Evaluation of Locomotor-Respiratory coupling (LRC) using the motion analysis system.

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***Abstract*—A breathing strategy to improve the endurance of the respiratory muscles during exercise is the synchronization between the respiratory and the locomotor muscles, named Locomotor-Respiratory Coupling (LRC). LRC refers to the frequency and the phase locking of running and breathing so that the same number of steps occur during each breath. This study aimed to find a way to exclusively utilize the motion analysis system to analyze LRC. Optoelectronic Plethysmography provides measurement of breathing ventilation and the gait events were detected by the acceleration signals from one marker placed on the trunk. Ten subjects (7 males, age 24.1 ± 1.3 years) were tested during 5 tasks of 5 effective minutes of exercise on a treadmill: walking at 4 km/h and at 6 km/h (W04, W06), uphill walking with 12% of slope at 4.5 km/h (S12) and running at 8 and 10 km/h (R08, R10). These 5 tasks were performed twice: with the individual breathing freely (SB) and with an imposed 2:1 LRC (CO). No correlation between the phase and frequency coupling and the type of activity was observed. Coupling had mostly an impact on time-related ventilatory parameters such as respiratory rate and minute ventilation by reducing their variability. The adaptation to this coupled rhythm could improve the control of ventilation during exercise leading to a more regular and efficient respiration and reducing the respiratory stress and fatigue during performance. We have shown that the motion analysis system can be used as a unique method for the evaluation of LRC.**

Keywords— Locomotor-Respiratory coupling, walking, opto-electronic plethysmography, running, entrainment

I. Introduction

Effective ventilation is essential to sustain locomotion in humans. During medium-high levels of exercise, the work of the respiratory muscle increases leading to fatigue and limiting performance. A breathing strategy to improve the endurance of the respiratory muscles during exercise is the synchronization between the respiratory and the locomotor muscles, named Locomotor-Respiratory Coupling (LRC). LRC refers to the frequency and the phase locking of running and breathing so that the same number of steps occur during each breath [1]. The frequency entrainment occurs when the individual can maintain the same ratio between the cadence and the respiratory frequency during the performance. Phase coupling means that the expiratory and inspiratory events occur in a preferable phase of the stride. Behind the locomotor-ventilatory interactions, there are both neural and mechanical factors [1].

Some authors investigated the beneficial effects of LRC on performance in terms of metabolic and energetic costs [1], [2]; others tried to understand if training may influence LRC and if it is possible to instruct the subject to increment the entrainment [3]. However, despite many attempts to determine if LRC is advantageous for humans, an ultimate conclusion has not been reached yet.

The most used techniques for measuring LRC are:

- Frequency coupling ratio between average number of strides and average number of breaths in a given period [4].
- Evaluation of phase locking based on the delay between respiratory transitions and the antecedent heel strike with respect to the stride time [4].
- Return maps to visualize both phase and frequency coupling [4].

Most of these studies used separate technologies to acquire the locomotory and the ventilatory parameters, namely IMU sensors, and pressure sensors for gait analysis and pneumotachograph or a spirometer for respiration. However, these systems may have low accuracy in lung volume measurements due to losses, additional dead space and artefacts for flow integration. Moreover, they are not comfortable for the individual during the activity because of the presence of valves in the mask which leads to more strenuous breath.

This study aimed to find a way to exclusively utilize the motion analysis system to analyze LRC in three different activities (walking, uphill walking and running). This system, through Optoelectronic Plethysmography (OEP), allows a more precise measurement of lung volume variations from the chest wall motion, and it allows also to explore thoraco-abdominal compartmental changes in volume between coupled and non-coupled activity. The gait events were detected by acceleration signals from one marker placed on the trunk. To evaluate the impact of LRC on the ventilatory parameters, performances, where subjects breathe spontaneously, were compared with those where 2:1 coupling was imposed.

II. Materials and Methods

A. Subjects

The protocol for the entrainment analysis was completed by 10 subjects (7 males and 3 females) age of 24.1 ± 1.3 years, weight of 67.5 ± 13.2 kg and height of 175.2 ± 12.7 cm. Each participant performed 5 tasks of 10 minutes: 1' of quiet breath, 5 effective minutes of exercise on a treadmill and 3' of recovery. The 5 tasks were: walking at 4 km/h and at 6 km/h (W04, W06), uphill walking with 12% of slope at 4.5 km/h (S12) and running at 8 and 10 km/h (R08, R10). These 5 tasks were performed twice: with the individual breathing freely (SB) and with an imposed 2:1 LRC (CO). After each performance, the subject was asked to rate their Perceived Exertion for both leg and breathing using the Borg Scale.

