COORDINATION BETWEEN LOCOMOTION AND BREATHING DURING RUNNING

William J. McDermott, Richard E.A. van Emmerik and Joseph Hamill
Department of Exercise Science, University of Massachusetts, U.S.A.

This study investigated the coupling between locomotory and breathing rhythms based on speed, and running experience level. Findings in the current literature are inconclusive because of the wide variety of techniques used as well as their insensitivity to half-integer couplings and/or changes from one coupling to another. Male subjects (5 runners, 5 non-runners) ran at three treadmill speeds. The relative phase between heel strike and end-inspiration allowed for the assessment of the strength and variability of frequency coupling. Results indicate strong individual differences that are masked by grouping subjects. The difference between runners and non-runners may not lie in the coupling strength but in the stability of the dominant coupling across running speeds.

KEY WORDS: locomotion, respiration, coupling

INTRODUCTION: Coordination between limb movements and breathing rhythms has been investigated in both animals and humans during locomotion. The strength of frequency coupling between limb movements and breathing rhythms is used as a measure of entrainment. Entrainment can vary with mode of locomotion, speed, and running experience level (Bramble & Carrier, 1983). Comparisons between studies as well as drawing general conclusions, however, are difficult because there is a wide variety of techniques used to asses and quantify the frequency coupling. All of these techniques have focused on the identification of entrainment through specific criteria defined apriori. Many of these techniques are insensitive to certain aspects of polyrhythmic coordination such as half-integer couplings and changes from one coupling to another. Although variability in entrainment seems to be the only consistent finding, no measure of variability has been used to describe the coordination between exercise and breathing rhythms.

From a dynamical systems perspective, coordination between two components, is often modeled as two non-linearly coupled oscillators. The emphasis of this strategy when applied to human coordination is on the nature of variability and non-linear qualitative change in the behavior of the system. To do this specific tools have been developed to study changes in frequency and phase coupling in complex dynamical systems. The purpose of this study was to investigate the coupling between locomotory and breathing rhythms using a dynamical systems approach to make comparisons based on speed and running experience level.

METHOD: Male subjects (5 runners, 5 non-runners) ran on a treadmill for five minutes at the following speeds: running at the preferred transition speed (R-PTS), preferred run (PR), and 20% above preferred run (PR+20%). Discrete relative phase (RP) between heel strike of the right foot and end inspiration (EI) was calculated as follows:

$$RP = \frac{t}{T} * 360^{\circ} \qquad (1)$$

where T is the period of the stride and t is the time from heel strike to the next EI (see Figure 1). Note that if there are n heel strikes within one breath, the relative phase value of the first heel strike will fall within the specific range:

$$(n*360) > RP_n \geq ((n-1)*360) \qquad (2)$$

Periodicity of the relative phase data was assessed by constructing return maps with lags ranging from 1 to 6. Frequency couplings were identified by applying specific range criteria to specific return maps (lags). Non-couplings (NC) were breaths that did not fit any of the above frequency coupling criteria. Three variables were used to assess the frequency coupling: The percentage of breaths occurring with the *dominant frequency coupling (DC)* was used as a measure of the strength of coupling. Variability in coupling was measured in terms of the contributions of the *second dominant coupling (SC)* and *non-coupling (NC)* (see McDermott, 1999 for details).

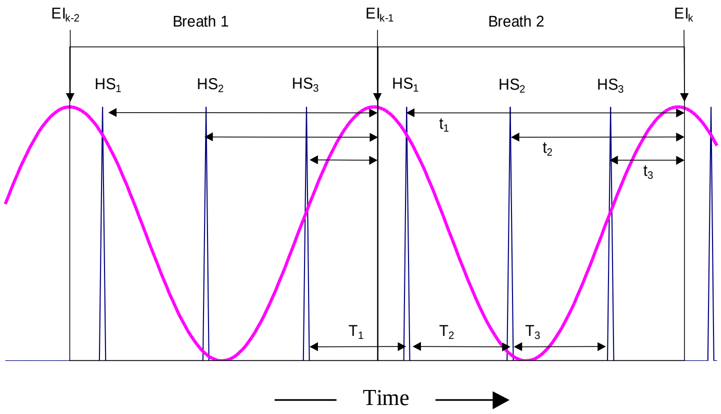

Figure 1 - Simulated breath signal (sinusoid) and heel strike (HS) signal (pulse). One breath ranges from end inspiration (EI) to the next end inspiration.

