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Effects of dynamic upper-body exercise on lower-limb isometric endurance

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Abstract

Following preliminary indications that in some individuals arm exercise enhanced rather than reduced simultaneous leg endurance, ten young men and women performed three forms of intermittent work to volitional exhaustion, under duty cycles of 45 s work, 15 s rest. The protocols were as follows: (A) knee extensions at 30% maximum voluntary contraction (MVC); (B) 30% MVC knee extensions combined with arm cranking at 130% of their own lactate threshold; (C) combined 30% MVC knee extensions and arm cranking at 20% of their own lactate threshold. Heart rate, oxygen uptake ($\dot{V}O_2$), and blood lactate concentration were among the variables recorded throughout. All physiological indicators of demand were substantially higher in protocol B than in protocols A or C [heart rate: (A) 154 beats \cdot min⁻¹, (B) 171 beats \cdot min⁻¹, (C) 150 beats \cdot min⁻¹; $\dot{V}O_2$: (A) 11.9 ml \cdot kg⁻¹ \cdot min⁻¹, (B) 21.7 ml \cdot kg⁻¹ \cdot min⁻¹, (C) 14.2 ml \cdot kg⁻¹ \cdot min⁻¹; blood lactate concentration: (A) 3.3 mmol \cdot l⁻¹, (B) 5.1 mmol \cdot l⁻¹, (C) 2.8 mmol \cdot l⁻¹], yet there were no significant differences ($P > 0.05$) in the endurance times between the three conditions [(A) 11.43 min, (B) 11.1 min, (C) 10.57 min] and seven participants endured longest in protocol B. Results from protocol (C) cast doubt on explanations in terms of psychological distraction. We suggest that lactic acid produced by the arms is shuttled to the legs and acts there either as a supplementary fuel source or as an antagonist to the depressing effects of increased potassium concentration.

Keywords: *Arm cranking, dinghy sailing, dynamic exercise, endurance, isometric exercise, knee extension*

Introduction

As widely acknowledged in this issue and elsewhere (reviews Blackburn, 1994; Spurway, 1999, 2007), fresh-breeze dinghy sailing combines sustained load on the lower-body muscles, especially the quadriceps (as the sailor “hikes” to counteract the capsizing force of the wind), and dynamic upper-body exercise (trimming the boat, steering, and controlling the sail). The quadriceps force required to hold the body in a full hiking posture is at least 30% maximum voluntary contraction (MVC) (Vogiatzis, Spurway, Wilson, & Boreham, 1995), a load that substantially impedes blood flow (Hallen, Osada, Verburg, & Spurway, 2001; Spurway, 2007). Consonant with this, it is chiefly the pain of fatigue in the quadriceps, perhaps supplemented by that in the abdominals and/or anterior tibial muscles, but not those in the upper body, which limits endurance.

Considering the effect of upper-body activity upon this lower-body performance limit, the simple physiological prediction must surely be that endurance

would be reduced – for example, by competition for oxygenated blood and by the increased concentrations of metabolic waste products in the circulation. Nevertheless, coaches and performers consistently maintain that endurance during real sailing is longer, not shorter, than in laboratory studies of the lower-body effort alone or in equivalent dry-land training exercises. Mechanisms commonly suggested include a reduction of quadriceps load by the sail’s force on the “sheeting” (sail-controlling) arm, and/or psychological distraction from the leg discomfort. Both these suggestions are almost certainly pertinent.

However, in recent years certain observations in our laboratory have indicated that there may be an additional, and arguably more basic, effect. The experimental conditions studied involved the addition of arm cranking to isometric knee extension. A number of participants endured longer, not shorter, in the combined exercise than when performing the knee extension alone – yet the arm cranking, unlike sheeting, provides no net horizontal force on the upper torso, and any psychological distraction it

offers must be much smaller than the excitement of real sailing.