B. Motion analysis system

Both stride and respiratory cycle were tracked using the motion analysis system (OEP System; BTS, Milan, Italy) which is equipped with 8 special infrared cameras that project infrared beam and acquire data from retroreflective markers applied to the subject with 100 Hz of sampling frequency. SmartSuite package was used for the motion acquisition and the 3D reconstruction, which includes SmartCapture and SmartTracker software.

C. *Gait cycle detection*

The gait cycle was measured from one heel strike to the subsequent heel strike (HS) of the same foot. A preliminary test was conducted to find a method for the detection of the heel strike from one of the markers that belong to the geometrical model for OEP. Starting from a previous study [5] two markers placed at the level of L2 and L5 vertebrae were chosen to detect HS from their acceleration signals. The methods for HS detection were evaluated by comparing with the anteroposterior motion of a marker placed on the heel. It was chosen to detect the foot strikes through a peak method from the anteroposterior (AP) acceleration during walking and a relative max method during running from vertical (Vt) acceleration (Figure 1) of the marker number 72 at L2 level. The signals were filtered with an 8 Hz low pass filter (LP) for AP and 15 Hz LP for Vt to remove artefacts related to the double derivation of position. The right and the left HSs were separated using the lateral position of the same marker placed at L2 level: the right HSs were those which happened after a maximum in the x-signal. From the heel strikes the cadence was calculated as the number of steps per minute.

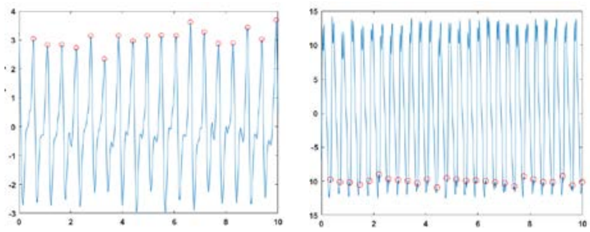

Figure 1. Heel strike detection method in trunk accelerations: from AP for walking a (left) and from Vt for running (right).

D. *Chest wall volume measurements and respiratory events detection*

The optoelectronic plethysmography computes the respiratory volumes from the chest wall motion by modelling the thoraco-abdominal surface with a triangular mesh obtained from the placement of 89 markers. The absolute volume is derived from the triangles surfaces through Gauss' theorem. OEP allows a compartmental study of the chest wall volume which is portioned into pulmonary rib cage volume (RCp), abdominal rib cage volume (RCa) and abdominal volume (AB).

The respiratory signals were filtered with a LP 1.2 Hz filter to remove the artifacts related to locomotion. Next, the maxima and minima position were saved to determine respectively the end-inspiratory and the end-expiratory time (tEI and tEE). For each acquisition 5 different periods were selected: during the first minute of quiet breathing (QB) as baseline value; the first and the last 90" of exercise (EX1 and EX2) and two periods of recovery (REC1 and REC2). From tEE and tEI were determined the end-expiratory and end-inspiratory volumes (EEV, EIV). Tidal volume (VT) was obtained by the difference between EIV and EEV, while the respiratory rate (RR) was calculated as the number of breaths per minute. From the product between RR and VT it was obtained the minute ventilation (VE).

E. *Entrainment analysis*

The analysis of entrainment was done only for EX1 and EX2 periods. To study LRC, tEE and tEI from the respiratory cycle and the right HSs were identified as previously described. Three methods were used to evaluate the LRC:

Stride-per-Breath Ratio: calculated as the ratio between half of the cadence and the respiratory rate (Eq.1) It gives information only about frequency entrainment.

$$R = \frac{\frac{cadence}{2}}{RR} \quad (1)$$

To evaluate the presence of frequency coupling the SBR is not enough, so the number of strides for each breath was counted and saved in a vector called N. Then to discover the dominant coupling (DC) and the non-coupled (NC) degree, the percentage of each number present in N was calculated considering them only when there were at least two consecutive equal numbers. The NC% was counted with all those different consecutive numbers.

