**LOCOMOTOR-RESPIRATORY COUPLING
DURING AXILLARY-CRUTCH AMBULATION**

by

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for the degree of Master of Science**

at

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DEDICATION

This thesis is dedicated to Chris, Darren, Dave and Sushu who were there at the beginning, to Julian, Colin and Sean who were there at the end and to all those who have gone before, making an unfamiliar road strangely welcome.

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ABSTRACT

Locomotor-respiratory coupling (LRC) has been detected in a number of mammalian and avian species. In running species, visceral movement due to impact loading is believed to be responsible for this phenomenon, whereas the effect of the wing muscles on the timing of respiration appears to be a dominant influence in the flying species in which LRC has been described. To test the hypotheses that i) LRC occurs in humans ambulating on axillary crutches (where both impact loading is present and the arms assist in the locomotion) and ii) that the timing of the respiratory events is consistent, within and among subjects, 18 able-bodied persons were trained and studied on a motorized treadmill. Coupling was considered to be present when i) the gait and breathing rates were within 5% (or 2.5%) of each other ("loose" and "tight" coupling respectively) for a minimum of 10 consecutive gait cycles and ii) qualitatively there was no drift of the respiratory phases relative to the onset of the gait cycle. These criteria were validated by comparison with a subject who coupled intentionally. Ten (56%) of the 18 subjects exhibited LRC. Thirty-two episodes met the criterion for loose coupling and 9 of these episodes also met the criterion for tight coupling. One episode of coupling was identified as having a 2:1 locomotor-respiratory pattern whereas the other identified episodes were 1:1. The timing of the respiratory phases relative to the gait cycle was fairly consistent among the subjects who exhibited LRC. Inspiration was found to usually occur during the crutch-swing phase of the gait cycle whereas expiration usually occurred during crutch-stance. This suggests that, under these experimental conditions, the visceral-piston phenomenon could contribute to LRC. This study provides insight into the basic mechanisms of LRC and may have implications for training in the use of axillary crutches.

LIST OF ABBREVIATIONS

LRC - locomotor-respiratory coupling	cm - centimetre
OH - Ohio	kg - kilogram
DC - Direct Current	M - male
ECG - electrocardiography	F - female
A-D - analog to digital	R - right
m - metre	L - left
s - second	FREQ - frequency
Hz - Hertz	G - gait
SD - standard deviation	R - resp
BPM - beats per minute	TRED - treadmill
APM - age predicted maximum	RESP - respiration
HR - heart rate	CLFL - Clinical Locomotor Function
YRS - years	Laboratory

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Gentlemen, my sincerest thanks.

INTRODUCTION

Locomotion and respiration have been intensely studied as separate entities but there has been relatively little work on the interaction of the two. This synchronization of the respiratory cycle with the gait pattern is referred to as locomotor-respiratory coupling (LRC). Studies of varied forms of locomotion suggest that there may be mechanical and physiological benefits for an organism to link its respiration to its ambulation.

LRC has been studied in multiple species, employing very different patterns of locomotion. LRC has been documented in flying species (such as birds and bats), in quadrupeds (such as dogs, horses and rabbits), and in bipedal organisms (such as wallabies and humans). Interestingly, the ratio of locomotor-to-respiratory events and the timing of respiratory and gait events differs between types of locomotion.

As a result, two theories have been proposed to explain the LRC phenomenon: 1) the visceral piston and 2) the rhythmic contraction of the upper limbs. The visceral-piston theory proposes that the movement of the mobile abdominal viscera exerts forces on the diaphragm that make it advantageous to synchronize the two. This theory has been suggested to explain LRC in galloping horses, hopping wallabies and running humans. The alternate theory postulates that the rhythmic contraction of the upper-limb musculature exerts forces on the rib cage that would aid in respiration. This theory has been utilized to explain the presence of LRC in flying species and in humans rowing and arm-cranking.

Despite the long history of their use, very little research has been performed on crutch ambulation. These common ambulation aids provide an opportunity to test the two theories that have been used to explain LRC. When the swing-through gait pattern is employed with axillary crutches, the visceral-piston theory would suggest that expiration should occur during the crutch-phase of the gait cycle as the trunk is swung forward and the abdominal viscera are pushed into the diaphragm. Conversely, the rhythmic contraction of the upper-limb muscles produced with this mode of ambulation should cause inspiration to occur during crutch-stance, when the upper limb musculature is employed to support the entire body weight of the individual.

STATEMENT OF PURPOSE

The purpose of this study was to utilize both qualitative and quantitative procedures to detect LRC in humans employing axillary crutches in the swing-through gait pattern. The timing of the respiratory phases were compared to the gait-cycle phases to provide insight to the causes and mechanisms of LRC.

RESEARCH IMPLICATIONS AND RELEVANCE

The identification of LRC in humans employing axillary-crutches in the swing-through gait pattern may identify a previously identified physiological phenomenon in a new setting. The information gleaned may be used to shed light on the mechanisms involved and on such clinical issues as the most effective training in the use of axillary crutches.

RESEARCH HYPOTHESES

- 1) LRC occurs in humans employing axillary crutches in a swing-through ambulation pattern.
- 2) During LRC, the timing of breathing is consistent within and among subjects, with expiration corresponding to either the crutch-swing or crutch-stance phase of the gait cycle.

DELIMITATIONS

- 1) A subject population between 18 and 35 years.
- 2) A study population of $n = 18$.
- 3) Two subject populations, males and females.
- 4) A subject population of healthy individuals.
- 5) A subject population with no previous crutch experience.

LIMITATIONS

- 1) Motivation and lifestyle of the subject group were not controlled.
- 2) Nutritional status of the subject group was not controlled.
- 3) Physical conditioning levels of the subject group was not controlled.
- 4) Anthropometric characteristics of the subject group were not controlled.

STUDY SIGNIFICANCE

If LRC is documented in humans employing the swing-through gait pattern with axillary-crutches, it will contribute to the existing body of research in this area. The identification of LRC will reveal a recognized physiological phenomenon in a new setting and will have implications for clinical practise.

REVIEW OF THE LITERATURE

Among the biomechanical and physiological bases of locomotion, one increasingly recognized factor is how a species' locomotor pattern influences its respiratory behaviour (Bechbach & Duffin, 1987; Bramble, 1989; Carrier, 1987; Garlando, Kohl, Kohler & Pietsch, 1985; Hill, Adams, Parker & Rochester, 1988; Loring, Mead & Waggener, 1990). There is evidence that proprioceptive input influences the respiratory response to exercise (Iscoe & Polosa, 1976; Palisses, Persegol, Viala & Viala, 1988), but central oscillators (Eldridge, Millhorn, Kiley & Waldrop, 1985; Viala, Persegol & Palisses, 1987) have been shown to drive the muscles of locomotion and ventilation even in the absence of afferent feedback. Mechanical data suggest that activities, like flying and running, impose certain mechanical constraints on breathing that make it beneficial for the respiratory cycle to synchronize with the locomotor pattern. This phenomenon is referred to as locomotor-respiratory coupling (LRC) (Berger, Hart & Roy, 1970; Bramble, 1989; Carpenter, 1986; Carrier, 1987; Hart & Roy, 1966; Suthers, Thomas & Suthers, 1972).

A number of avian species have also been shown to demonstrate LRC, although the dominant observed ratios vary with the species. Barnacle geese have exhibited three wing beats per breath (Butler & Woakes, 1980), whereas pigeons have been reported to couple in a 1:1 ratio (Hart & Roy, 1966). Interestingly, birds and bats differ with respect to the timing of respiration during wing beat. Hart and Roy (1966) noted that peak expiration in pigeons coincides with the bottom of wing downstroke and peak inspiration with the top of upstroke.

