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PERCEIVED EXERTION: METROLOGICAL APPROACHES AND APPLICATIONS TO ENDURANCE PERFORMANCE IN ABLE-BODIED AND SPINAL CORD INJURED POPULATIONS.

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Introduction

I will review in this part the concept of perception of effort applied to physical activities and the physiological implications of spinal cord injury (SCI) in the production of endurance performance. This will provide the necessary knowledge to the reader to embrace the next sections.

I. Perception of effort

“The reason for the neglect of subjective reaction in favour of better-defined physiological indicators of exertion is that these reactions have been difficult to define and measure. Being a privately experienced event, perceived exertion, or any other subjective reaction to physical work can only be measured indirectly through the use of self-report techniques” (Gamberale, 1985).

It has been proposed that perceived effort can be defined as : “The process of investing a given amount of one’s perceived physical or mental resources out of the perceived maximum to perform a specific task” (Halperin and Emanuel, 2019; Morgan, 1973). The perception of exertion is “a very concrete experience that is easy to describe and identify over a large range of intensities. It also has many physiological cues that might help the subject to identify a certain intensity level” (Borg, 1998, p. 31). “Independent of the specific technique used to measure it, perceived exertion should be interpreted as constituting a ‘summing up’ of the influence from all structures under stress during exercise. [...] However, it should be obvious to everyone that the perception of exertion during physical work not only has a psychological validity, but it also reflects real conditions such as the interplay between the requirements of the job and the capacity of the individual” (Gamberale, 1985). Borg already pointed out that “factors in the environment, such as music, heat, and social context, may distract subjects or cause them to attend to special cues, resulting in their selection of a rating that is too high or too low” (Borg, 1998, p. 38). This affirmation has been confirmed later on by experimental evidences (Bigliassi et al., 2015; A. Blanchfield et al., 2014; Chow and Etnier, 2017; Van Cutsem et al., 2019). The fact that perception of effort resembles “a social psychophysiological phenomenon” and is presented as a “Gestalt” occurrence, then the meaning of its attribution to a specific body part is ambiguous as often reported in the literature.

1) Origin

The theoretical background of the perception of effort are of importance to understand the reason why it's so relevant in endurance performance. We will expand next the influence of central command (also called cortical irradiation) on the physiological response of the body.

Originally, the perceived effort was thought to be dependent on afferent discharges (Waller, 1891) and this remain central in practitioners' beliefs (Gibson and Noakes, 2004). Additionally, fusimotor drive could be expected to increase with a resultant increase in the activity of muscle spindles. This is the point of Granit's observation (1972) that "the periphery itself" is 'corollarized' by alpha-gamma linkage". However, perceived exertion can't originate from that reafferent discharges from muscle spindles. Indeed, subjects perceived a reduced muscular force when a superimposed isometric tension is performed with the assistance of a tonic vibration reflex (McCloskey et al., 1974). This observations support the hypothesis of an awareness of the descending motor command as the basis of the sensation (McCloskey, 1981). *This could be explained by the reduction in the necessary magnitude of central motor command generated by the involuntary reflex assistance provided by vibration.*

Perception of effort comes from central command

This idea is far from being recent as it was already known in the 19th century (Lewes, 1878). Gandevia (1982) studied two patients, who became suddenly hemiplegic, without sensory symptoms, noted that attempts to move when first paralysed were not accompanied by a sense of effort, but that attempts to move when movement first returned were accompanied by distinct sensations of effort or heaviness. The return of sensation of effort as hemiplegia progresses to paresis is that activity in corticofugal paths contributes to generation of the sense of effort. During complete hemiplegia there is no neural traffic in motor corticofugal paths below the internal capsule and a sense of effort is absent. But during paresis, there is increased neural traffic in the uninterrupted corticofugal fibres and there is a strong sense of effort. Alternatively, a subcortical structure with a critical ascending projection to motor cortical areas may co-operate in generating the sense of effort. Afferent information, while important for calibrating and scaling the sense of effort which usually signals force or weight, is not essential for generation of a crude signal of descending motor command or effort (Gandevia and Mccloskey, 1978).

“In situation, when a greater command is required to lift an object […] it will feel heavy.” (Gandevia and Mccloskey, 1977a).

A century ago, Holmes (1917) supported this idea with patients with unilateral cerebellar lesions perceived heavier load in the affected hand carrying a weight due to the higher effort involved in the task.

This has been demonstrated when muscle capacity are impaired following a period of physical task induced-fatigue (McCloskey et al., 1974), successive to inhibition of the motoneurons of a contracting muscles by activation of muscle spindles in its antagonist (McCloskey et al., 1974), in patients with unilateral cerebellar lesions (Holmes, 1917), or by regional use of neuromuscular blockers inducing partial paralysis (Gandevia and McCloskey, 1977; Gandevia and Mccloskey, 1977a, 1977b). It’s true as well in the situation where the workload is increase (Gearhart et al., 2005).

Experimental anaesthesia interventions demonstrated an increase in the perceived exertion through higher activation of voluntary command to motoneuron induced by weaker muscular capacity to produce a movement (Galbo et al., 1987; Gandevia and McCloskey, 1977; Gandevia and Mccloskey, 1977a). This can be achieved for example from the suppression of stretch reflex with anaesthesia leading to increase of motor command to compensate the loss of facilitator reflexes arising from the consequences of sensory inputs (Gandevia and Mccloskey, 1977b). “Achieving a contraction with the assistance of a tonic vibration reflex […] reduces the centrally generated motor command required in a contraction, and the perceived muscular force is reduced” (McCloskey, 1981). This author advanced the hypothesis of perceived effort coming from the way corollary discharges (introduced by Sperry (1950) of central command are treated and perceived in the brain (Taylor, 2013).

Henneman (1980, p. 849) noted in a textbook that “in many paretic limbs, weights feel heavier than they actually are because of the greater effort involved in all performance.” The arguments of Henneman (1980) provide the assumption that motor command can be perceived (Somodi et al., 1995) by some means. A role for corollary discharges in this phenomenon must be considered consequently.

Experiments on subjects with split-brain (surgical disconnection of the cerebral hemispheres) comes to support the idea that corollary motor discharges reach both hemispheres (Gandevia, 1978). Hypnotic interventions strengthened this hypothesis by its ability to decrease the RPE for a given absolute workload while conserving cardiovascular responses. In contrast, intervention leading to increase RPE through hypnosis increase perceived effort and cardiorespiratory responses for the same absolute workload (see "Central command influence on physiology") (Morgan et al., 1973; Williamson et al., 2001). The physiological response of the body has to "function" at a minimum level to ensure the correct function of the body as long as it is able to cope with the intensity, but the perceived exertion is indirectly dependent from the response of the body as it reflects the way people perceive central command (itself dependent on the "physiological state") presumably through corollary discharges.

Central command (cortical irradiation) action on physiological responses

In the next section, we delve into the effect of the magnitude of the central motor command on the physiological responses. These knowledges are of importance to interpret the records of perceived exertion in regard to the physiological responses during endurance performance production.

Goodwin *et al.* (1972) indicated that elements of the descending motor command stimulate increases in blood pressure, heart rate (HR), and ventilation during voluntary muscular contraction (Gandevia and Hobbs, 1990). Another method of looking for an effect of central 'irradiation' has been to reduce muscular strength without paralysis by partial curarization of human subjects. In this type of experiments a greater central command is required to achieve a given level of muscular work when the subject is weakened than normally, and the increase in minute ventilation (V_E), blood pressure (BP) & HR accompanying the work are also greater (Asmussen et al., 1965).

V_E at the onset of one-legged cycling **was more augmented with arbitrary start** compared with cued start ***while the decrease in end-tidal carbon dioxide (ET_{CO2})*** at the start of exercise ***was not different*** between the two start modes. This is due to the activation of brain areas before the onset of movement (see Brain activity related to the (perceived) exertion). The **in-advance activation of central command contributes to an initial greater increase in ventilation**, even though central command may have sufficient time to increase breathing frequency (f_R) and V_E at the onset of exercise with cued start (Asahara et al., 2016). As a consequence, respiratory effort is thought to contributes to the overall perception of effort during aerobic exercises through the corollary discharges of the central motor command to the respiratory muscles (Grazzini et al., 2005; O'Donnell et al., 2007).

Additionally, the increase in prefrontal oxygenated-haemoglobin (Oxy-Hb) seems early enough to control the cardiovascular system at the onset of exercise (K. Ishii et al., 2016; Matsukawa et al., 2015) supporting that **the in-advance prefrontal oxygenation may appear in association with central command**, and could originates from sympathetic premotor neurons (Ishii et al., 2013)**.** This relates to a readiness phenomenon important in sport performance. In addition, the increase in prefrontal Oxy-Hb at the onset of one-legged cycling was independent of the extent of motor effort. The symmetric increase in the bilateral prefrontal Oxy-Hb occurred before and at onset of arbitrary one-legged cycling, whereas such an increase was absent with cued start. Furthermore, mental imagery or passive performance of one-legged cycling increased f_R and V_E and decreased ET_{CO2}, whereas neither intervention augmented the prefrontal Oxy-Hb (Asahara et al., 2016).

Based on the accumulating evidence, we speculated **that the prefrontal cortex may evoke a descending signal, which may in turn trigger neural circuits responsible for the generation of central command for cardiovascular and respiratory regulation** (Asahara et al., 2016; Decety et al., 1991)**.**

This is supported by experiments with partial curarization, highlighting the importance of central irradiation (Goodwin et al., 1972). Experiments on animals indicate that activation of muscle spindles primary afferents by vibration produces no appreciable ventilatory of CV responses (Hodgson and Matthews, 1968), and nerve block of only the large myelinated afferents, which include afferents from muscle spindles and Golgi tendon organs, does not alter the cardiorespiratory (CR) responses mediated by muscle afferents during contraction (McCloskey and Mitchell, 1972).

2) Measurements

The perception of effort is a subjective, also called qualitative variable. Similarly, to any variable in science, the instruments to measure and record it are of importance. Additionally, the instructions are crucial in subjective measures, because of the major inter-individual variability that could be introduced in the results on the opposite case. For this reason, we will detail succinctly in the next section the specificities of rating the perceived exertion in the literature to date.

According to Gamberale (1985), "no one […] techniques can be considered as being generally superior to the others" for measuring subjective reactions during physical work performance but because of their specificity, it's necessary in all studies to record explicitly what scale has been used. "The content of the questions to be asked and the construction of the method of assessment provide a natural, built-in validity. **There is no direct, 'outer' criterion to which the subjective responses can be correlated**" (Borg, 1998, p. 34).

Ratio-scaling techniques

A simple method of scaling with a high degree of intersubjectivity is *ratio setting*, such as halving or doubling. The stimulus-response relationship can be studied and demonstrated in such a simple way. There are two main methods of ratio scaling: production where subjects are asked to produce a physical work matching with a subjective intensity, and the estimation method where subjects are asked to provide their subjective estimation of an imposed working intensity. The direct scaling methods give subjective intensities on a scale with an absolute zero and equidistant scale steps.

An exponent greater than 1.0 indicates that the perceptual intensity is a positively accelerated function of the physical stimulus defined with "at a strenuous exercise intensity a small increase in physical performance is perceived as requiring a larger subjective effort than the same increase at a lower exercise intensity" (Borg, 1998, p. 21), while an exponent less than 1.0 indicates that the function is negatively accelerated.

In *ratio estimation* the subject is asked to estimate the percentage magnitude of a stimulus in relation to a standard. In *(free) magnitude estimation* the subject is first presented with a stimulus and asked to select to represent the perception it procures. Then, the subject is asked to assign numbers to the following stimuli in such a way that if the stimulus is twice as the first one, the number should the double of the first selected number (Borg, 1998; Gamberale, 1985; Neely, 1995).

There is strong empirical evidence that perceived exertion is a positively accelerated function of the workload. Although there are inevitable interindividual differences, on the average, the exponent of the function will fall within a limited range (1.6 – 1.9) (Ljungberg et al., 1982) irrespective of the type of work performance or the muscle groups involved (Gamberale, 1985). This ratio has been challenged and confirmed only for cycling and running while as an example, the positively accelerating function for walking is closer to an exponent of 3 (Borg, 1978).

There are also drawbacks with this method: They give ratings that are sufficiently valid for general descriptions of growths functions, but not for differential use or direct estimations of intensity levels (Borg, 1998; Stevens, 1975) and interindividual or intermodal comparisons (Gunnar Borg, 1982). Moreover in methods like magnitude estimation, subject's ratings didn't correlate with HR or workload because people choose numbers according to their own experience with numbers and without predefined framework (Stevens, 1971).

Category scaling

Category scaling offer a practical use but with no possibilities of direct ratio comparisons of perceptual intensities (Gunnar Borg, 1982). The category scale is closely matched by a logarithmic transformation of the magnitude scale (Ekman and Künnapas, 1962). Subjective estimates of effort were also found to be linearly related to endurance time during treadmill performance (Lloyd and Claskey, 1971). However, the suggestion of spurious linearity is indirectly supported by experiments where subjects had to rate their effort at the end of submaximal exercises from different duration. The efforts were overestimated regarding the percentage of time limit the subjects had completed (Kilbom et al., 1983). Then, the relation of perceived effort expended and time on task is not linear.

Category-partitioning procedure

This method is not well known but present no disadvantage on a first glance and doesn't receive any critics yet. Briefly, it's an interval scale with verbal anchors for range of numbers (usually every ten) where subjects have to first name the verbal category and then use the number associated with that category to make a fine graded response (Neely, 1995).

The accelerating function of this method is far less important than the one obtained from category-ratio scales of Borg (e.g., CR-10 or CR-20) (Neely, 1995).

Borg's scales

To obtain a linear relationship between the RPE and workload was in fact one of the objectives in the construction and development of the scale (Borg, 1998). However, it has been demonstrated experimentally that heart rate doesn't reflect effort as it can be dissociate to the RPE with autonomic blocking drugs (Ekblom and Golobarg, 1971; Sjöberg et al., 1979) or environmental manipulation like temperature (Pandolf et al., 1972). This calls into question the method used to validate the Borg's RPE scale and the CR-10 scale (Borg, 1998).

Despite this important measurement characteristic and the obvious advisability of employing ratio scaling when the goal is the description of general psychophysical functions, this method does not allow the possibility of making interindividual comparisons. Borg rejected ratio setting and magnitude estimation because of their lack of validity in terms of direct determination of intensity levels and interindividual comparisons (Borg, 1998).

Stevens had gone on record condemning the use of category scaling (Stevens, 1971). However, Borg eloquently makes the point that magnitude estimation for example, cannot be directly used in clinical settings when two subjects might rate a perceptual intensity as 50 and 75 but still feel the load to be "slightly painful"; **that is, the difference is in the use of numbers not in the perceptual intensity evaluated.** Thus, Borg developed a category scale in the early 1960s (Noble and Robertson, 1996).

These scales must be well administered because of their hidden complexity as first glance. It was proposed by Borg that the perceptual range from a minimal to a maximal subjective intensity is the same for all individuals while not necessarily for the stimulus range (Borg, 1962).

"Information that covers most of the important aspects of scale administration should include the four W's and the two H's: why?, what?, where?, when?, how to rate?, and how to evaluate?" (Borg, 1998, p. 44) "The subject must understand that it is not the physical difficulty (e.g., what the weight is or how warm it is) that counts, but the inner feeling of exertion, strain, and fatigue" (Borg, 1998, p. 46).

Assessment of Interindividual differences

The foundation for the development of Borg's category scale was established in his 1961 paper, "Interindividual Scaling and Perception of Muscular Force." He states that certain assumptions must be accepted for a scale to claim that it assesses individual differences:

- There is interindividual variation in the stimulus range; that is, maximal capacity varies among individual.
- For every stimulus range there is a corresponding perceptive range.
- The intensity of an individual's perception is explicitly determined by its place in the perceptive range.
- The perceptive range may be set equal for all individuals.

The terminal response (R_t), however is set equal, because this is the point where each experiences *maximal* effort. Likewise, the stimulus threshold is set equal at R = 0 since one can theoretically imagine a weight too light for subject to detect. As the stimulus increases, the response curves diverge according to the known psychophysical power law, and both terminate on a common R_t line.

Thus, no matter what the physical capacities of the subjects that one wishes to compare, the range from the point at which the subjects cannot identify any response intensity to the point of maximal response intensity is equal (Noble and Robertson, 1996).

The RPE or CR-10 scales has the advantage over previous scales to fulfil the demands of absolute identification of levels of intensity (*not really true for the CR-10 scale*). According to Borg, one of the main advantage of his RPE scale is that "the given ratings grow linearly with exercise intensity, HR, and VO_2" (Borg, 1998, p. 15). However, we need to put in perspective regarding the influence of fatigue and various intervention demonstrating a non-linear relationship between RPE and these variables.

Quantitative semantics

The perceptual response is dependent on both the number of categories and the verbal definitions used to anchor each category (Gamberale, 1985). Gamberale (1985) maintains that Borg was able to achieve linearity "by a careful choice of verbal categories" (Noble and Robertson, 1996).

Borg states, "If I want to construct a scale over the whole range of intensities, I can use the meaning of adjectives and adverbs and put them in the right place on a scale according to the meaning of the expressions" (G. Borg, 1982).

Studies performed in quantitative semantics show that there are good possibilities to choose words that have about the same meaning among people according to the perceptual intensities "behind" the words. If for instance, the words like "very weak", "rather weak", "moderate" and "somewhat hard" are used, theses expressions do not only follow a rank order but also that the subjective interval between the expressions is fairly constant."

"The category scale that we in this way can construct is enough to satisfy the demands of an interval scale". This, of course, represents Borg's argument that his scale is a category scale; that is, the scale does not merely rank sensations categories by also satisfies the equal interval criterion (Noble and Robertson, 1996).

Since the normal curves depicting the dispersion of intensity ratings for each expression do not overlap one another, it should not be possible for subjects to confuse the meaning of the expressions or, therefore, the intensity implied.

A major change, which probably contributed greatly to the move to increased linearity, was the change from the neutral term "neither light nor laborious" to the more assertive term "somewhat hard". This change also eliminated the bipolar nature of the scale (Noble and Robertson, 1996).

The first category scale

Category scales are partition scales that "are created by requiring the subject to divide a segment of continuum parts" (Stevens, 1974). Borg fist developed a 21-grade scale (1-21) giving a slightly negatively accelerated function with exercise intensity and HR (Borg, 1998).

The 15-graded scale

Thereafter, modification to create the RPE-scale starting with 6 (instead of 0) shows that the scale is not a ratio scale with an absolute zero. “Number 20 on the scale refers to a kind of ‘absolute maximum’, and intensity that most people never will have reached previously in their lives” (Borg, 1998). The RPE-scale validity has been mainly performed computing correlation with HR (Bar-Or, 1977) with poor relationship despite the fact that the scale has been constructed with the aim to correlate with HR (Borg, 1998, p. 39). Moreover, the validity results are contradictory between studies, where some find good association between RPE and HR and other not in young subjects (Bar-Or, 1977; Miyashita et al., 1986).

Since heart rate can be considered an interval scale, from resting to maximum, and perceptual ratings are linear with heart rate, we might say that this relationship supports the contention that the Borg scale is a category scale because of its interval properties. In addition, as we mentioned earlier, the quantitative semantic basis of the category expressions also supports this contention (Noble and Robertson, 1996). *However, the nonlinearity with his scales still exists in non-incremental exercises or if fatigue is induced.*

Borg said in 1978 that the scale he constructed satisfied the demands of an interval scale and, therefore, can be called a category scale. What Gamberale (1985) said that he would classify data received from the Borg scale as ordinal rather than interval.

Borg’s Category-ratio scale

Borg wanted to develop a scale that satisfied the psychophysical requisites of ratio scaling but, at the same time, was capable of eliciting interindividual comparisons.

The Borg CR-10 scale gives responses that may be said to belong to a ratio scale to overcome the critics of category scales mainly from Stevens (1974). *In fact, it has been constructed in such a way that it correlates with exponential physiological parameters during subjective assessment of increment intensities.* “CR10 scale makes it possible to determine growth functions for different modes, to compare them with physiological growth functions, and to make direct estimates of intensity levels for interindividual comparisons” (Borg, 1998, p. 15). Nevertheless, the requirements to support these statements are not present in the data his team has provided (Neely et al., 1992). “The CR10 scale is a general intensity scale that can be used to estimate most kinds of perceptual intensities" (Borg, 1998, p. 15). For this reason, the dot above 10 and outside the range of numbers on the scale should not be changed to 10+, because it represents an absolute maximum and avoid a "ceiling effect". People can experience a sensation (e.g., pain) higher than what they had experienced before and therefore it's important to let them respond with a number higher than what they expected based on those experiences. "Its construction encouraged ratings with decimals below 0.5, between the anchors, and also above 10, such as 11 or 12 or even higher" (Borg, 1998, p. 41).

