

Research article

Effect of Adaptive Paced Cardiolocomotor Synchronization during Running: A Preliminary Study

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Abstract

Cardiolocomotor synchronization (CLS) has been well established for individuals engaged in rhythmic activity, such as walking, running, or cycling. When frequency of the activity is at or near the heart rate, entrainment occurs. CLS has been shown in many cases to improve the efficiency of locomotor activity, improving stroke volume, reducing blood pressure variability, and lowering the oxygen uptake (VO_2). Instead of a 1:1 frequency ratio of activity to heart rate, an investigation was performed to determine if different harmonic coupling at other simple integer ratios (e.g. 1:2, 2:3, 3:2) could achieve any performance benefits. CLS was ensured by pacing the stride rate according to the measured heartbeat (i.e., adaptive paced CLS, or forced CLS). An algorithm was designed that determined the simplest ratio (lowest denominator) that, when multiplied by the heart rate will fall within an individualized, predetermined comfortable pacing range for the user. The algorithm was implemented on an iPhone 4, which generated a 'tick-tock' sound through the iPhone's headphones. A sham-controlled crossover study was performed with 15 volunteers of various fitness levels. Subjects ran a 3 mile (4.83 km) simulated training run at their normal pace on two consecutive days (randomized one adaptive pacing, one sham). Adaptive pacing resulted in faster runs run times, with subjects running an average of $26:03 \pm 3:23$ for adaptive pacing and $26:38 \pm 3:31$ for sham ($F = 5.46$, $p < 0.05$). The increase in heart rate from the start of the race as estimated by an exponential time constant was significantly longer during adaptive pacing, $\tau = 0.99 \pm 0.30$, compared to sham, $\tau = 1.53 \pm 0.34$ ($t = -6.62$, $p < 0.01$). Eighty-seven percent of runners found it easy to adjust their stride length to match the pacing signal with seventy-nine percent reporting that pacing helped their performance. These results suggest that adaptive paced CLS may have a beneficial effect on running performance and may be useful as a training aid.

Key words: CLS, pacing, coupling, entrainment.

Introduction

Entrainment (defined here as the process whereby two interacting periodic systems, such as the heart, lungs, and voluntary musculature, become synchronized) of physiological rhythms has been the subject of increasing investigation (Niizeki, 2004; Nomura et al., 2006). Rhythmic entrainment between various organs in the body comes about due to the extremely large number of electrical connections between them. It has been surmised that the greatest question on this topic is not why entrainment occurs, but why it is not even more prevalent (Glass, 2001). For example, researchers have found significant coupling between the cardiovascular and respiratory sys-

tems. The relationship can be identified using an integer ratio (Kenner et al., 1976; Schafer et al., 1998; 1999; Seidel and Herzog, 1998) and is most prevalent during sleep and in a relaxed state, but decreases during exercise (Kenwright et al., 2008) and periods of stress or disease (Lotric and Stefanovska, 2000). In general, it has been thought that such coupling establishes a feed-forward system (Eldridge et al., 1985) of economical co-action and thus favors the functional economy of the organism (Lotric and Stefanovska, 2000).

In addition to coupling of internal organs to each other, there is an increasing amount of evidence to show that coupling can exist between organs and voluntary activity as well. For example, the existence of cardiolocomotor synchronization (CLS) has been well established for an individual performing a rhythmic activity, such as walking (Coleman, 1921; Kirby et al., 1989; Niizeki et al., 1993; Novak et al., 2007), running (Kirby et al., 1989; Nakazumi et al., 1986; Niizeki et al., 1993; Nomura et al., 2001; 2003; 2006; O'Rourke et al., 1993; Udo et al., 1990), or cycling (Blain et al., 2009; Kirby et al., 1989). Coupling has even been shown to occur by passive mechanical oscillation as well (Bhattacharya et al., 1979). In all cases of CLS, the rhythmic activity was tailored such that its frequency was at or near the heart rate. It was thought that entrainment occurs primarily through a hydraulic mechanism, which plays a dominant role in the efficiency of heart function (Bhattacharya et al., 1979). This conclusion was reached in part because activities that involved significant vertical motion (Bechbache and Duffin, 1977), like running or passive mechanical oscillation (Bhattacharya et al., 1979), tended to result in greater entrainment compared to walking or cycling (Kirby et al., 1992; Nomura et al., 2003). In comparison Niizeki (2004) showed the use of a thigh-cuff occlusion rhythm to generate significant entrainment while sitting, which would indicate that vertical motion per se may not be necessary to induce CLS.

