank; CY is cycle; T_{re}, T_{es} and T_{ty} are rectal, esophageal and tympanic temperatures, respectively; $\dot{M}_{sw}$ is total body sweating rate; K_{sk} is thermal conductance; $\downarrow$ is lower than CY; = is equal to cycle lower during arm-crank than leg-cycle ergometer exercise. Since both indices of core temperature were lower during arm-crank exercise, they concluded that upper body exercise results in a reduced thermoregulatory set-point than lower body exercise.

In 1968, Nielsen (48) examined two subjects' core (rectal and esophageal) temperature responses to arm-crank and leg-cycle exercise over a range of metabolic rates. Rectal temperature values (mean of values obtained at four depths) were found to be lower (0.20 to 0.40° C) during arm-crank than leg-cycle exercise. In contrast, the esophageal temperature values were not different between the two exercise types. Figure 5 presents the steady-state esophageal temperature responses in relation to absolute metabolic rate (watts) during arm-crank and leg-cycle exercise (48). In addition, the subjects' sweating rates and thermal conductances were not different between the two modes of exercise. She concluded that thermoregulatory control during exercise was not modified by the muscle groups employed.

Subsequent investigators have found no difference in either tympanic (54) or esophageal (53) temperatures between upper and lower body exercise performed at a given metabolic rate. These observations confirmed Nielsen's thesis that exercise type does not modify the thermoregulatory control (48). Nielsen's data, however, raised the possibility that rectal temperature might provide systematically low values for upper body exercise. This possibility was consistent with some indirect observations made by Nielsen and Nielsen in 1962 (49). These authors (49) found that during leg exercise esophageal temperature was lower that rectal temperature, but that during arm exercise esophageal temperature was equal to rectal temperature values. The investigators measured rectal temperature at four depths (12, 17, 22 and 27 cm) during either leg-cycle or arm-crank exercise. They found that during leg-cycle exercise the measurement depth did not influence rectal temperature values, but that during arm-crank exercise the deeper rectal measurements (22 and 27 cm)) tended to produce lower temperature values. Therefore, rectal temperature measurements at a depth of 20 cm or greater may result in spuriously low core temperature estimates during upper body exercise.

Several investigators (55,56,57) have compared rectal temperature (10 cm) responses between upper and lower body exercise. Sawka *et al.* (55) measured rectal temperature responses during arm crank and leg-cycle exercise in nine subjects at the same metabolic rate as well as relative intensity (% of peak $\dot{V}O_2$ for specific modes of exercise). During the experiments with matched metabolic rates, the subjects' steady state rectal temperatures and total body sweating rates were the same for both exercise types. On the other hand, during the experiments with matched relative intensities, the subjects' rectal temperatures and total body sweating rates were lower during arm-crank than leg-cycle exercise. Pivarnik and colleagues (57) measured eight subjects' rectal temperature responses to arm-crank and leg-cycle exercise at the same metabolic rate in both a 22°C and 33°C environment. They found that the rectal temperature responses were the same for both modes of exercise. Young *et al.* (56) found that subjects had the same rectal temperature responses for both arm-crank and leg-cycle exercise in a 38°C environment while wearing a microclimate cooling system over the torso. It seems clear that rectal temperatures measured at 10 cm are the same for both upper and lower body exercise.

The question remains why the deep (>20 cm) rectal temperature measurements are systematically lower during upper body exercise? For lower body exercise, the rectal temperature is not influenced by depth (greater than 5 cm), and these lower body exercise values are equivocal to shallower (10 cm) rectal temperature measurements during upper body exercise at a given metabolic rate. The problem seems to be that deep rectal areas are not warmed as much during upper body exercise (48). For an average adult, the rectum and anal canal length is approximately 12-16 cm (58); therefore, the deeper (20-27 cm) measurements were obtained well within the sigmoid colon. The rectum receives its blood supply from the inferior mesenteric, as well as branches of the iliac and internal pudendal arteries. The sigmoid colon receives its blood supply only from the inferior mesenteric artery. During upper body exercise, the greater sympathetic output should cause a greater constriction of splanchnic beds and result in reduced blood supply from the mesenteric artery. Perhaps this compensatory vasoregulation reduces the supply of warm blood more to the sigmoid colon than the rectum. Also, since the mucous membrane in the rectum is thicker and more vascular than in the colon (59); therefore, it should receive a richer supply of warm blood during exercise. Finally, it is possible that the sigmoid colon area could be influenced more than the rectum by warmed venous blood from the legs during lower body exercise (48,60); however, there is no anatomical evidence to support this notion.