Quantitative semantics of adjectives is of great importance in that scale because they provide multiplicative constants to a sequence of numbers with additive intervals. Empirical results showed that the new scale produced data that grew with an exponent of 1.6 and substantiated its ratio properties (Noble and Robertson, 1996). However, when he creates his scale Borg (1982) claimed the "high" correlation of his scale with HR; a variable increasing linearly with the intensity in the test he performed.

Four main considerations were employed to construct the CR-10 scale (Neely, 1995; Noble and Robertson, 1996):

- The acceptance of the ratio scaling techniques as the best for general descriptions of perceptual variation
- A method to make valid interindividual comparisons (but VAS respect this requirement)
- Adjectives and adverbs may function as multiplicative constants *(and allow to manipulate the scale according to a willingness and objective)*
- The fourth consideration was the relationship between category rating and ratio scale rating of perceived exertion.

Other category scales for monitoring perceived effort

It is believed that placement of maximal and minimal expressions is all that is necessary for a successful category scale (Noble and Robertson, 1996).

Borg proposed "that we use this scale [15-graded] in most cases." It might also be argued that these data support the use of the other scales in the study and application of perceived exertion (Noble and Robertson, 1996).

Remarks

With the category scale, the willingness of their "creators" to stick to a ratio scale made it less reliable and precise at for lower perception level (see, Neely, 1995, Fig. 7 & Studies 2 & 3).

The main issue regarding actual scaling methods to evaluate perceived exertion (Borg, 1998) is the willingness and belief that the measuring instrument must give results that correlate with physiological variable(s) and workload (Henriksson et al., 1972). As an example is the claim by Borg (1982) that his category-ratio scales has as good correlation than is category(-interval) scale with HR whereas in situation of non-linearities, the correlation coefficient is uninformative (Taleb, 2019a).

In that direction, however, the category-ratio is the less biased methods as being the most close to natural subjective measurement (Neely, 1995; Stevens and Mack, 1959).

3) Limits of endurance performance

From its psychophysiological characteristics, the RPE is crucial in endurance performance. It's one of the reasons why we decided to focus on this response to exercise in our subsequent work. We will detail in the next section the implication of the RPE in the limitation of endurance performance. Indeed, we can understand and improve the endurance performance solely when we have highlighted its limitations.

As early as 1971, the basis of psychobiological model of endurance performance were laid out (Lloyd and Claskey, 1971). Indeed, during a walking test to exhaustion, the maximum endurance time wasn't "the maximum amount of work that subjects could demonstrate. Rather, it was the amount of dynamic work that they were willing to tolerate. […] Therefore, although subjects were working, they were not approaching physiological exhaustion. […] It appeared that subjects' willingness to take part in physical work and continue walking on the treadmill were additional factors of extreme importance." This observation was more recently supported by Swart *et al.* (2009) showing that human endurance exercise performance is substantially prolonged by a stimulant (amphetamine) acting principally on the central nervous system (CNS). The ingestion of a centrally acting stimulant thus allowed subjects to exercise for longer at higher cardiorespiratory and metabolic stress indicating the presence of a muscular reserve in the natural state.

Looking at the limit of endurance performance through a different lens, Souron *et al.* (2020) investigated central fatigue kinetics in the knee extensors during a low-intensity sustained isometric contraction. All central and neuromuscular events didn't decrease to a large amount and plateau rapidly during the task to failure test. However, RPE as expected increased linearly during the exercise to be almost maximal at task failure (TF) (Lloyd and Claskey, 1971; Zhang et al., 2021). These findings confirm that TF is due to the subjects reaching their maximal perceived effort rather than any particular central event or neuromuscular limitations since maximum voluntary contraction (MVC) at TF was far from 10% of its original value (Souron et al., 2020). A similar observations has been reported during exercises with local ischaemia where neuromuscular events where unaffected compared to control condition while psycho-physiological variables were impacted concurrently to the performance in a 4-k TT (Azevedo et al., 2021).

Finally, from experimental studies (Coelho et al., 2015; Davies et al., 2021; Froyd et al., 2016; Keller et al., 2021; Marcora and Staiano, 2010a; Racinais and Girard, 2012; Staiano et al., 2018; Swisher et al., 2019), we know that locomotor muscle fatigue, varying differently between muscle groups (Colosio et al., 2022), is not the factor limiting TTE during high-intensity cycling exercise in healthy and fit adults. Furthermore, exhaustion is not related to physiological events associated to a disruption of homeostasis (Baron et al., 2008; Morales-Alamo et al., 2015) similarly in males and females (Martin-Rincon et al., 2021) and psychological manipulations by themselves lead to an improvement in performance (Barwood et al., 2008). All these findings have raised the importance of RPE to fully embrace the limitation of endurance performance.

4) Implication of the Perception of effort in the optimisation of endurance performance

The first theory trying to explain this phenomenon was the central governor model (Gibson et al., 2018), but was currently refuted (Marcora, 2008a). According to the psychobiological model of endurance performance based on motivational intensity theory (Brehm and Self, 1989; Wright, 2008a), people consciously decide to stop to exercise during a TTE test when the effort required is perceived to exceed their potential motivation. In highly motivated people willing to exert a maximal effort (Borg, 1998, p. 28) in order to succeed in the TTE test, volitional exhaustion occurs when effort is perceived as maximal and continuation of the TTE test seems impossible (Marcora, 2008a; Marcora et al., 2008, 2009a; Marcora and Staiano, 2010a). Worded differently, resource mobilization is governed by an energy conservation principle and effort is mobilized proportionally to the level of subjective task demand as long as success is possible and justified (Gendolla, 2012). Effort is resource mobilization for instrumental behaviour. By contrast, performance is the outcome of that behaviour – and several quantifications of "outcome" are possible (Gendolla, 2015).

In their study, Staiano *et al.* (2018) showed that the rate of RPE increase during TTE test correlate with TTE. More generally, perception of effort increases over time during prolonged constant workload exercise (Kerhervé et al., 2017; Smith et al., 2007; Søgaard et al., 2006). This is known since five decades now. To carry a load for a prolonged period increases its weight perception. It has been demonstrated experimentally by asking people to bear a weight for a prolonged period. Meanwhile, at some points, they must choose weights that seem as heavy as the continuously with the opposite arm. The matching load were carried during a brief duration in order to not induce fatigue in the opposite arm. The subject selected heavier weights all along the experiment to match the gradual increase in perceived heaviness of the continuously supported weight (McCloskey et al., 1974).

Stronger evidence that perception of effort is an important determinant of TTE during aerobic exercise comes from experimental studies in which perception of effort has been manipulated without changes in the cardiorespiratory, metabolic and neuromuscular factors thought to determine endurance performance. For example, mental fatigue increases RPE and reduces TTE during cycling exercise similarly between males and females (Lopes et al., 2020) while self-talk reduces perceived exertion and increases TTE in fit and healthy adults (A. W. Blanchfield et al., 2014; Wallace et al., 2017). Interestingly, psychological manipulations can change perception of effort and endurance performance (Mentzel et al., 2021; Mottola et al., 2021) even when the participants are not consciously aware of the experimental manipulation (A. Blanchfield et al., 2014).

Interestingly, perceived exertion is impacted with hypnotic intervention. The subjects' perceived exertion was manipulated in a predictable fashion which supports the view that perceived exertion is dependent in part upon psychologic processes. More importantly, the hypnotic suggestion of heavier and lighter workloads was generally accompanied by physiological changes (Morgan et al., 1973). This demonstrates as we explained earlier that psychological events influence the physiological response of the body.

Perceived exertion is independent from group 3 & 4 muscle afferents

Studies employing partial blockade of sensory signals from skeletal muscle afferents with epidural anaesthesia show that RPE is unchanged or even augmented during exercise with partial sensory blockade (Fernandes et al., 1990; Kjaer et al., 1999, 1989, 1987; Smith et al., 2003). Perceived effort is independent of joint and skin afferent feedback too, demonstrated with anaesthesia intervention (Gandevia and Mccloskey, 1978). In the case where afferent feedback would have been important sensory cue for perceived exertion, RPE should have decrease in these experiments (Cafarelli, 1978).

The increase observed in some studies likely occurs because the anaesthetic used to block afferent signalling unavoidably also blocked some motor outflow to the exercising muscles, weakening them and necessitating increased central command to produce the target muscle force (White and Bruce, 2020). As explained previously this would have concurrently increase the RPE. Moreover, a significant increase in perception of effort has been observed during constant-workload cycling exercise to exhaustion after induced eccentric muscle fatigue in the leg muscles, without affecting afferent feedback from the muscles (Lopes-Silva et al., 2015; Marcora et al., 2008).

Pain influence

Motor units activated at low forces were inhibited while those recruited at higher forces increased their activity in response to pain. When analysing lower- and high-threshold motor unit behaviour at high forces we observed differential changes in discharge rate and recruitment threshold across the motor unit pool. An increase in excitatory drive to high-threshold motor units is likely required to compensate for the inhibitory influence of nociceptive afferent inputs on low-threshold motor units (Martinez-Valdes et al., 2020). This has the consequence to increase the signal responsible for the generation of perceived exertion as explained previously.

Physiological Influences

Heat rate *per se* is not an important cue for the perception of exertion and does not appear to make a significant contribution to the close association between RPE and the relative work load performed by the individual in short-term exercise (Davies and Sargeant, 1979). Indeed, RPE can be dissociated from the heart rate with experimental interventions (Robertson, 1982). Autonomic blocking drugs has been used to affect heart rate during physical work. In these interventions, while heart rate changed in the expected direction as a result of the drugs, RPE was unaffected (Ekblom and Golobarg, 1971; Myers et al., 1987; Sjöberg et al., 1979). Pandolf *et al.* (1972) and Morgan (1973) reported that while heart rate was unchanged during the course of work on a bicycle ergometer, RPE (measured as RPI) tended to increase after 5 min of work. Similar results were obtained by Ljungberg *et al.* (1982) during horizontal lifting. RPE collected after 4 and 12 min of work, respectively, showed a significant increase while heart rate did not display any noticeable differences.

This also applies to resistance exercises in the context of varied workload and/or frequency of contractions (Asfour et al., 1983). Additionally, the RPE is correlated with %VO_{2max} during incremental test independently of performance level in cycling (Pérez-Landaluce et al., 2002).

As presented briefly in the previous parts, the theoretical perspective posits that physiological manipulations do not inherently impact endurance performance; rather, their positive or negative effects on endurance are mediated by alterations in the perception of effort, as opposed to direct influences. Notably, the influence on endurance performance stems from changes in the psychophysiological variable of Rating of Perceived Exertion (RPE). Consequently, interventions of a psychological nature or variations among individuals can similarly shape endurance performance through this common proxy, namely, the perception of effort. This is the juncture where traditional physiological models of endurance performance, such as Critical Power (Jones et al., 2010; Jones and Vanhatalo, 2017; Monod and Scherrer, 1965; Poole et al., 2016) and Joyner's model (Joyner and Coyle, 2008a), falter in their attempts to elucidate the intricacies of endurance performance.

5) Psychological interventions

The psychological interventions are not detectable or explained with traditional markers of endurance performance at the contrary to the RPE that helps to understand their influence and impact.

The intricate interplay between intrinsic motivation, cognitive factors, pharmacological influences, and social dynamics is integral to understanding the complex web of psychophysiological responses during physical activities. Of particular significance is the profound influence of motivation on performance, as evidenced by its impact on perceived exertion. This part will emphasize the crucial role some psychological interventions play in shaping individuals' perceived effort during tasks, underscoring its importance in optimizing performance and enriching the overall experience of those engaged in diverse physical activities.

Motivation

The principle of motivation. The strength of motivation to perform some act is assumed to be a multiplicative function of the strength of the motive, the expectancy (subjective probability) that the act will have as a consequence the attainment of an incentive, and the value of the incentive: Motivation = *f* (Motive X Expectancy X Incentive).

As explained in the psychobiological model derived from Brehm's theory (Marcora, 2019), (potential) motivation is central to describe and asses endurance performance. Motivation plays a pivotal role in shaping the psychophysiological responses of individuals engaged in physical tasks. Gendolla et al. (2021) assert that intrinsic motivation, specifically task choice, acts as an immunization against incidental affective influences, particularly when task demand is objectively low. This intricate relationship between motivation and performance involves a dynamic interplay of various psychological factors, as elucidated by Falk et al. (2022) and Atkinson (1957).

Factors Influencing Motivation and Performance:

Atkinson (1957) identifies three key variables (i.e., motive, expectancy, and incentive) essential for understanding the strength of motivation. Expectancy, a cognitive anticipation influenced by situational cues, plays a crucial role in determining an individual's commitment to a given task. The motivational equation proposed by Atkinson encapsulates the multiplicative function of motive, expectancy, and incentive, emphasizing their combined influence on an individual's motivation to perform a specific act.

Furthermore, Boat *et al.* (2018) explored whether exerting self-control reduces performance, increases perception of pain, and reduces motivation during a subsequent, unrelated physical task that requires self-control. To this end, subjects performed an easy and a difficult Stroop task before a lower limb endurance task (i.e., a "wall-sit") until volitional exhaustion. Difficult cognitive task reduces performance compared to the easy task and motivation during the early stages of the wall-sit task explained the reductions in performance among the variables assessed. Their results suggest that motivation to perform task goals, through its influence on the maximal effort people are willing to exert, may be an important explanatory mechanism behind performance decrements on physical tasks following the exertion of self-control (Dornic, 1986; Heath et al., 1999).

Influence of Music on Performance:

The impact of music on physical performance has been a subject of extensive research. English *et al.* (2019) examined whether listening to motivational music mitigates heat-related reductions in exercise performance, and leads to a greater increase in thermal and cardiovascular strain. Listening to motivational music mitigated heat-related reductions in exercise performance with an improvement in performance in the heat of ~10%. This improved exercise performance led to a greater increase in thermal and cardiovascular strain. Moreover, listening self-selected motivational music tends to increase endurance performance (Jebabli et al., 2022) but most importantly, decreased the perception of effort during running (Bigliassi et al., 2015; Clark et al., 2021) and cycling time trial (Vasconcelos et al., 2023) in normoxia and hypoxia (O'Keeffe et al., 2021). Music has also a positive impact on performance and enjoyment of an acute bout of sprint interval training (Stork et al., 2015), and improves wingate test performance in well-trained athletes when listened prior to the effort during the warm-up (Jarraya et al., 2012). These effects are translated by a reduction of the RPE for a given workload.

The Importance of incentives:

Andreacci et al. (2002) emphasize the significance of encouragement in improving physical performance. Their findings suggest that both the frequency and nature of encouragements play a crucial role, with verbal encouragements proving more effective than compliments, as demonstrated by Sahli et al. (2022).

Mood

Whether positive or negative mood, both have a joint effect with objective task difficulty on perceived effort. This is related to systolic blood pressure response too, being weak in a negative mood and strong in a positive mood situation. However, this effect is observed only with challenging task not perceived as impossible, otherwise leading to no positive impact of positive mood (Gendolla, 2012).

6) Influence of prior fatigue on RPE and consequently on exercise performance

Fatigue resistance

As early as Borg (1962), the implication of RPE in the concept of durability was highlighted. Borg performed an experiment where subjects had to repeat an incremental exercise to exhaustion 20 times and already highlighted the relevance of RPE in this topic. The maximal power output and heart rate was recorded every times. He demonstrated that the resistance to fatigue is different interindividual and in general the performance decreases quickly during the first 3-4 attempts and then decrease much slower from trial to trial while this durability characteristic allows to classify athletes (Borg, 1962, pp. 42–46). Endurance performance is influenced by a prior exercise performed upstream and the effect is driven by the duration and the intensity of the first exercise (Brownstein et al., 2022b; Fullerton et al., 2021; Kesisoglou et al., 2020; Sanchez-Jimenez et al., 2023). Maximal exercise performance is reduced following a prior maximal test. This is reflected by the increase rate of RPE (Eston et al., 2007). This phenomenon was first observed as early as 1991 by Crawford *et al.* (Crawford et al., 1991) and is transferable to different disciplines like judo (Franchini et al., 2019).

Muscle fatigue: Mechanisms and influence during exercise (Marcora, 2008b)

Skeletal muscle fatigue is characterized by a reduction in the anticipated force output during sustained or repeated contractions (Edwards, 1978).

The technique of twitch interpolation has helped to reveal the changes in drive to motoneurons during fatigue. Voluntary activation usually diminishes during maximal voluntary isometric tasks, that is central fatigue develops, and motor unit firing rates decline. Transcranial magnetic stimulation over the motor cortex during fatiguing exercise has revealed focal changes in cortical excitability and inhibitability based on electromyographic (EMG) recordings, and a decline in supraspinal “drive” based on force recordings. Some of the changes in motor cortical behaviour can be dissociated from the development of this “supraspinal” fatigue. Central changes also occur at a spinal level due to the altered input from muscle spindle, tendon organ, and group III and IV muscle afferents innervating the fatiguing muscle (Gandevia, 2001).

Fatiguing muscle involved an increase muscle activation to counteract this effect during exercise at constant workload. When pursued until exhaustion muscle activation reflected by normalised EMG increased in a similar fashion as RPE all along the test confirming the role of central command in the generation of perceived exertion (Pincivero and Gear, 2000). This alteration is independent of the activation of central motor drive during the fatiguing task (Laginestra et al., 2022) which doesn’t mean that central motor drive is independent of the subsequent alteration in endurance performance.

The rate of muscle fatigue development during the TTE test and the contribution of central and peripheral mechanisms depend primarily on the relative exercise intensity (Burnley and Jones, 2018). In addition, the mode of locomotion trigger different mechanisms of muscle fatigue while the final performance outcome (reduction in MVC) is similar (Brownstein et al., 2022a).

The basic assumption of this muscle fatigue model of endurance performance is that **cessation of high-intensity exercise occurs when muscle fatigue is so severe that the locomotor muscles are no longer able to generate the power required by the TTE test despite a maximal voluntary effort** (Allen et al., 2008; Burnley and Jones, 2018; Hepple, 2002)**.**

The magnitude of the changes implied by the critique of Allen and Westerblad (2010) (a 77% reduction in maximal voluntary cycling power (MVCP) at exhaustion and a subsequent 498 W increase in 3 – 4s of partial recovery) is not plausible in intact humans (Coelho et al., 2015; Sargeant and Dolan, 1987) and is observed only in non-physiological conditions (Lannergren and Westerblad, 1986).

Muscle induced-fatigue during endurance exercise is represented by the reduction in maximal voluntary contraction (MVC) and evoked peak twitch (PT) few minutes after time-to-exhaustion test (TTE) (Amann et al., 2007; Amann and Dempsey, 2008; Romer et al., 2007, 2006). Likewise, a significant decline in MVCP has been found after both non-exhaustive (Beelen and Sargeant, 1991; Sargeant and Dolan, 1987) and exhaustive (Marcora and Staiano, 2010a; Swisher et al., 2019) bouts of high-intensity cycling exercise in healthy adults. This is confirmed in real-world condition where professional cyclists are unable to develop their maximal power output capacities at the end of races (Robin et al., 2021).

Actually the three-component model of critical power predicts that, immediately after exhaustion, MVCP should be very close to critical power (Jones et al., 2010) and, thus, lower than the power required by the TTE test which was clearly above the critical power.

From experimental studies (Coelho et al., 2015; Davies et al., 2021; Froyd et al., 2016; Keller et al., 2021; Marcora and Staiano, 2010a; Racinais and Girard, 2012; Staiano et al., 2018; Swisher et al., 2019) locomotor muscle fatigue is not the factor limiting TTE during high-intensity endurance exercise in healthy and fit adults.

From the knowledge accumulated thanks to the experimental studies described, according to the psychobiological model of endurance performance, muscle fatigue will decrease the performance of people engage in endurance events, but indirectly by the concurrent increase in central command required to maintain a given level of muscle contraction. This increase in cortical irradiation increases the RPE and decrease the performance for a specific workload.