One potential method of action for CLS is related to the phase relationship between heart beat and muscle contraction (Nomura et al., 2006; Udo et al., 1990). The cardiac cycle may be timed to deliver blood when the intramuscular pressure is not maximal (i.e. when the muscle is relaxed) (Kirby et al., 1989; Niizeki, 2004; Udo et al., 1990), and the cardiac rhythm is influenced from a neural circuit arising from peripheral inputs (Niizeki et al., 1993).

It has also been shown that respiratory rate may be entrained by locomotor rhythms. This entrainment generally occurs at an integer ratio (Iscoe and Polosa, 1976)

and is more significant when the exercise increases in intensity (Bernasconi et al., 1995; Bernasconi and Kohl, 1993; Jasinskas et al., 1980) and when the locomotor rhythm is paced (Bechbache and Duffin, 1977; Bernasconi and Kohl, 1993). Also, the coupling seems to be more prevalent in more experienced runners (McDermott et al., 2003). Interestingly, during walking and running this entrainment is more affected by stride rate instead of work rate (Raßler and Kohl, 1996), and tends to decrease in the presence of CLS (Niizeki et al., 1993). There is a definite cardio-respiratory entrainment, as has been shown through respiratory-sinus arrhythmia (RSA) (Blain et al., 2009; Nomura et al., 2001; Schafer et al., 1999), which may also be a contributing factor for the existence of CLS. Oxygen uptake has been shown to be significantly lowered during running when cardio-respiratory entrainment occurs (Bernasconi and Kohl, 1993), but is not significantly affected during walking, likely due to the lowered energy expenditure during walking (Raßler and Kohl, 1996).

Cardiolocomotor synchronization has been shown to improve the efficiency of locomotor activity. In a seminal paper by Coleman (1921) a man always became breathless when halfway up a hill, but was able to climb without breathlessness when he timed his steps with his heart beat, additionally the increase in blood pressure was only half as great. Economy of locomotor activity is measured as the amount of oxygen required for a particular activity (VO_2) (Conley and Krahenbuhl, 1980). O'Rourke et al. (1992) noted that the natural stride rate of highly competitive runners was very close to their exercise heart rate. Oxygen uptake has been shown to be significantly less when CLS occurs than when it does not (Udo et al., 1990), along with an increase in stroke volume (Zhang et al., 2002). It has also been shown that blood pressure varies during running, and that the frequency of variation is equal to the difference between heart rate and stride rate (O'Rourke et al., 1993; Palatini et al., 1989). However, a more stable blood pressure may allow for more efficient blood perfusion to the muscles (Palatini et al., 1989), which would also contribute to an improvement in efficiency during CLS.

As mentioned earlier, all studies of CLS for runners conducted thus far involve creating a scenario where the stride rate and the heart rate are almost identical. However, the natural stride rate and heart rate during running may not have a 1:1 ratio. The purpose of the present study was to investigate the potential performance benefit of harmonic coupling other than a 1:1 ratio resulting from runners using an audio pacing signal to allow them to match their stride to the simplest integer ratio of the heart rate (e.g., 1:2, 2:3, 3:2) in which the pacing signal falls within an individualized comfortable range for each test subject (i.e. adaptive paced CLS, or forced CLS). A generally accepted range from 160 to 190 steps per minute is expected, though this may vary between individuals, depending on fitness level, stride length, and average running speed (Cavanagh et al., 1977; Cavanagh and Williams, 1982; Heiderscheit et al., 2011).

Heart rate variability occurs naturally both at rest and during exercise (Blain et al., 2009). Therefore, when

providing an adaptive pacing signal, the pacing frequency was based on a time-averaged heart rate value instead of a point measurement. Time-averaging prevents moment-to-moment variations in pacing frequency (and therefore stride rate), which may be difficult for a runner to follow. An added benefit of adaptive paced CLS may be a reduction in heart rate variability, due to the entrainment effect of a relatively constant stride rate at a simple integer ratio of the heart rate. A constant stride rate and reduced HR variability may both help increase the overall efficiency of the heart and voluntary musculature involved in running, thereby improving performance.