<u>Phase coupling</u>: for each respiratory transition the relative phase (RP) was calculated as the ratio between the delay of the respiratory transition with respect to the previous foot strike and the corresponding stride period (Eq.2).

$$RP(i) = \frac{t_{EI}(i) - HS(j)}{HS(j+1) - HS(j)} \quad (2)$$

RP was calculated for all inspirations and expirations. Two vectors were constructed from RP values: one containing the sequence of deciles in which the respiratory event occurred (vector w) and a vector of length 10 with the sum for each decile (vector v) (Figure 2). The strength of the phase coupling (PC) is given by the highest percentage of event that occur in the preferred phase respect to the total. Two graphs were derived from these vectors:

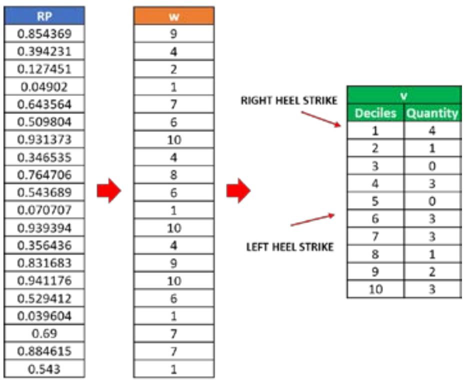

Figure 2. Schematic example of the procedure for the construction of the w (orange) and v (green) vectors.

histogram from v that shows dominant phase coupling; scatter plot from RP vector to get the trend relative phase. In Figure 3 there are both expiration graphs for SB (blue) and CO (green) cases. In the second case it is possible to see the phase locking between respiration and locomotion. Meanwhile in the SB case both the histogram and the scatter plot show a distribution of the expiration occurrence in various deciles, therefore there is no phase-locking between the two mechanisms.

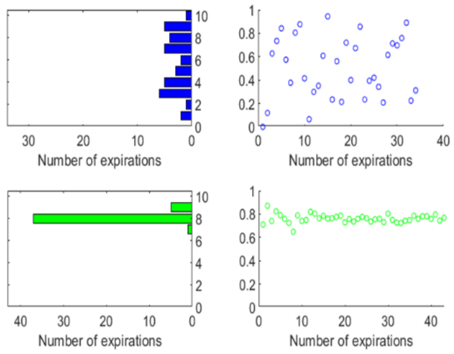

Figure 3. Example of histogram and scatter plot for both spontaneous (blue) and coupled (green) breathing.

Return maps-DRP: it gives visual information on both frequency and phase coupling. It is based on the calculation of discrete relative phase (DRP) (Eq.3).

$$DRP(i) = \frac{HS(i) - EI(j)}{T} \times 360° \qquad (3.1)$$

$$T = mean(\Delta HS_i) \qquad (3.2)$$

The return maps were constructed by plotting the DRP respect to the DRP shifted by n (depending on the SBR). From this type of graph, it is possible to see which SBR is followed and also how strong it is the phase locking from the distance of the points respect to the identity line. For example, in Figure 4 the second row of graphs refer to a CO: it is possible to see two agglomerates of points near the identity line for the plot with n=2: this means the subject was able to keep 2:1 frequency ratio and lock the phase. In the plot with DRP shifted of n= 3 the points are far from the identity line. For the SB condition, points were more disperse, but it could be observed that in the plot with n=2 they were more spread along the identity line than for n=3. This means that the subject during free breath had a SBR closer to 2 than 3.

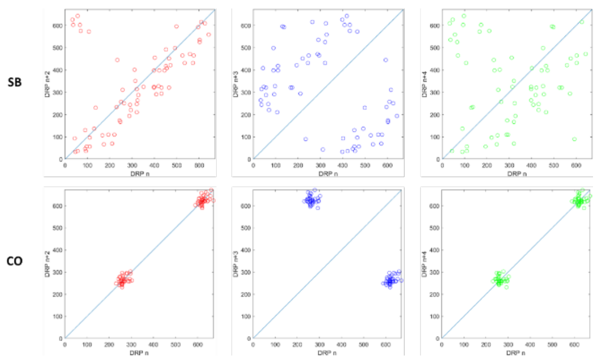

Figure 4. Example of return maps plot for n=2 (red, left panels), n=3 (blue, middle panels) and n=4 (green, right panels) in both spontaneous (SB, top panels) and coupled (CO, bottom panels) breathing.