The preceding studies all examined core temperature responses but did not attempt to quantitate the regional differences in evaporative and dry heat exchange between upper and lower body exercise. Sawka and colleagues (25) examined the relative contribution of local evaporative, radiative and convective heat exchange between arm-crank and cycle exercise at the same metabolic rate. These experiments were conducted in an 18°C/78% relative humidity (rh) environment, which facilitated dry heat exchange, and in a 35°C/28% rh environment, which facilitated evaporative heat loss. In both environments, esophageal temperatures were not different between exercise types. Figure 6 illustrates the torso net radiative energy flux values during exercise in the two environments. In each environment, these values increased over time for both modes of exercise, with arm-crank exercise eliciting greater values than cycle exercise. Although this was a new finding, it was not unexpected. During upper body exercise, the muscles of the back torso areas (i.e., latissimus dorsi, trapezius, infraspinatus) are employed to a greater extent than during lower body exercise. Therefore, these skeletal muscle groups would generate and release a greater metabolic heat that would be conducted directly through the surrounding tissues to the overlying skin (61).

These investigators found that torso and arm evaporative heat loss as well as arm dry heat exchange were not different between exercise types in each environment (25). Leg dry heat loss was greater during leg-cycle than. arm-crank exercise in the 18°C environment; likewise, leg evaporative heat loss was greater during cycle than arm-crank exercise in the 35°C environment. These data indicate that to compensate for greater torso dry heat loss during upper body exercise, lower body exercise elicits additional dry or evaporative heat loss from the legs. The avenue for this compensatory heat loss depends upon the differential heat transfer coefficients which influence tissue conductivity and mass transfer.

Sawka and colleagues (25) attempted to determine if mode of exercise altered the control of thermoregulatory sweating. They found that the sweating threshold and slope were not significantly different between arm-crank and leg-cycle exercise. Therefore, local sweating rate (back) appears to be independent of the active skeletal muscle mass and wholly dependent on the thermal drive. Previously, Tam *et al.* (51) suggested that arm-crank exercise might elicit a non-thermal drive to sweating through increased sympathetic activation. Their experiments, however, were performed on only two subjects (one was a spinal cord injured subject) and only during arm-crank exercise.

The previous studies also indicate that differences in the surface area-to-mass ratio between the exercising arms and legs have nominal thermoregulatory effects in air. Water, however, has a heat conduction approximately 25 times greater than still air. It seems that during cool-water immersion, exercise performed with the arms (relatively large surface area-to-mass ratio) and with the legs (relatively small surface area-to-mass ratio) would be expected to have different heat exchanges. Toner *et al.* (62) examined the thermal responses of subjects performing 45 minutes of arm-crank or leg-cycle exercise while immersed in stirred water at 20, 26 and 33°C. Metabolic rate was not different between exercise types at each water temperature. Rectal temperatures (10 cm) were lower for arm-crank than leg-cycle exercise. These lower core temperatures were supported by both mean weighted skin temperature and mean weighted heat flow values; both of which were greater during arm-crank than leg-cycle exercise at each water temperature. These data indicate that individuals are at a thermoregulatory disadvantage (for hypothermia) when performing upper body exercise in environments with a high convective heat transfer coefficient.

AEROBIC CROSS-TRAINING - Peak oxygen uptake levels are dependent on central (cardiac output) and peripheral (ability of muscle cells to extract and utilize oxygen) components (63). Aerobic training adaptations pertaining to the enhanced myocardial contractility and increased cardiac hypertrophy would occur regardless of whether the upper or lower body muscle groups were trained. Aerobic training adaptation pertaining to the peripheral components such as increased muscular capillarization and increased vascular conductance as well as increased oxidative capacity would occur primarily in only the trained skeletal muscle groups. As a result, it would be expected that central component adaptations would provide some aerobic cross-training between the upper and lower body, but that the lack of peripheral component adaptations in the untrained limbs would limit the magnitude of aerobic cross-training between the upper and lower body.