Methods

The algorithm

An algorithm was implemented that dynamically adjusted an auditory pacing signal based on heart rate as measured by a portable heart rate monitor (Wahoo Fitness® Run Pack for iPhone, #WFFISICHR). Given a particular heart rate, the algorithm determined the simplest integer ratio (i.e. pace factor) that, when multiplied by the heart rate, would give a pacing frequency that fell in the acceptable pacing range. The acceptable pacing range was defined by a high and low pacing rate, within which the subject was easily able to match the pacing frequency while maintaining a comfortable speed. The pacing range was unique to each subject and determined through a test and adjustment phase before beginning the run. During the run, the algorithm updated the pace factor and pacing frequency once every 15 seconds. The inputs to the algorithm were:

- Normal Pacing Rate (NP) – The stride rate that the subject would use in the absence of any pacing signal to maintain a comfortable speed.
- High Pacing Rate (HP) – The highest pacing frequency that the subject could easily maintain. Above this rate, the subject reported that s/he was forced to dramatically shorten his/her stride length to keep the pace and maintain a comfortable speed.
- Low Pacing Rate (LP) – The lowest pacing frequency that the subject could easily maintain. Below this rate, the subject reported that s/he was forced to dramatically lengthen his/her stride length to keep the pace and maintain a comfortable speed.
- Heart Rate (HR) – The average heart rate since the previous time the algorithm was run.
- Pace Factor (A/B) – The current pacing factor used to set the pacing frequency. A is the numerator and B is the denominator. The factor was initialized to unity before the run began.

The algorithm outputs were:

- Updated Pace Factor (A/B)
- Pacing Frequency (PF) - Updated pacing frequency, based on HR and the new A/B.

The algorithm is shown in Equation 1. The purpose was to update the pacing frequency and pace factor based

on the average heart rate over the prior 15 seconds. First, the algorithm checked to see if the pacing frequency calculated from the current pace factor (A/B) multiplied by the heart rate HR fell in the acceptable pacing range. If so, then the pacing frequency was updated and the pace factor remained the same. If not, the algorithm attempted to find the pace factor with the smallest denominator that fell in the acceptable range. Once that occurred, the algorithm selected the numerator that resulted in a pacing frequency PF as close as possible to the normal stride rate (NP) of the individual.

The result of the algorithm was a pace factor that was the simplest integer ratio possible that, when multiplied by the heart rate, resulted in a pacing frequency that was in the acceptable range and as close as possible to the normal stride rate of the subject.

The iPhone application

An application on the iPhone 4 was created, which communicated wirelessly with a Wahoo Fitness® heart monitor torso strap. It calculated the heart rate based on input from the torso strap, then calculated the pace factor and pacing frequency according to the algorithm previously described. During a run, the algorithm was run every 15 seconds, and various metrics (heart rate, pace factor, pacing frequency) were recorded to a log file that could be downloaded.

The application generated a ‘tick-tock’ sound

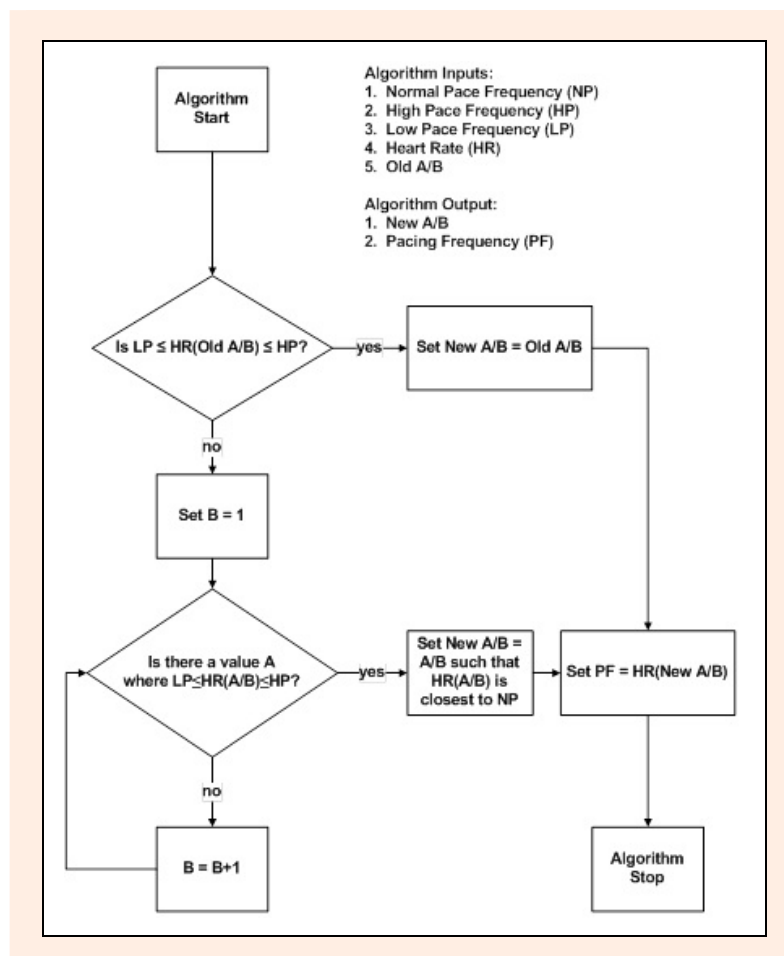
through the iPhone’s headphones. The volume could be adjusted to maximize comfort for the subject. The iPhone was carried in an armband during the run.