Cineradiography of European starlings has revealed that the U-shaped furcula (the fused clavicles) bends laterally during downstroke, aiding inspiration, and recoils during upstroke (Jenkins, Dial & Goslow, 1988). In bats that couple at a 1:1 ratio of wing beats to breaths, inspiration coincides with the power downstroke of the wings and expiration with the recovery upstroke (Carpenter, 1986; Suthers et al., 1972).

Quadrupedal species, such as jackrabbits, horses and dogs, normally synchronize their running and breathing within a few gait cycles, depending on their speed of locomotion (Bramble, 1989; Hornike, Meixner & Pullman, 1983). In running quadrupeds, the thorax is alternately loaded as the forelimbs strike the ground, which aids expiration, and stretched as the forelimbs reach toward the next ground contact in the free-flight phase, aiding inspiration (Bramble, 1989; Persegol, Jordan & Viala, 1991).

LRC has also been demonstrated in upright species, including mammals (Baudinette, Gannon, Runcinman, Wells & Love, 1987; Bramble, 1989). In human runners, the LRC pattern adopted varies among subjects (e.g., 2:1, 5:2) (Bramble, 1989). One explanation for LRC in both upright and quadrupedal species is that the abdominal viscera (particularly the liver) may act like a piston, rhythmically placing pressure or traction on the diaphragm as a result of the running motion (Bramble, 1989; Bramble & Jenkins, 1993). Baudinette et al. (1987) proposed a similar mechanism in their study of hopping Tammar wallabies. A study of LRC and wheelchair propulsion was performed by MacDonald, Kirby, Nugent and MacLeod (1992) in the hope of identifying LRC in the absence of the visceral-piston effect.

No coupling was detected, which is consistent with the theory that the visceral piston is important to LRC. The authors concluded that rhythmic arm movements alone were insufficient to induce the phenomenon in this setting. However, LRC has been described in cycling, arm-cranking and rowers (Mahler, Hunter, Lentine & Ward, 1991; MacLennan, Silvestri, Ward & Mahler, 1994; Paterson, Wood, Morton & Henstridge, 1986) where rhythmic arm movements are the major form of motion, suggesting the converse.

Very little information is available at present on the physiology of crutch ambulation, and none with respect to LRC. Crutches and other ambulation aids (e.g., canes, walkers) are very commonly used when one or more of the lower limbs is painful, deformed or has been amputated. Of the various crutch gaits (e.g., four-point, three-point, alternating two-point, tripod), the one that most closely resembles galloping in quadrupeds (without the airborne phase) is the swing-through gait. This gait is used most commonly when one limb is injured (e.g., by an ankle sprain) or absent. The swing-through gait begins with both crutches in front of the subject while the body weight is supported by both the crutches and the lower limb(s). Weight is then transferred exclusively to the crutches as the body is elevated and swung forward beyond the points of crutch contact. The body weight is again supported by both the crutches and the lower limb(s). Weight is then transferred exclusively to the lower limb(s) as the crutches are lifted off the ground and swung forward to a position in front of the subject. The gait cycle then repeats itself (Childs, 1964; Varghese, 1980). Used in this fashion, axillary crutches transiently transfer 100% of the subject's body weight to the upper limbs (Eldridge et al., 1985; Jebsen, 1967).

In considering whether LRC might occur during swing-through ambulation with axillary crutches, two opposing theories for this phenomenon can be tested. Such a gait might permit the downward stroke of the visceral piston to function at, and shortly after, foot strike (assisting inspiration). The upward stroke of the visceral piston might occur after the initial contact of the crutches, which decelerates the forward movement of the body (assisting expiration). Also, the contraction of the abdominal musculature (Chantraine & Onkelinx, 1975; Peacock, 1966) and the resultant forward lumbar flexion during the lower-limb swing phase of the gait cycle should increase intra-abdominal pressure and force the abdominal contents vertically into the diaphragm, enhancing expiration during crutch stance.

An alternate theory for LRC suggests that the observed phenomenon results from the rhythmic movement of the upper limbs during locomotion (Mahler et al., 1991; MacLennan et al., 1994; Paterson et al., 1986). The upper-limb musculature is active during crutch stance when the body weight is supported exclusively by the upper-limbs. Many of the upper-limb muscles involved in the crutch-stance phase (e.g., pectoralis major, pectoralis minor, latissimus dorsi) are attached, either directly or indirectly (via a stabilized scapula), to the rib cage and function in closed kinetic chain as accessory muscles of respiration, aiding inspiration with their contractions during heavy work (Peacock, 1966). The rhythmic actions of the upper limb should promote inspiration during the crutch-stance phase, the opposite of what would be expected from consideration of the visceral-piston (and associated intra-abdominal pressure) influences.

If LRC can be convincingly demonstrated during the swing-through gait with axillary crutches, it will add to the body of evidence about LRC in humans. Furthermore, if axillary-crutch ambulation induces LRC, the timing of respiratory events in the locomotor gait cycle may shed light on the relative importance of the visceral piston versus the upper-limb muscle contractions in the genesis of LRC.

METHODOLOGY

Subjects

A sample of 20 subjects was felt to be practical to recruit, train, test and analyse with the time and resources available. LRC in human subjects has been reported in 53% of subjects walking and 80% of runners (Bechbach & Duffin, 1977). Axillary-crutch ambulation with the swing-through gait has been quantified as exercise more demanding than walking (Bard & Ralston, 1959; Erdman, Hettinger & Saez, 1960; Fisher & Patterson, 1981; Waters & Yakura, 1989) and equal to a comfortable run (Bhambhani & Clarkson, 1989; Patterson & Fisher, 1981), therefore it was felt that this activity would be strenuous enough to produce LRC within the proposed sample if it existed. Earlier studies that have reported LRC in humans have been able to demonstrate the phenomenon with smaller sample sizes (Mahler et al., 1991; MacLennan et al., 1994; Persegol et al., 1991).

Able-bodied subjects were selected for safety and convenience. Also, previously reported biomechanical evidence suggests that a healthy subject suspending the non-dominant foot is a mechanically close approximation of the disabled state (Goh, Toh & Bose, 1986; Stallard, Sankarankutty & Rose, 1978). Many users of the axillary-crutch swing-through gait are otherwise able-bodied people who have sustained an injury to one lower limb (e.g., a fracture near the ankle). Subjects were excluded if they habitually used crutches or had previous crutch experience. Novice crutch users were selected and enrolled in a uniform training protocol (described later) to produce subjects with comparable skill levels.

Subjects were requested to refrain from consuming food or caffeine, from smoking, and from strenuous exercise for two hours before testing. Although subjects were informed of the protocols of training and testing, they were blinded to the goal of observing LRC until after the test data were obtained. Subjects wore short pants, a t-shirt and a pair of running or court shoes with good tread. Each subject completed a questionnaire containing information about age, gender, height, weight, previous crutch experience and general medical information. All subjects who entered the study were accounted for.

Twenty-two subjects (9 females and 13 males) were enrolled in the pre-study training regimen, of which 20 subjects (7 females and 13 males, aged 18-35 years) successfully completed the training program and were formally tested. Subject demographics are shown in Table 1. The subjects' handedness was based on which hand was used for writing and the footedness was based on which leg was reported as being used to kick a ball. The two female subjects who dropped out of the training regimen did so for reasons of shoulder discomfort. All but one of the 22 subjects selected the dominant foot to elevate. Eighteen of the 20 subjects were deemed of sufficient skill and comfort after three sessions of training to proceed onto testing, the remaining two subjects required a fourth training session. The data obtained on two of the 20 subjects tested were not properly recorded and lost to subsequent analysis.