RESULTS: Strength of coupling as well as the contributions of second dominant couplings and NC are plotted in Figure 2 for comparisons. There were no group differences found in any of the three frequency coupling measures indicating coupling strength and variability in coupling was unaffected by running experience level. Although running speed seems to influence the coupling strength and variability, only the NC during the PR condition was found to be significantly lower than the other conditions ($p<0.01$). For both groups, the variability in coupling was due mostly to NC.

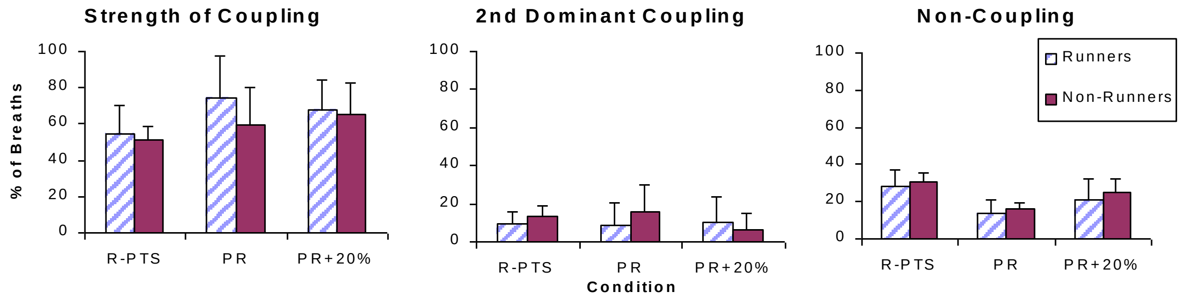

Figure 2 - Contributions of dominant frequency coupling (left), second dominant coupling (middle), and non-couplings (right) during each of the conditions.

To illustrate individual differences that were not apparent from the group data, time series of RP and the resulting frequency couplings for three subjects are plotted in Figures 3 and 4. These data were taken from the PR+20% condition. S1 was a recreational runner averaging 10 miles per week. S2 was a competitive runner training about 60 miles per week. And S3 was a non-runner.
In Figure 4A is plotted an example of return maps with lags of 1-4 for each of the 3 subjects. These figures illustrate different relative phase patterns found across the speeds tested. S1 displays two groupings of points that converge to the line of identity when plotted with a lag of 2 or 4 indicating a rhythm of period 2 or 4. S2 displays a tendency for a period 2 rhythm because of the convergence of points to identity with a lag of 2. There is, however, no distinct grouping of points along the line of identity as seen in S1. S3 shows no convergence to identity with any of the lags used indicating that either there is no periodicity in the relative phase data or that it is made up of several different rhythms.

Both runners have a higher contribution of the dominant coupling than the non-runner does (Figure 2B). S2 and S3 predominantly used non-couplings as a source of variability whereas the non-runner (S3) showed more couplings other than the dominant present. Additionally, the higher mileage runner (S2) showed less strength in coupling than the less experienced runner (S1).