Subjects

Fifteen volunteers (8 men, 7 women), who regularly ran mid- to long-distances, participated in the study. The subjects’ physical characteristics were (mean ± sd): age, men: 22.6 ± 10.5, women: 18.4 ± 4.3 years; height, men: 1.74 ± 0.08, women: 1.56 ± 0.03 m; weight, men: 66.8 ± 10.4, women: 53.7 ± 7.2 kg. The number of times subjects ran per week was 3.2 ± 2.5, with an average distance per run of 4.64 ± 3.08 miles (7.46 ± 4.96 km). Two subjects regularly ran while listening to music. None regularly used a heart rate monitor. To participate in the study, subjects were required to be able to run 3 miles (4.83 km) on an oval track without stopping, and be able to wear a heart monitor. All subjects signed an informed consent before being enrolled in the study. If subjects were under 18 years old, a parental signature was also required. The study was reviewed and approved by an Institutional Review Board (IRB).

Procedures

The study design was an adaptive and a sham arm crossover. Subjects were instructed to perform a simulated training run of 3 miles (4.83 km) (12 laps on a ¼ mile oval track) at their normal speed, while wearing the heart



Equation 1. The algorithm.

monitor strap and the iPhone in the armband on the right arm. For adaptive pacing, subjects were told to adjust their footfalls to be in time with the auditory pacing signal played through headphones. For sham pacing, the iPhone application was set to generate a pacing sound at 120 beats per minute ($\text{b}\cdot\text{min}^{-1}$), independent of the heart rate, which is slower than a normal running pace. Subjects were told to ignore the pacing sound and to run at their normal stride rate. The reason for the $120 \text{ b}\cdot\text{min}^{-1}$ sound was to control for a potential distractive effect of a rhythmic beat, independent of any benefits of CLS. Subjects ran the 3-miles on each of two consecutive days, one adaptive and one sham. The adaptive day was randomized in blocks of four to the first or second day with equal probability. Runs were performed at approximately the same time each day.

In addition to the iPhone and heart monitor strap, all subjects wore a pedometer to record the number of steps taken on the two days. Subjects ran alone to prevent any competition from affecting the results. Subjects were only informed of the lap number. Subjects were not allowed to wear a watch and were not informed of any interim lap times.

Settings for normal, high, and low pacing rate were determined at the track before the run on the first day. The same parameters were loaded on the second day as well. To find the pacing rates, the iPhone application was placed in simulation mode, which generated a preset fixed pacing frequency independent of heart rate. To find the normal pacing rate, pacing frequency was set to an initial estimate of 180 steps per minute, based on a generally accepted population average (Daniels, 2005). Each subject ran approximately 50 metres, matching his/her stride to the pacing beat, to determine if a particular frequency matched his/her normal stride rate, or if it was too low, or too high. If necessary, the application pacing frequency was adjusted based on the subject's feedback, and the subject ran another 50 metres to see if the new pacing frequency was appropriate. Iterations continued until the right frequency was found. This iterative procedure was also used to determine the high and low pacing rates. Note that the accuracy of parameters was not critical to achieve effective pacing, since the parameters only defined a comfortable zone. Subjects were required to rest for at least 5 minutes after finding their pacing rate parameters before being allowed to start the 3-mile run.

To determine any potential performance benefit for adaptive paced CLS, run times (the time required for a subject to complete 3 miles) were evaluated for all subjects comparing the adaptive pacing to the sham condition. In addition, the increase in the subject's heart rate

after the start of the run was estimated by finding the time constant of a decaying exponential with the best least-squares fit to the heart rate data (*i.e.* $\text{HR}_{\text{init}} + (\text{HR}_{\text{ss}} - \text{HR}_{\text{init}})(1 - e^{-t/\tau})$, where HR_{init} is the initial heart rate at the start of the run, HR_{ss} is the steady-state heart rate, t is time, and τ is the time constant).

Temperature ($21.7 \pm 1.9^\circ\text{C}$ adaptive, $21.9 \pm 1.9^\circ\text{C}$ sham), and wind speed (less than 1 km/hr for all days) were recorded on each test day to ensure similar conditions for both adaptive and sham trials. All subjects ran at approximately the same time on each day.