Ethical Issues

This study was approved by the Research Ethics Committee of the Nova Scotia

**TABLE 1: SUBJECT DEMOGRAPHICS
(n=18)**

SUBJECT	SEX	AGE (yrs)	HEIGHT (cm)	WEIGHT (kg)	HAND	FOOT
1	M	25	171	55	R	L
2	M	22	187	94	L	L
3	M	26	180	77	R	R
4	M	23	170	72	R	R
5	F	23	165	52	R	R
7	M	26	182	96	R	R
9	M	27	173	73	R	R
10	F	27	170	57	R	R
11	M	25	180	76	R	R
12	M	29	186	95	R	R
13	F	25	165	46	R	R
14	F	24	167	55	R	R
15	F	25	165	61	R	R
16	M	25	178	72	R	R
17	M	24	185	101	R	R
18	F	21	163	56	R	R
19	M	20	177	75	R	R
20	M	21	182	77	R	R
MEAN	M=12 F=6	24	174	70	R=17 L=1	R=16 L=2
SD		2.4	8.1	16.7		

HAND = Handedness (based on writing preference)

FOOT = Footedness (based on kicking preference)

M = Male

F = Female

R = Right

L = Left

SD = Standard Deviation

Rehabilitation Centre, one site of the Queen Elizabeth II Health Sciences Centre, and the Faculty of Graduate Studies. All subjects were informed as to the time commitment (approximately two hours over four occasions), required activity and potential risks, and gave their informed consent.

Training

Recent studies suggest that LRC in humans performing learned tasks such as rowing may only develop LRC after several weeks of training (Mahler et al., 1991; MacLennan et al., 1994). Likewise, it was a concern that coupling might not occur if the subjects could not attain sufficient steady state velocity to necessitate LRC. It is known that comfort and consistency during treadmill ambulation can be enhanced through training (Wall & Charteris, 1980, 1981). Therefore, it was felt necessary to develop and implement a uniform training program for subjects, to ensure their familiarity with, and velocity during, axillary-crutch ambulation. The training protocol was developed during pilot testing.

All training and testing was performed at the Clinical Locomotor Function Laboratory (CLFL) at the Nova Scotia Rehabilitation Centre. The training regimen (See Appendix A) was used to accustom the subjects to the use of axillary crutches and the swing-through gait with one foot held aloft on the motorized treadmill, under conditions similar to those of later testing. At least three separate training sessions, within a two-week period, were used for each subject.

During the first session, subjects were fitted with adjustable wooden axillary crutches. The axillary cross-pieces were positioned approximately 5 cm below the upper anterior axillary border and the hand grips such that the elbows were flexed 20-30° while the crutch tips rested on the floor 15 cm ahead of and 15 cm lateral to the 5th metatarsal heads (Joyce & Kirby, 1991). The adjustment values were recorded to ensure that the same settings were used in subsequent sessions. Foam rubber pads were used to cushion the axillary cross-pieces and the handles.

During the training sessions, the subjects ambulated over ground and on the treadmill in the swing-through pattern with one foot elevated to get accustomed to, and comfortable with, crutch walking. Subjects chose which foot was held aloft during ambulation based on comfort and the selection was recorded. The same foot was held aloft for all training and testing sessions. Subjects were informed about the control of the treadmill and its safety features. The training program was considered complete when, after a minimum of three sessions, the subject reported feeling comfortable with the experimental conditions, when the investigator observed a steady, confident gait and when the exercise intensity corresponded to “somewhat hard” on the Borg perceived exertion scale.

Treadmill Protocol

Although it is well recognized that treadmill ambulation differs subtly from over-ground ambulation (Nigg, De Boer & Fisher, 1995), a motorized treadmill was chosen for ease of data collection, velocity control, safety and equipment availability. The treadmill (model

ELG2, Woodway-Ceres GmbH, Weil am Rhein, West Germany) had a 70-cm wide, 204-cm-long belt. Side rails 15 cm high were installed on either side of the track to aid the subjects in placing the crutch tips on the tread during crutch strike. An emergency stop button was positioned next to the subject and another on the control console for subject safety. Treadmill function was tested before each trial.

Gait Cycles

For the purposes of this study, the gait-cycle *events* consisted of initial contact of crutches (0 and 100% of the gait cycle) and lift-off of crutches. The *phases* of the swing-through gait cycle were crutch stance (between initial contact and lift-off of the crutches) and crutch swing (between lift-off and the next contact of the crutches) (Goh et al., 1986). Change in treadmill motor current, as measured by an ammeter (model 10, Type 2, Triplet Corporation, Buffon, OH), was employed in pilot work to document gait cycles (MacDonald et al., 1992) but it was determined that the resulting signal was too noisy to allow precise timing of the gait cycle. The number and timing of the crutch gait cycles was therefore assessed by a pressure-sensitive wafer switch under the tip of the left crutch. In the swing-through gait, pilot work indicated that the crutch tips contacted the ground at approximately the same time, so one crutch switch was deemed sufficient to provide consistent information about the crutch gait cycle. Pilot work demonstrated that this switch provided a clean, rectangular (on-off) signal that facilitated the data reduction (Figure 1). The current in the switch-signal circuit was passed into a separate low-level DC preamplifier (model 7P1 A, Grass Medical Instruments) and a low-pass filter (500 Hz) was used. The switch was validated before each

FIGURE 1: THERMOCOUPLE AND CRUTCH SWITCH OUTPUT SIGNALS

NOTE: INCREASED TEMPERATURE IS DOWN IN ABOVE FIGURE

trial to ensure that it was operating effectively.

Respiration

For the purposes of this study, the respiratory *events* consisted of the initiation of inspiration and the initiation of expiration. The *phases* of the respiratory cycle were inspiration (between the initiation of inspiration and the initiation of expiration) and expiration (between the initiation of expiration and the initiation of inspiration). Breathing frequency was recorded by using a temperature-sensor thermocouple (model TCT-IR, Grass Medical Instruments) that responded to the temperature increase that occurred during expiration (Carpenter, 1986; Loring et al., 1990; MacDonald et al, 1992; Suthers et al., 1972) (Figure 1). A low-level DC preamplifier (model 7P1 A, Grass Medical Instruments) was used with a low-pass filter (500 Hz). The thermocouple was chosen over a pneumotachometer (that was assessed in pilot testing) for reasons of equipment availability, signal clarity, reduced weight and reduced interference with the subject's vision. The thermocouple was attached to the distal aperture of a disposable cardboard mouthpiece held in the subject's mouth. A mouthpiece has been reported to interfere with respiration (Weissman, Askanazi, Milic-Emili & Kinney, 1984) but pilot work without a mouthpiece did not provide a satisfactory signal (MacDonald et al., 1992). A fan was placed at the side of the subjects, because pilot testing revealed that a fan blowing across the end of the mouthpiece returned the thermocouple signal to baseline more rapidly. Nose clips were not used because they were demonstrated in pilot work to be unnecessary and it has been reported that their use may affect tidal volume, minute volume, inspiratory flow and respiratory frequency (Waters & Yakura,

1989). The thermocouple was validated before each testing session by recording isolated inspiration and expiration events.

Heart Rate

Heart rate was electrocardiographically (ECG) monitored by a telemetry system (Gemtel model TTX-12, three-electrode CM5 lead placement). Heart rate was used to document exercise intensity as a percentage of the age-predicted maximum ($220 - \text{age}/100$).