Table 3 presents a compilation of data from studies that examined aerobic cross-training between the upper body and lower body muscle groups (45,64-68). Four studies (64-67) are presented that aerobically trained the legs and measured the changes in peak oxygen uptake for the upper body muscle groups. Note that leg training increased peak oxygen uptake by a mean of 5% and 16% for upper and lower body exercise, respectively. Five studies (45,65-68) are presented that aerobically trained the arms and measured the changes in peak oxygen uptake for the lower body muscle groups. Note that arm training increased peak oxygen uptake by a mean of 22% and 5% for upper and lower body exercise, respectively. Together these findings indicate that only minor aerobic cross-training effects between occur between the arms and legs. Clearly, if space mission-related tasks continue to require substantial amounts of upper body exercise, then the exercise countermeasure programs should specifically train those muscle groups.

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TABLE 3. Review of studies examining aerobic cross-training between the upper and lower body muscle groups.

Study	Year	TRAINING PROGRAM Mode	Session (min)	Intensity (HR)	Frequency (d/wk)	Duration (wks)	MAXIMAL TESTS Mode	Peak VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) pre-	post-	%Δ
Leg Training										
Clausen et al.	1973	CY	35	>170 bpm	5	5	CY	46.4	54.3	17
							AC	36.5	40.2	10
Lewis et al.	1980	CY	30	75-80% max	4	11	CY	39.2	45.1	15
							AC	25.0	27.3	9
Ridge et al.	1978	CY	30	85-90% max	4	4	KY	30.7	31.0	1
Stamford et al.	1978	CY	15	≥180 bpm	3	10	CY	42.1	48.4	15
							AC	37.0	37.0	0
						Mean	Legs			16
							Arms			5
Arm Training										
Lewis et al.	1980	AC	30	75-80% max	4	11	CY	37.2	41.7	12
							AC	22.8	30.8	35
Loftin et al.	1988	AC	32	80-95% max	4	5	CY	---	---	7
							AC	---	---	32
Magel et al.	1978	AC	20	≥85% max	3	10	TM	56.4	57.2	1
							AC	33.9	39.3	16
Ridge et al.	1978	KY	30	85-90% max	4	4	KY	31.9	34.6	8
Stamford et al.	1978	AC	10	≥180 bpm	3	10	CY	42.7	43.1	1
							AC	36.9	43.9	19
						Mean	Legs			5
							Arms			22

AC is arm crank; CY is cycle; KY is kayak ergometer; TM is treadmill.