Subjects were interviewed following the second day of running and asked about the adaptive pacing. Eighty-seven percent found it easy to adjust their stride length to match the pacing signal with seventy-nine percent reporting that pacing helped their performance.

Statistical analysis

Shapiro-Wilk test for the normality of data distribution was used for the running time variables. None of them was statistically significant (P varied between $P = 0.21$ and $P = 0.86$) indicating that they do not reject the null hypothesis that the data came from a normally distributed population. Significant outliers for other variables (Mean Heart Rate and Number of Steps) were also tested and removed from further statistical analysis. Analysis of variance with repeated measures (ANOVA) was used to test the treatment effect on running time at each consecutive distance check points, *i.e.* first, second, and third mile, respectively. Effect of treatment by distance interaction was also tested followed by a post-hoc t-test to delineate any group difference at each check point. Criterion of smaller than 5% type I error ($p < 0.05$) was used to determine the statistical significance to reject the null hypotheses for all tests.

Results

Two cases were rejected from the final analysis due to unavailability of data - caused by a poor connection of the pulse rate sensor during the run. One case was later rejected as an outlier that caused significant kurtosis in data distribution. Using the remaining data from 12 subjects, the following results were obtained:

Environmental conditions were nearly identical for both days, and so were not considered a factor. The results of each trial are given in Table 1.

None of the demographic data (height, body mass) had a significant effect on run time. In addition, the order of adaptive and sham days did not affect run time. Adaptive pacing resulted in faster run times compared to

Table 1. Results for 12 subjects showing cumulative run times in minutes (min) and seconds (s), heart rate (HR) variation coefficient, the exponential time constant for the increase in heart rate, and the number of steps taken during the run for adaptive and sham condition. All values are expressed as mean (\pm SD) as applicable.

	Sham	Adaptive	P value
1 st mile time (min:s)	8:28 (1:08)	8:29 (1:18)	.87
2 nd mile time (min:s)	17:41 (2:28)	17:25 (2:34)	.08
3 rd mile time (min:ss)	26:38 (3:31)	26:03 (3:23)	.02
HR variation coefficient	.03	.01	.09
Time constant	.99 (.30)	1.53 (.34)	.00
Number of steps	3 770 (673)	4 001 (517)	.40

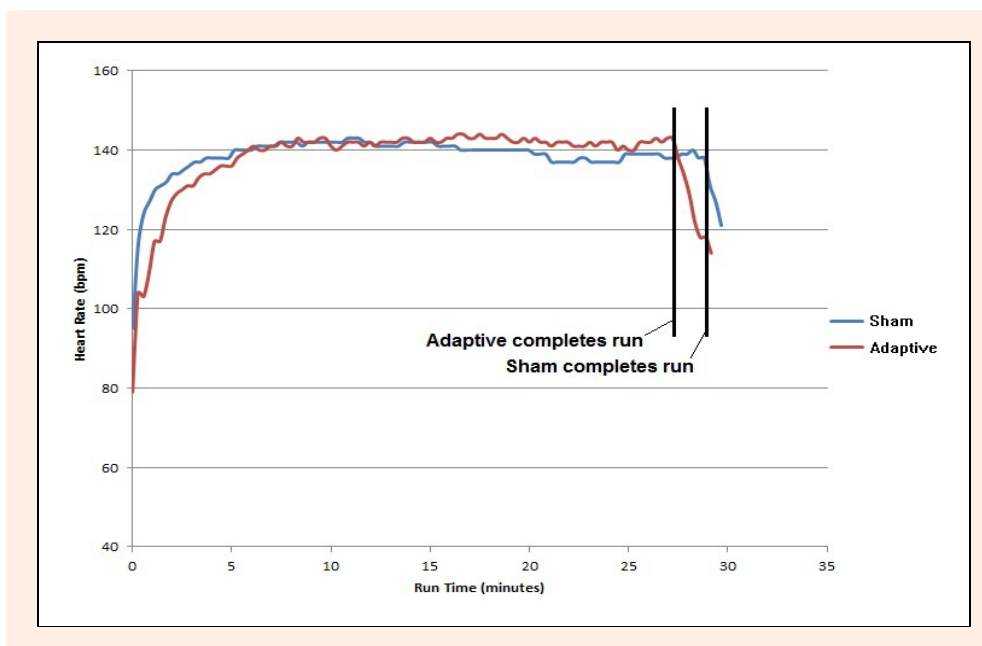


Figure 1. A representative example of the subject's heart rate during sham versus adaptive pacing.

sham ($F = 5.46$, $p < 0.05$), as well as a significant interaction between treatment and run time at the different check points ($F = 5.08$, $p < 0.05$). Overall, adaptive pacing resulted in a 35 second decrease in run time, with subjects running an average of $26:03 \pm 3:23$ for adaptive pacing and $26:38 \pm 3:31$ for sham ($p < 0.05$). Ten out of 12 subjects improved their time using adaptive pacing. Those who did improve showed an average 49 second faster time.