Testing Protocol

At the beginning of the testing session (at least one and no more than seven days after completion of the training), the subjects were reminded of the procedures and precautions in place. The crutch-switch and thermocouple functions were validated with each subject. Subjects were asked not to speak unnecessarily during testing because pilot work had identified this as a source of error in the respiratory signal. If visibly abnormal breathing (e.g., vocalization, coughing) or ambulation (e.g., bipedal walking, hopping) occurred, the timing of this was noted. With the testing equipment in place, subjects ambulated at increasing speeds up to their self-selected comfortable crutch-ambulation speed and remained at that speed for a distance of 200 m, which acted as a warm-up period. Subjects were then brought to rest at which time subject comfort with the experimental conditions was confirmed. The subjects then began ambulating at increasing speed over one minute until they reached a self-selected velocity that corresponded to "somewhat hard" activity on the Borg perceived exertion scale (Borg, 1982), approximately equivalent to a heart rate within

60-80% of their age-predicted maximum. (As can be seen in Table 2, the actual mean heart rate achieved was 77% of the age-predicted maximum.) This velocity was maintained for 5 minutes, while data were recorded for later analysis. It was assumed that five minutes of ambulation at this intensity would permit the subjects sufficient time to reach a steady exercise state, in accordance with oxygen-consumption principles. After the 5 minutes of data collection, the subjects resumed normal walking and the speed of the treadmill was reduced to 0 m/s over a period of several minutes to provide a warm-down period.

As a standard for LRC comparison, subject 16 intentionally performed LRC after the original data collection was performed. The subject synchronized inspiration to crutch-strike, expiration to crutch-strike, inspiration to crutch-swing and expiration to crutch-swing. The subject also performed a trial of intentional non-coupling. This information was subjected to raster analysis (described below) and employed in the qualitative evaluation of coupling morphology and timing of respiratory events.

Data Collection & Analysis

The crutch-switch and thermocouple signals were recorded on a Grass polygraph (DC driver amplifier model 7DA) to monitor signal quality. The signals were also digitized at 200 Hz using an A-D card (12 bit, AT-MIO-16), stored in an Excel data sheet and processed through a customized Lab Windows program (National Instruments) on computer (Compaq 80386) for later analysis. Low-pass digital filtering of the thermocouple signal at 500 Hz was used to further smooth the signal and to facilitate the automatic detection of the inflection points

TABLE 2: HEART RATE DATA
(n=18)

SUBJECT	AGE	MEAN HR (BPM)	APM (220-age)	MEAN HR/APM (%)
1	25	175	195	90
2	22	175	198	88
3	26	142	194	73
4	23	142	197	72
5	23	165	197	84
7	26	143	194	74
9	27	135	193	70
10	27	160	193	83
11	25	135	195	69
12	29	132	191	69
13	25	160	195	82
14	24	136	196	69
15	25	135	195	69
16	25	167	195	86
18	21	126	199	63
19	20	182	200	91
20	21	152	199	76
MEAN	24	151	196	77
SD	2.4	17.6	2.4	8.6

Note : mean heart rate calculated over final 100 seconds

HR = Heart rate

BPM = Beats per minute

APM = Age-predicted maximum

that defined the onset of inspiration and expiration. The crutch-switch signal was used to identify the beginning and end of gait cycles and, in a representative number of gait cycles, the duration of crutch-stance phase.

There was no consensus in the literature on the definition of LRC or the most accurate method of its detection. Past studies have defined the LRC phenomenon as the presence of integer ratios between locomotor and respiratory cycles, through a variety of analytical methods such as visual inspection (Hart & Roy, 1966), linear regression (Baudinette et al., 1987; Butler & Woakes, 1980), correlational tests (Butler & Woakes, 1980; Duffin & Graham, 1981) and spectral analyses based on the fast Fourier transformation (MacDonald et al., 1992; Nigg et al., 1995).

For this study, initially gait and respiratory frequencies were calculated, averaged over 100-second intervals and plotted to qualitatively screen for potential coupling episodes. Figure 2 shows the respiratory and gait frequencies plotted over the course of a 300-second trial of subject 20. The crutch gait cycles were normalized to 100% and the respiratory latency (of the thermocouple signal minima) was determined (via computer search, validated by the investigator) as a percentage of the crutch gait cycle. Statistical analysis of the latencies (in percentage of the gait cycle) of the respiratory latency for each group of ten consecutive gait cycles (progressing in one-gait-cycle increments) was used to generate mean values and standard deviations for that moving average of 10 gait cycles. Coupling was defined as being present using two criteria, both of which needed to be met.

FIGURE 2: GAIT AND RESPIRATORY CYCLE FREQUENCIES
SUBJECT 20

The first criterion was that the respiratory latency did not vary with respect to the onset of the crutch-gait cycle more than $\pm 5\%$ of its value during 10 consecutive gait cycles. A logical formula was applied to the standard deviation values to determine if the values met this first criterion. A variance of $<5\%$ was defined as “loose” statistical coupling from the perspective of the first criterion. For descriptive purposes, a second logical formula was applied to determine if less statistical variation existed (a variance of $<2.5\%$). This value was defined as “tight” statistical coupling. If these possible coupling episodes identified in this fashion met the second criterion, they were described in terms of the total number of consecutive cycles, the corresponding time interval within the trial period and the duration.

The second, more qualitative, criterion for LRC consisted of reviewing raster plots, generated by plotting the thermistor signal during successive crutch gait cycles that had been normalized to 100%, with each cycle plotted slightly above the preceding one (Donville, Kirby, Doherty, Gupta, Eastwood & MacLeod, 1993; MacDonald et al., 1992) (Figure 3). These graphs were utilized to validate the statistical identification of coupling and to screen for drift of the onset of expiration through the presumed coupling episode.

The raster plots were also used to test the second hypothesis, related to the timing of the respiratory phases in relationship to crutch stance or swing. The raster analyses were also performed on the data obtained from the subject who was requested to intentionally couple as a gold-standard reference for comparison.

**FIGURE 3: SAMPLE RASTER PLOT
RESPIRATORY CYCLES VS NORMALIZED GAIT CYCLES**
SUBJECT 18 (279.5-295.4 s)

The mean duration of crutch-stance ($n = 10$ gait cycles) was determined for each subject during an identified coupling episode. This information was employed in the evaluation of the second hypothesis. No attempts were made to identify other LRC ratios (e.g., 3:2).

For descriptive purposes, the mean stride lengths were calculated from the mean stride frequencies and the treadmill speeds (Equation 1) for each subject over the 300 second trial period. These were reported in both absolute terms and normalized as a percentage of subject height.

Equation 1:

$$\text{stride length (m/cycle)} = \frac{\text{treadmill speed (m/s)}}{\text{stride frequency (cycles/s)}}$$

RESULTS

Descriptive Analysis

The mean stride lengths, both absolute and normalized to subject height, are shown in Table 3. The mean self-selected treadmill speed was 1.36 m/s and the mean stride length was 170 cm or 97% of the subjects' height. The gait and respiratory frequencies that were determined over 100-second intervals and screened for potential coupling are shown in Table 4. The gait frequencies were found to be relatively constant throughout the test period with an overall mean of 0.80 Hz. The respiratory frequencies displayed greater variability and generally increased from a mean of 0.61 Hz over the initial 100 seconds to a mean of 0.70 Hz for the remainder of the trial (Table 4).

Coupling Episodes

All coupling episodes are summarized in Table 5. Coupling was statistically identified and confirmed by raster plot in 10 (56%) of the 18 subjects. Seven of the 10 subjects displayed more than one coupling episode. Thirty-one episodes of "loose" 1:1 LRC were identified including 9 episodes of "tight" LRC. Although there had been no intention of looking for LRC ratios other than 1:1, one episode of 2:1 LRC was identified in subject 3 (Figure 4). Subject 16 was successful in intentionally coupling expiration to both crutch-stance and crutch-swing. Figure 5 displays inspiration on crutch-swing, Figure 6 displays expiration on crutch-swing and Figure 7 displays intentional non-coupling. The raster plots for the intentional coupling conditions were regular and consistent. There was little drift evident.