The new results described here represent a structured investigation of this phenomenon. They are preceded by a fuller outline of the earlier (“preliminary”) findings, following descriptions of the methods used.

Methods

Participants

The first preliminary series (J. G. Gallacher *et al.*, unpublished) involved only three young adult males, all non-sailors. The second preliminary series (S. Collins *et al.*, unpublished) was undertaken first by the senior author (then aged 65 but sailing frequently), then by 11 young adults (six females, five males), about half of whom were regular university-team dinghy sailors, with the remainder being active in other sports. For the new experiments, reported in full here, five healthy males and five healthy females (mean age 20.8 years, $s = 0.75$; body mass 68.4 kg, $s = 13.9$; height 1.73 m, $s = 0.12$) volunteered. All were physically active, but none was a dinghy sailor. (Only two or three age-matched sailors were available, and it was considered that their inclusion would complicate the data.) Each participant provided informed written consent, following the requirements of the Glasgow University Ethics Committee, and completed a questionnaire on physical activity and health. As all participants were unfamiliar with the apparatus used, they each had the opportunity to familiarize themselves with it before entering the study proper.

Apparatus

For all experiments reported in this paper, the dinghy-hiking load on the lower limbs was simulated by a bespoke-built isometric, two-legged knee extension device embodying a goniometer measuring knee angles and a load cell indicating total force production. The equipment was closely similar in these respects to that illustrated earlier in this issue by Spurway (2007, figure 3), except that it used the load cell instead of the weight stack described there. The participants were able to see all instrument readings. They were required to push against the pads of the knee extension equipment at a knee angle of 1.13 rad (65°) flexion and a force equalling 30% of their individual MVC, as measured when fresh. Dynamic upper-body load was provided by a cycle ergometer (model 818, Monark, Sweden) converted for hand cranking by replacement of the pedals with handles. The arm-crank ergometer was bolted to a wooden platform with the pedal axis in front of the

participant’s shoulders, so that the handles could be turned without significant net force in either the vertical or the horizontal plane. (The concern here was not that such a force would alter the knee-extension moment, as it would in a dinghy, for in the laboratory the participant’s back was supported. Instead, the objective was to minimize any upper-body effort not monitored by the ergometer.) Revolutions per minute were detected by a reflective strip attached to the flywheel, which interrupted a light beam once each revolution; the readout from this was displayed continuously to the participant on a second monitor. A final computerized display gave the participant visual indications of the progress of the time intervals, supplemented by auditory signals at the beginning and end of each activity period. These activity periods were defined in terms of work–rest duty cycles (detailed below). Intermittent protocols were consistently chosen because it had been the senior author’s earlier experience, performing experiments in both Glasgow and Oslo, that few individuals – especially non-sailors – could sustain an uninterrupted 30% MVC long enough to provide an informative series of Douglas bag and capillary lactate measurements. (Breath-by-breath respiratory equipment was only available for the first, small preliminary series.)

General pattern of tests

Throughout these studies, the broad pattern was to establish first a participant’s maximum knee-extension torque (taken as indicating quadriceps MVC), then his or her endurance at 30% MVC following the selected duty cycle. Next, the lactate threshold for arm cranking was determined, then the other physiological responses to arm-cranking, and finally the effects of combining leg endurance with simultaneous arm cranking at one or a series of work rates close to or above the threshold – all under the same duty cycle.

Principal features of preliminary series

Duty cycles in these two series were 18 s work, 12 s rest. In the first series, respiratory parameters were measured breath-by-breath and the lactate threshold was estimated indirectly from these with 1-min increments of work rate. Almost certainly, however, this indirect method produced overestimates, as *post hoc* indications from direct blood lactate concentration assays were that the participants were exercising their arms at about 110% of the lactate threshold for arm cranking, although the aim had been 90% of this threshold. In the second, substantially larger, preliminary series, the lactate threshold was estimated from direct blood sampling, with 2-min workload

increments. Finally, arm loads of “90%” (really about 110%?) of the lactate threshold in the first series and respectively 90%, 110%, and 130% in the second were combined with the 30% MVC knee extension.