(Negative) Effects of prior cognitive task

For a full review on the effects of mental fatigue on sport-related performance, see Pageaux *et al.* (2018)*, &* Habay *et al.* (2021) for a review on sport-specific psychomotor performance. The fatigue-related impairments could however be subject to interindividual variability as suggested by a recent meta-analysis (Habay et al., 2023). The mechanisms in the brain related to this state of mental fatigue is still equivocal and needs more investigations (Brietzke et al., 2021) while a recent review reports the different strategies to tackle mental fatigue states (Proost et al., 2022). Applied before or during a physical task, a state of mental fatigue induce an increased RPE during weight lifting and training and impaired subsequent cycling performance (Staiano et al., 2023). This is the central point of this topic because RPE has been demonstrated to be the only variable dealing with physiology able to discriminate the influence of these psychological factors.

Mental fatigue impairs muscle endurance and motivation for the physical task but not the neural drive to the muscle at any frequency bands. Although it is physiologically possible for mentally fatigued subjects to generate an optimal neuromuscular function, the altered perception of effort and motivation seems to limit physical performance (Alix-Fages et al., 2022). Additionally, mental fatigue (through its action on inhibitory control) impairs passing decision-making performance in football following whether 15 or 30 min of Stroop task (Gantois et al., 2019).

The role of inhibitory control in endurance performance is highlighted by its critical role in maintaining goal-directed behaviour and attentional control (Hyland-Monks et al., 2018). “Observations on fatigue during maximal exercise suggest that trained subjects are able to use their muscles to an extent for which the untrained do not have competence because of central inhibition” (Secher, 1993). Furthermore, athletes exhibit greater resistance to mental fatigue than non-athletes (Cona et al., 2015; Martin et al., 2016) but they are also affected by it (Lopes et al., 2020). It is therefore suggested that habitual exercise may reduce the negative effect of mental fatigue on a prolonged cognitive task (Jaydari Fard et al., 2019).

The negative effect of mental fatigue on performance need to be taken with caution, because many experiments have demonstrated no effect on performance and RPE even with extended duration (1.5h) of prior cognitive task (Vrijkotte et al., 2018). In another study, physical performance measured during a specific test for judokas is not impaired by a previous 30-minute cognitive task that causes mental fatigue. In addition, this cognitive task did not influence the physiological changes induced by the specific physical test (Campos et al., 2019). Based on recent meta-analysis on this topic (Brown and Bray, 2018; Giboin and Wolff, 2019; McMorris et al., 2018b), the results reported in these last two studies should be considered as not trivial in the literature.

The centrality of Rating of Perceived Exertion (RPE) in endurance performance underscores its neurobiological underpinnings, as a subjective measure originating from the brain, thereby establishing a reciprocal relationship where the brain's activity in response to physical activity becomes a consequential focus of scientific interest.

7) Brain activity related to the (perceived) exertion

As the supplementary motor area (SMA) was previously implicated in coding prospective task-demands (Zenon et al., 2015), Emanuel *et al.* (2021) tested its role in producing the stuck in the middle (STIM) pattern. The results of the main experiments showed a more pronounced STIM following inhibitory SMA stimulation compared to control. A control analysis showed that the overall level of effort was similar in both conditions, rendering alternative accounts in terms of motor inhibition unlikely. These findings are consistent with the possibility that the SMA may play a role in moment-to-moment coding of effort value, or in related sub-processes, which can cause effort to be distributed more equally over the course of a task.

On an other hand, Shibuya *et al.* (2009) provided evidence indicating that perceived exertion was not necessarily related with prefrontal cortex activation during exercise using an elbow-flexion exercise with or without muscle-spindle stimulation (vibration) and an increase in effort sense has been related to a decrease in corticospinal excitability (Yunoki et al., 2016).

The willingness to exert effort fluctuates on a moment-to-moment basis, with shifts in the value of exerting effort for reward depending on a recoverable and an unrecoverable state of fatigue. These states covaried with neural activity in distinct brain regions previously linked to effort-based decision-making, namely in the anterior rostral cingulate zone (RCZa) and middle frontal gyri (MFG), as well as in the posterior rostral cingulate zone (RCZp), when making choices about whether exerting effort is worth for the reward (Müller et al., 2021).

In line with the relation between the brain activity and the perception of effort, one key experimental intervention used to deepen our understanding of the RPE was the use of caffeine supplementation. Indeed, the ergogenic effects of caffeine on exercise performance predominantly appear related to caffeine’s binding to adenosine receptors in the brain (Mclellan et al., 2016; Salamone et al., 2018). Mizuno *et al.* (2005) reported that trained men have greater adenosine receptor densities than untrained subjects; it might be that this increase in adenosine receptor density in trained individuals allows greater binding of caffeine to those receptors, increasing the magnitude of the acute improvements in exercise performance following caffeine ingestion. Caffeine binds to adenosine receptors, subsequently reducing RPE during exercise (Doherty and Smith, 2005) or allowing to produce a higher power output for the same RPE (Desbrow et al., 2012; Green et al., 2016; Quinlivan et al., 2015). As a consequence, the report of the RPE response to caffeine ingestion is of importance to expand our overall description of the perception of effort.

Caffeine effects on a broad range of exercise modes (Christensen et al., 2017; Conger et al., 2011; Cristina-Souza et al., 2022; Doherty and Smith, 2005, 2004; Grgic, 2018; Grgic et al., 2018; Grgic and Pickering, 2018; Polito et al., 2016; Ribeiro et al., 2018; Shen et al., 2019; Southward et al., 2018; Warren et al., 2010) and fitness level (Santos et al., 2020) are well-established. Ergogenic effects appears to be extended in open-loop compared to close loop trial following caffeine ingestion, supposing that the open-loop exercise impose a higher central demand (Couto et al., 2022).

Several studies compare the effects of caffeine amongst **males and females**, reporting similar effects in both sexes (Butts and Crowell, 1985; Sabblah et al., 2015; Suvi et al., 2017). Moreover, caffeine ergogenic effects appears to be repeatable (Astorino et al., 2012). Caffeine improves time to task failure and at the same time increase tidal volume and inspiratory time without altering V_E (Marinho et al., 2022). The effect on endurance performance are still visible while using a virtual opponent providing an additional benefit (Tomazini et al., 2022). The maintenance of the ergogenic effect is likely explained by caffeine’s half-life, which is generally 4 – 6 h (Graham, 2001). This acute benefit of caffeine has been confirmed in a study where caffeine consumers were abstained from dietary caffeine sources for 4 days and then take caffeine the day before an exercise test, or the day of the test, or both. What’s come out is an improvement in performance in both conditions where caffeine was consumed the day of the test. The ingestion of caffeine the day before has no influence though on performance (Irwin et al., 2011).

Having in mind the relation between caffeine consumption and alteration in the perceived exertion response to given workload, this further outline the omniscience of the RPE in endurance performance and physical activity broadly speaking.

8) RPE & Pacing strategies

Effort regulation over time is of importance in the context of this thesis as some part of our work will focus on self-regulated exercises. Due to the central role of PE in this process, as we will detailed later, we will expand here the research findings shedding light on the importance of RPE in pacing regulation that will help us to understand further how RPE works and its implications in the context of endurance performance.

People adjust their pacing during maximal self-paced exercise according to their perceived exertion and the remaining duration (Faulkner et al., 2008) or distance (even when this last is just perceived without feedback) (Pinheiro et al., 2016) as presented in the psychobiological model independently of the duration / distance of the trial (Joseph et al., 2008). We have to noticed that the knowledge of endpoint whether it's in distance or duration has the effect to increase the perceived exertion at isotime compared to a TTE test (Coquart and Garcin, 2008; Wingfield et al., 2018). Important remark to raise, is the reproducibility of the pacing strategy and perceptual responses (Thomas et al., 2012). To note and make the link with the previous parts, this context is related to an increase activation across the PFC (Wingfield et al., 2018).

Pacing is regulated according to the psychobiological principles to avoid a disengagement from the task arising from effort being too high to be tolerated and physiological responses aren't modify during a time-trial and stayed barely constant (Alves et al., 2020; Chaffin et al., 2008). Indeed, the effort regulation seems to be unaffected by duration of exercise and follows the same pattern irrespective of the length of the exercise (Jones et al., 2015). This has been demonstrated on a field study with recreational runners during a marathon race where pacing seems regulated by perceived exertion too, independently of physiological responses (Billat et al., 2022). In a different mode of locomotion, during a time trial the power output is adjusted continuously in order to keep the perception of effort in the range to be supported and don't lead to exhaustion before the end of the test (Cohen et al., 2013; Renfree et al., 2012).

Traditional pacing pattern are U-shaped and it's observable in the different mode of locomotion (Tijani et al., 2021). This response has been modelized in term of effort distribution over time as the perceived impact (Emanuel, 2019). In that way, the end-spurt demonstrate an increase in power output when the cardiovascular strain is at its highest, paradoxical with traditional interpretations (Marino, 2022). To note, performing a maximal sprint during the warm-up does not affect 10km cycling time-trial performance neither the pacing or RPE time course (Veen et al., 2019).

The pacing strategy is even more complex in a context of high-level competition. Elite open-water swimmers adopted different pacing strategies depending if they are on top position or elsewhere during indoor pool race. Despite no significant differences, it is evident that the non-medallists' RPE increased halfway throughout the race, specifically for the female athletes, where the increase in RPE obliged them to decrease speed in order to finish the race (Baldassarre et al., 2021). *The different pacing strategies can be thought to be competition-dependent. That's to say, non-medallists increased their speed at the start to stick with the best athletes in order to win but were unable to keep the pace for the entire race. Their own pace if the race was a time-trial could have been different and more linear.*

Effort-based choice

Physical fatigue can result in a diminished willingness to exert effort that might be performed in a more rested state. Previous work has established a network of brain regions, including the anterior cingulate cortex (ACC), bilateral anterior insula, and ventromedial prefrontal cortex (vmPFC) in computing the value of effortful options and making effort-based decisions (Aridan et al., 2019; Arulpragasam et al., 2018; Bonnelle et al., 2016; Chong et al., 2017; Croxson et al., 2009; Hogan et al., 2019; Klein-Flügge et al., 2016; Kurniawan et al., 2013; Prévost et al., 2010; Skvortsova et al., 2014). Using computational modelling of choice behaviour, a study found that fatiguing exertions cause participants to increase their subjective cost of effort, compared to a baseline/rested state (Hogan et al., 2020).

In summary, the intricate network of brain regions shed light on the adaptive nature of decision-making under physical fatigue and is a promising research area in the process of better understanding the perception of effort and its action.

II. Physiological implications of spinal cord injury (SCI) in the production of endurance sports performance

Transitioning from the foundational aspects of the (rating of) perceived exertion, the forthcoming sections delve into the intricacies of the current knowledge dealing with the physiological implications of SCI on endurance sports performance. The significance of constructing such a framework is essential given the particularity of this population, for the subsequent qualitative investigations undertaken in this doctoral thesis.

The theoretical underpinnings laid herein serve as the scientific bedrock, guiding our inquiry into the psychophysiological responses of the body and the intricate interplay between SCI and the production of optimal performance in endurance sports.

1) Respiratory function

Initial findings

The reflex control of the respiratory pathways in Spinal Cord Injury (SCI) is complex and remains poorly understood at present, however...

Individuals with more rostral injuries exhibit the most significant alterations, including vital capacity, forced expiratory volume in one second, peak expiratory flow, maximal inspiratory static pressure, and maximal expiratory static pressure. Consequently, it is generally accepted that individuals with upper cervical or thoracic SCI show pulmonary restrictions characterized by a reduction in lung and thoracic wall compliance ($\Delta V/\Delta P$), paradoxical inward movement of the anterior thoracic cage during inspiration, and deformation of the thoracic cage.

Vital capacity, forced expiratory volume in one second, and inspiratory capacity increase (in line) with the decreasing level of SCI up to T10. Inspiratory capacity increases proportionally with the caudal level of the injury (up to L1).

Changes in the spectral power of muscle activity (EMG) are more associated with disruptions in action potential transmission than with the process of fatigue at the sarcomere level. The absence of diaphragmatic fatigue, despite a presumed shortening of inspiratory muscle length, could have been linked to absolute ventilation values during exercise.

The reduction of voluntary diaphragmatic inspiratory capacity is the most common parameter for high cervical SCIs. Individuals with lower incomplete cervical injuries (C6-C8) exhibit greater reductions in vital capacity and more significant restrictive impairment than those with thoracolumbar lesions. This occurs due to partial or complete paralysis of other inspiratory muscle groups, including parasternal intercostals (T1-T7), lateral external intercostals (T1-T12), and scalenes (C4-C8). Paralysis of abdominal musculature (T7-L1) further leads to an inability to increase abdominal pressure during inspiratory efforts, thus impairing optimal diaphragmatic contraction. Additionally, individuals with cervical SCI may be particularly prone to inspiratory muscle fatigue during exertion. Regarding autonomic control of respiration, the parasympathetic nervous system predominates in the control of the bronchopulmonary system (Krassioukov, 2009).

Vital capacity & forced expiratory volume in 1 second are affected up to T8 lesion levels. The motor nerves of the diaphragm and scalene (main muscles of inspiration) leave the spinal cord between C3-C5 and C3-C7, respectively, while the motor neurons of the main expiratory muscles (abdominal & internal intercostal muscles) are distributed in the T7-L1 region.

The paralysis of the inspiratory & expiratory muscles for cervical SCI appears to be compensated for in part by activation of the trapezius (inspiratory) and the clavicular portions of the pectoralis major and dorsalis major (both expiratory) (De Troyer et al., 1986; Fujiwara et al., 1999; Terson de Paleville and Lorenz, 2015). The result is a disproportionate reduction in vital capacity, which is dependent primarily on expiration, relative to total lung capacity, which is primarily an inspiratory action (West et al., 2012a).

Impact of position

Expiratory reserve volume is measurable even in cases of high cervical injury, and is generally lower in the supine position.

Vital capacity values, the volume of forced exhalation in 1 second, tend to be greater in the supine position than in the seated position for people with spinal cord injury up to T1, caudal to which they are lower than in the seated position. The increase in vital capacity in the supine position is linked to the effect of gravity on abdominal content and the increase in inspiratory capacity.

Specificity of Thoracic SCI

It is currently recognised & documented that many athletes with cervical SCI exhibit pulmonary obstruction, whereas this characteristic is not observed in individuals with thoracic SCI. In addition, there are currently no data relating to lung volumes in athletes with thoracic SCI. However, cardiovascular responses to exercise show that there appears to be a decrease, but to a lesser extent.

Respiratory muscle endurance training (RMET)

Respiratory muscle training is an effective strategy for increasing strength and endurance and protecting against the effects of fatigue (Gross et al., 1980; Mueller et al., 2008; Rutchik et al., 1998). However, cessation of this training results in a loss of the gains made within 6 weeks (Gee et al., 2019). For individuals with cervical or upper thoracic SCI, positive effects of respiratory muscle training have been reported regarding inspiratory muscle strength and endurance.

Although the mechanisms underlying the increase in associated $\dot{V}O_2$peak remain elusive, the increase in aerobic capacity may be generated by an increase in diaphragm strength and/or a change in the configuration of the rib cage.

To ensure that the partial pressure of CO_2 does not fall below resting values during voluntary hyperpnoea, it is necessary to increase F_iCO_2, either by partially re-breathing exhaled air or by titrating the CO_2 in inspired gases.

Abdominal binding

Finally, there is evidence that abdominal binding can support respiratory function and performance, as recently demonstrated in armchair rugby players (West et al., 2014).

The use of an abdominal belt exerts beneficial pulmonary effects by promoting expansion of the lower rib cage through increased diaphragmatic forces following an increase in belt-induced diaphragmatic pressure production. This 'tool' may also allow the diaphragm to operate on a more efficient portion of its force-tension relationship.

On one hand, preservation of diaphragmatic contraction should improve ventricular filling during inspiration due to the associated reduction in transthoracic pressure. In addition, when a lap belt is used tightly on individuals with cervical SCI, the associated increase in intra-abdominal pressure promotes venous return and increases resting systolic ejection volume, presumably by increasing venous return through compression of the abdominal inferior vena cava (West et al., 2012b).

2) Cardiac electrophysiology

Autonomic control of the cardiovascular system

The regulation of blood pressure and heart rate is constantly under the control of the ANS, which is divided into two parts: the sympathetic and parasympathetic systems.

The activation of the sympathetic nervous system plays an excitatory role and results in an increase in sympathetic nerve activity, leading to an elevation in heart rate, cardiac contractility, and generalized systemic vascular constriction. This, in turn, results in an increase in blood pressure. Regarding the parasympathetic division, the vagus nerve exits the central nervous system at the supra-epinal level as the cranial nerve X, reaching target organs such as the heart and cerebral blood vessels without traversing the spinal cord. Its activity is generally limited to reducing heart rate and cardiac contractility (via the vagus nerve), and it is widely accepted that it does not extend to the vascular system itself, except for specific regions containing blood vessels in salivary glands, gastrointestinal glands, genital erectile tissue, and potentially the cerebrovascular system (Hamner et al., 2012; Kano et al., 1991; Suzuki et al., 1990).

Sympathetic and parasympathetic preganglionic neurons (from the sacrum) receive tonic and inhibitory control from the supraspinal nervous system via spinal autonomous pathways (Calaresu and Yardley, 1988; Lebedev et al., 1986), which unfortunately are frequently disrupted after SCI (Furlan et al., 2003). Although the site of SCI is typically localized to a small region (including neurons, glial cells, as well as ascending and descending neuronal pathways), the effect of this disruption is often associated with a wide range of dysfunctions due to the malfunction of the ANS.

Disturbances in descending cardiovascular spinal pathways lead to at least five neuroanatomical changes influencing cardiovascular autonomous control:

1. Initial sympathetic hypoactivity due to the loss of supraspinal sympathetic tonic excitation (Maiorov et al., 1997; Mayorov et al., 2001),
2. Alterations in the morphology of sympathetic preganglionic neurons (Krassioukov et al., 1999; Krassioukov and Weaver, 1995),
    a. These alterations may be reversible, but too few data are currently available to definitively pronounce on this aspect.

3. Morphological changes in spinal circuits (e.g. afferent sprouting from the dorsal root, potential formation of aberrant synaptic connections (Krenz et al., 1999) or aberrant inputs into spinal interneurons) (Krassioukov et al., 2002),
4. Altered sympathetic-sensory plasticity (Ramer et al., 2012),
5. Impairment of peripheral neurovascular reactivity (Arnold et al., 1995).

Sympathetic innervation

The sympathetic nervous system (SNS) controls cardiac and vascular smooth muscles to increase heart rate (HR), contractility, and blood pressure during exercise (Phillips et al., 1998).

Sympathetic innervation to the heart and blood vessels of the upper limbs originates from spinal segments T1-T5. Sympathetic innervation critical to the splanchnic vascular system and the lower limbs occurs at spinal segments T6-L2. Sympathetic preganglionic neurons involved in controlling the myocardium and vascular system of the upper limbs arise from spinal levels T1 to T5, while those located at T6-L2 are involved in mesenteric control and the vascular system of the lower limbs (Krassioukov, 2009).

The loss of descending sympathetic drive to the vascular innervated below the level of SCI results in hypotension, triggering a baroreflex-mediated increase in sympathetic flow and a decrease n parasympathetic flow to the heart. However, injuries above T6 lead to an impairment in the ability to increase HR and actively enhance contractility.

Complete lesion:

Any increase in HR in individuals with a complete lesion above T1 will result from decreased vagal input, significantly reducing maximal HR during exercise (Coutts et al., 1983; Van Loan et al., 1987). Indeed, a high-level complete SCI leads to the loss of supraspinal control over sympathetic spinal circuits, resulting in decreased sympathetic activity below the level of the injury (Hopman et al., 1998; Krassioukov, 2012; Phillips et al., 1998). The consequence of this dysfunction is bradycardia, hypotension and a significantly reduced hemodynamic response to exercise compared to individuals with incomplete autonomic SCI (West et al., 2013).

Specificity of thoracic SCI:

Paraplegics differ significantly based on whether their injury is above or below T5, particularly concerning autonomic splanchnic function. With a lesion below T5, sympathetic and parasympathetic innervation to the heart is preserved. However, sympathetic control over the splanchnic bed and blood vessels in the lower extremities is lost below the affected segments. The loss of innervation to the splanchnic region (innervated by T5-L2) impairs the ability to effectively redistribute blood flow (Rothe, 1983).

When the spinal cord is injured at or below T5, cardiovascular control becomes markedly imbalanced. The heart and blood vessels innervated by the upper thoracic segments remain under brainstem control, while vascularization of the lower body is influenced by unregulated spinal reflexes. Consequently, there is a significantly elevated sympathetic cardiac activity and reduced parasympathetic cardiac activity, leading to myocardial damage, cardiac dysfunction, and low of arterial baroreflex control below the level of the injury.

