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THE BIOENERGETICS OF POWER PRODUCTION IN COMBINED ARM-LEG CRANK SYSTEMS

by Richard Powell* and Tracey Robinson†

SUMMARY

Tests on young adults of average athletic ability showed that maximum power output could be increased by over thirty percent using combined arm-and-leg cranking compared with leg cranking alone. Furthermore, the efficiency of lower-power steady-state power production was found to be higher for arm-and-leg cranking. Some differences between male and female subjects in the contribution from the arms was found.

INTRODUCTION

A considerable volume of research has been generated over the years which has investigated the optimal speeds and expected work outputs for leg, arm, and rowing ergometry. When combined arm and leg ergometry has been studied in the past, findings suggest a greater *maximum* work output is possible (11-20% higher) when compared to leg ergometry along (Reybronck et al. 1975; Nagel et al. 1984). However, the efficiency of performing submaximal work using arm, leg, or combined arm-leg production systems is unclear.

Because sport and recreational cycling is predominantly a steady-state effort, the possibility of capturing greater muscle power through an arm-and-leg-powered mechanical drive system at an equivalent steady-state cardiac cost (heart-rate response) could translate into a more efficient human-powered cycling device. We were interested in determining if it is bioenergetically feasible to expect improved work output using arms and legs at equivalent submaximal physiological efforts when compared to work production using arms or legs alone.

BACKGROUND

It's a well-known fact that maximum oxygen uptake (VO_2 max) is about 10% higher if a person is tested on a treadmill rather than on a bicycle ergometer. The reason for this occurrence is explained as being due to a greater total active muscle mass involvement in running compared to stationary bicycling; hence, VO_2 max is higher in running even though maximum heart rates achieved (cardiac cost) are the same in both types of all-out tests.

Because conventional bicycling uses only the legs for power production it seemed that using arms and legs together to produce steady-state work could result in a higher VO_2 at any given submaximal cardiac cost, and a larger potential work output as well compared to using legs alone. While it is clear that maximum work output is better in combined arm-leg systems when compared to legs alone, such maximum efforts are largely anaerobic and demonstrate little with regard to steady-state efforts.

The intention of our research was to compare the physiological cost of producing work under three types of conditions: arm ergometry, leg ergometry, and combined arm-and-leg ergometry. Two immediate questions to be answered were as follows:

1. *is combined arm-leg ergometry under various levels of steady-state work more physiologically efficient compared to arm or leg ergometry alone?*
2. *under maximum-power production conditions, how do the three ergometry methods compare?*

APPROACH

A structural housing was developed in which subjects sat in a seat 500 mm. high with an arm-crank ergometer centered in front of them. The axis of the arm crank ergometer was 1220 mm. high and positioned to allow complete arm extension at the farthest point of the cranking cycle. A second leg-crank ergometer was centered in front of each subject with its axis 280 mm. high and positioned to allow complete leg extension at the farthest point of the cranking cycle. Both ergometers were electrically-braked systems.

Thirty-two subjects (17 males and 15 females; mean age - 25.3 years) were tested over three separate sessions at the same time one week apart. All three sessions were used to test progressive leg- and/or arm-cranking performance, with the order of testing (arms only, legs only, or arms and legs) randomly split among the subjects.

During all three exercise tests, oxygen consumption (VO_2) and carbon-dioxide production (VCO_2) were calculated every 15 seconds based on minute volume of expired air (V_E), true O_2 and CO_2 concentrations. In addition, heart rate (HR) was recorded every 30 seconds.

The exercise protocols were in two-minute step increments. The arm cranking started at 25 watts output and increased 25 watts following each two-minute step. This protocol, while not adjusted to body weight, conformed closely to similar protocols followed elsewhere (Williams et al. 1983). The leg cranking started at 33.3 watts output and increased 33.3 watts following each two-minute step; the approach conformed to protocols used elsewhere (Niemela, 1980). A two-minute leg-crank warm-up work stage at 33.3 watts preceded the combined arm-leg treatment. The combined arm-leg cranking started at 25 and 33.3 watts respectively (total watt ouput = 58.3) with 25 and 33.3 watt increments, respectively, following every two minutes (total watt increments = 58.3). All cranking was performed at 50 RPM and continued until fatigue.

Because of the expected differences among subjects in work-production capability, linear-regression equations were computed for each individual, plotting VO_2, V_E, and HR each against cumulative workload in watts; group equations were subsequently derived from individual ones. Cumulative workload was calculated by determining the workload in watts for each successive minute completed, plus the fraction (to the last completed 15 seconds) of the final minute of work. A 7:48 maximum work time for arms, for example, would yield a maximum cumulative workload of 475 watts (25 + 25 + 50 + 50 + 75 + 75+ 100 + [0.75 (100)]. In this way, every 15-second measure of VO_2 and V_E and every 30-second measure of HR could be plotted against a cumulative work output to that point, and individual patterns of continuing physiological adaptation to discrete workload steps could be derived for each of the three exercise treatments.

FINDINGS

After calculating linear-regression equations (the best "fit" for the data) for each individual, we then grouped the equations by sex. We examined the

*Associate Professor, †graduate student, Department of Physical Education and Recreation, New Mexico State University

slopes of the equations as an index of relative physiological cost of the exercise treatments in producing power output; the larger or more vertical the slope, the more taxing was the exercise treatment relative to the physiological variable examined. The ventilation data when plotted against cumulative workload (Figure 1) showed no statistically significant changes in the slopes of the equations for women and a significant difference in the men for arm cranking. Women, in particular, probably find arm cranking more taxing than legwork due to a relatively weaker upper body musculature compared to men; they stopped sooner than the men due to rapid local muscle fatigue long before breathing became labored at the higher workloads encountered by men. There appeared a tendency for combined arm-leg work to yield slightly more work output for a given ventilation, but it was not significant.