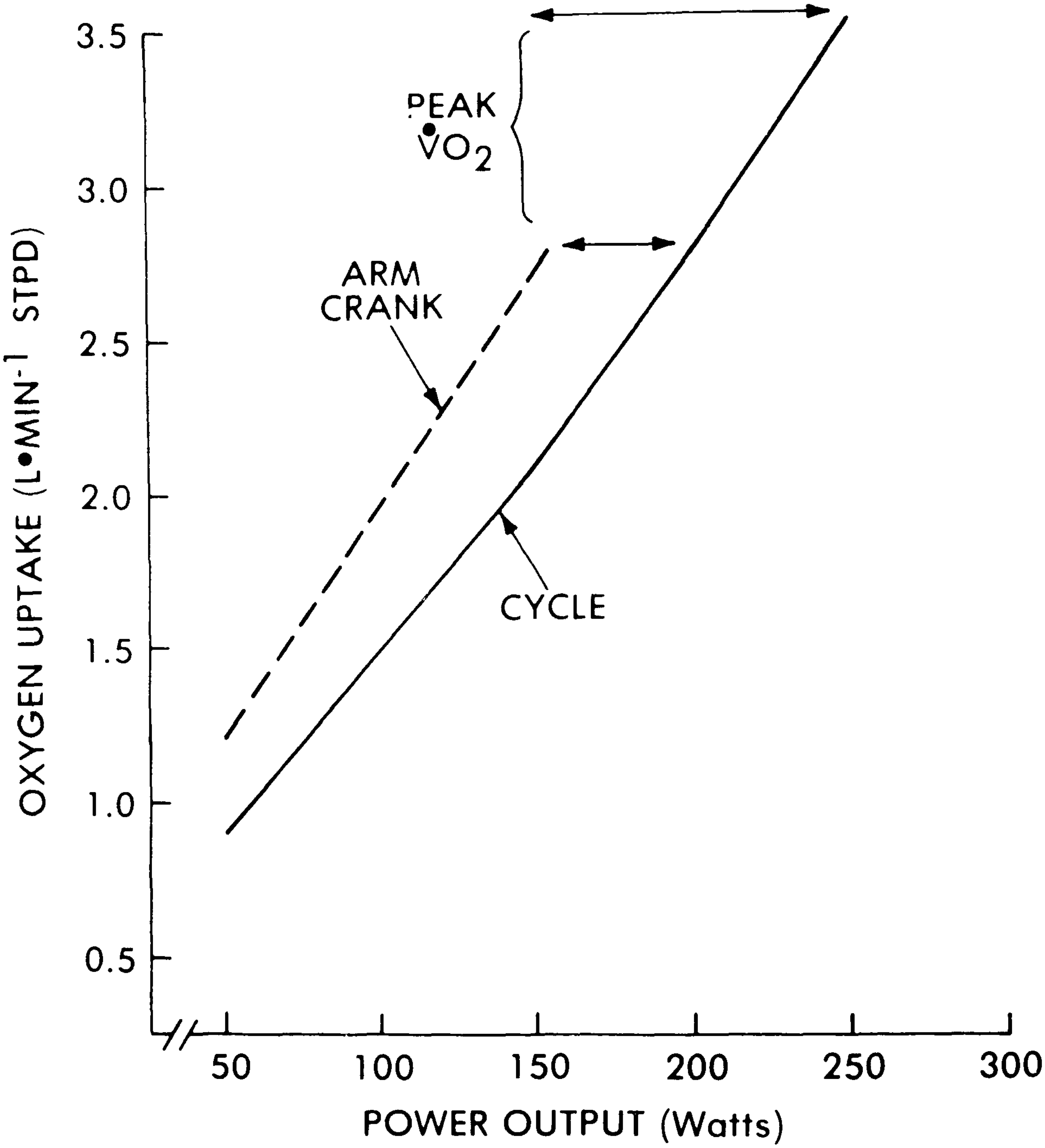

Figure 1. Oxygen uptake responses to arm-crank and leg-cycle ergometer exercise (5).