Detailed test procedures in the new series of experiments

In this series, each participant completed five different experimental sessions. As the first of these, knee extension MVC was determined and a preliminary bout of 30% MVC extensions was then undertaken, with arms inactive, to volitional exhaustion. In this test, and every subsequent one, each participant was asked to rate his or her perception of effort (RPE) at 1-min intervals by pointing to a figure on a 6–20 Borg scale.

With arms folded across the chest, the participant, vigorously encouraged by the experimenters, pushed as hard as possible against the pads of the isometric knee extension device, and the maximum force generated was recorded. Three such efforts were made, with 1 min rest between attempts. The largest force achieved was taken to be that participant's MVC. After a further 10-min rest, the participant was asked to push against the pads at 30% of the MVC just determined, adhering to an intermittent duty cycle different from that used in the preliminary series, namely 45 s work and 15 s rest, until volitional exhaustion (defined as RPE 19–20, together with an inability to maintain 30% MVC despite vigorous exhortation). The primary purpose of this first effort to exhaustion was familiarization. It was expected that both the unfamiliarity and a degree of fatigue following the MVC trials would impair the endurance achieved on this occasion. Accordingly, subsequent selection of 40% and 80% of this duration, as the time points for physiological measurements in later tests, should ensure that these measurements fell safely within the endurance periods then achieved.

In the second session, each participant's lactate threshold was determined at 60 rev · min⁻¹ with legs inactive, using an intermittent, incremental test on the arm crank ergometer and the same 45 s work, 15 s rest duty cycle as used previously for the legs. The load was initially set at 25 W and increased by 12.5 W after every 4 min of exercise. Capillary blood samples were taken from a thumb-tip, before the first exercise and after every 4-min bout, and analysed enzymatically (LM5 analyser, Analox, UK), 90 s after collection, for blood lactate concentration. Heart rate was recorded immediately before the blood sample (chest-strap monitor, Polar, Finland). Each participant was asked to continue the intermittent arm cranking until one of the following limits was reached: (1) a blood lactate concentration

>4 mmol · l⁻¹; (2) a heart rate of 180 beats · min⁻¹; (3) the participant could not maintain the crank frequency of 60 rev · min⁻¹; or (4) the participant requested that the experiment be terminated. Blood lactate readings were then plotted against work load. The last point on the graph before blood lactate concentration began to rise significantly was judged visually and a line of best fit drawn by eye through this point and those previous to it; another line of best fit was similarly drawn through all the subsequent points. The intersection of these two lines was taken as that participant's lactate threshold and the equivalent workload noted.

The remaining three sessions embodied conditions designated A to C, and were conducted in randomized sequence. Participants were required to attend the laboratory once or twice a week at the same time each day, with at least 2 days' interval between tests. In each of the three conditions, the participants were once more asked to perform intermittent (45 s work, 15 s rest) isometric quadriceps contractions, at 30% of the MVC calculated in the first experimental session, until volitional exhaustion. Protocol A consisted of this action alone. In protocols B and C, the participants were required to accompany the quadriceps contractions with 60 rev · min⁻¹ arm cranking at 130% and 20% of their lactate threshold respectively. Thumb-tip blood samples were always taken and analysed for blood lactate at the point of volitional exhaustion and 4 min afterwards; in protocols A and B, they were also analysed at 40% and 80% of the endurance time that each participant had achieved in the first trial. For reasons of cost, blood was not sampled at rest in any of these conditions, or at the 40 and 80% time points in protocol C. In all three conditions, expired air was collected in a Douglas bag at rest, and during each minute of every exercise bout and the first 6 min of recovery, and was immediately analysed for volume (dry gas meter, Harvard, USA), temperature, fractional O₂ content (570a paramagnetic analyser, Servomex, USA), and fractional CO₂ content (infrared analyser, P.K. Morgan, UK). From these data, minute ventilation (\dot{V}_E), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were calculated, and expressed in terms of standard temperature and pressure (dry). Heart rate was recorded every minute throughout the experimental period, immediately before the rating of perceived exertion.