Alterations in autonomic function, specifically the low of descending sympathetic drive to the vascular system below the level of SCI, result in hypotension and a critical baroreflex-mediated increase in sympathetic tone, accompanied by a decrease in parasympathetic tone to the heart (Moffitt, 2010).Arterial baroreceptors (i.e., baroreflex: detects changes in blood pressure in the body) respond to a decrease in blood pressure by reflexively decreasing parasympathetic division activity and reflexively increasing sympathetic division activity of the ANS. Sympathetic flow to the heart is increased for injuries caudal to T5, while upper injuries cause at least sympathetic dysfunction related to the heart, making this consequence not universal. Chronic increases in sympathetic activity and reductions in parasympathetic activity have deleterious long-term effects on cardiac performance and electrophysiology (Billman, 2009).

The increased sympathetic flow is attributed to multiple mechanisms, including increase cardiac sympathetic innervation density, alterations in the morphology of postganglionic sympathetic neurons in stellate ganglia, and structural neuroplasticity of cardiac sympathetic preganglionic neurons in the T1-T5 spinal cord segments (Lujan et al., 2012, 2010).

Gastrointestinal tract

The heart, pulmonary system, and upper portions of the gastrointestinal (GI) tract are under parasympathetic control through the vagus nerve.

The lower GI tract receives parasympathetic innervation from spinal segments S2-S4. In individuals with a SCI, the GI transit times can be significantly prolonged compared to able-bodied (AB) individuals. Parasympathetic cardiac nerve fibers pass though the spinal cord, so SCI does not directly cut off parasympathetic cardiac activity.

Parasympathetic Innervation & Baroreceptors

The baroreflex, previously introduced, is the primary mechanism responsible for short-term blood pressure regulation (La Rovere et al., 2008; Phillips et al., 2012) and also plays a crucial role in long-term blood pressure regulation (Heusser et al., 2005). The baroreflex consists of two interdependent systems: a low-pressure system comprising cardiopulmonary stretch receptors located in the heart and lungs, increasing SNS activity in response to reductions in pressure and central venous volume (Abboud and Thames, 1983); a high-pressure baroreflex system consisting of stretch receptors located in the adventitia of the aortic arch and carotid bulbs (Fadel et al., 2003). The signal is transmitted from the carotid bulb via the glossopharyngeal nerve (i.e., vagus nerve) and from the aortic arch via the vagus nerve to the nucleus of the solitary tract in the medulla oblongata (Krassioukov and Weaver, 1996). Following an SCI, although baroreceptors certainly detect reductions in central blood volume during body up righting, disruption of sympathetic descending pathways hinders the ability to regulate vascular tone, often resulting in abnormal blood pressure fluctuations with changes in body position (Phillips et al., 2012).

Benefits of Physical Activity

The beneficial effects of physical activity are, in part, mediated by an increase in plasma volume, venous return, cardiac function, as well as an increase in efferent parasympathetic activity and a decrease in efferent activity (Chen and Dicarlo, 1998; DiCarlo et al., 1989; Scheuer and Tipton, 1977; Stone and Liang, 1984; Tipton, 1991).

It is well-documented that individuals with SCI, despite limitations in muscle mass and strength available for training, exhibit significant adaptations in response to training

(DiCarlo, 1988, 1982; DiCarlo et al., 1983; Huonker et al., 1998; Knutsson et al., 1973; Oscai, 1973).

Despite vasomotor and sudomotor pathways being assumed to share a similar spatial orientation within the spinal cord, damage to one pathway may not necessarily lead to damage to the other. This assertion is supported by the observation that athletes with intact cutaneous sympathetic responses had attenuated maximal HR and orthostatic hypotension. Conversely, athletes without cutaneous sympathetic responses exhibited a maximal HR response indicating sympathetic stimulus presence and did not experience orthostatic hypotension.

Finally, dynamic exercise can also serve as countermeasure to autonomic dysreflexia by reducing sympathetic nerve activity, as a single exercise session often reduces post-exercise sympathetic nerve activity.

Autonomic dysreflexia (AD)

AD presents a unique stimulus to the heart, resulting in extremely high sympathetic drive coupled with elevated vagal tone through the arterial baroreflex (Courtois et al., 2004; Karlsson, 1998). AD episodes are characterized by a sudden elevation of systolic blood pressure by at least 20 mmHg, which may or may not be accompanied by a decrease in HR. Many AD episodes are asymptomatic (the individual may not be aware even when blood pressure increases) or characterized simply by sweating and/or piloerection. However, they remain observable through simple blood pressure measurements (Kirshblum et al., 2002).

Generally, individuals with a SCI at or above T6 are at risk of AD and boosting (Blackmer, 2003). Typical signs include: high blood pressure, headaches, hot flushes, profuse sweating (above the level of injury), pupil dilation (mydriasis) or blurred vision, pale and moist skin due to vasoconstriction (below the level of injury), nasal congestion, bradycardia, cardiac arrhythmia, atrial fibrillation, etc.

An additional alteration associated with AD after an SCI includes heightened reactivity of blood vessels to alpha-adrenergic stimulation (promoting vasoconstriction). Sympathetic system deficiencies can also adversely affect exercise performance, including attenuated catecholamine release in response to exercise and disruption of peripheral vascular system control, leading to venous pooling and reduced venous return (Currie et al., 2015).

AD occurs in response to noxious afferent stimuli below the level of the injury. Common triggers for AD include bladder and bowel distention, but it can also be provoked by other noxious stimuli such as spasms, pressure sores, or even something as simple as tightly tied shoelaces. Catheterization or manipulation of an indwelling catheter, urinary tract infection, dyssynergia of the bladder sphincter, and bladder percussion can also induce AD. There are also several iatrogenic triggers, including cystoscopy, vibratory or electrical stimulation of the penis for ejaculation, and electrical stimulation of muscles (as often occurs in physical therapy or occupational therapy). AD results in sympathetic response, causing vasoconstriction below the neurological injury. Vasoconstriction leads to a rapid increase in blood pressure, which can reach 300 mmHg for systolic and 220 mmHg for diastolic pressure (Karlsson, 1999), this causing the mentioned symptoms. Physical activity has been demonstrated as a safe therapeutic approach to mitigate the severity of AD. Changes in the autonomic circuits of the spinal cord are major factors contributing to the development of AD (Krassioukov et al., 2002). Some individuals with SCI deliberately induce AD to increase their blood pressure, as it can, in some cases, enhance athletic performance (Harris, 1994).

Orthostatic hypotension

Hypotension appears immediately after injury due to the loss of supraspinal tonic excitatory drive to sympathetic spinal neurons (Calaresu and Yardley, 1988). Subsequently, resting blood pressure returns to normal but remains low, and episodic periods of hypertension frequently occur in conditions of AD (Naftchi, 1990). In addition to AD, individuals with an SCI may experience episodes of orthostatic hypotension daily, requiring management. Clinically, orthostatic hypotension is defined as a decrease in systolic pressure of at least 20 mmHg or a decrease in diastolic pressure of at least 10 mmHg upon changing from a supine to an upright position, regardless of symptom presence (Kaufmann, 1996). Similar to AD, orthostatic hypotension does not necessarily lead to presyncopal symptoms, and more that 40% of individuals with a SCI are asymptomatic during episodes of orthostatic hypotension (Claydon and Krassioukov, 2006).

3) Cardiovascular responses to exercise

The psycho-physiological responses to exercise are generally similar to those of able-bodied people (Antunes et al., 2022) , although there are a few specific features to be taken into account. The limits of oxygen consumption are identical in quadra- & paraplegic individuals to those traditionally observed and demonstrated by modifying the fraction of inspired oxygen concentration (Hjeltnes, 1986; Hopman et al., 2004). An increase in oxygen availability through a higher fraction of oxygen in the inspired air leads to an increase in the maximum capacity to use oxygen & in the mechanical power that can be developed.

During exercise, the lack of sympathetic innervation and muscle pump below the lesion in individuals with SCI results in a smaller increase in mean systemic filling pressure and diastolic end ventricular volume (due to reduced venous return), producing a smaller increase in systolic ejection volume in relation to the Frank-Starling mechanism. As a result, HR is higher (compared to an AB individual) during submaximal exercise in order to maintain cardiac output (Hopman et al., 1992; T. E. Hopman et al., 1993).

Physical activity enables the following adaptations:

- ↑ maximal HR (HRmax) & sympathetic skin response (SSR)
- ↓ systolic & diastolic blood pressure variation in response to a torso raise

The intrinsic frequency of the sinus node is >100 pulses per minute; consequently, the sole suppression of parasympathetic tone results in a HR around 100-130 bpm for tetraplegic people with a complete lesion or a completely inhibited sympathetic nervous system (Sethi et al., 1984).

Cardiovascular morphology

People with cervical SCI show significant reductions in cardiac function in the form of atrophy (Nash and Jacobs, 1998) 3-6 months post-injury, whereas people with thoracic SCI do not, suggesting the need for early rehabilitation to minimise cardiac consequences in this specific population (Balthazaar et al., 2022).

The same adaptation is present for inactive (lower) limbs. However, exercise of the inactive limbs counterbalances and partially reverses the unfavourable changes in arterial diameter (Bleeker et al., 2005). The use of electrical stimulation, for example, as a method of activating paralysed limbs in individuals with SCI increases the diameter of the femoral artery by 6% within 6 weeks (Thijssen et al., 2006). Interestingly, the changes in diameter were observed after only 2 weeks (i.e., 4 sessions of 25 min).

These data reinforce that structural changes in ductus arteriosus diameter are attributable to physical inactivity, whereas exercise training represents an effective stimulus producing a rapid, dose-dependent increase in arterial size. Physical training (of the motor muscles) does not alter the dimensions of the femoral artery, but does increase those of the subclavian arteries.

A 37% reduction in femoral artery diameter is observed in people with SCI compared to a AB control group (Olive et al., 2003). However, when femoral artery diameter was expressed as a unit of muscle volume, no differences were apparent between groups. Vascular remodelling is closely linked to the level of muscle atrophy (caused by paralysis). Vascular reactivity in paralyzed areas is thus further reduced in people with complete SCI (Olive et al., 2003). Increased vascular resistance in the paralyzed limbs of individuals with SCI may also be the result of an impairment of the nitric oxide pathway where vasoconstrictors, such as endothelin-1 and angiotensin II, contribute to the improvement of vascular resistance in the lower limbs of individuals with SCI. The increase in vascular resistance caused by detraining cannot be explained by an alteration of the vasodilator pathways (but a reduction in the diameter of the artery).

Quadriplegic specificities

Quadriplegic people do not systematically have a linear HR-V̇O$_2$ relationship. HR is therefore not necessarily a relevant measure of intensity in these subjects, hence the interest and necessity to measure other indicators (e.g. perception of effort, mechanical power produced). The lower HR often observed in quadriplegic people is commonly due to a reduction in sympathetic stimulation (neuronal & circulating catecholamines) but other factors are also possible (neurological, humoral, temperature, etc.). This problem remains a subject of questioning without a clear answer at present.

A person with SCI and a lesion above T6 partly has disrupted cardiac innervation, meaning that a reduction in stroke volume during exercise is compensated by an increase in HR (Hopman et al., 1992). However, due to the limitation of the increase in heart rate caused by the lesion, cardiac output may decrease during exercise in quadriplegia, particularly with prolonged exercise and/or in hot environments (Fitzgerald et al., 1990; Hopman et al., 1993). The combination of these two factors greatly limits the ability to produce mechanical work.

Hemodynamic

People with SCI show a reduction in total blood volume and haemoglobin mass, and an increase in venous accumulation below the level of the lesion (Houtman et al., 2000).

At the onset of exercise, blood flow increases markedly in active regions in an exercise intensity-dependent manner, as an attempt to respond to increased metabolic demand (Green et al., 2005; Schreuder et al., 2014; Thijssen et al., 2009a). Conversely, in inactive regions (e.g. internal organs, non-active muscles, (sub)cutaneous tissues) a slight decrease is observed (Green et al., 2002). When exercise continues, the decrease in cutaneous blood flow in non-active regions is reversed and increases, which is most likely related to thermoregulatory requirements required to dissipate the heat produced during continued exercise (Simmons et al., 2011). Since these changes in non-active areas are largely mediated by neuronal pathways, such adaptation in non-active and paralyzed areas does not occur in subjects with SCI.

Despite this, femoral artery blood flow increases during handcycling exercise in subjects with a complete thoracic injury (Thijssen et al., 2009b). However, the increase in femoral blood flow was marginal and largely explained by an increase in mean arterial pressure (i.e., the pressure of blood circulating to the peripheral vessels). Upper limb exercise is therefore unlikely to lead to a significant increase in perfusion of non-active (paralyzed) areas in individuals with SCI.

4) Thermoregulation

Individuals with incomplete spinal cord lesions may retain some sympathetic control and therefore may have a better ability to thermoregulate. Normell (1974) determined the regions of loss of cutaneous vasomotor and sweat function for a given level of injury. The facial and short skin is innervated by T1-T4. Therefore, quadriplegics may have little or no control over sympathetically mediated vasodilation of the face, despite sensory control of these regions. The skin of the upper limbs is innervated by T5-T7 and that of the lower limbs by T10-L3.

Quadriplegia is associated with greater thermal stress whether at rest (+2.0°C in 2 hours in a room at 38°C & 9% Rh) or during exercise due to the absence of sweating on the entire body surface (Randall et al., 1966; Totel et al., 1971). In contrast, in paraplegics, most of the upper body may have intact skin and sweat systems allowing heat dissipation over a relatively large portion of the body surface. Therefore, alterations in thermoregulation are minimal and can be understood in the same way as for AB (Petrofsky, 1992).

Alterations

A spinal cord injury impairs a person's ability to thermoregulate due to:

1. Decreased control of the autonomic nervous system (ANS) over sweat & vasomotor responses in insensitive areas of the skin.

SCI results to an impaired ability to vasoconstrict cutaneous micro-vessels or to shiver below the level of the lesion, resulting in a significant loss of heat from the environment and a limited ability to compensate for this loss by producing metabolic heat.

Skin blood flow and the ability to sweat below the lesion are disrupted, while those with higher levels of lesions and complete lesion are most affected (Sawka et al., 1989). *Compared to AB athletes, paraplegic athletes' sweat rates, at the same relative intensity of upper body exercise, are reduced by 12-23% in cool and hot conditions* (Price, 2006). *Additionally, a person with SCI is associated with reduced sensitivity of sweat glands to cholinergic* (Yaggie et al., 2002). *These effects in sensitive areas are partially reversed in athletes with SCI, although chronic exercise was not able to regain the sweat gland characteristics of AB individuals.*

2. A reduced thermoregulatory effector response for a given core temperature

A more likely explanation for the reason for the delay in the onset of sweating at higher body temperatures is the reduction in afferent inputs. Thermoregulatory centres in the hypothalamus receive afferent inputs from central (located in the brain and spinal cord) and cutaneous thermoreceptors, and both impact thermoregulation. With SCI, there is a loss of afferent signals from spinal thermoreceptors below the level of injury and from cutaneous thermoreceptors *located in dermatomes innervated by spinal nerves below the level of injury, representing a reduction in the size of signals entering the hypothalamus.*

3. A loss of “pumping” activity of the skeletal muscles of the paralyzed limbs.

Responses to stress & Compensatory mechanisms

During exercise, the increased metabolic 'rate' puts the autonomic and cardiovascular systems under pressure to increase blood flow to the skin in order to divert warm blood to the skin surface and thus dissipate heat. Thermoregulation is a negative feedback system which relies on intact afferent & efferent pathways to function properly. As each branch is disrupted following an SCI, this physiological function is impaired.

No centrally mediated increase in sweating or cutaneous blood flow occurs in response to an increase in core temperature. The majority of studies support this idea, detecting no sweating below the level of the lesion in response to an increase in body temperature, either because of a high ambient (Guttmann et al., 1958; Pollock et al., 1951; Tam et al., 1978), or exercise, or a combination of both (Petrofsky, 1992). However, in some individuals, sweating has been reported on insensitive skin (i.e., incomplete SCI).

Although humans rely primarily on sweating and increased cutaneous blood flow to dissipate heat, respiratory heat loss can be significant in certain circumstances, particularly during exercise (Mitchell et al., 1972). In individuals with SCI, respiratory heat loss may serve to compensate for the reduced ability to sweat and redistribute blood flow to the skin. In tetraplegics (C5-C8) with a reduced ability to sweat, ventilation increases substantially at rest in a warm environment (Totel, 1974).

Vasomotor function

SCI is associated (due to the associated inactivity) with a generalised decline in vascular function and an increase in circulating vasoconstrictors, such as angiotensin-II (Groothuis et al., 2010) & entothelin-1 (Thijssen et al., 2007). Functional electric stimulation reduces this decline and proportionally reduces the effect of vasodilators (Thijssen et al., 2007). As a result, active vasodilation is attenuated even in the sensitive skin of individuals with SCI (Freund et al., 1984; Muraki et al., 1996).

Furthermore, in individuals with SCI the ability to divert any additional blood flow from inactive regions, such as inactive muscles, to active regions is impaired by the loss of sympathetic vasoconstriction and the loss of the "muscle pump". As a result, blood can pool in these inactive areas, restricting venous return to the heart and limiting cardiac output. In addition to this, people with SCI generally have a reduced blood volume (Knutsson et al., 1973). **The overall result is that the skin is supplied with insufficient blood flow to meet thermoregulatory demands.**

Because less muscle mass is brought into action during exercise in the arms than during leg or full-body exercise, there is a reduced need to redistribute blood flow to the muscles. In people with SCI who already have a reduced ability to redistribute blood flow due to the loss of sympathetic vasoconstriction, the loss of the muscle pump limits the increase in cardiac output.

Adaptation to training

Tetraplegic athletes (with a complete injury) are unable to achieve thermoregulatory adaptations during training, as intact transpiration and vasodilation systems are required to achieve these adaptations.

Improved cardiovascular fitness is associated with a greater cutaneous blood flow response to a given thermal stimulus. That said, there is also evidence that repeated exposure to heat stress, whether passive or exercise-induced, leads to greater sensitivity of the skin and sweat glands to a given neural or chemical signal. Cutaneous blood flow and the rate of sweating increase after acclimatisation to heat without any variation in vasodilation. The limit is not structural (vessel size) but rather in terms of cutaneous vascular function, which is improved during this stress by an increase in vascular conductance (⬆ Blood flow / Blood pressure) (Lorenzo and Minson, 2010).

Importantly, training improves nitric oxide availability and vasodilation depends on nitric oxide (Green et al., 2004; Hambrecht et al., 2003). Thus, training status will impact on active vasodilation in individuals with SCI & hence their ability to thermoregulate. As previously discussed, the use of beetroot juice may prove to be a strategy for improving vasodilatation, mainly in insensitive areas, and is all the more interesting as we have just seen that the limiting function appears to be vascular and not structural.

In addition, body temperatures of over 40°C have been recorded during handbike competitions. In these circumstances, cooling strategies and regular hydration (watch out for the appearance of autonomic dysreflexia as a result...) are recommended to avoid overheating and to optimise exercise performance. However, we often forget that disturbed thermoregulation can also have negative consequences in a cold environment. Wearing warm clothing and appropriate footwear to prevent frostbite is therefore essential for winter sports.

The two main dangers of exposure to cold environments are the risk of hypothermia and frostbite. Probable causes of hypothermia in individuals with SCI include inappropriate vasodilation, inappropriate sweating, or inadequate metabolic heat production (Menard and Hahn, 1991). In the latter case, this may be due to the absence of shivering under the lesion or to reduced thyroid function, which has been reported for SCI (Bloch, 1986). For athletes with SCI, it is important to tailor clothing according to their personal thermoregulatory disorders, the intensity and duration of the exercise they will be performing, and of course, the environmental conditions.

III. Aim of the thesis

All the works mentioned during this introduction relates the physiological mechanisms involved in the production of an effort and the psychological dealing with the subjective interpretation of the relevant signals constituting the psychobiological background of the perception of effort. Throughout this literature review, we highlight the importance and benefits to work with the RPE in the context of endurance sport. As a consequence, in view of the poor specific content dealing with the adaptations of the perceived exertion to endurance training, we have carried out in the thesis a systematic review of literature of the peer-review research publications reporting the adaptation of the perception of effort after a modification in the performance capacities (generated mainly by physical training).