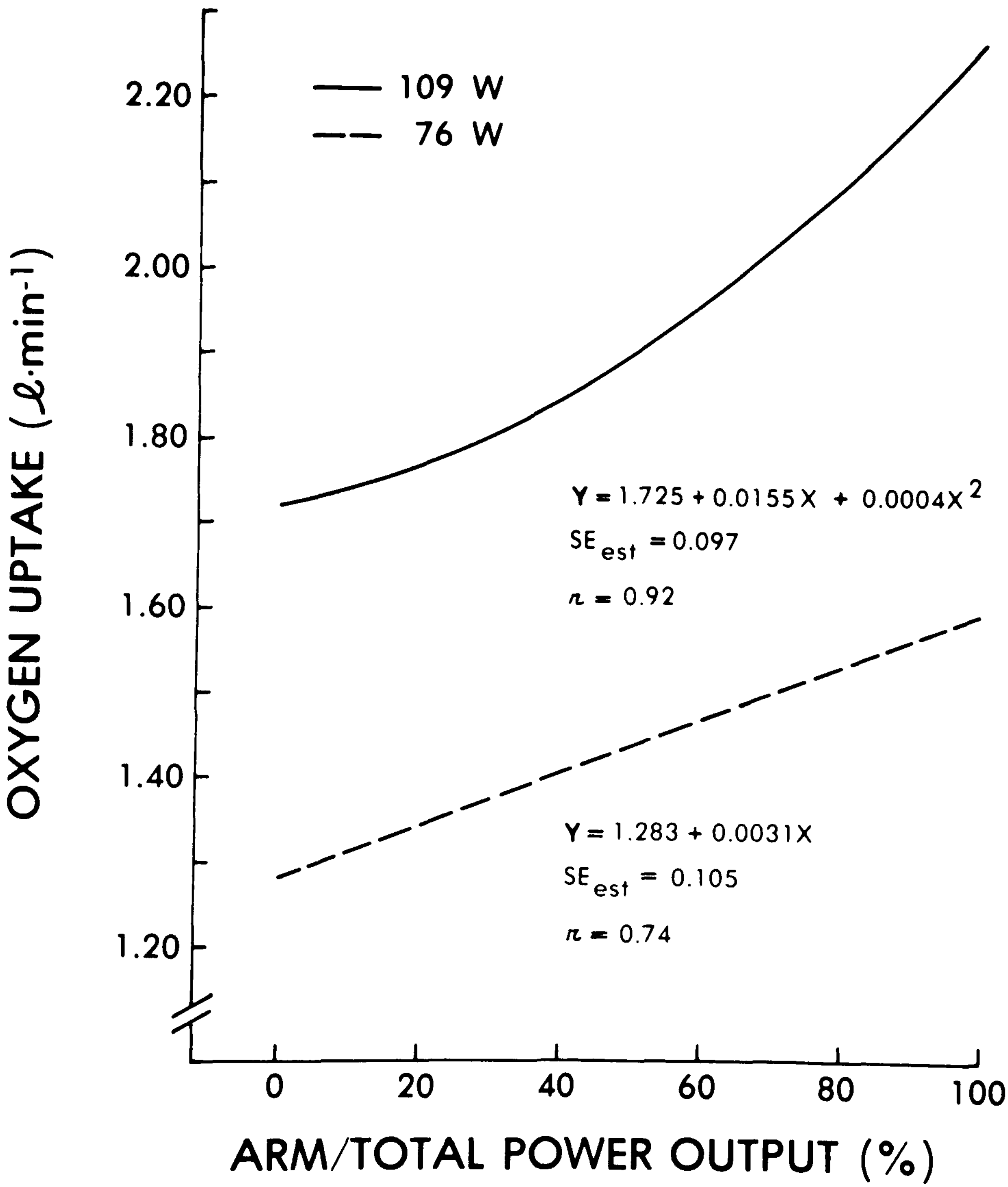

Figure 2. Regression lines of oxygen uptake values for arm and leg exercise performed at varied arm/total power output (%) at 74 and 106 watts (10).