F. Statistical analysis

The mean of each ventilatory parameter (RR, VT, VE, RCP%, AB%, EEV) were computed. Since the number of subjects was limited, we supposed the non-normality of the data; therefore, non-parametric tests were employed. The Friedman and its post-hoc Nemenyi test were done to identify significant differences among the phases of each acquisition (QB, EX1, EX2, REC1, REC2). To investigate the impact of LRC on the respiratory parameters, the two breathing conditions (SB and CO) were compared in both exercise periods using the Wilcoxon matched pair test. During the phase coupling analysis, the Kolmogorov-Smirnov test was done to quantify the uniformity of data distribution in the relative phase vectors and to verify if there was a preferred decile in which the respiratory transitions occur.

For EX1 and EX2 during both CO and SB, the variability of RR, VE, VT and its compartmental percentages was calculated. The variation coefficient (CV) was calculated as the ratio between the standard deviation and the mean to evaluate the influence of LRC on the regularity of breathing.

III. RESULTS

For the running tasks, the only 7 male subjects were considered for both the entrainment and ventilatory analysis because too many markers traces were registered for the three female subjects so it was not possible to reconstruct their chest wall motion.

A. Heel strike detection

All the adopted methods resulted reliable for the heel strike detection: the delays of the heel strikes identified from the L2-marker accelerations respect to the reference points obtained from the markers placed on the heels did not exceed 0.05 s and most of them were between 0 and 0.02 s. These values can be considered as not significative respect to the duration of the respiratory (1.3-3 s) and the gait cycle (0.75-1.4 s).

B. Entrainment results

The boxplots of the strength of phase locking (PC%), the dominant (DC) and the non-coupling (NC) degree among the different activities are shown in Figure 5.

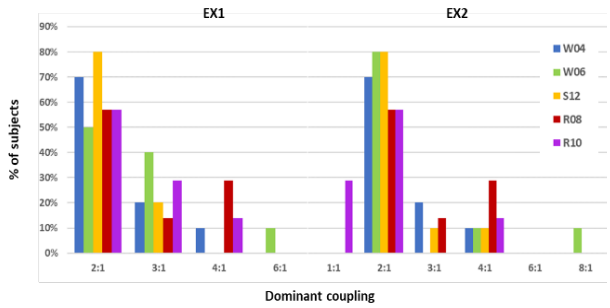

Figure 5. Prevalence rate of DC for both EX1 and EX2 in all the activities.

When 2:1 ratio was imposed, the phase coupling PC% moved from ~ 30% to > 80%. In terms of frequency coupling, during CO exercise, all subjects exhibited a dominant 2:1 LRC with a high percentage (DC> 85%) and consequently a very low non-coupled degree. For SB tasks DC% decreased in favor to NC%. The most common dominant coupling remained the 2:1 SBR, but other couplings were observed: 3:1, 4:1, 6:1 and 8:1 (Figure 6).

The Kolmogorov-Smirnov test confirmed the results obtained from phase coupling analysis: the test provided significative values (p<0.001) for all subjects in all CO activities, so expirations and inspirations were distributed not uniformly in the gait cycle, but they occur in preferred deciles. In the SB the test did not provide significative results, so there was no phase locking between respiration and locomotion, except for three subjects who lock the two rhythms in some of the tasks: one subject in both walking and running, one only in the ex2 walking at 4 and at 6 km/h, and the third only in running at 10 km/h