Subsequently, in the course of our work, we detected a methodological error at the metrological level regarding the measurement of the perception of effort leading to restructure the orientation of this doctoral thesis as far as possible. Indeed, this remark is important because it calls into question the scientific nature of the majority of studies working on the perception of effort and demonstrates the errors produced invalidating the majority of results published to date on this subject. This was the object of chapter 2 of this thesis, proposing exhaustive metrological work allowing anyone measuring the perception of effort to understand the functioning of a subjective measurement in the context of the perception of effort & carry it out scientifically by adapting the method to its own context of intervention.

The rest of the work of this thesis consists of the application of the preceding remarks in the field, in practical conditions of applications. In addition to its experimental nature, the research has an exploratory aspect through the novelty of the properties of the data. The themes of the following chapters focus on rating of perceived exertion’s kinetic and relation with body response in different context and adds the particularity of studying high-level competitive athletes suffering from a spinal cord injury, allowing us to deepen our knowledge of this population, containing a multitude of questions about their psychophysiological responses to exercise and in the context of longitudinal monitoring.

Chapter 1 - Adaptations of the perception of effort to endurance training: Systematic review and guidelines for future studies

I. Introduction

Responses and adaptations of the body to physical exercise has been an area of interest for physiologist for more than a century now (Lagrange, 1890). More specifically for endurance exercises that can be defined as whole-body, dynamic exercise that involves continuous effort not performed at maximal intensity and involving a pacing behaviour", scientist have focused in past decades on the physiological processes contributing to training-related modifications in endurance performance (Vollaard et al., 2009). This ranges from the traditional cardiorespiratory variables (Saltin et al., 1976) to deep muscle-proteomic analysis more recently (Deshmukh et al., 2021). While physiological effects of endurance training are well known, its psychological effects have not been investigated as deeply so far (Filipas et al., 2020).

The effects of training on psychological variables are less known and mainly focused on mood (Morgan et al., 1987; Rietjens et al., 2005) while as we will explain subsequently, limits of performance on endurance exercises are not directly related to physiology but a decision-making related process.

Research has advanced in the last decade on this topic and demonstrated that endurance exercise cessation (disengagement from the task) is not cause by central and neuromuscular events (Girard et al., 2020; Marcora and Staiano, 2010a; Souron et al., 2020) nor by lack of energy required for muscle contraction (Morales-Alamo et al., 2015) in a maximal endurance exercise; typically, time-to-exhaustion (TTE) or time-trial (TT). Strikingly, psychological manipulations can change endurance performance (Pageaux and Lepers, 2018) even when the participants are not consciously aware of the experimental manipulation (A. Blanchfield et al., 2014). Among them, the most important psychological variable determining endurance performance seems to be the perceived exertion.

The perception of exertion over the past decades has been hugely influenced by Borg's publications, however he was unable to give a proper definition of this construct between the confusion with what we would call "perceived intensity or workload" (Borg, 1962, p. 11) and suggesting different definition among contexts (Borg, 1998, pp. 8–9). To clarify this point, the perception of effort (PE) is defined as: “the conscious sensation of how hard, heavy, and strenuous a physical task is” (Samuele Maria Marcora, 2010, p. 380).

Experimental studies have manipulated perception of effort without changes in the cardiorespiratory, metabolic and neuromuscular factors thought to determine endurance performance highlighting its relevance in the context of TTE during aerobic exercises (Barzegarpoor et al., 2020; A. Blanchfield et al., 2014; A. W. Blanchfield et al., 2014; Marcora et al., 2009a; Morgan et al., 1973). To corroborate with these results, according to previous models, people terminate exercise when perceived effort is so intense that can no longer be tolerated (Gibson and Noakes, 2004; McMorris et al., 2018a). Instead, the psychobiological model adopted a different explanation provided by motivational intensity theory (Brehm and Self, 1989; Wright, 2008a). People terminate exercise (i.e., disengage from the task) when the perceived effort exceeds the maximum effort they are willing to exert in order to succeed in the task (Marcora, 2019). In highly motivated people willing to exert a maximal effort in order to succeed in a TTE test, volitional exhaustion occurs when effort is perceived as maximal and continuation of the TTE test seems impossible (Marcora, 2008a; Marcora et al., 2008, 2009a; Marcora and Staiano, 2010a). Therefore, we planned to focus our attention to perception of effort also qualified as the cardinal endurance exercise stopper (Staiano et al., 2018).

Differences in perceived exertion across population is well documented and known for decades (Borg and Linderholm, 1970, 1967) and a large amount of studies conducted specifically to deepen our knowledges on the differences in perceived exertion in between-subject studies where the RPE during submaximal incremental exercise was higher for people with lower fitness level (i.e., worse performance in endurance tests) and vice-versa, a lower RPE at submaximal workload for subjects with higher fitness level (Kuipers et al., 1985; Morgan and Pollock, 1977). However, the changes in perception of effort related to variations in fitness level (i.e., after training) during endurance exercises (Eston, 2012) has been poorly studied in within-subject design as the main goal of studies (Docktor and Sharkey, 1971) despite Borg proposed already in 1962 its potential benefits stating “that change in the perception of exertion […] normally accompany changes in the performance capacity” (Borg, 1962). It’s a common experience among practitioners to notice that training decreases the RPE at same absolute workload or similarly increase workload for a same level of perception of effort (Savage et al., 2009) and we would expect such a response similar to that observed in psychophysics for sense organs. “That it appears that changes in the behavior of sense organs under changing states of adaptation […] can be described by power-group transformations” (Stevens, 1971, p. 437). The latter article reviewing this topic to our knowledge have mentioned only three studies (Mihevic, 1981).

Therefore, the first aim of this article is to provide a systematic review on the relation between perception of effort and endurance performance in response to endurance training. On that part, regarding the theoretical background of endurance performance’s determinants, we expect the following outcomes: endurance training reduces PE and improves endurance performance whilst an increase in PE reduces endurance performance. Secondly, going through the process of our review, we observed a massive heterogeneity in the (mis-)usage of perceived exertion, it’s rating (RPE) and interpretation. Consequently, we introduce this review with methodological considerations going through essential theoretical explanations to get the most of RPE outcomes.

II. Methodological consideration to treat with perceived exertion

To investigate perception of effort, different solutions exist but a general rule to follow is that one parameter, whether the workload or the rating of perceived exertion (RPE), must be “locked” or in the opposite case a ratio between these two variables must be computed. For this last, measurement scale has to have interval properties at minima and ideally being a ratio scale according to Steven’s classification (Gescheider, 1997, pp. 189–190; Stevens, 1946) because results obtained with interval scales reduced its transferability and comparability. This lead to three ways to investigate this phenomenon: the perceived exertion estimation (PEE) (i.e., measure the RPE at an absolute selected workload during TTE or submaximal constant load exercise), production (PEP) (i.e., record power with instruction given to exercise at a selected level of RPE during TTE or submaximal constant load exercise) (Borg, 1962), and ratio (PER) (i.e., calculate the ratio between RPE and workload (RPE/WL) where none of these parameters are fixed) (Metcalfe et al., 2020). Additionally, subjective method can avoids many constraints encountered in different populations (Bok et al., 2022). For those purposes, TT & TTE are good tools as they allow during the same test to assess the perceived exertion and the endurance performance level concurrently.

However, during self-paced exercise (e.g., time trials), the effect of training on perceived exertion often manifests itself as a higher workload for the same or a very similar RPE. In other words, because of the decrease in perception of effort, athletes increase their power output/speed in order to improve their performance while remaining out of the risk to reach maximal effort (i.e. exhaustion) before the end of the race (James et al., 2017). In these cases, looking only at RPE result in a misleading interpretation that an experimental manipulation (e.g., endurance training) do not influence perception of effort. In these configurations, the effect of an intervention on perceived exertion have to always analysed concurrently with RPE and workload (Metcalfe et al., 2020).

A short but fundamental comment has to be made here. The experimental studies reported subsequently, all have used an ordinal scale (Gescheider, 1997) but treated them as a ratio scale leading to incorrect reports when using PEE or PER method of investigation. Respecting the scientific method using ordinal scale, only the PEP method provides interpretable outcomes because just the order of values is assessed (an increase remained an increase independently of this error). However, because to date not any comment is available on the literature to explain and demonstrate scientifically this issue with the use of RPE scales, we will consider them as ratio scales for the purpose of this review in the same way they are currently accepted and used in the scientific community simply warning the reader on that sophism that we will aim to fix shortly.

1) Investigation methods

RPE: a psychophysical measure

Some principles should be followed to study the perception of effort properly. From its very beginning, the Rating of Perceived Exertion has been conceptualized as a psychophysical measure (G. Borg, 1982). In other words, the psychological response (i.e., RPE) has to be interpreted in relation to the physical stimulus that elicits it. In the case of perceived exertion, such physical stimulus is the workload at which the person is exercising (e.g., power output on a cycle ergometer, the weight lifted, or the running speed). Therefore, in order to understand the effect of an experimental manipulation (in this case endurance training) on perception of effort, we have to consider both variables (RPE and workload) (Borg, 1998). Specifically, when RPE is measured during exercise at the same workload (e.g. during cycling at 200W) in both the "post-training" and the control condition, a difference in RPE represents a difference in perception of effort between the two conditions because the other parameter (workload) is constant (Docktor and Sharkey, 1971) and vice-versa, in a PEP design, a change in workload can also be interpreted as an effect on perceived exertion because the RPE is fixed.

JND

Additionally, researchers and coaches need to take care that athletes are familiar with the RPE measurements (Borg, 1998). The workload shouldn't be set up too low in intensity because it exist a stimulus threshold in psychophysics "defined as the smallest amount of stimulus energy necessary to produce a sensation" (Gescheider, 1997, p. 392) also called the "difference threshold defined as the amount of change in the stimulus necessary to produce a just noticeable difference (JND)" (Noble and Robertson, 1996). This notion was central in earlier development of measurement methods in psychophysics (British Association for the Advancement of Science, 1938) but has been abandoned in favour of other aims leading to decrease scale sensitivity. Hence at (very) low intensity accuracy of RPE data is more subject to not discriminate differences (Losnegard et al., 2021; Morgan and Pollock, 1977) and hence not optimal to observe the effect of an intervention (Houmard et al., 1989), putatively hampering it. Readers are referred to Green & Swets' book (Green and Swets, 1966) for more details.

Influence of context

One important remark to take into account is that perceived exertion increases over time whilst exercising at a given workload mainly because of fatigue (Garcin and Billat, 2001; Horstman et al., 1979). Therefore, during TTE tests at a given workload, the time at which the RPE is measured needs to be standardized in order to provide meaningful comparisons with the recommended "individual isotime method" (Nicolò et al., 2019a). As an example of the misuse of RPE during studies, Holgado *et al.* (Holgado et al., 2021) didn't understand the definition of "replication". They asked the RPE of the participants 10 min after a TTE while in the original study Marcora *et al*. (2009a) measured the RPE every minutes. Apart the concern of the influence of the time gap between the end of exercise and the measure of RPE (Tibana et al., 2018), perceived exertion recorded post-session as the overall exertion of the session (whether at the end or delayed) is referred as session-RPE in the literature and is a completely different metric (Haile et al., 2015). During a TTE, the RPE because of its properties (G. Borg, 1982) have to be measure at similar time intervals to be able to compare different interventions / conditions using for instance the "individual isotime method".

Error of not considering RPE kinetic

When the only RPE value recorded or reported is from the end of a trial of extended duration (Attene et al., 2016), whatever kind of exercise it is, it brings whether very few or no information at all to understand what's going on in a psychobiological perspective (Horstman et al., 1979). The RPE at the end of a submaximal exercise can bring few information but to broaden the quality of the report, the time course of RPE should be reported (Nicolò et al., 2019a) and must be if the exercise is self-paced (e.g., TT). In this situation the end-spurt (Emanuel, 2019) or any pacing strategies (Meur, 2010) will influence the workload and the RPE during the test and they have to be monitor "continuously". As a consequence, the reports of perception of effort can't be interpreted correctly as a psychophysical measure if data are scarce among a trial (Borg, 1998).

Likewise, average RPE is useless during constant load trial (even until exhaustion) of long duration because we don't have the initial value of RPE and its kinetic (Crewe et al., 2008; Pires et al., 2011). The RPE at the end can be influenced by the motivation (Brehm and Self, 1989; Wright, 2008a) and can be not similar to the one reported during the "reference" test (pre-test in a traditional pre-post research design). That's to say, the average can be the same but with different values at isotime during the trial and at the start and the end, which lead to a completely different interpretation of the results (Nicolò et al., 2019a). Similarly, the average RPE reported during TT before and after training intervention (Lorenzo et al., 2010; McCleave et al., 2020) isn't enough to produce inferences on potential adaptations. The perceived exertion is influenced by too many factors during an exercise trial (Fullerton and Cattell, 1892; Samuele Maria Marcora, 2010), starting with the influence of fatigue (Horstman et al., 1979) (or self-efficacy (Steele, 2020)) to report only the average value of an exercise test of extended duration by itself. Even if the investigation of perceptual responses is not the central aim of the study, we kindly recommend the authors to report the RPE related to a workload and in this case of TT to use the PER approach presented previously. For the reasons mentioned, the average RPE during incremental exercise is also a useless reported value of perceived exertion. It's a psychological response that can't be related to the physical stimulus that elicits it. Hence, it doesn't provide any scientific outcome (G. Borg, 1982).

We present thereafter the studies investigating perceived exertion adaptations to training according to the methodology used to quantify perception of effort. In the next sections, for more details about the results and designs of studies mentioned, readers are referred to the table 1 in the appendix.

2) Measurements instruments

Importance of measurement method

According to Gamberale (1985), "no one […] techniques can be considered as being generally superior to the others" for measuring subjective reactions during physical work performance. To this statement, we would have that it's however a priority that the method of measurement has as a main goal to report as objectively as possible (not to distort) the perception of effort of the subject. Moreover, because of their specificity, it's necessary in all studies to record explicitly what scale has been used. Indeed, experimental studies provide evidence on the influence of the scales on the result. "Sensory measurements that yield one type of scale do not always relate linearly to measurements that yield another type of scale" (Marks, 1974, p. 245). To date, every single study investigating the outcomes obtained from different category scales (Marks et al., 1983; Neely, 1995) lead to the following statement: There are as many different outcomes as we have scales used. We are facing to this issue since traditional psychophysics measurements principles have been abandoned (Gescheider, 1997; Stevens and Galanter, 1957). For instance, Marks (1968) used 9 category-scales to measure the same stimuli and they all gave a different result for brightness perception. Even if not directly applied to effort, this experiment had the objective to highlight the importance of the scale (or measurement method) and its influence it has on the outcome of an experiment. To give an example during exercise with RPE, CR-10 & CR-100 didn't give the same result (0.1 exponent gap) while they are constructed on the same principle. The difference being that CR-100 just theoretically allow for finer assessment of perception (Borg and Kaijser, 2006). This highlight more strikingly the importance of measurement method as even two scale constructed to give a similar outcome didn't.

Category scales

Category scales call for special consideration in perceived exertion measurements as they are the most used (i.e., Borg's RPE scale & CR-scale; see Table 1). Their development have been a long and complex process starting almost two centuries ago from psychophysics experiments (Borg, 1961; Borg and Dahlstrom, 1962; Borg and Dahlström, 1960; Neely, 1995; Noble and Robertson, 1996; Stevens, 1974, 1957). Borg aimed to obtain a linear relationship between the RPE and "objective" markers of effort like workload, heart rate (HR) or blood lactate concentration in the construction and development of the RPE and CR-10 scale (Borg, 1998). However, it has been demonstrated experimentally for example that heart rate doesn't reflect effort as it can be dissociated to the RPE with autonomic blocking drugs (Ekblom and Golobarg, 1971; Sjöberg et al., 1979) or environmental manipulation like temperature (Pandolf et al., 1972) and perceived exertion is also not linearly related to time on task (Kilbom et al., 1983). Furthermore, a meta-analysis on criterion-related validity of the RPE scale demonstrates lower (and less meaningful) correlations that what was pretended by Borg in his different communications (Chen et al., 2002). Regarding that point, we can give as we said previously to explain this discrepancy the result coming from Borg's thesis as example (P. 40). When correlation between RPE & HR was computed for the different submaximal intensities, the coefficient was very low (i.e., 0.40) while when he grouped all results together, he got a high coefficient of correlation of 0.85 (Borg, 1962) (for an explanation of this trick, we refer the reader to the paper of N.N. Taleb on correlation misapplications (Taleb, 2019a). As Borg conceded later, "the content of the question to be asked and the construction of the method of assessment provide a natural built-in validity. There is no direct 'outer' criterion to which the subjective responses can be correlated" (Borg, 1998, p. 34). For this reason, the willingness to associate the RPE to physiological responses with the aim to use this relation as a marker of validity of the measurement technique used is a logical nonsense.

Furthermore, studies on psychophysics found that there is little to justify the use of category-scaling in quantitative studies (Stevens and Galanter, 1957). "Whenever the subject is asked to categorize, he is forced to divide the continuum into parts or segments, he is obliged to attend to differences or distances. Under those circumstances, the subject is forced out of ratioing and into partitioning" (Stevens, 1971).

These facts presented here calls into question the relevance of these scales as their objective is to distort the rating of perceived exertion with a divergent aim to the one that should prevail over all others on this topic (*i.e.,* report as objective as possible the subject's rating of perceived exertion independently of any external factors). Hence, we encourage researchers not to stick and trust blindly current recognized measurement methods and continue in their effort in developing assessment methodologies.

III. Literature review

This systematic review was reported in line with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidance (Page et al., 2021). Peer-reviewed published articles, which reported perceived exertion adaptations to training were included. Study inclusion was based on the following criteria: The outcome was composed of whether a PER, PEP, or PEE record; The study included an endurance performance test; The study included a period of minimum 5 days of endurance training. Studies were also excluded if they didn't include direct statistical comparison pre- to post-training for RPE as a psychophysical measure (e.g., RPE reported during time trial and compared pre- to -post-training while the workload varied between conditions).

Search methods for identification of studies used the following terms: *((((((RPE) OR ("Perception of effort")) OR ("Perceived exertion")) OR ("Perceived effort")) OR ("Sense of effort")) OR ("effort sense")) AND (training)* in the Pubmed and Web of science Database and personal library until January 2023.

Results obtained from the screening were imported into EndNote (X8) bibliographic software. Duplicates were subsequently removed. Titles and abstracts of the studies obtained from the search strategy were screened by the author. Articles not meeting the eligibility criteria were discarded. Remaining articles were retrieved for further assessment. Using a standardised form tested prior to use, the author extracted data on methodological issues, eligibility criteria and interventions (see figure 1 —flow diagram below).