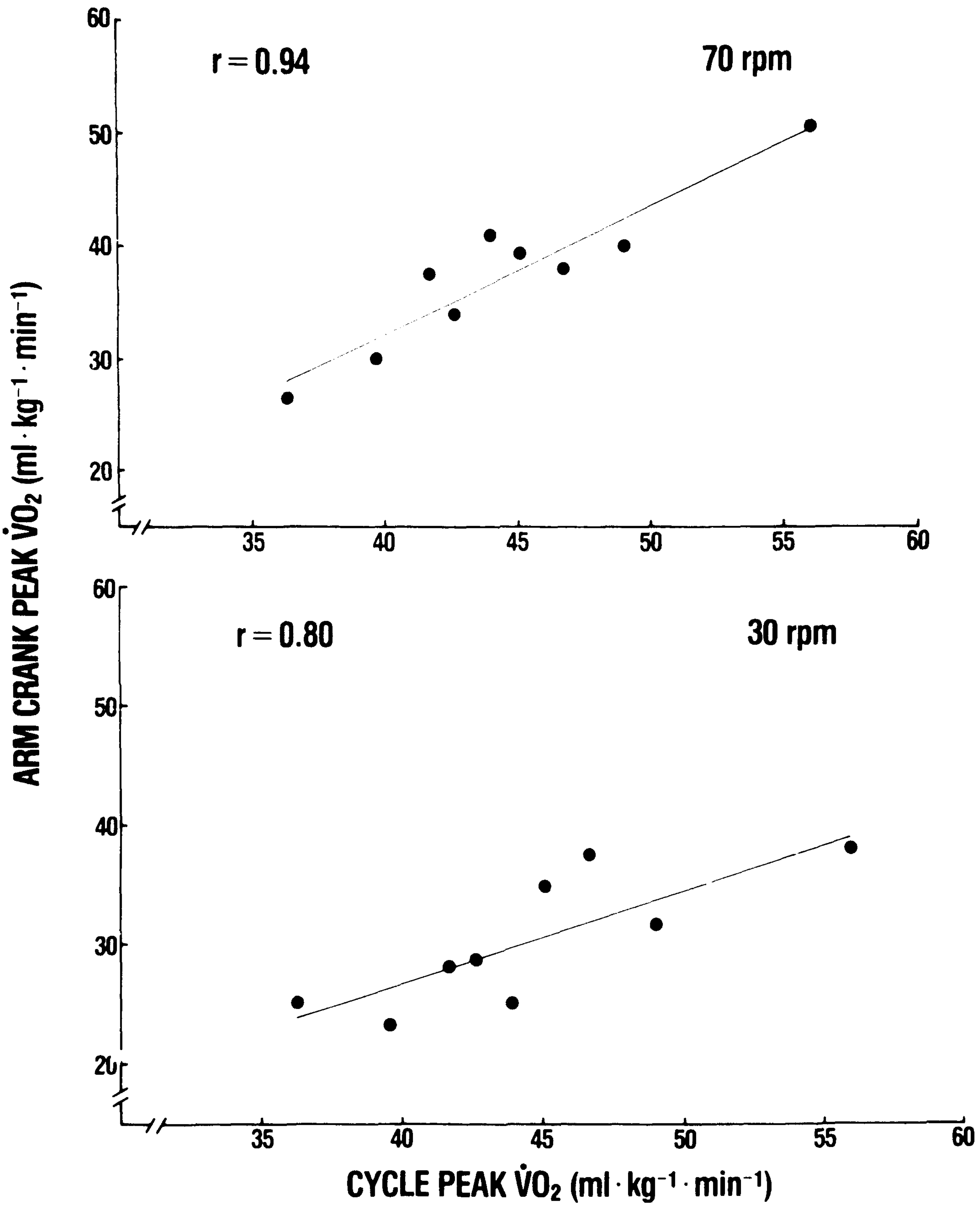

Figure 3. Comparison of peak oxygen uptake values obtained during arm-crank (at 30 and 70 rpm) and leg-cycle ergometer exercise (30).