A post-hoc t-test revealed that only the time at third mile check point was significantly different between treatment conditions ($t = 2.77$, $p < 0.05$), showing that adaptive pacing resulted in overall faster run times compared with the sham condition. Times at the first and second mile did not show any statistical difference between adaptive and sham, although the second mile data showed a trend for improvement with adaptive pacing.

The increase of heart rate from the beginning of the run until the point where the heart rate reached a steady-rate point was evaluated by identifying the time constant with the best least squares fit of a decaying exponential to the heart rate data. In every case, the subject's heart rate increased faster during sham versus adaptive pacing. Figure 1 shows a representative example. The time constant was found to be significantly greater for the increase in heart rate with adaptive running pace guidance as compared with sham ($t = 6.62$, $p < 0.01$). The correlation between run time and the time constant for the increase in heart rate showed a positive trend, but did not attain statistical significance ($p > 0.05$).

The heart rate variation coefficient was measured as the standard deviation divided by the mean heart rate following the point when the heart rate reached a generally steady-rate condition. Looking at the standardized heart rate variation during this period, 79% of subjects had a lower HR variation when using adaptive pacing. Overall, the HR variability showed a 40% reduction for adaptive pacing, 3.24 ± 1.59 s, compared to sham, $5.36 \pm$

3.88 s. However, this difference did not reach statistical significance ($p > 0.05$), and also did not show any significant relationship with run time.

On average, runners took $3\,633 \pm 756$ steps during sham compared to $3\,913 \pm 556$ steps for adaptive pacing (NS).

Discussion

The present study gave evidence to support the hypothesis that adaptive paced CLS may provide a performance improvement when running long distances. In general, subjects ran 3 miles (4.83 km) during a simulated training run in a faster time using adaptive pacing compared with a self-selected pace. Run times did not reach statistical significance until the third mile, which would indicate a potential benefit for longer runs, where cardiac efficiency plays a greater role. Subjects generally reported that running was easier when using adaptive pacing. Interestingly, some subjects who did not improve their run time thought that adaptive pacing improved performance; with a feeling of "more energy." Some subjects did report difficulty with the system. Three said the earphones kept falling out. Two thought the pacing signal was annoying.

Although running speed was very similar for the first mile, adaptive vs. sham, in every case heart rate rose more slowly while being paced, inferring that the heart may have been operating more efficiently during pacing. The heart rate variability during the run was generally lower while being paced (though not at a level to reach statistical significance), which may have had beneficial effects for sustained blood perfusion and oxygen uptake (O'Rourke et al., 1993; Palatini et al., 1989)

In general, the steady-rate heart rate for most runners fell close to their normal stride rate, so the algorithm often set the pacing frequency equal to the heart rate (*i.e.* ratio = 1:1) during this period. This lends support to the concept that CLS may be a naturally occurring phenome-

non.

It has been shown in earlier studies that heart rate variability (HRV) is affected by CLS (Blain et al., 2009). Although not statistically significant, the reduction of heart rate variability in the current study serves as evidence of the presence of CLS, which may increase the cardiac efficiency of the runner, helping to improve performance. When running with an optimized pacing signal that was kept constant over the short term, the stride rate of the runners was kept steady, encouraging CLS.

The sham condition involved playing a pacing sound that was independent of the subject's heart rate at a frequency outside a normal stride rate, and subjects were told to ignore the pacing sound. The sham was designed to control for any effect the sound itself may have had on the subject, such as a distracting effect. Therefore, the pacing on sham day should be equal to the subject's normal pace. In future studies, it would be interesting to provide pacing at the subject's normal pace frequency and have them match that. However, during adaptive pacing, the mean steady-rate heart rate (182 ± 15 b·min⁻¹) and average steady-rate pace frequency (181 ± 8 steps per minute) were very close to the sham values, so one would expect the performance of a subject running normally versus being paced at the same frequency would be identical, irrespective of any distracting effects of the pacing sound.