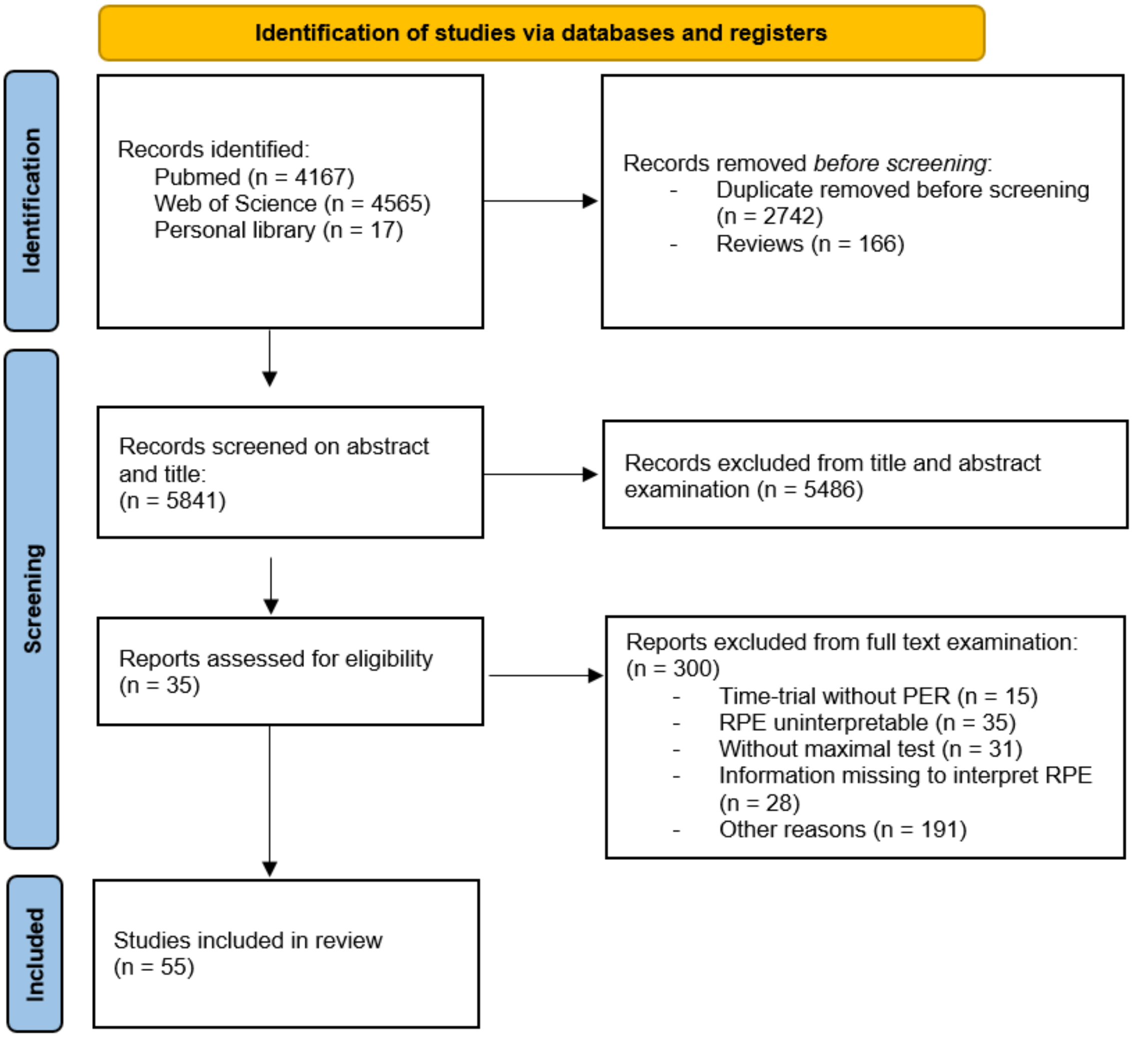


Figure 1: Flow diagram of articles included in systematic review

IV. Results

The descriptive parameters of the original articles that were included for this review are presented in Table 1. In total, 55 studies have been included in this review. Regarding the high heterogeneity of experimental interventions used, we decided not to group them in categories or to analyse them with a meta-analytic process. Indeed, sample size ranges from 5 to 361 subjects with intervention duration lasting from 5 days to 16 months. Among the included studies, 18 used running, 33 cycling, 4 walking and 7 a various kind of training activity modality. Lastly, regarding the subjects' characteristics, the same heterogeneity was found with 9 involving trained, 5 active, 15 healthy, 8 well-trained, and 19 unhealthy or patients with disease.

Among the articles included in the review, 47 reported an increase in performance post-intervention, 6 a decrease and 7 no significant differences. On another side, 4 studies reported an increase in PE, 47 a decrease of PE, and 13 no significant changes following their intervention. In regard to the aim of that article, 54 studies provided outcomes in line with our hypothesis among which 6 have concurrent contradictory results with our prevision down streamed from the theoretical base.

Technically speaking, exercise test used are distributed as follows 45 studies used TTE test while 41 of them were with an increment in intensity across the test. 14 studies tested their subjects with a TT, and two studies used a different less conventional performance test (Aoyagi et al., 1998; Kim et al., 2016). Regarding the submaximal exercise used to measure and compare RPE pre- to post-intervention, 30 experiments used independent constant workload bout, while 28 experiments compared the RPE values recorded during the maximal test between time-points. Finally, among the reported studies, 11 used the CR10-scale, 43 employed the Borg's RPE-scale, one the CR-100 and one the PCERT (Farhat et al., 2015).

V. Discussion

In this review, we sought to grab the current evidence regarding the adaptations of perceived exertion to endurance training. For that purpose, we have divided the results according to the methods used to record and analyse the perception of effort. Each of them provides their advantages and have been used in a wide different way in the past.

1) Effect of training of PE according to investigation methodology

Perceived exertion estimation (PEE)

The PEE consists of to measure the RPE during exercise at an absolute constant workload. The RPE is recorded at regular interval time laps during the trials. Thereafter, this method can be used to assess the influence of various interventions on endurance performance by two trials executed at two time points longitudinally. Using a TTE test for this approach has twofold benefits of providing submaximal RPE values at constant intensity in order to assess perceived exertion adaptation & an endurance performance measurement. For instance, PEE is used for fatigue monitoring during exercise at submaximal intensity and not performed until exhaustion (Rietjens et al., 2005). On the other hand, PEE is more often used with TTE tests to investigate interventions' effect, as example for the impact of mental fatigue (Marcora et al., 2009a) or to reject old beliefs (Marcora and Staiano, 2010a) on endurance performance. To assess endurance performance, the TTE provides the better approach as it removes the influence of external factors like pacing and ensure the suitability of the outcomes. More interestingly, the rate of RPE increase during TTE test correlate with TTE (Crewe et al., 2008; Horstman et al., 1979; Marcora and Staiano, 2010a; Pires et al., 2011; Staiano et al., 2018). This allows proper discrimination in studies comparing interventions with various available indices (RPE at isotime, kinetic of RPE over time, etc.). We have to pay attention on the analysis method used in order to correctly interpret the outcomes of such intervention by promoting the "individual isotime method" over group isotime or relative isotime method (Nicolò et al., 2019a).

As we will see, the PEE approach is the one providing the most data mainly because in physical activity research, experimenters prefer to use an absolute workload and fix it across an intervention to compare objective quantifiable variables between them. This provides an illusion of stronger outcomes (Klein, 2008).

This method has provided data for the adaptation of the perception of effort to endurance training across a wide range a domain of application:

- ***Training:*** For instance, perceived exertion adapts to training after 8 weeks of cross-country running for 5 to 7 days a week (Ekblom and Golobarg, 1971). Subjects performed four exercise bouts of 6 minutes at a workload to demand approximately 25, 50, 75 and 100% of the individual's maximal dioxygen consumption (VO_2max) measured before the training intervention. The same absolute workloads were used before and after the training period with a lower RPE in the post-test whereas at the same relative intensity, the RPE was similar between the two tests. Furthermore, the maximum RPE remained unchanged while the VO_2max (from 2.9 to 3.35 l/min) and associated workload (performance level) increased after the training intervention;
- ***Detraining:*** Perception of effort adapts to reduced performance level. 85 days of detraining induces a progressive decrease in maximal aerobic performance

(V̇O$_2$max) related to an increase in perceived exertion at fixed absolute exercise workload (from 12 to 17 on the 20-points Borg's RPE scale) (Coyle et al., 1985);

- ***Separate limbs:*** Lewis *et al.* (Lewis et al., 1980) explored the effect of 30 min of exercise 4 days a week for 11 weeks at an intensity of 75 – 80% or V̇O$_2$max with either the arms or the legs on responses to leg and arm exercises. The submaximal intensity was set to 70% of pre-training V̇O$_2$max and similar absolute intensity was used post-training. What comes out was a reduction of RPE during exercises in the trained limbs while the untrained limbs haven't a reduction of RPE at submaximal intensity after the training period. The maximum work rate increased at the same time during incremental test performed until exhaustion in arm and leg exercises whether after arm and leg training but to a much lower extent on the untrained limbs (15% vs. 9% & 35% vs. 12% respectively). This study demonstrate that local adaptations are important and influence the way perceived exertion adapts to training.
- ***Extreme conditions & non-locomotor activities:***
  - Patton *et al.* (Patton et al., 1977) examined a reduction in perceived exertion following 6 months of training in military personnel during running test at 6 mph.
  - Then, Balldin *et al.* (Balldin et al., 1994) investigated the effects of 12 months of physical training program on the endurance G tolerance of 17 pilots. The results indicate an increase of 40% of the TTE during simulated aerial combat manoeuvre while the RPE at 5 min of the test (used as submaximal value) decreased and is related to the improvement of the endurance G tolerance.

Perceived exertion production (PEP)

The perceived exertion production (PEP) imposes a pre-selected value of RPE the athlete has to produce, and he adjust his workload himself accordingly. This method of measurement is rarer because to have reliable outcomes, subjects need firstly to be familiarized and be used to rate their exertion. Additionally, fixed workload has also been preferred for research purposes as perceived being the better alternative to compare variables across an intervention as we detailed previously the why PEE is the widespread approach.

Out of our literature review, two researches (Hogg et al., 2018; Shephard, 1996) assessed training intervention using a PEP approach at submaximal intensity and concurrently achieving a maximal performance test. For instance, Shephard *et al.* (Shephard, 1996) used an original approach. People in their study performed a traditional incremental test with fixed workload and then, the authors interpolated the data to get the power output at an RPE of 13 on the Borg's RPE scale. By doing so, following the training intervention (see details in table 1), TTE during the incremental test was improved and the power eliciting an RPE of 13 increased from 59 W to 85 W.

This approach of physical exercise is popular for different purpose like interval-training sessions based on RPE targets instead of workload (Cochrane et al., 2015; Cochrane-Snyman et al., 2019; Dekerle et al., 2003; Hobbins et al., 2019; Kellogg et al., 2018; McEwan et al., 2018). PEP provides during perceptually regulated training intervention the kinetic of performance capabilities and avoid registering RPE which can be an advantage in many situations like on the track in running. To be exhaustive, we have to mention a new metric called “cumulated work” (i.e., the workload accumulated up to a given RPE value during an incremental exercise) has recently emerged (Hegbom et al., 2007; Wyckelsma et al., 2017). This provides another alternative considering a full appraisal of the perceived exertion as a psychophysical measure allowing a replicable and affordable assessment of a training intervention on traditional cardiorespiratory parameters as well as on perceived exertion which is, as we recall, central in endurance performance (Staiano et al., 2018).

This method yields to researcher a way during training interventions to adjust the workload with the progression of participants. It avoids adjusting “manually” the intensity over the sessions, most of the time a task done arbitrarily because of the cost (in time and resources) of a mid-intervention evaluation test. Additionally, for coaches, the utilisation of the production of a perceived exertion allow to train (work) at a desired relative intensity without the necessity of sophisticated technology (Bok et al., 2022).

Perceived exertion ratio (PER)

The ratio of workload (e.g., power output, speed) over rating of perceived exertion (WL / RPE) allows the investigation of perception exertion during self-paced exercise. This approach has the benefits to evaluate the response of performance and perceived exertion to training even if for performance by itself TT is influenced by pacing and is not a “perfect” measure of fitness level (Coakley and Passfield, 2018). The PER is still scarce in the literature but grow in popularity (Metcalfe et al., 2020) for its relevance to assess real-life encountered exercises composed of stochastics workload variations and non-imposed pacing (Levin et al., 2014). Properties of the scale or the way to measure RPE will influence the results. The traditional method used to record the RPE are not an interval scale. Hence, the ratio must be interpreted for exercise eliciting whether the same power and/or the same RPE and this rule can’t be overridden to avoid any misinterpretation due to computational properties (Curran-Everett, 2013). For instance, a ratio of 100 (W) / 10 (RPE) can’t be compared with a ratio of 150 / 15 because of the characteristics of the scale. Indeed, an increase in 10 W at the same RPE, depending on the value of the RPE will not have the same meaning.

The number of studies recording RPE and workload during TT are numerous (Abedelmalek et al., 2022; Boutcher et al., 1989; Choo et al., 2020; Costello et al., 2022; Davies and Daggett, 1977; Edwards et al., 2008; Faghy and Brown, 2019; Genaidy et al., 1990; Hill et al., 1987; Hughes et al., 2019; Lorenzo et al., 2010; McCleave et al., 2020; Salvadego et al., 2017; Silva et al., 2017; Skorski et al., 2015; Xavier et al., 2020). Unfortunately, few of them report these two variables in relation to each other as a ratio, depriving us of this wealth of potential information. Indeed, out of our research, we found only one study applying PER to assess the effect of a training intervention. Filipas *et al.* (Filipas et al., 2020) showed that physical training group increased power relative to RPE (and power only) at iso-time to a greater extent than the control group (no training) post-intervention during a 15 min time-trial. indicating a decrease in perceived exertion following a training intervention. Concurrently, the distance achieved during the time-trial (performance level) increases in the training group and not in the control group (no training).

The intervention using PER aiming to assess perceived exertion adaptations to training are scarce. Many studies employed this method of evaluation but didn't report the RPE as a psychophysical measure, that's to say in relation to power production whether it is power total (total energy consumed by the body) or power output. It limits the strength of the outcomes on that point and allow us only to relate tendencies coming out from these studies. Nevertheless, even if only deductive, when summing up the results of the studies presented in this part, the conclusion never contradicts the hypothesis postulated in regard of the adaptation of the perception of effort in response to training.

To sum up, the findings we have reported are in line with our hypothesis down streamed from the psychobiological framework (Marcora, 2019). During a physical activity, the perception of effort decreases following a training intervention concurrently to an improvement in endurance performance, and vice-versa (i.e., increases following a "detraining" intervention simultaneously to a decrease in performance). This interpretation is confirmed by most of the studies found (see Table 1) and regarding the studies with outcomes contradicting this framework, we have explained previously the (methodological) reasons of this disparity. However, what trigger these responses, give to the perceived exertion this relevance in the context of training adaptations, and what are the mechanisms behind that?

2) Perception of effort: What are the mechanisms that make its adaptations to training?

The answer comes in part from its neurophysiological roots. Potential mechanisms for the reduction in perception of effort during training is marked of debate in the literature. Many appealing theories at first glance are spread without verification of their underlying experimental basis like the central governor model (CGM) (Gibson and Noakes, 2004), afferent feedback model (Amann et al., 2010), etc.

The origin of perception or sense of effort (Merton, 1970) is still controversial among scientist (Amann et al., 2010; Cafarelli, 1977; Hampson et al., 2001; Luu et al., 2011; Marcora, 2009a; Samuele M. Marcora, 2010; Marcora, 2011; Monjo et al., 2018; Peelle, 2018; Proske and Allen, 2019). Henneman (1980) noted in a textbook on the motor control that "in any weakened limb, weights may feel heavier than they actually are because of the greater effort involved in all performance on the affected side.” This argument provides the assumption that motor command can be perceived (Somodi et al., 1995) by some means.

However, the alternative view of perceived exertion dependent on afferent discharges (feedback) (Waller, 1891) remains central in practitioner’s’ beliefs and has to be addressed with current experimental evidences. Fusimotor drive could be expected to increase with a resultant increase in the activity of muscle spindles. This is the point of Granit’s observation (Granit, 1972) that “the periphery itself is ‘corollarized’ by alpha-gamma linkage”. However, perception of effort can’t originate from that reafferent discharges from muscle spindles. Indeed, subjects perceived a reduced muscular force when a superimposed isometric tension is performed with the assistance of a tonic vibration reflex (McCloskey et al., 1974). This observation supports an awareness of the descending motor command as the basis of the perceived effort (McCloskey, 1981). This could be explained by the reduction in the necessary magnitude of central motor command generated by the involuntary reflex assistance provided by vibration. “Afferent information which usually signals force or weight, is not essential for generation of a crude signal of descending motor command of effort” (Gandevia, 1982).

Additionally, previous research have dissociated the generation of perception of effort from heart rate (Davies and Sargeant, 1979; Robertson, 1982). RPE is unchanged or even increased when heart rate is reduced by calcium channel and β-adrenergic blockade (Myers et al., 1987).

Metabolic stress, temperature, and mechanical stress are all known to increase during intense exercise (Kaufman and Hayes, 2002). However, studies employing partial blockade of sensory signals from skeletal muscle afferents with epidural anaesthesia showed that RPE is unchanged or even augmented during exercise with partial sensory blockade (Fernandes et al., 1990; Kjaer et al., 1999, 1989, 1987; Smith et al., 2003). Perceived exertion is independent of joint and skin afferent feedback too, demonstrated with anaesthesia intervention (Gandevia and Mccloskey, 1978). In the case where afferent feedback would have been an important sensory cue for perception of effort, the RPE should have decrease in these experiments (Cafarelli, 1978). The increase in perceived exertion observed in some studies likely occurs because the anaesthetic used to block afferent signalling unavoidably also blocked some motor outflow to the exercising muscles, weakening them and necessitating increase central command to produce the target muscle force (White and Bruce, 2020). Moreover, Marcora *et al.* (2008) showed a significant increase in perception of effort during constant-workload cycling exercise to exhaustion after eccentric muscle fatigue induced in the leg muscles, without affecting afferent feedback from the muscles.

Lastly, hypnotic interventions weakened the hypothesis of perceived exertion driven by afferent feedback with its ability to decrease the RPE for a given absolute workload while conserving cardiovascular responses. In contrast, intervention leading to increase the RPE through hypnosis increases perceived effort and cardiorespiratory responses for the same absolute workload (Morgan et al., 1973; Williamson et al., 2001). The cardiorespiratory response can be explained by the influence of central command on physiological responses (Asahara et al., 2016; Asmussen et al., 1965; Gandevia and Hobbs, 1990; Goodwin et al., 1972; K. Ishii et al., 2016; Matsukawa et al., 2015).

Contrarily, current scientific evidence stated for perception of effort being generated from central command. Such internal irradiation is called a corollary discharge (introduced by Sperry (1950) (Crapse and Sommer, 2008) when it influences perception, which it may do either by modifying the processing of incoming sensory signals or by acting directly, independently of incoming sensory signals (McCloskey, 1981). In the psychobiological model that we used as a framework to interpret results from training studies, the importance of reafferent corollary discharge is emphasized in the conscious awareness of the central motor command sent to active muscle to generate the perception of effort (H. M. de Morree et al., 2012; H. M. D. Morree et al., 2014).

This idea is far from being recent as it was already known in the 19th century (Lewes, 1878). “In situation, when a greater command is required to lift an object […] it will feel heavy” (Gandevia and Mccloskey, 1977a). A century ago, Holmes (Holmes, 1917) supported this idea with patients suffering from an unilateral cerebellar lesions who perceived heavier load in the affected hand carrying a weight due to the higher effort involved in the task.

This has been demonstrated when muscle capacity is impaired following a period of physical task induced-fatigue (McCloskey et al., 1974), successive to inhibition of the motoneurons of contracting muscles by activation of muscle spindles in its antagonist (McCloskey et al., 1974) in patients with unilateral cerebellar lesions (Holmes, 1917, p. 19), or by regional use of neuromuscular blockers inducing partial paralysis (Gandevia and

Mccloskey, 1977a, 1977b; Gandevia and McCloskey, 1977). Experimental anaesthesia interventions demonstrated an increase in the perceived exertion through higher activation of voluntary command to motoneuron induced by weaker muscular capacity to produce a movement (Gandevia and Mccloskey, 1977a; Gandevia and McCloskey, 1977). This can be achieved for example from the suppression of stretch reflex with anaesthesia leading to an increase of motor command arising from the consequences of sensory inputs to compensate the loss of facilitator reflexes (Gandevia and Mccloskey, 1977b).

"Achieving a contraction with the assistance of a tonic vibration reflex [...] reduces the centrally generated motor command required in a contraction, and the perceived muscular force is reduced" (McCloskey, 1981). Taylor (2013) advanced the hypothesis of perceived effort coming from the way corollary discharges of central command are treated and perceived in the brain. This hypothesis is supported experimentally with split-brain's people (surgical disconnection of the cerebral hemispheres) (Gandevia, 1978).

Studying two patients who became suddenly hemiplegic without sensory symptoms, Gandevia (1982) noted that attempts to move when first paralysed were not accompanied by a sense of effort, but that attempts to move when movement restored were accompanied by distinct sensations of effort or heaviness. Th return of the perception of effort as hemiplegia develops to paresis is due to activation in corticofugal pathways, which contributes to the generation of this perceived exertion. Under complete hemiplegia, there is no neural traffic in motor corticofugal paths and there is no perception of effort. However, there is greater neuronal traffic in the unbroken corticofugal fibres and a high sense of exertion during paresis and "a subcortical structure with a critical ascending projection to motor cortical areas may co-operate in generating the sense of effort" (Gandevia, 1982). For more details on brain regions activity generating perceived exertion, readers are referred to Ishii *et al.* (2016), Dettmers *et al.* (1996), Zenon *et al.* (2015), Otto *et al.* (2018), Perrey (2017) and Ramage *et al.* (2019) articles.

Through the process we just explained, training will reduce the perceived exertion by delaying the weakening of muscles (Digby et al., 2022) (confirmed by the study training limbs separately (Lewis et al., 1980) and/or improving inhibitory control or any related cognitive process related to endurance performance.