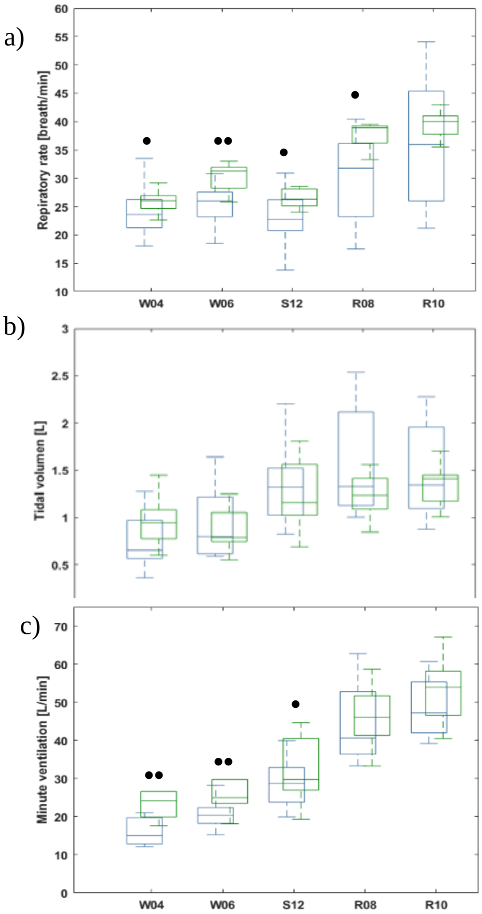

Figure 6. Respiratory rate (a), tidal volume (b) and minute ventilation (c) during W04, W06, S12, R08 and R10, without (blue) and with imposed 2.1 LRC (green). •,••: p<0.05,0.01 SB vs CO.

C. Ventilatory effect of LRC

The respiratory rate, the VT and the minute ventilation among the five activities are shown in Figure 7 comparing the SB (blue) and the CO (green) conditions. These parameters are those most influenced by the coupling. The RR during CO follow the trend of the cadence to keep the SBR equal to 2, so it is proportional to the velocity of the treadmill. During SB tasks RR increases with the sequence of the protocol activities (W04, W06, S12, R08 and R10). The statistical analysis with the Wilcoxon test provides significant difference of RR between SB and CO for both EX1 and EX2 except for the running at 10 km/h. VT increases for both conditions with the sequence of tasks. In the two running tests with spontaneous breathing, it was possible to observe from the plot that for few subjects the tidal volume reached higher values with respect to the CO condition. However, no significative differences emerged between CO and SB from the statistical analysis. The minute ventilation (i.e., the product of VT and RR) increases with the sequence of task moving from 20-30 L/min in the walking to 45-60 L/min in the running. Relevant differences between the two breathing conditions (CO vs SB) were provided during walking in both exercise periods, while during uphill walking and running only in the last 90” period. The variability of these three parameters was reduced by the coupled rhythm. In particular, the breathing frequency variability was the most reduced: its variation coefficient diminished from 15-30% to values under 6-8%. Tidal volume and ventilation regularity also increased, in particular for the three walking tasks as confirmed by a statistical analysis with the Wilcoxon test. CV of the tidal volume moved from 20-50% in SB exercise to 10-20% in CO and for the minute ventilation CV reached values between 15-20% in CO tasks respect to 30-40% in SB. CO had no impact on thoraco-abdominal compartments: both the RCP and the AB contributions to tidal volume did not change and there were no significant differences also between the end expiratory volumes (CW, RCP and AB). Moreover, CO had no effect also on the RPE for both leg (3.8 SB and 3.9 CO) and breathing (3.3 both).