Runners took more steps when being paced compared with normal running. Since their steady-rate stride rates were similar, the difference in total number of steps may have been due to subjects running with a lower stride rate (*i.e.*, a longer stride) at the start of the run when not being paced. It has been found in earlier studies that an optimal stride length exists to minimize oxygen uptake (Cavanagh and Williams, 1982), and that the more elite runners tend to have faster stride rates (Cavanagh *et al.*, 1977). Therefore, increasing the stride rate of subjects may have a beneficial effect on performance due to a possible improvement in mechanical efficiency (Heiderscheit et al., 2011). However, stride rate was not correlated with run time, and that could have been due to the small sample size.

Conclusion

The results of the present study suggest that adaptive paced CLS may have a beneficial effect on running performance. This conclusion was based on improved sub-maximal run times, larger time constant in the increase in heart rate, and a trend toward reduced heart rate variability. Additional studies should be performed that account for factors independent of CLS. Although not correlated with run times, adaptive pacing tended to have a higher stride rate versus sham. An increased stride rate may lead to improved performance, although this was not observed in the present study.

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References

- Bechbache, R.R. and Duffin, J. (1977) The entrainment of breathing frequency by exercise rhythm. *Journal of Physiology* **272**, 553-561.
- Bernasconi, P., Burki, P., Buhner, A., Koller, E.A. and Kohl, J. (1995) Running training and co-ordination between breathing and running rhythms during aerobic and anaerobic conditions in humans. *European Journal of Applied Physiology and Occupational Physiology* **70**(5), 387-393.
- Bernasconi, P. and Kohl, J. (1993) Analysis of co-ordination between breathing and exercise rhythms in man. *Journal of Physiology* **471**, 693-706.
- Bhattacharya, A., Knapp, C.F., McCutcheon, E.P. and Evans, J.M. (1979) Modification of cardiac function by synchronized oscillating acceleration. *European Journal of Applied Physiology and Occupational Physiology* **47**(3), 612-620.
- Blain, G., Meste, O., Blain, A. and Bermon, S. (2009) Time-frequency analysis of heart rate variability reveals cardiocomotor coupling during dynamic cycling exercise in humans. *American Journal of Physiology. Heart and Circulatory Physiology* **296**(5), H1651-H1659.
- Cavanagh, P.R., Pollock, M.L. and Landa, J. (1977) A biomechanical comparison of elite and good distance runners. *Annals of the New York Academy of Sciences* **301**, 328-345.
- Cavanagh, P.R. and Williams, K.R. (1982) The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise* **14**(1), 30-35.
- Coleman, W.M. (1921) The Psychological Significance of Bodily Rhythms. *Journal of Comparative Psychology* **1**(3), 213-220.
- Conley, D.L. and Krahenbuhl, G.S. (1980) Running economy and distance running performance of highly trained athletes. *Medicine and Science in Sports and Exercise* **12**(5), 357-360.
- Daniels, J. (2005) *Daniels' Running Formula*. 9th edition. Human Kinetics. 80-82.
- Eldridge, F.L., Millhorn, D.E., Kiley, J.P. and Waldrop, T.G. (1985) Stimulation by central command of locomotion, respiration and circulation during exercise. *Respiration Physiology* **59**(3), 313-337.
- Glass, L. (2001) Synchronization and rhythmic processes in physiology. *Nature* **410**, 277-284.
- Heiderscheit, B.C., Chumanov, E.S., Michalski, M.P., Wille, C.M. and Ryan, M.B. (2011) Effects of step rate manipulation on joint mechanics during running. *Medicine & Science in Sports & Exercise* **43**(2), 296-302.
- Iscove, S. and Polosa, C. (1976) Synchronization of respiratory frequency by somatic afferent stimulation. *Journal of Applied Physiology* **40**(2), 138-148.
- Jasinskas, C.L., Wilson, B.A. and Hoare, J. (1980) Entrainment of breathing rate to movement frequency during work at two intensities. *Respiration Physiology* **42**(3), 199-209.
- Kenner, T., Pessenhofer, H. and Schwaberg, G. (1976) Method for the Analysis of the Entrainment between Heart Rate and Ventilation Rate. *Pflugers Archive: European Journal of Physiology* **363**, 263-265.
- Kenwright, D.A., Bahraminasab, A., Stefanovska, A. and McClintock, P.V.E. (2008) The effect of low-frequency oscillations on cardio-respiratory synchronization. *The European Physical Journal B* **65**, 425-433.
- Kirby, R.L., Atkinson, S.M., Donville, J.E., Urdang, M.F., Stanley, D.A., Gupta, S.K. and MacLeod, D.A. (1992) Failure of accentuated vertical body movements to induce cardiac-locomotor coupling. *Journal of Applied Physiology* **72**(4), 1368-1374.
- Kirby, R.L., Nugent, S.T., Marlow, R.W., MacLeod, D.A. and Marble, A.E. (1989) Coupling of cardiac and locomotor rhythms. *Journal of Applied Physiology* **66**(1), 323-329.
- Lotric, M.B. and Stefanovska, A. (2000) Synchronization and modulation in the human cardiorespiratory system. *Physica A* **283**, 451-461.
- McDermott, W.J., Van Emmerik, R.E.A. and Hamill, J. (2003) Running training and adaptive strategies of locomotor-respiratory coordination. *European Journal of Applied Physiology* **89**(5), 435-444.
- Nakazumi, T., Watanabe, A., Kinugawa, K. and Udo, M. (1986) Entrainment of the heart beat into the running pitch during endurance running (I). *Japanese Journal of Physical Fitness and Sports Medicine* **35**(6), 340.
- Niizeki, K. (2004) Heart abhors contracting during elevated intramuscu-