Reflecting any psychophysiological stimuli that can affect performance through processing corollary discharges of central command, the perceived exertion coupled with motivational intensity theory (Brehm and Self, 1989; Wright, 2008a) provides the necessary tools to assess endurance performance (Marcora, 2019), and the related modification a training intervention (or any kind of intervention) can induce. Physiological variables comes at a second level of explanation in regard to endurance exercise regulation and performance, as they are not directly related to exhaustion (Morales-Alamo et al., 2015). With the aim to monitor endurance training-induced adaptations, we therefore kindly recommend researcher in the future to implement in their interventions one of the three method we detailed to investigate the perception of effort (i.e., ratio, production, estimation).

3) Practical applications | From research to the field

The reliability of usage for the coupling between RPE and workload has been demonstrated by some experimental studies. For instance, Smutok *et al*. (1980) recorded the RPE at different running speed in healthy subjects and then imposed on two different visits these subject to run at the RPE recorded during the first visit. They observed then that the speed during the two last visits were similar to the one imposed during the first visit. From scarce data available, the ratio WL / RPE decreases when performance level increases and vice-versa. To expand the scope of this review, it can be noted that numerous studies have reported in the past this adaptation for the perceived exertion sadly without a performance test in their assessment toolbox. However, each of them confirm our hypothesis of a reduction of the perception of effort after training and an increase of it after detraining (Baslund et al., 1993; Belman and Gaesser, 1988; Charlot et al., 2017; Choi et al., 2013; Donath et al., 2014; Dunbar and Kalinski, 2004; Ekelund et al., 1986; Gervasoni et al., 2014; Gill and Sleivert, 2001; Girard et al., 2017; Gutmann et al., 1981; Hansen et al., 2015a, 2015b; Hobbins et al., 2021; Kelly et al., 2016; Kirwan et al., 1988; Krüger et al., 2015; MacArthur et al., 1993; Malgoyre et al., 2018; Matomäki et al., 2023; McCleave et al., 2019; Merlet et al., 2020; Noble et al., 2012; O'Connor et al., 1991; Pandolf et al., 1975, 1975, 1975; Santamato et al., 2012; Tanaka et al., 1997; Voorn et al., 2021; Whitty et al., 2016; Wills et al., 2019; Witting et al., 1989; Wood et al., 2001; Wyckelsma et al., 2017; Zant and Bouillon, 2007).

The results of the presented studies confirm the importance of this approach as a tool to monitor training program interventions and track the evolution of performance capabilities along this process through the analysis of the PER (Filipas et al., 2020). This theoretical concept, proposed already more than a decade ago (Savage et al., 2009), is central to understand and investigate physical fitness and performance fully deeply.

In recent years, sport scientists focused on physiological markers (*e.g.,* $\dot{V}O_2max$) and/or performance metrics like the critical power (Podlogar et al., 2022) whose questions about its validity has not been answered for this last (Staiano et al., 2018) to deal with this question. However, the consideration of how these variables changes over time within the long-duration exercise bouts, characteristic of endurance training and competition is their Achilles' heel (Maunder et al., 2021). Assessment methods using perceived exertion (one of the three available that we have presented) are techniques allowing to deal with durability. Perceived exertion is the main determinant of endurance performance and is affected by time (Horstman et al., 1979) and intensity (Kesisoglou et al., 2020). As a consequence, from the relation between workload and perceived exertion, we got the performance capabilities of a subject at any time point and can compare it during the same session to assess "durability" or "fatigue resistance" (Erp et al., 2021) or across training sessions to monitor training adaptation (*i.d.,* the main outcome of this review). Carefully used, those techniques can be also used as a tool to measure acutely training load and or fatigue induced by a session comparing for the same intensity the PER at the start and end of a session. This can be used as a surrogate to assess the acute performance decrement (Kesisoglou et al., 2020) during and post-session.

Recently, Losnegard (2021) highlights once again the relationship between RPE and %HR or $\%VO_2$ and blood lactates. The RPE has not to be used like a marker of absolute relative exercise intensity like it has been tempted recently. However, RPE has to be used in the way that a given value represent a given relative physiological intensity on one subject and to date, evidence demonstrate that this relationship is stable across the time and variation in fitness level. Indeed, a large amount of evidence in the literature suggest that at relative exercise intensity, discriminated commonly with $\dot{V}O_2$, the RPE remains similar for a relative percentage of VO_2max with an increased in workload at this "intensity" after a training period (Houmard et al., 1994). Likewise, at relative level of VO_2max, the RPE remained similar following detraining with a lower corresponding absolute workload in this case (Coyle et al., 1985). This closed relationship between relative physiological variables and RPE following variations in fitness level (Garcin et al., 2002; Hammes et al., 2016; Lee et al., 2011; O'connor and Malone, 2019; Preobrazenski et al., 2019; Rosenkranz et al., 2007; Roussey et al., 2021; Stavrinou et al., 2019; Tanskanen et al., 2011; Verde et al., 1992; Womack et al., 1998; Zwierska et al., 2005) is of importance in endurance training. It allows coaches to overcome the difficulty regarding exercise intensity prescription, which is traditionally based on performance test performed but never the same day of the training sessions, neither often during the training program. Based on the large evidences highlighting the close relationship of perceived exertion with relevant relative physiological responses between pre- and post-training assessments (Allison et al., 2017; Andrade et al., 2017; Astorino et al., 2016; Batrakoulis et al., 2018; Beidleman et al., 2009; Clemente-Suárez et al., 2018; Coyle et al., 1985; Decroix et al., 2018; Garcin et al., 2002; Grange et al., 2004; Hagberg et al., 2000; Hammes et al., 2016; Ishak et al., 2016; Jabbour and Majed, 2018; Knapik et al., 1987; Lee et al., 2011; Marquet et al., 2016; Mcleod et al., 2020; O'connor and Malone, 2019; Paradis-Deschênes et al., 2020; Preobrazenski et al., 2019; Przyklenk et al., 2017; Rosenkranz et al., 2007; Roussey et al., 2021; Scholten and Sergeev, 2013; Seiler et al., 2013; Stavrinou et al., 2019; Tanskanen et al., 2011; Tijani et al., 2021; Verde et al., 1992; Womack et al., 1998; Zwierska et al., 2005), the utilisation of RPE to monitor training program and adaptation seems of high relevance (Hartzell, 1984).

The rules to follow are that the measurement technique for perceived exertion must be the same for one subject across the time to permits multiple comparisons. Then, practitioners and researchers need to be aware of the necessity to use correctly the rating of perceived exertion by defining it correctly (Samuele Maria Marcora, 2010) and being careful the lack of reliability at with very low intensities (Morgan and Pollock, 1977).

Additionally, linked to this approach we advise people using the Lamberts and Lambert Submaximal Cycle Test (Lamberts et al., 2011), an evaluation increasing in popularity across practitioners to compute the ratio between workload and RPE across the test to improve the strengths of this screening technique.

Here, we have to note that methods using RPE have been and can be criticized as a tool to prescribe training because for instance, it is influence by time (power decrease over time for a same RPE) but traditional physiological markers (e.g., critical power; respiratory compensation point) used for that purpose (i.e., training prescription) have the same pitfall that the perceived exertion have without its advantages we have presented here.

In practice, nowadays workload variables are recorded easily with portable devices. The main problem to apply this technique outside a laboratory is to record perceived exertion. There are different options: 1) If the coach is with the athlete during the training sessions, he can record “in live” perceived exertion at strategic time points for him when he wants data to analyse; 2) The coach can ask athlete’s perceived exertion for different time points of the session in the same way it is done for the session-RPE (Foster et al., 2021); 3) Using a physiological surrogate for perceived exertion like f_R (or Ttot), the most reliable one to date while more research are needed to validate this variable as a substitute of perception of effort on one side and on another side, to provide an analysis method to deal with some issues (*e.g.,* freewheel in cycling which means “zero” workload and irrelevant ratio outcome).

4) Total breath duration as a complementary tool

To provide a supplementary practical tool for future research, we have to mention the role of respiration in the production of perceived exertion. Respiratory effort is thought to contributes to the overall perception of effort during aerobic exercises through the corollary discharges of the central motor command to the respiratory muscles (de Morree and Marcora, 2015; Grazzini et al., 2005; O’Donnell et al., 2007).

Especially, respiratory frequency (f_R) has been highlighted in the last years for its relevance as a marker of effort because of its correlation with RPE (Nicolò et al., 2016, 2017d). Whether this correlation is the cause of the characteristic of the scale used (distorting the response of perceived exertion through its anchors) or because of a shared physiological mechanism will not be debated here. f_R is mainly regulated by afferent feedback from group III and IV and from central command (Nicolò et al., 2018a) with the latest taking a major part in the regulatory processes from moderate to high intensity (Girardi et al., 2020). It’s a reason explaining that at the beginning of an incremental test, f_R is not related to workload (unpublished observation) and give a reason to not use this marker to monitor low intensity exercise; a shared point with RPE.

However, f_R provides an objective marker of effort. For mathematical considerations, we recommend to use total breath duration (Ttot) to avoid confusion (Sheel et al., 2020) and researcher are encouraged to record this physiological variable. Indeed, it's one of the only very few physiological variables to discriminate at high-recording frequency even at very high intensity exercise (unpublished observations). Similarly to recording RPE during training sessions as recommended previously, the f_R will allow a deeper monitoring of training sessions (Nicolò et al., 2017c) and assessment across a research intervention leading to improve endurance performance.

Nonetheless we have to notice that the control of f_R during moderate- to high-intensity exercise is still a matter of debate (Nicolò et al., 2017a). Is it more influenced by central command from motor cortex (Nicolò et al., 2020) or the indirect influence of tidal volume through the Hering-Breuer reflex on f_R (Winning et al., 1985). This point should be addressed in future research to further our understanding on the spurious or causal relation between f_R and RPE and their influence on each other. It's of importance, in order to avoid future misinterpretation or misunderstanding when interpreting those data isolated (Taleb, 2007).

VI. Conclusion

We expand in this review the relevance coming from literature of perceived exertion in training monitoring with particular attention must be taken regarding the usage recommendations, and we have detailed the ones required. The main point arising from our work is that endurance training leads whether to improve performance and reduce perceived exertion, whether to impair performance and increase perceived exertion, or not modifying either performance or perceived exertion. These modifications have their training adaptation observed in relation and similar to the modality of the training used. Perception of effort reflects any psychophysiological stimuli that can affect performance and, through this lens, explain its relevance observed in this review. Hence, with the aim to monitor endurance training-induced adaptations, one of the three method we detailed to investigate the perception of effort is then indispensable.

These outcomes give to practitioners' additional tools to improve their intervention with their public. Perception of effort allows to individualise the training with few equipment and track monitoring through a wide variety of time frame from the in-session to years.

Additionally, according to the theoretical background we developed, it’s a promising approach to deal the recent “durability” issue raised in sport science. We hope this review will help to a deeper the unexplored application of perceived exertion in physical activity and sport science fields.

VII. Appendix

Background colour: blue=RPEE; yellow=RPEP; orange=RPER | Arrows = Significant increase or decrease; NS = non-significant differences

Table 1: Overview of the studies included in the chapter 1

	Sample size (intervention group)	Population	Activity modality	Training intervention			Performance test		RPE			Mean (+/- SD)		Variation	
				Duration	Frequency	Modality	Type / Duration	Variations in performance	Test used	Value measured	Scale Used	Pre / Control	Post / Intervention		Remarks
Flynn *et al.* (Flynn et al., 1994)	8	Trained	Running	12 weeks	Usual competitive training *see original study for training load details*		TTE @ 110% preseason $\dot{V}O_2$max	⇩	7 min @ 75% of preseason $\dot{V}O_2$max	At the end of the trial	Borg's RPE-scale	10,2 *(0,8)*	9 *(0,7)*	*NS*	
	5	Trained	Swimming	19 weeks			Time trial of 365.8m	⇧	365.8m @90% of preseason $\dot{V}O_2$max			11,2 *(1,1)*	9,4 *(0,7)*	*NS*	
Houmard *et al.* (Houmard et al., 1994)	16	Trained	Cycling	7 days	Everyday	15% reduction in training volume	5k-running TT	**NS**	10 min @80% $\dot{V}O_2$peak Speed of each subject was held constant at all sessions	Every minute *Average reported*	Borg's RPE-scale	11,7 *(0,3)*	11,4 *(0,3)*	*NS*	
			Running					⇧				11,7 *(0,4)*	11,4 *(0,4)*	*NS*	
Etxebarria *et al.* (Etxebarria et al., 2014)	14	Trained	Cycling	3 weeks	Twice a week	Either a long high-intensity interval training (6–8 × 5 min efforts) or short high-intensity interval training (9–11 × 10, 20 and 40 s efforts)	5k-running TT	⇧	1-h specific cycling protocol Absolute baseline power was kept constant during the study	Every 20 minutes	Borg's CR-Scale	*Graph*		⇩	
Ekblom *et al.* (Ekblom and Golobarg, 1971)	8	Active	Cycling	8 weeks	5 times per week	Outdoor cross country running	Step $\dot{V}O_2$max test	⇧	6 min steps at submaximal pre-intervention absolute $\dot{V}O_2$	At the end of each step	Borg's RPE-scale	*25%:* 9,3 *50%:* 11,6 *75%:* 15,3	7,2 10,2 13,5	⇩	
Lewis *et al.* (Lewis et al., 1980)	5	Healthy	Cycling	11 weeks	4 times a week	30 min arm training at 75-80% $\dot{V}O_2$max	Incremental exercise until exhaustion	⇧	10 min @70% of individual pre-training $\dot{V}O_2$max	At the end of the trial	Borg's RPE-scale	13,8 *(0,8)*	11 *(0,7)*	⇩	
	5					30 min leg training at 75-80% $\dot{V}O_2$max						14,4 *(1,5)*	11,4 *(1,1)*	⇩	
Rockefeller *et al.* (Rockefeller and Burke, 1979)	21	Active	Running	10 weeks	3 times a week	Aerobic training programme	Incremental exercise until exhaustion	⇧	5 min at 300 KPM	At the end of the trial	Borg's RPE-scale	11 *(1,8)*	9 *(1,7)*	⇩	
Zurawlew *et al.* (Zurawlew et al., 2016)	10	Active	Running	6 days	Everyday	40 min @65% $\dot{V}O_2$max	5k-running TT	⇧	40 min @65% $\dot{V}O_2$max	Every 5 minutes RPE at the end reported	Borg's RPE-scale	*Graph*		⇩	

Houmard *et al.* (Houmard et al., 1989)	5	Well-trained	Running	10 days	5 times a week	8 km / day	Incremental exercise until exhaustion	⇩	7 min @ 265m / min & 4 min @298m / min	Every minute *Average reported*	Borg's RPE-scale	8,4 *(1,52)* 10,4 *(1,14)*	9,2 *(3,11)* 12 *(1,74)*	⇧	
Hagberg *et al.* (Hagberg et al., 1989)	16	Healthy	Walking	26 weeks	3 times a week	40 min at 50-70% V̇O2max and at 75-85% V̇O2max for the first and last 13 wk of training, respectively	Incremental exercise until exhaustion	⇧	Constant absolute workload (not precised)	Every minute	Borg's RPE-scale	*No absolute values*	-2,0 *(2,5)*	⇩	
Fulcher *et al.* (Fulcher and White, 1997)	33	Unhealthy	Walking	12 weeks	5 times a week	5-15 min per days	Incremental exercise until exhaustion (increase slope over time)	⇧	During the middle third (6-12 min) of the maximal test	Every 2 minutes	Borg's RPE-scale	*Graph*		⇩	
Örlander *et al.* (ÖRlander et al., 1977)	16	Healthy	Cycling & Running	2x 7 weeks	3 times a week	20-30 min or aerobic exerticse below 80% of pre-intervention V̇O2max	Absolute constant speed run to reach exhaustion within 4 to 6 min V̇O2max was used as performance metric	⇧	6 min @750 kpm / min	At the end of the trial	Borg's RPE-scale	12,0 *(1,2)*	11,1 *(2,0)*	⇩	
Coyle *et al.* (Coyle et al., 1985)	7	Trained	Cycling & Running	84 days	Subjects stopped training for the duration of the study		V̇O₂max test	⇩	15 min exercise at the same absolute workload below lactate threshold	At the 12th minute	Borg's RPE-scale	12,3 *(1,1)*	17,1 *(1,1)*	⇧	
Le Meur *et al.* (Meur et al., 2017)	20	Trained	Running	5 weeks	7 times a week	Overload triathlon training intervention	Discontinuous incremental running test to volitional exhaustion (starting at 11 km/h for 3 minutes and increasing speed by 1 km/h every 3 minutes thereafter) on a 340-m running track. A passive rest period of 1 min was provided between each running step.	⇩	Submaximal speed of the incremental maximal test	At the end of each step	Borg's RPE-scale	Subjects variation varied from +1,1 *(0,9)* to +1,9 *(2,1)*		⇧	
Patton *et al.* (Patton et al., 1977)	60	Trained	Running	6 months		Military training program	Modified version of the interrupted treadmill test	⇧	Submaximal run at an absolute workload of 6 mph, 0% grade for 6 min	Every minute	Borg's RPE-scale	11,6	10,4	⇩	
Balldin *et al.* (Balldin et al., 1994)	17	Trained	G tolerance	12 months	Military combined strength and endurance training regime		Time to exhaustion during simulated aerial combat manœuvre	⇧	During the time to exhaustion test	At the 5th minute	Borg's CR-Scale	5,7	4,5	⇩	
Filipas *et al.* (Filipas et al., 2020)	10	Healthy	Cycling	4 weeks	3 times a week	Each week training consisted of: 60 min at 65–70% of the peak heart rate recorded during the incremental maximal ramp test; 20 min at 65–70%, plus 6 × 3 min at 85–90% of the peak heart rate, with 2 min of active rest between repetitions; and 20 min at 65–70% followed by 40 min at 75–80% of the peak heart rate.	15 min Time trial	⇧	During the time trial	Every 3 min	Borg's RPE-scale	*Graph (ratio computed)*		⇩	
Ades *et al.* (Ades et al., 1993)	43	Old Coronary Patients	Running	12 weeks		3 hours per week of a mix of cycling, runnning and rowing	Incremental exercise until exhaustion & Submaximal time to exhaustion test	⇧	During the time to exhaustion test	Every 5 min	Borg's RPE-scale	14,0 (2,2)	11,7 (2,2)	⇩ *Graph at isotime available*	
Williams *et al.* (Williams et al., 1985)	361 *4 groups according to age*	Cardiac patients	Running	12 weeks	3 times a week	40 minutes of circuit-station training using alternating arm and leg exercise	Continuous, multistage treadmill test	⇧	During the time to exhaustion test	Every steps *Calculated from comparable submaximal treadmill stages*	Borg's RPE-scale	12 (2) 12 (2) 12 (2) 12 (2)	9 (2) 10 (2) 10 (2) 10 (2)	⇩	

Heydari *et al.* (Heydari and Boutcher, 2013)	38	Overweight young men	Cycling	12 weeks	3 times a week	20 min of high intensity interval exercise	Incremental step $\dot{V}O_2$max test	⇧	During the incremental test	Every minute *Values reported for each exercise intensities*	Borg's RPE-scale	8,5 (1,8) 9,3 (1,8) 11,1 (1,8) 12,6 (1,8) 13,9 (1,8) 15,1 (1,8) 16,4 (2,2)	7,9 (1,8) 8,7 (1,8) 10,0 (1,8) 11,3 (1,8) 12,4 (1,8) 13,5 (1,8) 14,7 (1,8)	⇩	
Shephard *et al.* (Shephard, 1996)	36	Patients	Cycling	16 months	5 times per week	48 min @60-70% of peak $\dot{V}O_2$	Incremental step test	⇧	During the incremental test _*Predicted_	Every minute *Analysis was made on the variation of power at a RPE of 13*	Borg's RPE-scale	*Power output:* 59 (19)	*Power output:* 85 (30)	⇩	
Hogg *et al.* (Hogg et al., 2018)	24	Healthy	Running	6 weeks	4 times a week	2 HIIT + 1 recovery run + 1 tempo run	Graded exercise test & self-paced $\dot{V}O_2$max test	⇧	During the self-paced $\dot{V}O_2$max test	-----	Borg's RPE-scale	*Graph* Increased velocity post-training		⇧	
Ruscello *et al.* (Ruscello et al., 2014)	10	(Old) Healthy	Walking	6 weeks	5 times per week	20 min walking sessions	6-minute walk test	⇧	During the performance test	30 minutes after the end of the test	Borg's CR-Scale	7,3 (0,82)	2,3 (0,48)	⇩ *And the speed increased concurrently*	
Wadell *et al.* (Wadell et al., 2001)	10	COPD & Exercise-induced hypoxaemia patients	Walking	8 weeks	3 times a week	30 minutes of interval walking sessions with oxygen administered through a nasal cannula at a rate of 5 l/min	6-minute walk test *breathing air & oxygen*	⇧	During the performance test	Immediately after the test	Borg's RPE-scale	*Only median and Min / Max data available* *RPE decrease during the test only in the condition people have trained*		⇩	
	10					30 minutes of interval walking sessions with air administered through a nasal cannula at a rate of 5 l/min									
Abonie *et al.* (Abonie et al., 2021)	9	Healthy	Cycling	7 weeks	3 times a week	30 min @30% heart rate	Incremental test	⇧	During the incremental test	Every minute *Stage 2 / 4 / 6 reported for comparisons analysis*	Borg's RPE-scale	8,6 (1,2) 11,7 (1,7) 14,8 (2,4)	6,3 (0,5) 8,3 (1,5) 11,0 (3,2)	⇩	
Branch *et al.* (Branch et al., 2000)	10	Healthy	Cycling	12 weeks	3 times a week	80% of baseline $\dot{V}O_2$max *Training duration was adapted throughout the training intervention*	Incremental test	⇧	During the incremental test	During each step (2 min and then 1 min)	Borg's RPE-scale	Graph		⇩ *Significant for only 2 steps*	
	8					40% of baseline $\dot{V}O_2$max *Training duration was adapted throughout the training intervention*									