Statistical analysis

As the first preliminary series involved only three participants, and they all responded in the same direction, statistical analysis was not applied. In the second series, a Ryan-Joiner test was first performed

on all variables to determine whether the values were normally distributed. Where this condition was met, one- and two-way analyses of variance and paired *t*-tests were applied, using Minitab; otherwise, non-parametric methods (Kruskal-Wallis and Mann-Whitney) were employed instead, using SPSS.

In the new series, all data sets met the normality criterion so Minitab only was necessary. A one-way analysis of variance (ANOVA) was used to test for differences between the endurance times in protocols A, B, and C. The physiological variables were analysed with a two-way ANOVA for repeated measures, followed by a one-way ANOVA and Fisher's pairwise comparison test for group effects, and paired *t*-tests for time effects. Statistical significance was set at $P \leq 0.05$ throughout.

Results

Preliminary experiments

Although only three participants were involved in the first series, the striking finding was that each endured leg effort longer when his arms were also active. The second series had substantially more participants and put them through more tests; however, an arbitrary time limit of 20 min per test had been agreed with the ethics committee, and in the event only two participants fatigued within this period. Nevertheless, both of these participants endured longer with arm work, and both did so particularly at the higher arm-work loads. The senior author, undertaking the same tests but without a time limit, also lasted longer with arm work. Thus all six participants who exercised to fatigue in the preliminary experiments endured longer in the combined arm-and-leg exercise. Importantly also, they each displayed not only higher heart rate and $\dot{V}O_2$, but also higher blood lactate concentration, than during their leg-only efforts.

It was the experience with the 20-min time limit coupled to an 18 s/12 s duty cycle that led us, in the new series, to adopt the more demanding 45 s/15 s cycle: although no 20-min limit was imposed this time, we wished to minimize the extent to which boredom, rather than physiological fatigue, might confuse the results. In addition, protocol C was included for the first time, in an attempt to identify any contribution from psychological distraction.

New experiments

The endurance times for each participant, in protocols A–C, are shown in Table I. There were no significant differences in mean endurance times between the three protocols (Figure 1). However, individual analyses indicated that seven of ten

participants achieved a longer endurance time during the combined high-intensity arm cranking and quadriceps contractions (protocol B) than the quadriceps contractions alone (protocol A), whereas in protocol C only four participants did so.

Mean values of MVC and the lactate threshold determined in the first two protocols were $149.3 \text{ kg} \cdot \text{m}^{-1}$ ($s = 45.4$) and 46.9 W ($s = 8.1$) respectively. The main physiological data for the three subsequent protocols (A–C), determined on the basis of the above values, are presented graphically in Figures 2–4.

As might be expected, participants in protocols A and C attained very similar heart rates at each stage of the exercise, whereas in protocol B heart rate was significantly higher than in protocols A and C throughout the exercise, though not after 4 min

Table I. Volitional exhaustion times (min) for each participant performing 30% maximum voluntary quadriceps contractions (MVC) alone (protocol A), identical quadriceps contractions simultaneously with arm cranking at 130% arm-cranking lactate threshold (protocol B), and the quadriceps contractions with arm cranking at 20% the lactate threshold (protocol C).

Participant	Sex	Protocol A	Protocol B	Protocol C
1	Female	5.43	4.68	4.47
6	Male	10.45	7.37	8.57
9	Female	17.50	11.53	8.58
3	Female	8.63	8.75	7.53
2	Male	9.60	10.70	8.73
8	Male	12.78	14.82	12.75
5	Male	7.28	8.63	7.62
4	Male	9.48	10.87	9.57
7	Female	12.10	12.18	15.00
10	Female	21.02	21.80	22.77
Mean		11.43	11.13	10.57

Note: Participants are grouped by the following criteria: time B relative to A; within which time in C relative to A; within each of which time in A. Shaded areas = longer than protocol A.