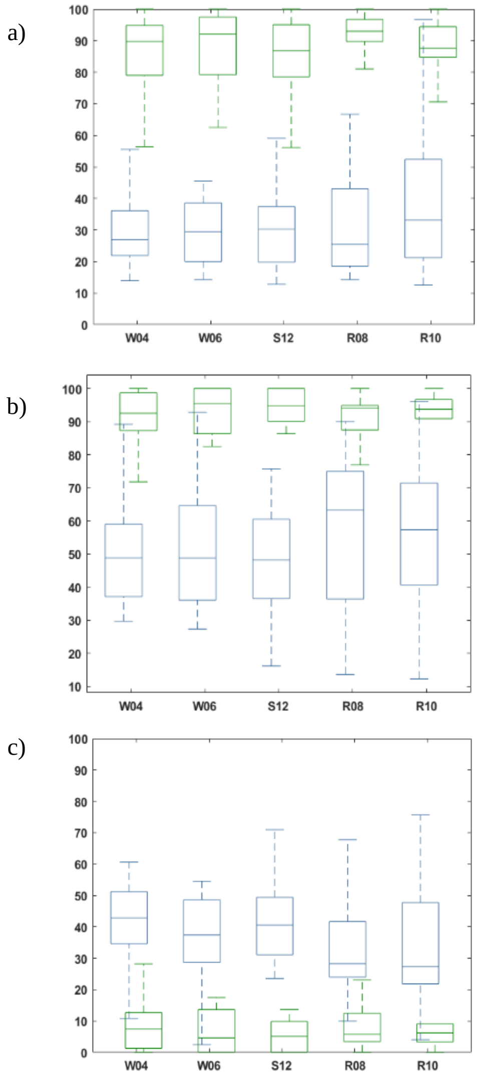

Figure 7. Comparison of LRC parameters between SB (blue) and CO (green) in all the activities: a) PC%; b) DC% and c) NC%.

IV. Discussion and Conclusion

Heel strike detection: The methods selected for the individuation of the right foot strike from the marker placed at the level of the L2 vertebra turned out to be reliable for both walking and running using respectively the antero-posterior and vertical accelerations. The delays respect to the reference point (i.e.: the marker placed on the heels) was negligible with respect to the gait and the respiratory cycle duration. Consequently, it was possible to analyse using only the motion analysis system and the 89 model markers both stride and respiratory cycle to evaluate the presence of LRC.

Analysis of LRC: Both the strength of phase locking (PC%) and the dominant coupling degree (DC%) were increased, while the non-coupled degree was diminished during the activities with imposed LRC. All individuals were therefore able to keep a 2:1 ratio and to lock respiration with locomotion. The preferred choice was a phase coinciding with a foot support, either right or left. Of course, it was not possible to determine if this strategy was due to a mechanical or neurological connection between locomotion and respiration. There were few subjects who showed a high PC% and DC% even in some of the SB tasks (e.g., S1, S3, and S10), meaning that they are more inclined to lock the two rhythms during exercise compared to others. The delays between inspirations and expirations with the preceding step were not uniformly distributed during coupled rhythm. No correlation between the phase and frequency coupling and the type of activity was observed. The significant difference was found only comparing SB and CO cases. No statistical differences were found between EX1 and EX2. Therefore, contrary to what could be hypothesized at the beginning, it was not seen any adaptability effect in terms of phase and frequency coupling. The stride-per-breath ratio is strongly correlated with the cadence and the respiratory rate. The cadence trends for the population were always the same, independently of the imposition of coupling as they depended on the treadmill speed. It is the breathing frequency that follows a different pattern between CO and SB. In the first, it reflected cadence to keep SBR equal to 2; while in the second, there was substantial variability among subjects, especially during walking where the effort was lower.

LRC effect on performance: Coupling had mostly impact on time-related ventilatory parameters such as respiratory rate and minute ventilation. LRC reduced the variability of all ventilatory parameters. The adaptation to this coupled rhythm could improve the control of ventilation during exercise leading to a more regular and efficient respiration and reducing the respiratory stress and fatigue during performance. The fact that both compartmental contributions and the EEV did not change significantly between CO and SB conditions means that LRC has no effect on the distribution of respiratory load and expiratory muscle activation.

Strengths and Limitations: For the first time, we have successfully presented an innovative method to evaluate the Locomotor-Respiratory coupling. The lack of references in the discussion section is because there are no other studies to allow for a comparison of the results The main limitation of the proposed approach is the study population. Firstly, the relatively small sample size may limit the generalizability of the findings. However, this was mainly a methodological study to verify the feasibility of using only one system (OEP) to detect both breathing and the gait cycle. Secondly, the gender disparity is another limitation, since only male subjects were considered for running, potentially introducing gender bias into the study outcomes. This gap can be filled by improving the tracking procedures of OEP

To conclude, the main goal of the project was achieved, as it was found a unique method for the evaluation of LRC (the motion analysis system). The LRC has effect on respiratory rate and minute ventilation reducing their variability without impacting on the thoraco-abdominal patterns. According to the results and the drawbacks the following implementations might be considered:

- Introduce simplify model for OEP reducing the number of markers to solve the problem of tracking during female running acquisitions.
- Increase the number of subjects to obtain more reliable results on LRC.
- Evaluate other coupling ratios such as 3:1 4:1 or a subject preferential SBR based on the previous spontaneous tasks.
- Evaluation of the LRC on professional athletes and patients with pulmonary diseases.

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