LOCOMOTOR RESPIRATORY COUPLING STRATEGIES DURING WALKING

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Recent research within human biomechanics has focused on variability in coordinative behavior. Using this approach, insight into the adaptive properties of the locomotor and respiratory systems was achieved by studying the coordinative properties that emerged in response to manipulating the constraints on these systems. Stride frequency (SF) was altered above and below preferred while participants walked at their preferred walking speed. Return map techniques allowed frequency and phase coupling strength and stability to be evaluated. As SF was decreased the dominant coupling was 2:1; when SF was increased the dominant coupling was 3:1. Strength of frequency coupling did not change with altered SF. The variability in locomotor respiratory coupling observed, particularly in phase coupling, strongly point to the necessity of variability, and not entrainment, in these rhythms.

KEY WORDS: locomotor, respiratory, entrainment, variability

INTRODUCTION: Stable, economical locomotion requires that the mechanical and metabolic demands of the movement be met in an ongoing fashion by the locomotory and respiratory systems. These systems do not act independent of one another. The optimal coordination between these systems must be achieved so that their respective task goals can be met. A wide range of frequency couplings between movement and respiratory rhythms has been observed in humans, including coupling ratios of 1:1, 3:2, 2:1, 5:2, 3:1, and 4:1, with the 2:1 ratio being used most often (Bernasconi and Kohl, 1993; McDermott et al., 2003). Despite the evidence that variability between these rhythms may be a necessary characteristic, most research on locomotor respiratory coupling (LRC) has its focus on entrainment. Entrainment is defined as frequency and phase locking (or synchronization) between two periodic systems (Kelso, 1995). Conventional views that entrainment between locomotor and respiratory rhythms is an optimal state have come from the observations that many animal species show strong mechanical constraints on respiration during locomotion. (e.g. horses have an almost fixed breathing to stride ratio of 1:1; Bramble and Carrier, 1983). In much of the literature investigating the LRC in humans there is evidence of entrainment occurring. However, these occurrences of entrainment are often variable and intermittent.

Within dynamical systems theory methodologies, the relative phase between oscillatory components in a system has been used as an order parameter to address issues of stability and change in the coordination. These changes come about in response to changing a control parameter such as movement cycle frequency. Relative phase has been identified as a relevant order parameter by Kelso (1984); it changes qualitatively at a critical value of the control parameter. The control parameter is an aspecific variable such as frequency or speed that can be used to drive the system from one stable state to another. It is unknown whether LRC is strongest at the preferred stride frequency (PSF) and how it varies when SF is varied. It has been speculated that greater limb frequency is associated with greater incidence of entrainment (Bechbache & Duffin, 1977). The aim of this experiment was to investigate the dynamics of the locomotor-respiratory system using SF as a control parameter.

METHODS: A total of 16 participants (age; 26±4years, mass; 79±13kg, height; 178±7 cm) were recruited from the population at large. All locomotion was performed on a motorized treadmill (Accumill P, Pacer Fitness Systems, TX). Heart rate was monitored using a Polar wireless heart rate transmitter and receiver (Polar CIC, MA, model Vantage XL). Respiratory airflow was recorded by means of the differential pressure transducer in a TEEM 100 Portable Metabolic Analysis System (Medical Graphics Corp, MN). Data were collected and stored using a custom written software program in Dasylab data acquisition software (Dasytec, MA). This system was also used to provide twenty-second averages of ventilatory and respiratory gas exchange variables during the experimental periods and breathing cycle events (end-inspiration, EI). The timing of heel strike (HS) was acquired by a force platform (AMTI) located beneath the front of the treadmill. Analysis of data was performed using custom written software in Matlab (The Math Works, MA). The experiment was designed in order to investigate the dynamics of LRC.

Three SFs were used: (a) walking at 20% below preferred stride frequency (PSF-20%), (b) walking at preferred stride frequency (PSF), (c) walking at 20% above preferred stride frequency (PSF+20%).

There were four test conditions, each involving a change of SF midway through the test. The four test conditions were (1) PSF-20% to PSF+20% (2) PSF+20% to PSF-20% (3) PSF to PSF-20% (4) PSF to PSF+20%. The four conditions were completed in a random order across participants walking at preferred walking speed (PWS). The PWS of the participants in this study was $4.1\pm0.45\ km\cdot h^{-1}$.