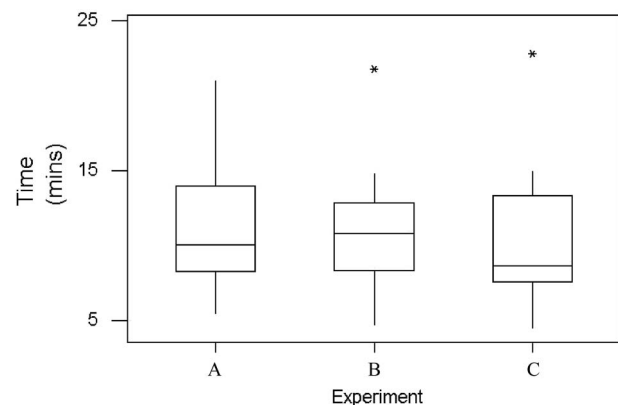


Figure 1. Box-plot of volitional exhaustion times for the three protocols considered in Table I ($n = 10$).

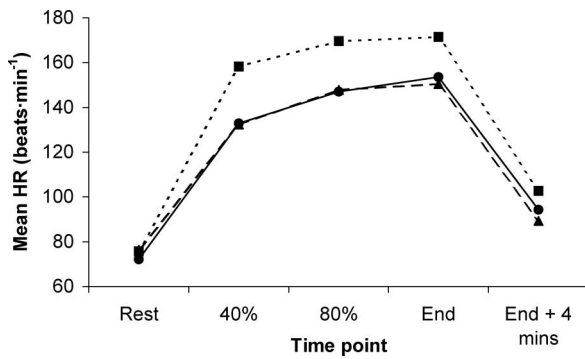


Figure 2. Heart rates (HR) at different times during exercise bouts under the various conditions (Time points 40% and 80% represent those percentages of the time to volitional exhaustion in the familiarization trial.) ●, protocol A; ■, protocol B; ▲, protocol C.

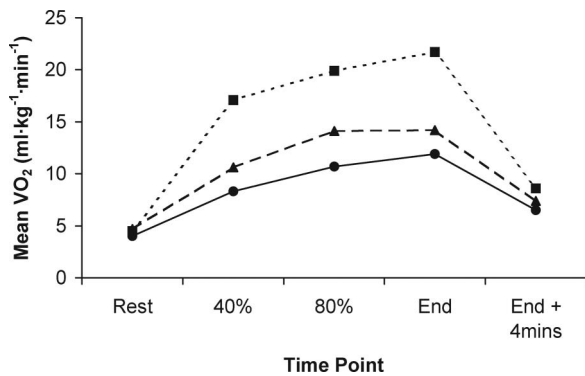


Figure 3. Oxygen consumption at different times during exercise bouts under the various conditions ("40%" and "80%" as in Figure 2). ●, protocol A; ■, protocol B; ▲, protocol C.

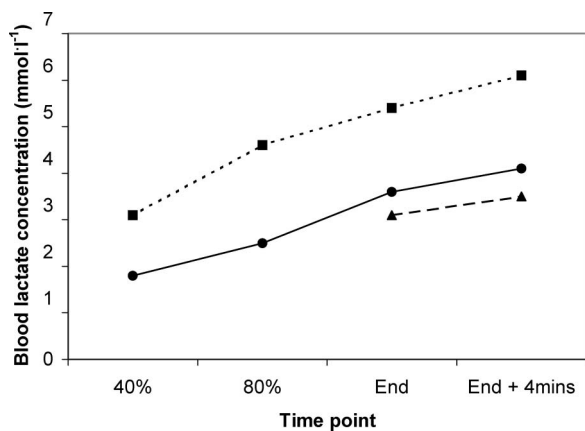


Figure 4. Blood lactate concentration at different times during exercise bouts under the various conditions ("40%" and "80%" as in Figure 2). ●, protocol A; ■, protocol B; ▲, protocol C.