TABLE 3: GAIT PARAMETERS
(n=18)

SUBJECT	x GAIT FREQ (Hz)	GAIT SD	TRED SPEED (m/s)	x STRIDE LENGTH (cm)	HEIGHT (cm)	x STRIDE LENGTH/HEIGHT (%)
1	0.84	0.07	1.57	186.2	171	108.9
2	0.84	0.04	1.35	160.2	187	85.7
3	0.97	0.07	1.41	145.7	180	80.9
4	0.82	0.05	1.40	170.1	170	100.1
5	0.81	0.17	1.25	154.8	165	93.8
7	0.79	0.08	1.40	177.9	182	97.7
9	0.84	0.07	1.45	173.0	173	100.0
10	0.91	0.08	1.21	133.6	178	75.0
11	0.74	0.10	1.34	180.9	180	100.5
12	0.75	0.06	1.31	175.4	186	94.3
13	0.69	0.06	1.20	172.7	165	104.6
14	0.84	0.07	1.30	154.9	167	92.8
15	0.71	0.13	1.35	190.2	165	115.3
16	0.77	0.05	1.35	174.4	178	98.0
17	0.75	0.06	1.36	180.3	185	97.5
18	0.76	0.04	1.29	168.7	163	103.5
19	0.81	0.04	1.50	185.0	177	104.5
20	0.81	0.05	1.50	184.7	182	101.5
MEAN	0.80		1.36	170.5	175	97.5
SD	0.07		0.10	15.2	8	9.7

x = Mean

SD = Standard Deviation

TRED = Treadmill (Self-Selected)

**TABLE 4: GAIT AND RESPIRATORY FREQUENCIES
(n=18)**

SUBJECT	0-100 SEC					100-200 SEC					200-300SEC				
	x GAIT Hz	SD	x RESP Hz	SD	G/R	x GAIT Hz	SD	x RESP Hz	SD	G/R	x GAIT Hz	SD	x RESP Hz	SD	G/R
1	0.85	0.10	0.49	0.12	1.73	0.85	0.04	0.69	0.13	1.23	0.84	0.04	0.74	0.14	1.13
2	0.85	0.04	0.47	0.09	1.83	0.83	0.03	0.44	0.09	1.89	0.84	0.04	0.46	0.10	1.84
3	0.95	0.10	0.52	0.10	1.81	0.97	0.04	0.54	0.10	1.79	0.98	0.04	0.78	0.22	1.25
4	0.82	0.03	0.72	0.15	1.14	0.82	0.04	0.78	0.14	1.05	0.82	0.04	0.79	0.17	1.03
5	0.81	0.04	0.53	0.18	1.53	0.81	0.05	0.71	0.14	1.13	0.77	0.23	0.47	0.39	1.63
7	0.80	0.10	0.58	0.20	1.38	0.79	0.10	0.73	0.19	1.08	0.78	0.03	0.70	0.19	1.10
9	0.86	0.09	0.80	0.17	1.08	0.84	0.04	0.85	0.14	0.98	0.82	0.04	0.85	0.16	0.97
10	0.92	0.07	0.55	0.12	1.69	0.91	0.11	0.67	0.12	1.38	0.89	0.05	0.73	0.13	1.22
11	0.74	0.05	0.41	0.12	1.80	0.74	0.12	0.43	0.26	1.74	0.73	0.12	LD	0.28	
12	0.74	0.09	0.59	0.16	1.26	0.76	0.05	0.68	0.16	1.12	0.74	0.03	0.58	0.30	1.28
13	0.70	0.07	0.45	0.13	1.58	0.69	0.06	0.54	0.11	1.28	0.69	0.04	0.49	0.24	1.41
14	0.85	0.06	0.76	0.12	1.12	0.83	0.06	0.82	0.13	1.01	0.84	0.09	0.84	0.11	1.00
15	0.72	0.10	0.66	0.17	1.09	0.68	0.16	0.74	0.18	0.93	0.73	0.12	0.76	0.17	0.96
16	0.78	0.07	0.73	0.15	1.06	0.78	0.02	0.78	0.05	1.00	0.77	0.03	0.76	0.07	1.00
17	0.76	0.09	0.50	0.13	1.50	0.76	0.03	0.66	0.12	1.15	0.75	0.03	0.52	0.33	1.44
18	0.76	0.03	0.77	0.13	0.99	0.76	0.05	0.78	0.11	0.98	0.77	0.03	0.76	0.13	1.00
19	0.80	0.04	0.70	0.24	1.15	0.81	0.04	0.82	0.26	0.98	0.81	0.04	0.70	0.22	1.16
20	0.79	0.05	0.78	0.07	1.02	0.82	0.03	0.81	0.05	1.00	0.80	0.04	0.78	0.14	1.03
MEAN	0.81		0.61		1.38	0.80		0.69		1.21	0.80		0.69		1.20
SD	0.07		0.13		0.31	0.07		0.13		0.30	0.07		0.13		0.25

Note : 100 second intervals

x = Mean

SD = Standard Deviation

G = Gait (crutch gait cycles)

R = Respiration (breaths)

LD = Lost Data

RESP = Respiration (breaths)

TABLE 5: SUMMARY OF COUPLING EVENTS

SUBJECT	TIGHT COUPLING (<2.5%)			LOOSE COUPLING (<5%)			PROPORTION (%)	COUPLING RATIO
	CYCLES	INTERVAL (sec)	DURATION	CYCLES	INTERVAL (sec)	DURATION		
3				15	146.3-161.7	15.4	5.1	2:1
				11	275.4-286.7	11.3	3.8	1:1
4				10	258.7-271.0	12.3	8.5	1:1
				11	278.3-291.6	13.3		1:1
7				10	122.2-134.7	12.5		1:1
				22	224.6-252.8	28.2		1:1
				11	242.6-256.7	14.1		1:1
				28	246.3-282.9	36.6		1:1
	12	258.0-273.8	15.8				30.5	1:1
9				10	244.1-256.6	12.5	4.2	1:1
14				10	265.7-277.6	11.9	4.0	1:1
16				12	37.8-53.1	15.3		1:1
				16	100.7-121.4	20.7		1:1
				10	121.4-134.2	12.8		1:1
				19	123.9-148.4	24.5		1:1
				19	179.4-203.7	24.3		1:1
				20	205.0-231.3	26.3		1:1
				17	247.0-269.1	22.1		1:1
				13	270.3-287.2	16.9		1:1
17				13	276.9-293.8	16.9	59.9	1:1
				11	190.9-204.0	13.1	9.2	1:1
				12	205.2-219.7	14.5		1:1
18				11	63.4-77.6	14.2	23.4	1:1
				15	168.9-188.5	19.6		1:1
				13	232.9-249.8	16.9		1:1
				15	275.9-295.4	19.5		1:1
19				12	89.0-103.9	14.9	4.9	1:1
20	29	9.93-47.4	37.5	43	7.4-62.8	55.4		1:1
	11	116.3-129.7	13.4	28	105.4-139.5	34.1		1:1
	10	120.0-132.2	12.2	16	140.7-160.3	19.6		1:1
	10	184.9-197.4	12.5	29	150.6-186.1	35.5		1:1
				56	176.5-246.0	69.5		1:1
				14	235.8-253.4	17.6		1:1
MEAN	14		17.5	17		21.6	21.0	
SD	6		8.0	10		12.9	25.4	

CYCLES = number of crutch-gait cycles over which the coupling occurred

INTERVAL = when in the 300 second interval the coupling occurred

DURATION = in seconds, that the coupling lasted

PROPORTION = percentage of the total time coupling occurred

COUPLING RATIO = number of gait cycles per respiratory cycle

SD = Standard deviation

FIGURE 4: 2:1 COUPLING
SUBJECT 3 (146-161.7 s)

**FIGURE 5: INTENTIONAL COUPLING
(INSPIRATION ON CRUTCH-SWING)
SUBJECT 16**

**FIGURE 6: INTENTIONAL COUPLING
(EXPIRATION ON CRUTCH-SWING)
SUBJECT 16**

FIGURE 7: INTENTIONAL NON-COUPPLING
SUBJECT 16

The plot of intentional non-coupling shows no organized activity.