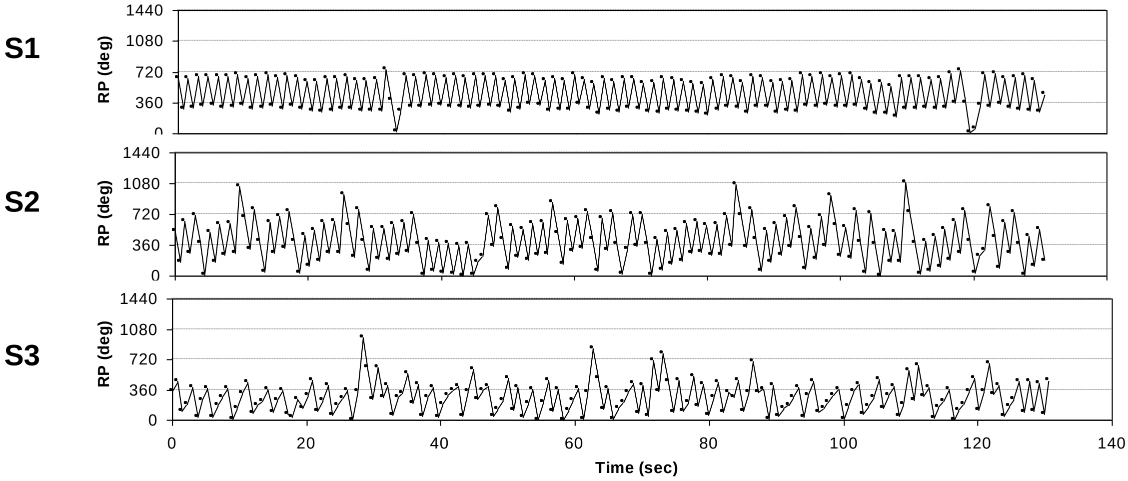

Figure 3 - Time series of RP for three subjects during the PR+20% condition.