recovery (Figure 2). Similarly, during protocol B the participants reached a higher $\dot{V}O_2$ than in protocols A and C, and in this case the difference remained

significant throughout (Figure 3). Although participants in protocol C appeared to attain higher $\dot{V}O_2$ than in protocol A despite similar heart rates, these differences failed to reach statistical significance. The \dot{V}_E and $\dot{V}CO_2$ data (not shown) produced similar comparisons to those of $\dot{V}O_2$. It is noteworthy, however, that participants in protocol C had significantly *lower* blood lactate concentrations at the volitional exhaustion point, and after 4 min recovery, than in protocol A (Figure 4). Conversely, as would be presumed from inspection of the graph, blood lactate concentrations in protocol B were significantly higher at each stage than in protocol A.

Discussion

In the preliminary studies, all participants who exercised to voluntary fatigue endured longer with their arms working above the lactate threshold than with arms inactive. In the new study, seven of ten participants did so. The second preliminary series might raise the question whether those who fatigue sooner are the ones who display this phenomenon; however, in the new series, the mean endurance of the two groups (protocol A) differed only in the third figure, and such trend as there was, was in the opposite direction. As to the 100% record in the preliminary series yet only 70% in the new one, this is likely to be due simply to sampling variation. However, our data do not allow us to exclude the possibility that the arms can help the legs more when the duty cycle is rather less demanding.

Considering now a detail of our procedure, the method of determining MVC was basic [cf. more sophisticated approaches mentioned, for example by Gandevia (2001), such as re-measuring MVC each day]. However, by using the same load to represent "30% MVC" for each individual in all three protocols (A–C in the new series, and equivalently in the second preliminary study), we consider that the effects of arm action upon leg endurance were clearly demonstrated. The inherent subjectivity of volitional exhaustion probably adds substantially to the variance encountered in all results of the kind presented in Table I. Nevertheless, the refutation, by these data, of the *prima facie* physiological prediction that endurance in protocol B would be less than in protocol A, can scarcely be challenged. Indeed, the fact that 13 of 16 participants from whom a result was obtained endured longer in this condition suggests that this may even be the majority trend in the population at large, irrespective of sex or (within the normal adult range) of age. Whatever the mechanisms involved, they clearly represent an unexpectedly helpful substratum for the ability of the active dinghy sailor to sustain long periods of hiking.

Turning from the comparison of protocols A and B to what can be learned from protocol C, we consider first the light it throws on the hypothesis that arm cranking might provide a significant psychological distraction from the leg discomfort (cf. Szabo, Small, & Leigh, 1999; although see also Fillingim, Roth, & Haley, 1989). If this were the case, and the purely physiological effects of heavy upper-body exercise were – in accordance with our *prima facie* prediction – detrimental to endurance, one would have to argue that in protocol B the favourable psychological and unfavourable physiological influences approximately cancelled out. In that case, protocol C should have allowed substantially the greatest endurance of the three conditions – psychological distraction coinciding now with neutral (or even, since blood lactate concentration was decreased relative to protocol A, marginally favourable) physiological state. In fact, endurance in protocol C was not significantly different from that in either of the other protocols and such trend as there was, was for it to be the poorest. We therefore conclude that our results offer no support for the hypothesis that arm cranking provides effective psychological distraction from quadriceps discomfort. This was also the view of our participants. While the real, on-water situation may provide substantial distraction, no participant felt that the laboratory arm work, even at high intensity, did so.