Timing

The mean duration of the crutch-stance phase of coupling subjects was 47.3 % (SD 3.7) and the mean duration of the crutch-swing phase was 52.7% (SD 3.7) of the gait cycle (n = 10). For 29 (94%) of the 31 episodes identified as 1:1 LRC, the raster plots indicated that the inspiratory phase corresponded to the latter half of the crutch-gait cycle (e.g., crutch-swing) and the expiratory phase corresponded to the first half of the crutch-gait cycle (e.g., crutch-stance). Subject 3 displayed one episode of coupling that was an exception to this general rule (Figure 8). Another exception occurred for the initial episode of coupling for subject 20 (Figure 9). Subject 20 exhibited two such timing episodes whereas the other five episodes observed the general rule (described in more detail later).

Proportions

As shown in Table 5, subject 3 displayed 2:1 LRC for 5.1% (15.4 s) and 1:1 LRC for 3.8% (11.3 s) of the trial period. Subject 4 displayed 1:1 LRC for 8.5% (25.6 s) whereas subject 7 displayed 1:1 LRC for 30.5% (91.4 s) of the trial period. Subject 9 displayed 1:1 LRC for 4.2% (12.5 s) and subject 14 displayed 1:1 LRC for 4.0% (11.9 s) of the trial period. Subject 16 displayed 1:1 LRC for 59.9% (179.8 s) of the trial period. Subject 17 displayed 1:1 LRC for 9.2% (27.6 s) of the trial period. Subject 18 displayed 1:1 LRC for 23.4% (70.2 s) of the trial period. Subject 19 displayed 1:1 LRC for 5.0% (14.9 s) of the trial period. Subject 20 displayed 1:1 LRC for 77.2% (231.7 s) of the trial period.

FIGURE 8: SUBJECT 3 (275.4-286.7 s)

FIGURE 9: SUBJECT 20 (7.4-62.8 s)

Selected Subjects

Detailed descriptions of the data for Subject 16 (59.9% coupling) and Subject 20 (77.2% coupling) follow as both examples and to illustrate specific findings.

Subject 16

Polygraph The gait signal was regular and consistent in waveform throughout the trial. There were three areas within the first minute where a signal was not recorded for a presumed gait event. The thermistor signal showed several short regions of variability within the first 100 seconds but then it became very consistent in waveform and periodicity. No episodes of phonation or nose breathing were noted. The subject stumbled at approximately 65 seconds.

Frequency The gait frequency plot clustered tightly about the mean of 0.77 Hz throughout the trial after some instability within the first 50 cycles. There were a few outliers but no appreciable drift. The initial 100 seconds revealed a respiratory frequency of 0.73 Hz whereas the interval of 100-200 seconds had a frequency of 0.78 Hz. The frequency of respiratory events over the final 100 seconds was 0.76 Hz.

Statistical analysis There were nine episodes of loose statistical coupling evident which contained three episodes of tight coupling. The first consisted of 12 consecutive gait cycles with variability around the mean $< 5\%$. The second episode consisted of 16 consecutive gait cycles with variability around the mean $< 5\%$. The third episode consisted of 10 consecutive gait cycles with variability around the mean $< 5\%$. The fourth episode consisted of 19 consecutive gait cycles with variability around the mean $< 5\%$ with a period of 12

consecutive gait cycles with a variability around the mean of $< 2.5\%$. The fifth episode consisted of 19 consecutive gait cycles with variability around the mean $< 5\%$ with a period of 13 consecutive gait cycles with a variability around the mean of $< 2.5\%$. The sixth episode consisted of 20 consecutive gait cycles with variability around the mean $< 5\%$ with a period of 16 consecutive gait cycles with a variability around the mean of $< 2.5\%$. The seventh episode consisted of 17 consecutive gait cycles with variability around the mean $< 5\%$. The eighth episode consisted of 13 consecutive gait cycles with variability around the mean $< 5\%$. The final episode consisted of 13 consecutive gait cycles with variability around the mean $< 5\%$.

Raster Twelve episodes of coupling were identified and plotted. The first episode ran from 37.8 to 53.1 seconds and demonstrated no appreciable drift of the inflection points (Figure 10). The second episode ran from 100.7 to 121.4 seconds and demonstrated no appreciable drift of the inflection points (Figure 11). The third episode ran from 121.4 to 134.2 seconds and demonstrated no appreciable drift of the inflection points (Figure 12). The fourth episode ran from 123.9 to 148.4 seconds and demonstrated no appreciable drift of the inflection points (Figure 13). This episode contained a period of tight coupling which ran from 130.4 to 145.8 seconds and showed no organized drift of the inflection points (Figure 14). The fifth episode ran from 179.4 to 203.7 seconds and demonstrated no appreciable drift of the inflection points (Figure 15). This episode contained a period of tight coupling which ran from 179.4 to 196 seconds and showed no organized drift of the inflection points (Figure 16). The sixth episode ran from 205 to 231.3 seconds and demonstrated no appreciable drift of the inflection points (Figure 17). This episode contained a period of

FIGURE 10: SUBJECT 16 (37.8-53.1 s)

FIGURE 11: SUBJECT 16 (100.7-121.4 s)

FIGURE 13: SUBJECT 16 (123.9-148.4 s)

FIGURE 14: SUBJECT 16 (130.4-145.8 s)

FIGURE 15: SUBJECT 16 (179.4-203.7 s)

FIGURE 16: SUBJECT 16 (179.4-196.0 s)

FIGURE 17: SUBJECT 16 (205.0-231.3 s)

FIGURE 18: SUBJECT 16 (209.1-229.9 s)

FIGURE 19: SUBJECT 16 (247.0-269.1 s)

FIGURE 20: SUBJECT 16 (270.3-287.2 s)

FIGURE 21: SUBJECT 16 (276.9-293.8 s)

tight coupling which ran from 209.1 to 229.9 seconds and showed no organized drift of the inflection points (Figure 18). The seventh episode ran from 247 to 269.1 seconds and demonstrated no appreciable drift of the inflection points (Figure 19). The eighth episode ran from 270.3 to 287.2 seconds and demonstrated no appreciable drift of the inflection points (Figure 20). The ninth episode ran from 276.9 to 293.8 seconds and demonstrated no appreciable drift of the inflection points (Figure 21). The patterns of all the plots was suggestive of 1:1 coupling.

SUBJECT 20

Polygraph The gait signal was of good quality throughout the trial. The tracing was regular in timing and consistent in appearance. The thermistor signal was of good quality. The waveform was consistent throughout the trial. No episodes of phonation or nose breathing were noted. No stumbles or interruptions in gait were witnessed.

Frequency The gait frequency plot was tightly clustered about the mean of 0.81 Hz throughout the trail. The initial 100 seconds of the respiratory plot revealed a frequency of 0.78 Hz whereas the interval of 100-200 seconds had a frequency of 0.81 Hz. The frequency of respiratory events over the final 100 seconds was 0.78 Hz. This was very suggestive of 1:1 coupling throughout the trial.

