Coordination-related changes in the rhythms of breathing and walking in humans

Abstract Coordination of the respiratory rhythm with the rhythm of limb movements has often been observed during rhythmical exercise (e.g. in locomotion). It is usually associated with changes in the respiratory time course, but not in the locomotor rhythm. Therefore, we hypothesised that in walking, the extent of coordination-related changes (CRC) in respiratory parameters would increase with closer coordination. With respect to the controversially discussed question of a possible energetic advantage due to coordination, we devoted particular interest to the CRC in oxygen uptake ($\dot{V}O_2$). In addition, we investigated the incidence and the extent of CRC in the stepping rhythm. We examined 18 volunteers walking on a treadmill at three different workload levels, which were adjusted by altering either the velocity or slope of the treadmill. Each walking test was carried out twice, once with spontaneous breathing and once with breathing paced by a step-related acoustic signal to enhance the coordination between breathing and walking. No correlation was found between the CRC in the analysed parameters and the degree of coordination. However, the extent of CRC of ventilation and $\dot{V}O_2$ decreased with increasing workload. With the transition to coordination, increases and decreases of $\dot{V}O_2$ occurred about equally often. From this we conclude that energetic economisation in walking, as reflected by a reduction in $\dot{V}O_2$, is rather a side-effect of coordination, and is probably due to a more precise regulation of the breathing pattern. The economisation was more pronounced at higher work loads than at lower work loads. Our results revealed that coordination is also associated with changes in the stepping rate, which occurred more frequently when the variability of breathing was restricted by acoustic pacing of the breathing rhythm. This finding suggests that the choice of walking rhythm is not completely free, but can be influenced by the breathing rhythm. CRC in the walking rhythm might contribute to the avoidance of excessive CRC in the respiratory time course, which would entail an inefficient breathing pattern and thus, an energetic disadvantage.

Key words Coordination · Breathing-walking interactions · Breathing pattern · Oxygen uptake · PACed breathing

Introduction

Between simultaneous rhythmical movements, an integer rate ratio and a significant coincidence of certain phases of both movements, or even their synchronisation, can occur. This is termed “entrainment” or “coordination”. Coordination was described systematically for the first time in fin movements of fish by von Holst (1939). He demonstrated that the phenomena mentioned above were based on nervous interactions on a central (e.g. spinal) level. The rhythm generators of the processes concerned exert a mutual attraction, which by definition is an effect directed towards “entraining” the rate of either process to the intrinsic rate of the other. However, each process also tries to defend its intrinsic rate against the attraction exerted by the other rhythm. The resulting phenomenon, which is termed coordination, is determined by the relationship between the strength of attraction and the strength of the processes in maintaining their intrinsic rates.

In some combinations of rhythmical movements one process clearly predominates, so that the interaction seems to be unidirectional, as can be observed with the relationship between breathing and other rhythmical movements of the body. The coordination between breathing and rhythmical eye tracking movements
(Waurick 1973), finger tapping (Wilke et al. 1975), rhythmic arm and leg movements (Raßler et al. 1990), or locomotor movements such as walking and running (Bramble and Carrier 1983; Hill et al. 1988; Loring et al. 1990; Bernasconi and Kohl 1993; Bernasconi et al. 1995; Raßler and Kohl 1996), cycling (Kohl et al. 1981; Jasinskas et al. 1980; Bernasconi and Kohl 1993) and rowing (Mahler et al. 1991; Maclennan et al. 1994) has been characterised by entrainment of breathing to the simultaneous movement and by coordination-related changes (CRC) in the breathing rhythm. CRC in the rhythm of the other movement have seldom been reported (Raßler et al. 1990; Raßler and Kohl 1996).

The majority of motor activities (with the exception of breathing) are intended movements of limited duration. Intention, motivation, attention and, in part, mechanical constraints, for these movements are additional drives that can amplify their attractive effect on a commonly unconscious process like breathing.