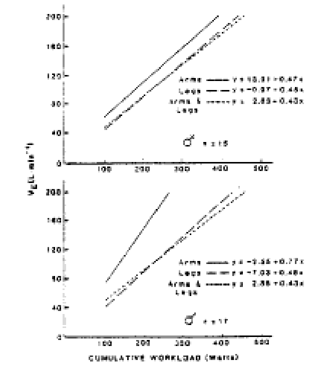

Figure 1 Ventilatory Response to Three Conditions of Power Production

The oxygen-consumption data when plotted against cumulative workload (Figure 2) showed no statistically significant changes in the slopes of the equations for the men or women. This seems reasonable because oxygen consumption should relate directly to power produced. The tendency again for arm cranking to appear less efficient probably reflects the more anaerobic nature of such work by itself.

What was most revealing was the heart-rate data plotted against power outputs (Figure 3). In both the men's and women's grouped data, there was significantly more power output at heart rates beyond 140 beats/minute using combined arm-leg cranking. In short, even at a given steady-state cardiac cost,

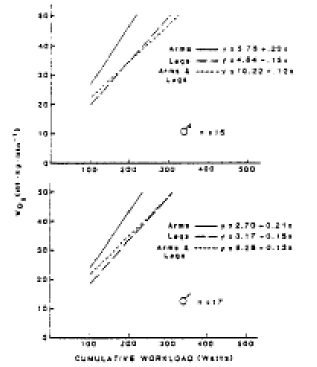

Figure 2 Oxygen Consumption Response to Three Conditions of Power Production

power output is highest when using arms and legs together; further, it appears that this advantage increases as one approaches fatigue.

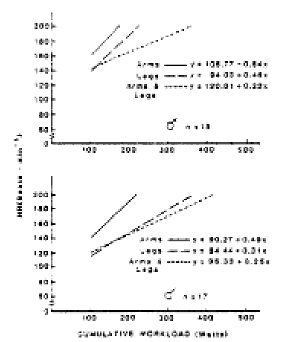

Figure 3 Heart Rate Response to Three Conditions of Power Production

When we looked at the "maximum" data of all subjects combined (the maximum cumulative powerloads reached at fatigue and the physiological data corresponding to that failure point), the advantage of combined arm-leg cranking over legs only was dramatic (Table 1). The maximum cumulative power output was approximately 31% greater using arms and legs compared to legs alone. To achieve that difference cost approximately 15% more in oxygen consumption. One could roughly assume that the 31% advantage in all-out power production was partly due to greater aerobic metabolism (15/31 = 48%) and partly due to anaerobic metabolism (17/31 = 52%). Arm cranking can clearly be seen to be an inferior method of power production by itself, and, at least at maximum effort, is probably limited by local muscle fatigue rather than aerobic support systems (given that an average maximum heart rate achieved by our subjects was only 160).

CONCLUSIONS

Based upon the foregoing research, we concluded the following.

1. Combined arm-and-leg power production provides a decided advantage over leg cranking alone, especially in all-out work. About half of this advantage seems to be due to increased aerobic metabolism and half due to anaerobic work.
2. The efficiency of steady-state power production can be enhanced by combined arm and leg work. We cannot say decisively by how much at this time, because the power advantage is apparently influenced by how intense the steady-state work is, and by the relative contribution of arm power to leg power.
3. The advantage of any arm-leg powered machine is largely going to be offset by the possibility of additional weight/frictional resistance of a drive-train system that would enable all limbs to generate power.

POSTCRIPT

While we are not alone in our endeavors to develop an efficient and *practical* arm-leg powered cycle, the obstacles we have experienced and observed in other prototypes revolve around

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TABLE 1

MAXIMUM POWER OUTPUT AND CORRESPONDING PHYSIOLOGICAL RESPONSES TO THREE TYPES OF HUMAN POWER-PRODUCTION SYSTEMS

EXERCISE SYSTEM (Rotary Cranking)	MAX. H.R. -1 (Beats min)	VO_2 max (ml kg min)	VE_{max} -1 (L min)	MAX CUMULATIVE Power Watts
Arms	160.06[a]	23.73[a]	76.98[a]	499.09[a]
Legs	169.75[b]	33.75[b]	97.85[b]	1021.86[b]
Arms & Legs	170.03[b]	38.77[c]	103.33[b]	1339.55[c]

Note: Components with different letters are significantly different ($p<0.05$) when compared columnwise.

ARM-LEG POWER

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devising acceptable steering systems that are comfortable, compatible with more conventional rear-wheel drive/transmission systems, and yet elegant in simplicity.

In pedalling some of our arm-leg powered prototype cycles, I've noticed (more subjectively) that there is some unknown "equation" that would make combined arm-and-leg powered cycles more efficient. I find that periodically resting my arms while still pedalling with legs, "feels" the best. On the theoretical side of this issue, the next step we are following is to look at the bioenergetics of producing power under varying contributions of arm and leg efforts; the purpose here would be to determine what kind or length of rest periods might be optimum for the arms under sustained arm-leg pedalling.

Physiologically speaking, the arm musculature is not designed for aerobic (endurance) work. There seems to be found naturally a disproportionate number of fast-twitch fiber types (anaerobic) in the arms compared to the more aerobic slow-twitch fibers. The results we reported were based on average young adults. My suspicion is that specific endurance training in the arms (witness wheelchair sports) would enhance still further the advantage already demonstrated in combined arm-leg power production.

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AUTHORS

Richard Powell and Tracey Robinson
Dept of Physical Education & Recreation
New Mexico State University
Box 3M
Las Cruces, NM 88003 USA
505-646-2215