Breath cycles were determined by choosing peaks corresponding to EI of each breath. Discrete relative phase (DRP) was calculated between the breathing rhythm and HS (see McDermott et al, 2003 for detailed procedures). Using the time series of relative phase, it was possible to identify specific frequency couplings. Frequency couplings were defined as ratios of HS per breath occurring in more than one consecutive cycle. DRP was calculated between each left HS within a breath cycle and EI as follows:

$$DRP = \frac{t + nT}{T} * 360$$

Where
n is the number of complete stride cycles between each HS and the subsequent EI
T is the time duration of the stride in which EI occurred
t is the time lag from the beginning of the stride in which EI occurred to the subsequent EI.

Using return maps and systematic time lags consistent frequency couplings as well as specific phase relations that occur were found. Two variables obtained from the return maps were used to quantify the coupling in each condition. Firstly, the percentage of breaths occurring with the dominant frequency coupling (DC), independent of the value of the coupling, was used as a measure of the strength of frequency coupling. Secondly, the return maps were also used to quantify the strength of phase coupling (PC) in each condition. The strength of PC between EI and the preceding HS was assessed by the dispersion of points from the line of identity in the lowest range of each of the return maps (between 0° and 360° degrees). These data were all identified as frequency couplings. Perfect PC would be evident if all points were lying on the line of identity and variability in PC would be shown as deviations from this line. PC was quantified by first calculating the Euclidian distance of each point (d_n) from the line of identity and then summing the weighted distances (wd_n):

$$wd_n = \begin{cases} 1 - \dfrac{|d_n|}{40 * \cos(45)} , & d_n \le 40 \\ 0 , & d_n > 40 \end{cases}$$

$$PC = \frac{\sum_{n=1}^{m} wd_n}{m} * 100$$

Statistical analysis was performed by means of a repeated measures analysis of variance.

RESULTS: Increasing the stride frequency caused an increase in the dominant frequency coupling towards 3:1. Conversely decreasing the stride frequency caused a decrease in the dominant frequency coupling towards 2:1. The dominant frequency coupling at PSF was 2:1 (41%), followed by 3:1 (28%) and 4:1 (22%). At PSF-20% the dominant frequency coupling was 2:1 (56%), followed by 3:1 (18%) and 4:1 (12%). At PSF+20% the dominant frequency coupling was 3:1 (38%), followed by 2:1 and 5:1. The dominant coupling strategy utilized changed systematically when the stride frequency was altered (See Figure 1 for example transition data). In this Figure it can be seen that the DRP changed immediately after the change in SF (a). We can see the frequency coupling before (Figure 1- b, d, f) and after (Figure 1- c, e, g) this SF change.

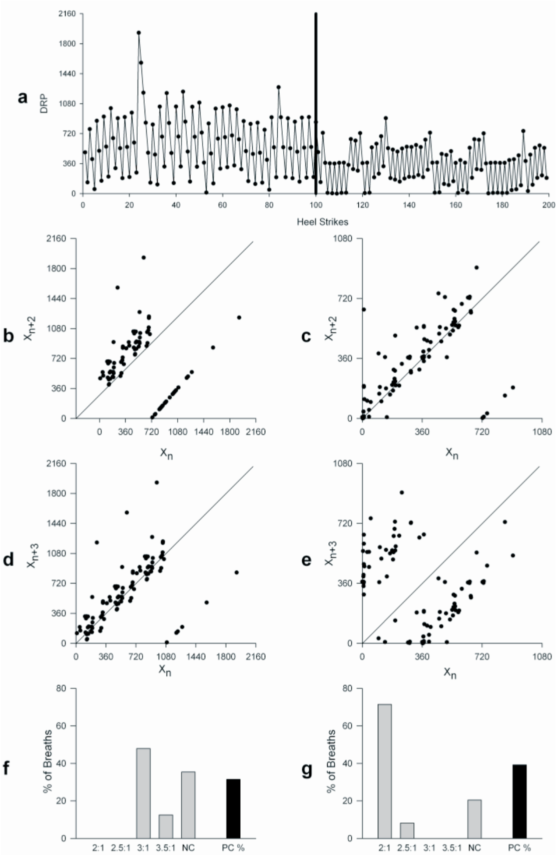

Figure 1: Example participant transition from PSF+20% to PSF-20%; SF change indicated by vertical line (a). Dominant frequency coupling changes from 3:1 (PSF+20%) to 2:1 (PSF-20%). Figure displays time series DRP (a), return maps with lag 2 (b &c) and with lag 3 (d & e), and frequency coupling used (f & g). PC represents strength of phase coupling. Columns represent data before (b, d, f) and after (c, e, g) SF change.