- lar pressure: implication for cardiac-locomotor synchronization. In: *Proceedings SICE 2004 Annual Conference*. August 4-6, Sapporo, Japan. **3**, 2109-2112.
- Niizeki, K., Kawahara, K. and Miyamoto, Y. (1993) Interaction among cardiac, respiratory, and locomotor rhythms during cardioloomotor synchronization. *Journal of Applied Physiology* **75**(4), 1815-1821.
- Nomura, K., Takei, Y. and Yanagida, Y. (2001) Analysing entrainment of cardiac and locomotor rhythms in humans using the surrogate data technique. *European Journal of Applied Physiology* **84**, 373-378.
- Nomura, K., Takei, Y. and Yanagida, Y. (2003) Comparison of cardio-locomotor synchronization during running and cycling. *European Journal of Applied Physiology* **89**(3-4), 221-229.
- Nomura, K., Takei, Y., Yoshida, M. and Yanagida, Y. (2006) Phase-dependent chronotropic response of the heart during running in humans. *European Journal of Applied Physiology* **97**(2), 240-247.
- Novak, V., Hu, K., Vyas, M. and Lipsitz, L.A. (2007) Cardiolocomotor Coupling in Young and Elderly People. *Journal of Gerontology: Medical Sciences* **62A**(1), 86-92.
- O'Rourke, M. and Avolio, A. (1992) Improved cardiovascular performance with optimal entrainment between heart rate and step rate during running in humans. *Coronary Artery Disease* **3**, 863-869.
- O'Rourke, M., Avolio, A., Stelliou, V., Young, J. and Gallagher, D.E. (1993) The rhythm of running: can the heart join in? *Australian and New Zealand Journal of Medicine* **23**, 708-710.
- Palatini, P., Mos, L., Mormino, P., Di Marco, A., Munari, L., Fazio, G., Giuliano, G., Pessina, A.C. and Dal Palu, C. (1989) Blood pressure changes during running in humans: the "beat" phenomenon. *Journal of Applied Physiology* **67**(1), 52-59.
- Raßler, B. and Kohl, J. (1996) Analysis of coordination between breathing and walking rhythms in humans. *Respiration Physiology* **106**(3), 317-327.
- Schafer, C., Rosenblum, M.G., Abel, H.H. and Kurths, J. (1999) Synchronization in the human cardiorespiratory system. *Physical Review E* **60**(1), 857-870.
- Schafer, C., Rosenblum, M.G., Kurths, J. and Abel, H.H. (1998) Heart-beat synchronized with ventilation. *Nature* **392**, 239-240.
- Seidel, H. and Herzel, H. (1998) Analyzing Entrainment of Heartbeat and Respiration with Surrogates. *IEEE Engineering in Medicine and Biology Magazine* **17**(6), 54-57.
- Udo, M., Yoshida, T., Nakazumi, T., Kinugawa, K. and Watanabe, A. (1990) Occurrence of entrainment of heart beat into endurance running pitch and its significance in energy consumption. In: *Fitness for the aged, disabled, and industrial worker*. Ed: Kaneko, M. Champaign, Ill: Human Kinetics Books. 79-83.
- Zhang, D., Celler, B.G. and Lovell, N.H. (2002) The effect of heartbeat-synchronized running on the cardiovascular system. In: *Proceedings. EMBS-BMES 2002 joint conference*. October 23-26, Houston, Texas. 1295-1296.

Key points

- Sham-controlled crossover study using 15 experienced runners running 3 miles (4.83 km).
- Adaptive CLS pacing resulted in statistically significant 35 second average decrease in run-time ($p < 0.05$).
- Increase in heart rate during the run was significantly slower during adaptive pacing ($p < 0.01$).

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