Statistical analysis There were six episodes of coupling, four of which were tight. The first episode consisted of 43 consecutive gait cycles with variability around the mean $< 5\%$ with a period of 29 consecutive gait cycles with a variability around the mean of $< 2.5\%$. The second episode consisted of 28 consecutive gait cycles with variability around the mean $<$

5% with a period of 11 consecutive gait cycles with a variability around the mean of $< 2.5\%$. The third episode consisted of 16 consecutive gait cycles with variability around the mean $< 5\%$ with a period of 10 consecutive gait cycles with a variability around the mean of $< 2.5\%$. The fourth episode consisted of 29 consecutive gait cycles with variability around the mean $< 5\%$. The fifth episode consisted of 56 consecutive gait cycles with variability around the mean $< 5\%$ with a period of 10 consecutive gait cycles with a variability around the mean of $< 2.5\%$. The sixth episode consisted of 14 consecutive gait cycles with variability around the mean $< 5\%$.

Raster Ten episodes of coupling were identified and plotted. The first episode ran from 7.4 to 62.8 seconds and demonstrated no appreciable drift of the inflection points (Figure 9). This episode contained a period of tight coupling which ran from 9.9 to 47.4 seconds and showed no organized drift of the inflection points (Figure 22). The second episode ran from 105.4 to 139.5 seconds and demonstrated no appreciable drift of the inflection points (Figure 23). This episode contained a period of tight coupling which ran from 116.3 to 129.7 seconds and showed no organized drift of the inflection points (Figure 24). The third episode ran from 140.7 to 160.3 seconds and demonstrated no appreciable drift of the inflection points (Figure 25). This episode contained a period of tight coupling which ran from 120 to 132.2 seconds and showed no organized drift of the inflection points (Figure 26). The fourth episode ran from 150.6 to 186.1 seconds and demonstrated no appreciable drift of the inflection points (Figure 27). The fifth episode ran from 176.5 to 246.0 seconds and demonstrated no appreciable drift of the inflection points (Figure 28). This episode contained a period of tight coupling which ran from 184.9 to 197.4 seconds and showed no

FIGURE 22: SUBJECT 20 (9.9-47.4 s)

FIGURE 23: SUBJECT 20 (105.4-139.5 s)

FIGURE 24: SUBJECT 20 (116.3-129.7 s)

FIGURE 25: SUBJECT 20 (140.7-160.3 s)

FIGURE 26: SUBJECT 20 (120.0-132.2 s)

FIGURE 27: SUBJECT 20 (150.6-186.1 s)

FIGURE 28: SUBJECT 20 (176.5-246.0 s)

FIGURE 29: SUBJECT 20 (184.9-197.4 s)

FIGURE 30: SUBJECT 20 (235.8-253.4 s)

organized drift of the inflection points (Figure 29). The sixth episode ran from 235.8 to 253.4 seconds and demonstrated no appreciable drift of the inflection points (Figure 30). All of the plots were suggestive of 1:1 coupling.

Several of the raster plots displayed a small notch in the inspiratory phase (e.g., Figure 23).

DISCUSSION

In light of the statistical and graphic evidence, it was felt that LRC had been observed in humans employing axillary crutches in the swing-through ambulation pattern in accordance with the first hypothesis. The presence of LRC in this setting documents a physiological phenomenon that has not previously been reported. This supports the findings of other investigators that LRC occurs in humans in several mechanically distinct situations (Hill et al., 1988; Mahler et al., 1991; MacLennan et al., 1994; Paterson et al., 1986; Persegol, 1991). LRC was witnessed in 10 subjects (56% of those studied).

As evidenced by the raster plots, the timing of respiratory events relative to the gait cycle was found to be generally consistent among LRC episodes and across subjects. Inspiration most often occurred during the crutch-swing phase of the gait cycle and expiration coincided with the crutch-stance phase, in accordance with the second hypothesis. Of the 31 1:1 LRC episodes, only 3 (10%) violated this general rule. Two of these episodes were in the same subject (subject 20) and in a subject who more commonly exhibited the usual pattern. This lends credence to the theory that the visceral piston is important for LRC in humans and is in agreement with earlier work (Baudinette et al., 1987; Bramble, 1989; Bramble & Jenkins, 1993; MacDonald et al., 1992). Likewise, the rhythmic action of the upper limbs, which has produced LRC in humans previously (Mahler et al., 1991; MacLennan et al., 1994; Paterson, 1986), appears not to be the dominant influence in the axillary-crutch swing-through gait. It would appear that, in those subjects who exhibited LRC, the visceral piston might aid in

expiration during the crutch-stance phase of the gait cycle as the mobile abdominal organs (propelled via inertia, the contraction of the abdominal musculature and the forward flexion of the lumbar spine) place upward pressure on the diaphragm. Conversely, during the crutch-swing phase of the gait cycle, trunk extension could allow the viscera to place downward traction on the diaphragm, aiding in inspiration. Interestingly, there was minor variation among coupling subjects with respect to the exact onset of expiration during crutch-stance. Since the visceral piston effect would be expected to augment expiration at similar portions of the gait cycle, the difference may be accounted for by individual differences in anthropometry and technique. Several of the raster plots displayed a brief interruption in the inspiratory phase which appeared as a notch on the tracing (Figures 9, 10, 11). This could possibly be due to a learned, anticipatory effect or a small priming breath before full inspiration.

Of the subjects who coupled for less than 10 % of the time, the coupling events were found to have occurred in the latter half of the test period. This is in agreement with the notion that coupling occurs during vigorous, steady-state exercise. The steady state presumably is a physiologic mechanism intended to conserve energy and become more efficient in repetitive, strenuous activity. Acquisition of this state may require varying amounts of time between subjects of differing experience, comfort and fitness levels. Possibly in those subjects who did not couple, insufficient testing time was permitted to initiate LRC. Unfortunately, due to the demanding nature of the testing conditions, longer test periods would have been difficult for the subjects to tolerate. As an organism's actions become increasingly more

demanding, the cardiorespiratory reserve diminishes and the efficiency potentially gained by coupling of locomotor and respiratory patterns should become increasingly more significant. Once the ability of an organism to supply the required amounts of oxygen to the active tissues is insufficient, hypoxia and anaerobic metabolism ensue and coupling is lost (Paterson, Wood, Marshall, Morton & Harrison, 1987). Longer test periods than the 300-second ones used may have led to enhanced subject comfort and more coupling. Conversely, they may have also led to the loss of coupling with fatigue and hypoxia.

The training protocol was found to be adequate. The novice subjects had very little difficulty in acquiring, and feeling comfortable with, the axillary-crutch skills necessary for participation in the study. The subjects had no difficulty in achieving moderate levels of exercise intensity as measured by the Borg scale (corresponding to 60-80% of the age-predicted maximum heart rate).

Two of the subjects dropped out of the training protocol due to shoulder discomfort, but this was uncommon among other subjects. None of the subjects fell or injured themselves in a serious manner as a result of participation in this study. Minor abrasions on the medial aspect of the wrists were reported by several participants, but this was easily remedied through the application of padding to the affected area(s). The abrasions appeared to be caused by frictional contact between the crutch and the wrist as a result of the crutches being held too close to the side of the subjects. Due to the limited treadmill width and the presence of safety side rails, this configuration could not have been avoided. Several participants

experienced minor abrasions of the axillae during both testing and training. This was felt to be due to individual technique as padding did little to relieve the friction in the afflicted subjects. It is likely that more training would have enhanced the subjects' skills and possibly the incidence, duration and/or the tightness of coupling episodes, but time constraints prohibited additional practise.