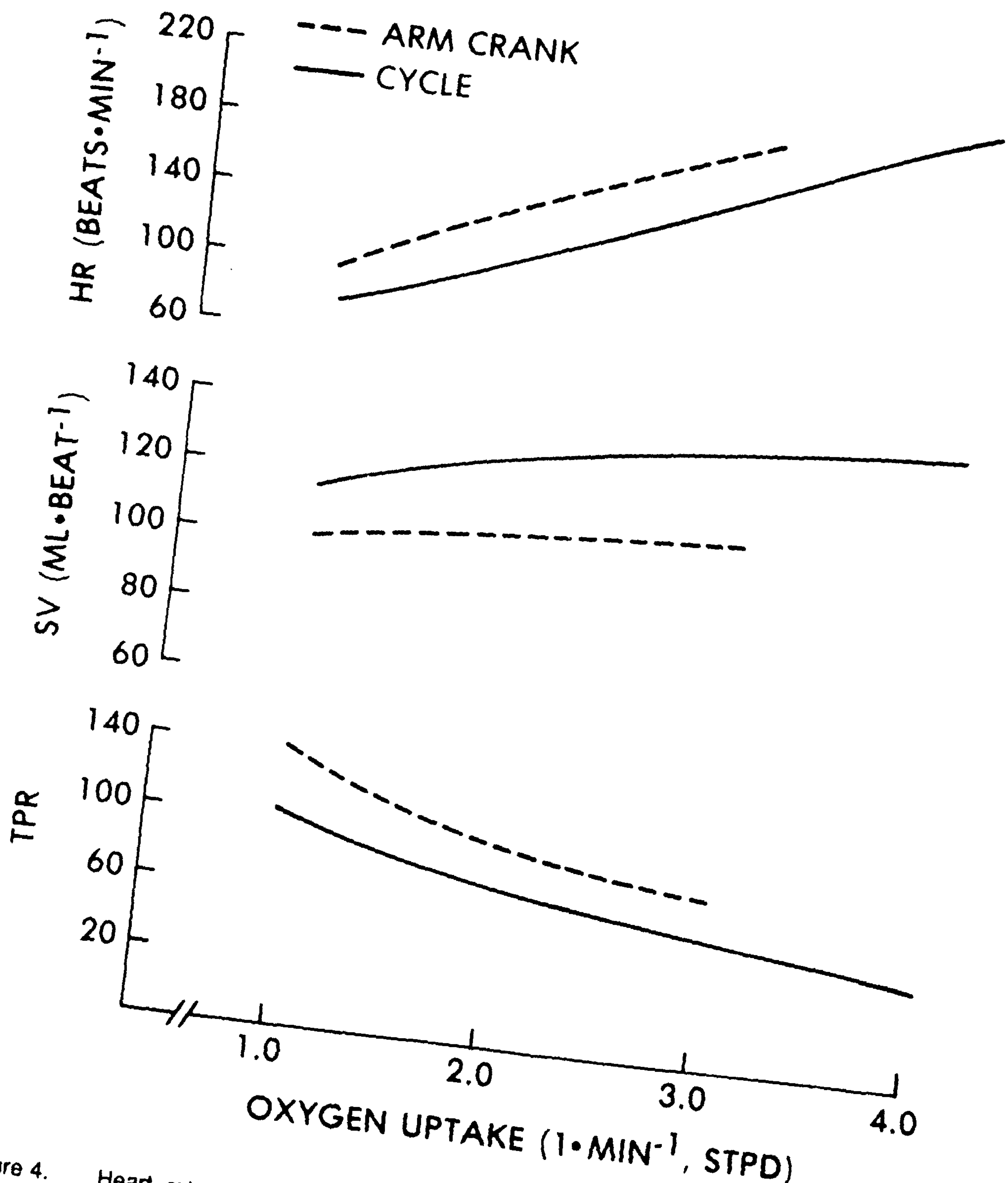

Figure 4. Heart rate (HR), stroke volume (SV) and total peripheral resistance (TPR) responses to arm-crank and leg-cycle ergometer exercise.

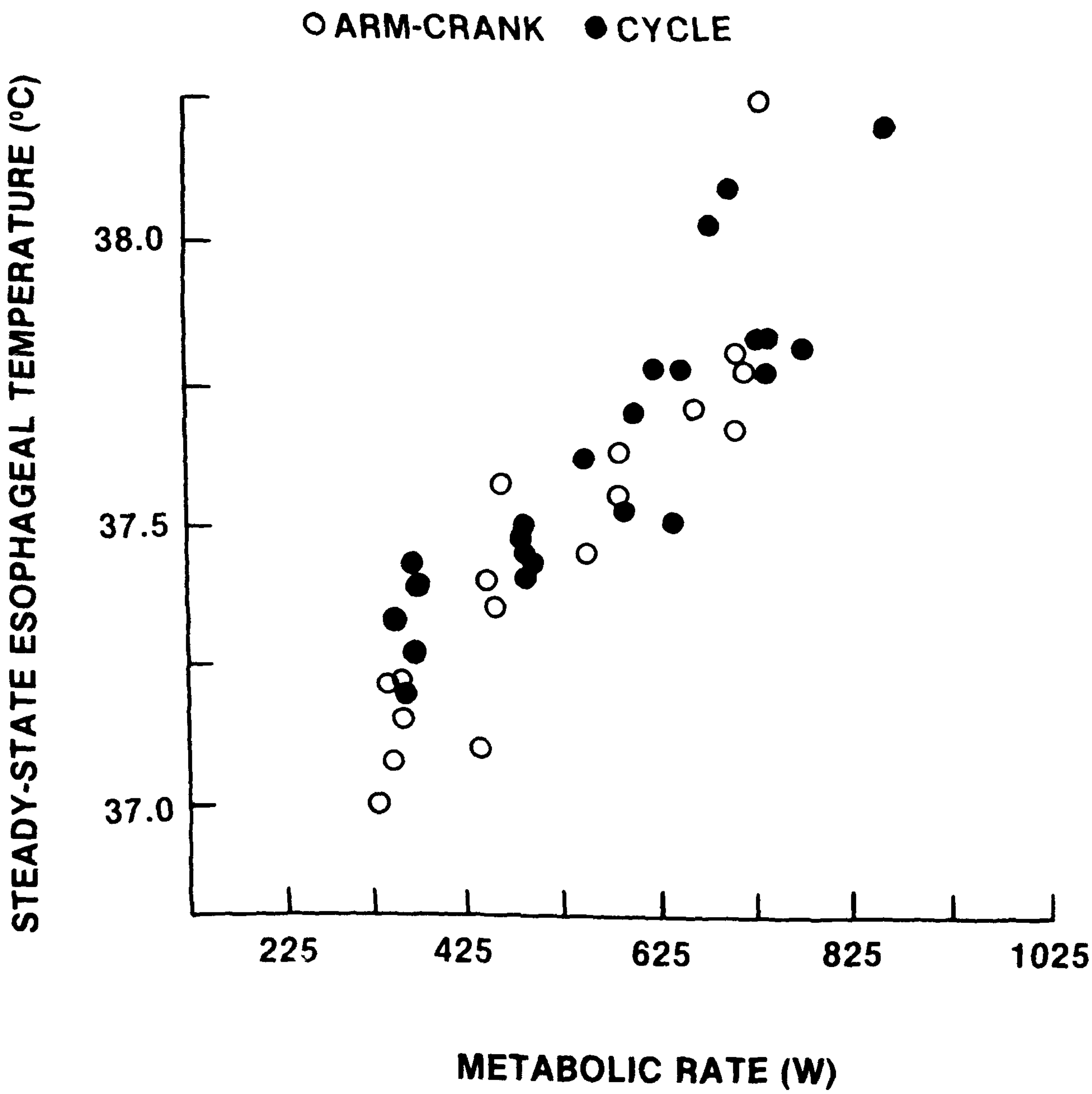

Figure 5. Relationship of steady-state esophageal temperature responses to arm-crank and cycle ergometer exercise (48).