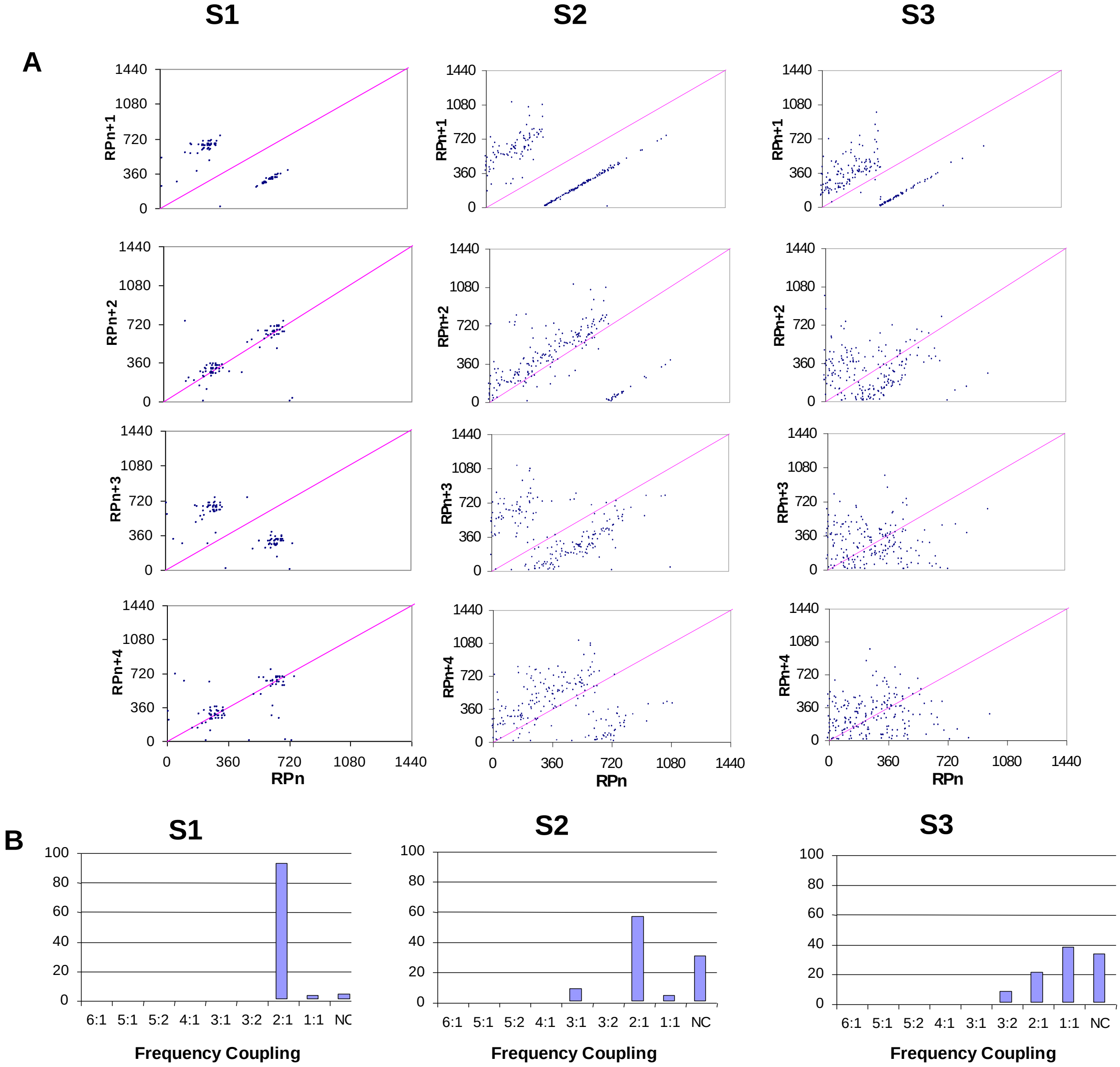

Figure 4 A - Example returm maps for the data presented in Figure 3. The data for each subject (columns) is plotted with lags of 1-4 (rows). B. Percentage of breaths occurring at each frequency coupling based on lag and range criteria.

Individual differences were also observed in the patterns of frequency couplings across conditions. The predominant pattern was that of no transition in the dominant coupling (Figure 5A). This was observed in four of the five runners. A gradual transition in the dominant coupling was observed where the dominant coupling changed from 2:1 to 1:1 using an intermediate 3:2. During these transitions, the second dominant coupling becoming the new dominant.

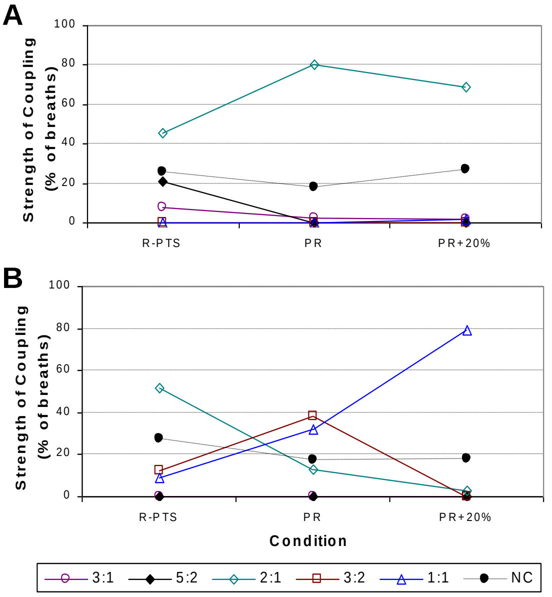

Figure 5 - Percentage of breaths occurring at each frequency coupling for two subjects. A. No transition in dominant coupling was observed in most runners. In this example, the 2:1 coupling remained as the dominant across speeds. B. Gradual transition observed in most non-runners. The dominant coupling changed from 2:1 to 3:2 to 1:1 with increasing speed.

DISCUSSION: The technique used in the present study allowed description of coupling strength and variability between locomotory and respiratory rhythms in which multiple frequency couplings are present. The group results suggest that there is little difference in terms of strength of coupling and variability in coupling between runners and non-runners. Across running speeds, subjects tend to maintain a dominant coupling for about 60% of the breath cycles. Grouping subjects according to running experience, however, masks individual differences. For example, experience level in terms of mileage and competition may not be indicative of coupling strength.

Differences between runners and non-runners may lie in the stability of the dominant frequency coupling across running speeds. The higher level of stability observed in the runners may reflect the adaptability of the respiratory system to meet the metabolic demand of the activity.

Insight into the nature of the coupling between locomotory and respiratory rhythms as observed in individuals could be beneficial for a training or rehabilitation program where respiratory efficiency is an important factor.

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