The thermistor functioned well throughout testing. Subjects reported very little difficulty or discomfort with the thermistor or its housing. Problems experienced with the thermistor were phonation by the subjects, periods of nose breathing and incidental contact with saliva. The pressure-sensitive wafer switch placed under the tip of one crutch worked well. Subjects reported little difficulty or discomfort as a result of the switches, aside from the associated wires travelling up the crutch to the belt, which slightly altered the natural state. Signal quality from the pressure switches was inconsistent at times, due to subject technique and incidental damage that occurred during the testing period as a result of repeated contact with the treadmill side rail. Overall, the thermistor and the crutch switch appeared to provide a reasonably valid means of identifying the events of both the respiratory and gait cycles.

Several sources of error were nevertheless identified. The definitions of coupling employed were rational for testing the hypotheses, but arbitrary because there is no consensus in the literature. Pilot testing and evaluation of the experimental data suggested that the numerical definition employed was specific enough to detect episodes. Subject 16, who was requested to intentionally couple, provided another source of empirical validation of the criteria used.

As previously noted, crutch ambulation might have been too demanding or not demanding enough, mechanically and physiologically, to elicit LRC in all subjects, but this limitation was felt to be necessary in light of subject safety. Similarly, if subjects had insufficient time to reach a steady state, either due to testing duration or miscues (stumbling, speaking or nose breathing), coupling may not have had sufficient time to be initiated. The self-selected comfortable maximum speed was employed for safety, but it is possible that other coupling situations could be revealed at different velocities.

Subjects were controlled for gender and age but not directly for anthropometric characteristics. This was not felt to be necessary as LRC was expected to occur independent of individual body parameters, such as mass (Viala, 1997). No anthropometric trends differentiating subjects who coupled and those that did not were identified. The use of a self-selected speed for ambulation was expected to facilitate coupling by permitting individual variations in body size, type and fitness.

Chance alone cannot be completely ruled out as an explanation for apparent LRC. The “stage-coach phenomenon” refers to the appearance of paradoxical motion due to sampling rate. If the natural frequency of an action (like the timing of a spoked stage-coach wheel) is a harmonic of the sampling frequency (the field or frame rate for videotape and film respectively), there will be no apparent movement of the wheel. If the sampling frequency is slightly greater or less than the wheel, the wheel may seem to be rolling slowly forward or in reverse. If, by chance alone, the frequency of the gait cycle was a harmonic of the

respiratory cycle, then a false-positive apparent coupling would result. This phenomenon could not be excluded within the experimental design. Other integer ratios of coupling may have been present (e.g., 3:2) but they were not included in the analysis and represent a potential source of false-negative findings.

The absence of LRC in some subjects, and for some periods even for the subjects who did couple, could have occurred for several reasons. As previously mentioned, the mode of locomotion used may have been too strenuous (causing hypoxia) or not strenuous enough (not requiring increased efficiency). The visceral-piston effect may not have induced coupling due apprehension on the part of the subject which may have produced a degree of guarding and subsequently a more rigid trunk. Similarly, heightened subject arousal or concentration may have led to conscious control over the respiratory process which could have overridden any more primitive drive. For animals, coupling could have evolutionary significance as the increased efficiency of the system and decreased metabolic requirements could yield a survival advantage in predator:prey interactions. For humans, the great degree of conscious control over body systems coupled with decreased evolutionary pressure could be cited to explain why coupling is not as readily apparent as it is in animals.

It was assumed that the sample population studied was representative of the larger community of actual axillary-crutch users. The literature supports the assumption that a healthy subject holding one leg aloft is sufficiently similar to the disabled condition that extrapolations of results can be made (Goh et al., 1986; Stallard et al., 1978). Likewise, it

was assumed that most patients employing the swing-through gait ambulate on only one limb. However, long-term crutch users and those with assorted motor, sensory and neurologic abnormalities may well have different experiences. The findings from this study may have general physiological applicability with upper-limb impact loading, LRC and its similarity to quadrupedal LRC. Specific applicability should be restricted to axillary-crutch users employing the swing-through gait on one lower limb.

CONCLUSIONS

When humans employ the swing-through gait using axillary crutches, 1:1 LRC occurs. Episodes of LRC in this setting are generally transient and brief. Inspiration is generally associated with the crutch-swing phase of the gait cycle and expiration with the crutch-stance phase.

RECOMMENDATIONS

The above information suggests several potential areas of future study:

1. The subject pool should be expanded to include long-term crutch users. These subjects would have had much more experience with the axillary-crutch swing-through gait. This would be expected to enhance comfort with the experimental procedure. Presumably these subjects would have developed habits (such as LRC with quicker onset or higher order coupling ratios) surrounding their form of locomotion. This would help identify if LRC is a true physiological phenomenon or if the results presented are due to chance.
2. Objective measures of exercise intensity and metabolic efficiency should be made among subjects who intentionally couple and decouple. If there is an increase in the efficiency of the system when coupling is employed, one would expect to see decreased VO_2 values when coupled. One might also achieve higher VO_2 max levels while coupled. Perceived levels of exertion could also be obtained and compared to test for any real or perceived advantages of LRC.
3. With respect to rehabilitation, this information should prove useful in the selection of axillary-crutches and the swing-through gait pattern for specifically disabled individuals. It may also aid in the development of better, more mechanically sound training practices for axillary-crutch users.

4. The synchronization of locomotor activity with respiratory pattern may help patients with obstructive lung disease (e.g., cystic fibrosis) enhance their expiratory efforts. Studies should be conducted to see if LRC is a useful adjunct to the normal respiratory effort in the diseased or fatigued state.

APPENDIX A:

TRAINING PROTOCOL

Training Session 1

On the first session, subjects were fitted with axillary crutches (approximately 5 cm below the upper anterior axillary border with the elbow flexed 20-30° and the crutch tips resting on the floor 15 cm in front of, and 15 cm lateral to the fifth metatarsal head) (Joyce & Kirby, 1991) and the values recorded. The subjects ambulated over ground in the swing-through pattern with one foot off the floor to get accustomed to, and comfortable with, crutch walking. Subjects were informed about the control of the treadmill and its safety features. Subjects then walked without crutches on the treadmill at increasing speeds up to a maximum of 1.25 m/s (a slow walk) for a distance of 100 m and then brought down to 0 m/s. With crutches aloft, subjects were brought up to 1.00 m/s walking normally and then asked to begin crutch ambulation. The subjects were informed that it is acceptable to resume normal walking at any time if the crutch gait was unsteady and to resume the crutch gait when they felt comfortable. When the subject was comfortable at 1.00 m/s, the speed was increased to a comfortable self-selected speed and maintained for a distance of 400 m (approximately 5 minutes), at which time the subject was asked to begin normal walking and the speed was returned to 0 m/s. After a brief rest period (5 minutes), the preceding training regimen was repeated.

Training Session 2

At the second training session, each subject was brought up to 1.00 m/s walking on the

treadmill and then asked to begin crutch ambulation. When the subject was comfortable at 1.00 m/s, the speed was increased to a comfortable self-selected speed and maintained for a distance of 500 m (approximately 5 minutes), at which time the subject was asked to resume normal walking and the speed was returned to 0 m/s. After a 5 minute-rest period, the training regimen was repeated.

Training Session 3 (4 and 5 if Necessary)

On subsequent training sessions, each subject was brought up to 1.00 m/s walking on the treadmill and then asked to begin crutch ambulation. When the subject was comfortable at 1.00 m/s, the speed was increased (to a self-selected target speed) and maintained for a distance of 500 m, at which time the subject was asked to resume normal walking and the speed was returned to 0 m/s. After a 5-minute rest period, the training regimen for the self-selected target speed was repeated for a distance of 500 m. If the subject was not deriving the expected benefits from the three training sessions, additional sessions of similar activity were added until the subject and investigator felt confident and comfortable in the subject's ability to execute smooth, continuous crutch walking for the testing needed. If this condition was not met after a reasonable amount of training, the subject was accounted for and excluded from the testing protocol.

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