Strength of frequency coupling did not change significantly (P>0.05) between the initial SF and the second SF in any condition. On average the frequency coupling strength was between 45% and 60%. This data indicates that when adopting a new strategy in response to the change in control parameter, the strength will remain similar.

Strength of phase coupling did not significantly change (P>0.05) between stride frequencies. There were large inter individual differences in the phase couplings across all conditions. This can be seen in the standard deviation bars in Figure 2. It can also be seen that the phase coupling average is below 30% in all conditions.

The initial SF did not play a significant role in the coupling strategy employed during the final SF in each condition. The majority of the participants utilized the same dominant coupling strategy when altering SF twice to PSF-20% (75% of participants) and also when twice altering to PSF+20% (75% of participants) regardless of what the initial stride frequency was. The majority of the participants (87.5%) used the same dominant coupling strategy at the PSF condition.

DISCUSSION: The variability in LRC is observed in the low strength of phase coupling. Previous perspectives on this relationship support a greater entrainment between the rhythms. Contrary to this, our data strongly points to the necessity of variability in these rhythms. The importance of variability is consistent with newer perspectives concerning the study of complex rhythms that has recognized variability, not regularity to be a hallmark of

healthy, flexible control (Glass, 2001). The participants were consistently able to locate a new frequency coupling ratio when the control parameter was altered.
However, even when this consistent coupling was maintained, the phase of the cycle at which it occurred varied from cycle to cycle.
Contrary to our hypothesis that an increase in coupling would occur with increased frequency of movement, we found no significant change in phase coupling when stride frequency was increased to PSF+20%. The results showed the strength of coordination to be highly variable and individual in nature. Driving the stride frequency above preferred tended to change the frequency coupling used but not the strength of coupling. Decreasing the stride frequency, however, resulted in maintenance of 2:1 frequency coupling. Limb frequency does influence how the systems interact with each other with regard to dominant coupling used. However it does not increase the incidence of entrainment as had been speculated.

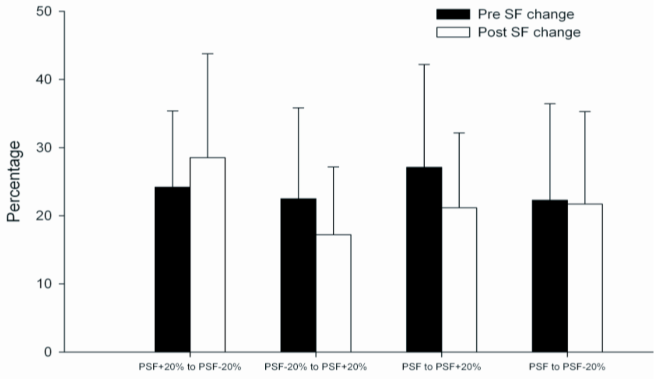

Figure 2: Phase Couplings before and after SF changes in all conditions. Error bars represent standard deviation

CONCLUSION: Previous research designed to alter the frequency of limb movement has found no consistent effect of the manipulations on the strength of LRC. However, this current research has investigated whether specific frequency and phase relationships occur between a locomotor rhythm and respiration to gain further insight into LRC. The results of the coordination measures within and across stride frequencies served to assess the coordinative dynamics and adaptive strategies of these systems. This study has illustrated the differential properties of locomotor respiratory frequency and phase coupling. This research provides further understanding of the adaptive properties of these rhythms to maintain stable locomotion. The methods used in this study provide a deeper view of the intricacies than previously used methods. Sports biomechanists should endeavor to examine the more complex details of the interactions between elements of the human locomotor system in order to gauge the true complexity of the system. The perspective of coupled non-linear oscillators where the primary aspects of the coordinative and adaptive behavior are a function of the individual oscillators, the cycling frequency, and the nature of the coupling between them can be adapted into all aspects of coupling across the biomechanics domain.

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