Some studies have revealed that an increased load level or higher movement velocity and rate can enhance the coordination between movement and breathing (Bechbach and Duffin 1977; Raßler et al. 1990; Loring et al. 1990; Bernasconi et al. 1995). This was also confirmed by the results of our previous study on the coordination between breathing and walking in humans (Raßler and Kohl 1996). We had assumed that the attractive effect of walking movements increased under these conditions, and hence, breathing would more strongly subordinate to the walking rhythm. If closer coordination is based on stronger subordination of breathing to the additional movement, one should expect that closer coordination would increase the CRC in the respiratory rhythm. Hitherto, the extent of changes in the respiratory time course and in the ventilation accompanying the transition from a non-coordinated to a coordinated state, has not been investigated. Therefore, the purpose of the present paper was to re-analyse the results of Raßler and Kohl (1996) and to answer the following questions:

1. How do respiratory rate (f_R) and tidal volume (V_T) change with the transition to coordination between breathing and walking?
2. Are CRC in the breathing pattern associated with CRC in ventilation (V_E) and oxygen uptake (V_O_2)?
3. Is coordination between breathing and walking also associated with changes in the stepping rhythm (f_S)?
4. Does the extent of CRC in breathing and walking patterns depend upon the degree of coordination?
5. Is the extent of CRC in breathing and walking patterns influenced by the workload level?

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**Methods**

**Test persons**

We examined 18 healthy volunteers (10 males, 8 females) who had an average age of 32.8 years (range 22–53 years). They were informed in detail about the experimental protocol and all applied methods, but not about the purpose of the study. All subjects gave their written consent to participate in this study.

**Equipment and parameters**

The subjects exercised on a treadmill (Woodway-Geres, Loerrach, Germany) with adjustable velocity and slope. Respiratory air flow was measured continuously by an ultrasonic pneumotachograph (TUBA, GHG, Zurich, Switzerland) that was connected to a face mask. Concentrations of oxygen and carbon dioxide in the inspired air were measured continuously by a mass spectrometer (M3, Varian MAT, Zug, Switzerland). From the flow and gas concentration signals, further respiratory parameters such as inspiration time (t_in), expiration time (t_ex), f_R, V_E (BTSP), V_E (BTSP) and V_O_2 (STPD) were calculated continuously by an automatic breath-by-breath respiratory analysis system (Boutellier et al. 1987; Bührer et al. 1993). An on-line display of all of these parameters was available continuously. Leg movements were recorded by mechano-electrical goniometers that were constructed in the Department of Physiology at the University of Zurich. When the legs passed a pre-set angle (θ_Right and θ_Left for the right and left legs, respectively) starting from an approximately vertical leg position, an electronic signal marked the onset of a right or a left half-step. From these signals, we calculated the stride duration (s), the stride rate (s: number of full steps per minute), the rate ratio between stepping and breathing rates (s/s), and the relative phase-interval (RP) between respiratory and walking rhythms. The RP may be described as the interval between the onset of the right half-step and the starting points of inspiration or expiration (RP_R and RP_E, respectively) relative to a s ranging from 0 to 1.

**Experimental protocol**

We applied different load levels, produced by varying either treadmill velocity (L * V) or slope (L * S), to test whether the extent of CRC in the temporal patterns of breathing and walking depends upon the metabolic load per se, or on the walking velocity. The experimental protocol consisted of the subject standing quietly for about 5 min and then performing five walking tests at three load levels with the following characteristics:

1. Load level 1 (test L1): velocity = 1 m · s⁻¹, slope = 0, average V_O_2 = 655 (161) ml · min⁻¹.
2. Load level 2 (test L2V): velocity = 1.5 m · s⁻¹, slope = 0, average V_O_2 = 842 (173) ml · min⁻¹.
3. Load level 2 (test L2S): velocity = 1 m · s⁻¹, slope = 5%, average V_O_2 = 821 (166) ml · min⁻¹.
4. Load level 3 (test L3V): velocity = 1.8 m · s⁻¹, slope = 0, average V_O_2 = 1008 (230) ml · min⁻¹.
5. Load level 3 (test L3S): velocity = 1 m · s⁻¹, slope = 10%, average V_O_2 = 1037 (236) ml · min⁻¹.

The differences in V_O_2 between corresponding V and S tests (i.e. for load levels 2 and 3) were not significant.

The sequence of the walking tests was randomised. Each walking test was performed twice, once with spontaneous breathing (non-paced breathing, NPB) and once (in order to enhance coordination between breathing and stepping rhythms) with a step-related acoustic signal pacing the inspiration onset (step-guided breathing, SGB). During SGB subjects were allowed to choose which rate ratio between stepping and breathing rates they preferred. In addition, the subjects performed a walking test at their individually preferred treadmill velocity, the results of which are not included in the present analysis. The experimental protocol was approved by the local ethics committee.

**Evaluation**

From all parameters obtained, we calculated mean (SD) values. These were compared between NPB and SGB experiments.