We have, therefore, to ask whether there are *physiological* mechanisms arising from upper-limb activity that can act in the direction of enhancing lower-limb endurance, despite the *prima facie* negative features of protocol B compared with those of protocol A. In protocol A, heart rate, \dot{V}_E , $\dot{V}O_2$, and $\dot{V}CO_2$ were all significantly higher, at every time-point during effort. Now the juxtaposition of body parts, in relation to gravity, is not radically dissimilar in these experiments to that during cycling, for which it has been shown that the addition of upper-body activity to ongoing lower-body effort reduces blood flow in the latter's musculature ("blood stealing": Andersen & Saltin, 1985; Saltin, 1985; Secher, Clausen, Klausen, Noer, & Trap-Jensen, 1977). Accordingly, we need to identify a physiological mechanism that can *assist* leg function, and so help to counteract the detrimental effects of competition for cardiac output. Noting that, at 30% MVC, the quadriceps retains some blood flow even during isometric effort (Hallen *et al.*, 2001; Spurway, 2007), and that our experimental situation in any case allows free perfusion during 15 s out of every 60 (or 12 of 30 s in the preliminary studies), we find two possible mechanisms documented in the recent literature. Both depend on lactic acid, but in the first case it is the anion, and in the second the cation, which is the active component.

Lactate, shuttled from one region of the musculature to another, can be taken up by the best-adapted fibres of the second region (chiefly the oxidative-glycolytic fibres: Baldwin, Hooker, & Herrick, 1978), converted back to pyruvate, and taken into the mitochondria as a supplementary metabolite (Gladden, 2000; Miller *et al.*, 2002). Alternatively, it has recently and importantly been shown (Nielsen, De Paoli, & Overgaard, 2001) that the excitability-suppressing influence of potassium ion accumulation in the extracellular space of contracting muscles (Sjogaard, 1990) can be partially or completely counteracted by hydrogen ions – such as those produced by the dissociation of lactic acid.

A final comment should be made on our use of isometric lower-body exercise. This of course arose from our view (Spurway, 2007) that this is a closer approximation than purely dynamic exercise to real dinghy hiking. However, should this prove incorrect for the elite sailor, as Cunningham and Hale (2007) contend elsewhere in this issue, the phenomenon described here may well still apply. Lower-limb blood flow would be greater in the dynamic situation, allowing readier access of lactate from the arms. Indeed, Richter and colleagues (Richter, Kiens, Saltin, Christensen, & Savard, 1988) and Bangsbo *et al.* (1997) have both shown that the addition of upper-body dynamic exercise to that of the lower body causes the legs to switch from net lactate release to net lactate uptake. The leg exercise used by Bangsbo and colleagues actually was a series of repeated knee extensions. The effect on volitional endurance, however, was not investigated in either of these studies.

Conclusions

When dynamic upper-body work of substantial intensity is undertaken in parallel with sustained lower-body effort – certainly where this is isometric and probably where it is dynamic also – conflicting physiological mechanisms interact. Competition for cardiac output tends to impair lower-limb activity and decrease endurance; however, in one or both of the two ways noted, increased lactic acid concentration in the circulating blood tends to enhance lower-limb function. It is likely that the balance between the impairing and enhancing effects varies between individuals, so the fact that some participants endured longer while others capitulated sooner in protocol B than in protocol A would be unsurprising, even if the compounding effects of psychological inconstancy on volitional exhaustion were not also present.

Whether or not this speculation about mechanisms is correct, evidence has been provided indicating that enhancement of leg endurance by fairly intensive arm

work is found in a substantial fraction, quite possibly the majority, of adults of working age and either sex. Clearly it would be convenient for dinghy sailors if the effect were particularly marked in them but the attempt of Collins *et al.*, in their preliminary study, to investigate this did not succeed, the time limit preventing any significant difference from showing up. An obvious further question is whether appropriate training (including sailing itself) enhances the phenomenon. We shall not be able to pursue these points, but hope that other groups may take them up.

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