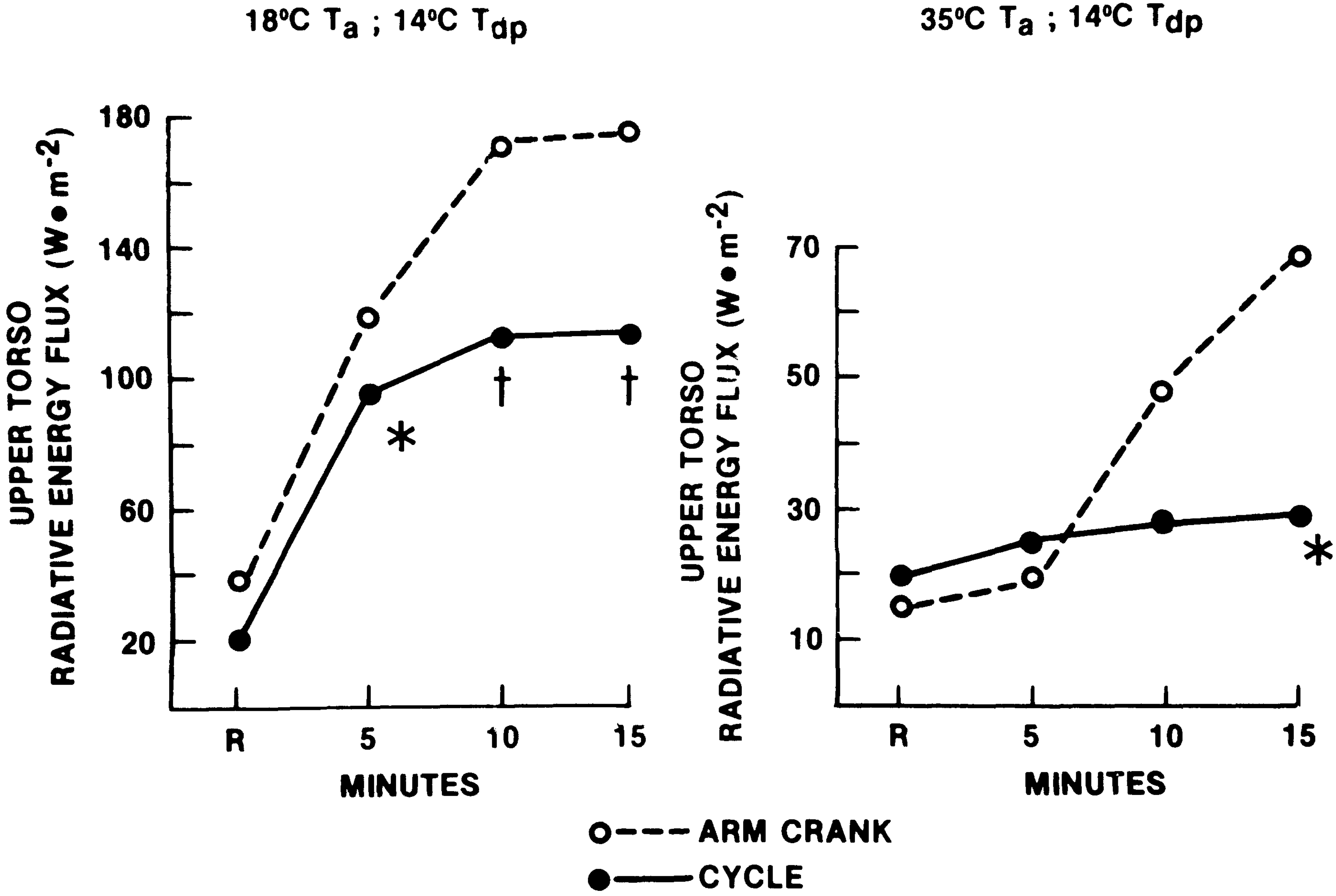

Figure 6. Torso radiative energy flex values, measured by a net radiometer, during arm-crank and leg-cycle exercise at a given metabolic rate (25).