Williams *et al.* (Williams and Morton, 1986)	25	Healthy	Running	12 weeks	3 times a week	45 min sessions of aerobic dance (60-90% of heart rate reserve)	Incremental test	⇧	During the incremental test	At the intensity equivalent to 70% of the pre-treatment $\dot{V}O_2$max of each individual	Borg's RPE-scale	12,0 (2,0)	10,0 (2,0)	⇩	
Ekblom *et al.* (Ekblom et al., 1975)	23	Patients with rheumatoid arthritis	Cycling	6 weeks	Twice a day	Interval training on the bicycle ergometer ando muscle strength training. The bicycle training session consisted of 2-5 work periods of about 3-5 minutes with rest periods of 3-5 minutes between each one. The workload was about 50 to 70% of the maximal load carried out in the pretraining test.	Step $\dot{V}O_2$max test	⇧	6 min steps at submaximal pre-intervention absolute $\dot{V}O_2$	At the end of each step	Borg's RPE-scale	11,4 (2,0)	9,6 (0,3)	⇩	
Nordemar *et al.* (Nordemar et al., 1976b)	10	Patients with rheumatoid arthritis	Cycling	6 weeks	Everydays	5 days a week of strength and mobility training & 2 hours a day of cardiorespiratory training on the bicycle ergometer, strength training of the quadriceps muscle, and walking	Patients performed at least 2 submaximal 6-min workloads and I maximal 4-6 min workload on the bicycle ergometer.	⇧	6 min steps at submaximal pre-intervention absolute $\dot{V}O_2$	At the end of each step	Borg's RPE-scale	*Graph*		⇩	
Nordemar *et al.* (Nordemar et al., 1976a)	10	Patients with rheumatoid arthritis	Cycling	7 months	2-3 hours a week of cycling training at 50-70% of their $\dot{V}O_2$ max in intervals of 3-4 min with 2-5 min rest or half-rest between work periods.		Patients performed at least 2 submaximal 6-min workloads and I maximal 4-6 min workload on the bicycle ergometer.	⇧	6 min steps at submaximal pre-intervention absolute $\dot{V}O_2$	At the end of each step	Borg's RPE-scale *central & local*	local = -1,2 points central = -1,5 points *Both reductions were significant*		⇩	
Saanijoki *et al.* (Saanijoki et al., 2015)	13	Healthy	Cycling	2 weeks	3 times a week	4-6 × 30-s maximal sprints with 4 min of recovery between sprints The number of sprints, starting from 4, increased by one in every second training session	Ramp Incremental test	⇧	During the training sessions	After each sprints	Borg's RPE-scale	N/A			
	13					40- to 60-min continuous aerobic cycling exercises at the intensity of 60% of peak workload predetermined individually in a maximal exercise test. Training duration increased by 10 min in every second training session starting from 40 min in the first session				Every 10 minutes (average reported)		*Graph*		⇩	

Aoyagi *et al.* (Aoyagi et al., 1998) - Exp.1	7	Active	Running	8 weeks	3-4 times a week	30-45 min sessions at 60-80% of the subject's initial $\dot{V}O_2$max	Determination of maximal oxygen intake (not precise how)	⇧	Walking continuously on a treadmill set at 1,34 m/s, 2% grade until appearance of the first of the following criteria: (1) a rectal temperature of 39,3°C, (2) a heart rate >95% of the subject's maximum HR,maintained for 3 min, (3) unwillingness of the subject to continue exercising owing to dizziness, nausea or other reasons, or (4) the elapse of 120 min.	Every 10 min	Borg's CR-Scale	*Graph*		⇩ *with normal clothing* *NS* *with protective clothing*	Control groups / conditions with no improvements in Performance & no changes in RPE
Aoyagi *et al.* (Aoyagi et al., 1998) - Exp.2	8	Active	Running	12 days	Everydays	Treadmill walking or running was held to a speed (1,34 - 2,23 m/s) and grade (0 - 8%) that elicited between 45 and 55% of the subject's current $\dot{V}O_2$max in a hot environment (40°C, 30% RH).	Tolerance time walking continuously on a treadmill set at 1,34 m/s, 2% grade.	⇧						⇩ with normal clothing ⇩ with protective clothing	
Farhat *et al.* (Farhat et al., 2015)	14	Children with developmental coordination disorder	Cycling	8 weeks	3 times a week	60-min sessions consisting of a 10-min warm-up, 35–45 min of skill and agility training, and 5 min of recovery time (activities detailes in the article).	Step Incremental test	⇧	During the performance test & a 6-min walk test	During the final period ofeach exercise test	The Pictorial Children's Effort Rating Table (PCERT)	*Tables in the article*		⇩	
Kim *et al.* (Kim et al., 2016)	55	Patients with acute coronary syndrome	Running	6 weeks	3 times a week	The training program was composed of 10 minutes of warm-up (stretching), 40 minutes of main aerobic exercise, and 10 minutes of cool down. Exercise intensities of 40% and 85% HR reserve was used.	Modified Bruce Protocol	⇧	During the performance test	Not precised *Seems to be at the end of every step* Value at stage 3 reported	Borg's RPE-scale	*Subjects with peak respiratory exchange ratio <1,1* 12,4 (2,5) *Subjects with peak respiratory exchange ratio >1,1* 10,2 (2,6)	*Subjects with peak respiratory exchange ratio <1,1* 10,2 (2,6) *Subjects with peak respiratory exchange ratio >1,1* 8,5 (1,9)	⇩	
Callovini *et al.* (Callovini et al., 2021)	12	Trained	Cycling	5 days	Everydays	90 min exercise (10min at 30% of PPO+80 min at 50% of PPO) in heat (35°C with 50% RH) with 48h of recovery post-training (pre-test).	Time to Exhaustion Tests at 75% of normothermic peak power output	⇧	During the training sessions	Every 10 min	Borg's CR100-scale	56	49	⇩	
Wong *et al.* (Wong et al., 1990)	69	Healthy	Running	1 year	3 times a week	Walking or joggin for 30 min per session	Step Incremental test (+1,33 m/s every 2 min)	⇧	During the performance test	At the end of each step	Borg's CR-Scale	*Graph* *RPE decreases of 1 point at the same absolute $\dot{V}O_2$ after training*		⇩	
Flynn *et al.* (Flynn et al., 1998)	20	Well-trained	Running	6 weeks	~50 km/week	One group substituted 2 running sessions per week with bicycle ergometer sessions	5 km Time trial	⇧ *Improvement from pre to mid and from mid to end*	10-min submaximal run at the same absolute intensity (velocity to elicit 75% of initial $\dot{V}O_2$max)	*Not precised*	Borg's CR-Scale	*Graph* Decrease from pre-test to mid-intervention and from pre-test to end. But not from mid-intervention to end.		⇩	⚠ pre-mid and mid-end different

Davidoff *et al.* (Davidoff et al., 1992)	25	Patients with acute dysvascular amputation	Hand-cycling	108 days (average length)	5 times per week	15 minutes of aerobic exercise per sessions at an intensity of 50 to 70% *The program was accompanied by morning and afternoon sessions of progressive resistance exercise for major muscle groups of the upper and lower extremities and functional training with a prosthesis when clinically appropriate.*	Incremental step test	⇧	During the performance test	At the end of each step	Borg's RPE-scale	1st stage: 8,8 (2,0) 2nd stage: 12,7 (2,3) 3rd stage: 15,1 (3,1)	7,8 (1,5) 11,4 (2,1) 13,1 (2,0)	⇩	
Borel *et al.* (Borel et al., 2015)	19	Women with metabolic syndrome	Cycling	12 weeks	3 times a week	45 min per sessions The patients had to adjust, without any information or feedback, the power output of the cycle ergometer during the first 4 min of exercise, so that the adjusted power at the end ofthe 4-min period correspond to the targeted RPE. At the end of the 4-min period of adjustment, power output was recorded and was adjusted to reach at least the targeted power if required. The use of RPE value at the COP allows progressive adjustment of the exercise intensity throughout the training program.	Incremental step test	⇧	During the performance test	At the end of each step	Borg's RPE-scale	RPEmax: 18,6 (1,7) RPE at VT: 11,0 (2,7) RPE at COP: 11,7 (2,8) RPE at LIPOXmax: 12,0 (3,4)	17,7 (2,6) 8,6 (2,2) 9,4 (2,4) 9,8 (3,3)	⇩	Power at the three defined intensities increases in parallel / Not precise if the absolute intensity used to compare RPE is the same or not pre- vs. post-training
Hooker *et al.* (Hooker and Wells, 1989)	6	Spinal cord injured patients	Wheelchair	8 weeks	3 times a week	20 min at 50-60% of maximal heart rate reserve	Incremental step test	NS	Subjects exercised for 4 min at 5, 10, and 15 W power outputs separated by a 6-min rest interval	At the end of each stage (last 15 sec)	Borg's RPE-scale	5W: 7,4 (1,1) 10W: 12,0 (2,6) 15W: 13,2 (2,1)	6,6 (0,5) 10,8 (3,3) 12,4 (3,2)	*NS*	
	5					20 min at 70-80% of maximal heart rate reserve						5W: 8,8 (3) 10W: 13,2 (3,7) 15W: 14,8 (3,5)	7,2 (1,6) 12,4 (4,4) 14,5 (3)	⇩ ⇩ *NS*	
Williams *et al.* (Williams et al., 1984)	361	Old cardiac patients	Functional training	12 weeks	3 times a week	40 min of circuit-station exercise using alternating arm and leg exercise. The intensity of exercise training resulted in heart rates which ranged between 70% and 85% of the maximal heart rate attained at the initial symptom-limited exercise testing and within five beats of each patient's heart rate prescription.	Continuous, multistage, treadmill exercise test	⇧	Submaximal RPEs were calculated from comparable submaximal stages between the two exercise tests	At the end of each step	Borg's RPE-scale	Group 1: 12 (2) Group 2: 12 (2) Group 3: 12 (2) Group 4: 12 (2)	9 (2) 9 (2) 10 (2) 10 (2)	⇩	Separated in age groups
Talsnes *et al.* (Talsnes et al., 2020)	24	Well-trained	Roller-ski skating	6 months	12 sessions a week	Standardized XC ski-specific training Around 14h a week	Incremental step test	⇧	Testing performed at a constant speed (2,5 m/s) and starting incline of 1° using a graded protocol, including 3–6 periods of 5-min stages with a stepwise increase in workload (1°) and 60-s recovery in between each stage.	At the end of each stage	Borg's CR-Scale	Low-responders: 3,5 (0,9) High-responders: 3,1 (0,6)	3,2 (0,5) 2,7 (0,7)	*NS* ⇩	Not precised which stage is used. Divide the analysis between "low-" and "high-responders"

Hegbom *et al.* (Hegbom et al., 2007)	15	Chronic atrial fibrillation patients	Cycling	2 months	3 times a week	Each training session lasted for 1.25 h and consisted of5 min warm-up, three 15-min periods ofaerobics at 70% to 90% of maximal heart rate (HRmax) interrupted by strengthening exercise for the back, thighs and abdomen.	Incremental step test	⇧	During the performance test	Every minute	Borg's RPE-scale	*Graph for results at isotime during the incremental test* Cumulated work at RPE of 17: 989 (460) vs 1288 (455)	⇩	
Ronnestad *et al.* (Rønnestad et al., 2011)	11	Well-trained	Cycling	12 weeks	[redacted]	Usual endurance training copmbine to strength training performed consisting of four lower body exercises [3 x 4–10 repetition maximum], which were performed twice a week.	5 min TT	⇧	185 min of cycling at 44% of pre-intervention Wmax.	Every 30 minutes	Borg's RPE-scale	*Graph*	⇩	
	9					Usual endurance training		**NS**					*NS*	
Ghiarone *et al.* (Ghiarone et al., 2019)	8	Healthy	Cycling	3 weeks	3 times a week	Twice a day. The first training session was an endurance exercise to reduce muscle glycogen stores. The second training session involved HIIT. The two training sessions was performed on the same day, with 2 h between each session.	Incremental step test & 48-kJ TT	⇧	100-Min Constant-Load exercise	The rating of perceived exertion was assessed at 15, 25, 75, and 100 min of exercise.	Borg's RPE-scale	*Graph*	⇩	
	7				6 times a week	The first training session (endurance exercise) in the evening and the second training session (HIIT) on the morning of the next day (14 h between each session).								
Halson *et al.* (Halson et al., 2002)	8	Trained	Cycling	6 weeks	The training of each subject lasted 6 weeks in total, which was divided into three distinct phases each of 2-wk duration. The first phase consisted of moderate training with a small number exercise testing sessions. Subjects completed their normal or usual amount and type of training. The second phase consisted of an increase in training volume and intensity as well as the number of exercise tests performed. Subjects trained 7 days/wk for these 2 wk in addition to the laboratory tests. The third phase of the study was one of reduced training and aimed to provide subjects with a period of recovery.		Incremental step test & TT	⇩ *during the intense training phase and doesn't change the rest of the time* **(NS)**	During the performance test. *Values of the step at 200 W used.*	At the end of each step	Borg's RPE-scale	*Normal training :* Week 1: 9,4 (0,8) | Week2: 9,2 (0,9) *Intensified training:* Week 3: 10,0 (1,3) | Week 4: 10,9 (1,2) *Recovery phase:* Week 5: 9,4 (1,1) | Week 6: 8,5 (0,8)	*NS*	
Kavanagh *et al.* (Kavanagh et al., 1988)	36	Orthotopic cardiac transplant patients	Cycling	8 months	5 times per week	The main prescribed activity was walking, initially 1.6 km at an intensity based on the results of the stage I test with respect to 60% to 70% peak oxygen intake. The distance was then extended in stages by 400 m, the aim being to have the patient jogging 6,4 km in 48 min.	Incremental step test	⇧	During the performance test	At the end of each step	Borg's RPE-scale	*Graph* Reduction of perceived exertion significant at every isotime measurements.	⇩	
Snyder *et al.* (Snyder et al., 1995)	8	Well-trained	Cycling	4 weeks	The study consisted of thre time periods: normal training (7 days, NORM), overtraining (15 days, OVER), and recovery training (6 days, REC). During the OVER period the cyclists rode 18h/wk, during the NORM and REC training periods, the cyclists rode about 12,5 and 7,5 h/wk respectively.		Incremental step test	**NS**	During the performance test	At the end of each step	Borg's CR-Scale	*see Table 4 of the original paper*	*NS*	

Sire *et al.* (Sire, 1987)	15	Patients after an isolated aortic valve implantation	Cycling	12 months	Daily	The total duration of daily training was 3 to 4 hours. The sessions started with a bicycling warm up of 15 minutes followed by a short programme of 30 minutes with 20 different dynamic and isometric arm and leg exercises of one to two minutes duration. Calisthenics of alternating heavy (e.g. repeated knee-bending, jogging with knees waist high, semi-spread eagle jumps, arm circling in a fast windmill action) or light (e.g. neck and shoulder movements in the erect position, arnj flinging at slow speed, lying on back with leg-overs in a tuck position, rocking sit-ups) exercises were then carried out for one hour. Volley-ball was then played for 30 minutes followed by a one hour intermission. Selected exercises from the aforementioned short programme were then repeated before training was concluded with a 30 minutes cooling down period.	Incremental step test	⇧	During the performance test (value at 100 W reported)	At the end of each step	Borg's RPE-scale	15 (2)	After 6 months: 12 (1) After 12 months: 13 (2)	⇩ *For both compare to baseline*	
Rodríguez-Marroyo *et al.* (Rodríguez-Marroyo et al., 2017)	7	Well-trained	Cycling	10 months	Training program of professional athlete		Incremental step test (pre vuelta vs. post vuelta)	⇩	During the performance test *RPE values obtained at the desired workload from regression and extrapolated*	At the end of each step	Borg's CR-Scale	RPE @300 W: 4,0 (1,0) RPE @225 W: 2,1 (1,1)	6,1 (1,2) 3,4 (1,0)	⇧ *NS at 225 W*	
Beidleman *et al.* (Beidleman et al., 2008)	10	Healthy	Cycling	7 days	Exercise was performed on a cycle ergometer for 45 min at approximately 70% of maximal heart rate in the first hour at altitude and then rested for the remainder of each 4-h altitude exposure.		Time trial	⇧	15 min constant bout at two different intensities (40% and then at 70% of altitude-specific VO$_2$peak)	Between minute 10 and 15 of each exercise bout	Borg's RPE-scale	40%: 10 (1) 70%: 14 (1)	8 (1) 12 (1)	⇩	Training + altitude exposure
Sanne *et al.* (1973)	10	Patients recovery from Acute myocardial infarction "angina pectoris" group	Cycling	6 months	Aerobic exercises individualised (details in the original paper).		Incremental step test (4 min steps duration)	⇧	During the performance test	At the end of each step	Borg's RPE-scale		200 kpm/min : 6,8 (2,4) 400 kpm/min : 9,9 (1,4) 600 kpm/min : 11,0 (1,2) 800 kpm/min : 13,3 (0,5)	⇩ *Values detailed in the original article*	Data after 1 year of training reported & comparisons with a control group without training during the same period.
	23	Patients recovery from Acute myocardial infarction "fatigue" group											400 kpm/min : 9,1 (1,9) 600 kpm/min : 11,7 (1,8) 800 kpm/min : 13,9 (1,9) 1000 kpm/min : 14,8 (0,7)		
Knuttgen *et al.* (1973)	20	Active (military)	Cycling	2 months	3 times a week	15 sec of exercise (high intensity), 15 sec of rest During 30 min per session (of running)	Incremental (tested 3 times: Pre, mid, & post)	⇧	Cycling at 150w (duration not specified)	"Average value"	Borg's RPE scale	Pre: 14,4 (0,5)	Post: 13,0 (0,4)	⇩	

	9				3 times a week	3 min of exercise (high intensity), 3 min of rest During 30 min per session (of running)						Pre: 15,2 (0,5)	Post: 13,6 (0,8)	⇩	
	8			1 month	5 times a week							Pre: 14,2 (0,8)	Post: 12,1 (0,8)	*NS*	
Talsnes *et al.* (Talsnes et al., 2022)	22	Well-trained	Running and roller-ski skating	8 weeks	~7 training sessions / week	Focus on low intensity. Detailed description of the training content in the original paper.	● Uphill running TT ● Incremental treadmill running test to exhaustion ● Incremental treadmill roller-ski skating test to exhaustion	NS NS ⇧	● 5 min run @7 km/h (women) or 8 km/h (men) ● 5 min skating @10 km/h (women) or 12 km/h (men) ●5 min skating @12 km/h (women) or 14 km/h (men)	Immediately after the test	Borg's RPE scale	12,7 (1,3) 11,2 (1,9) 14,4 (1,3)	12,4 (1,6) 11,6 (1,8) 14,1 (1,4)	*NS* *NS* *NS*	
	20					Focus on high intensity. Detailed description of the training content in the original paper.		NS ⇧ ⇧				12,8 (1,4) 11,9 (1,2) 14,6 (1,2)	12,2 (1,1) 11,8 (1,7) 13,9 (1,2)	*NS* *NS* ⇩	
Philp *et al.* (Philp et al., 2022)	5	Well-trained rowers	Cycling and rowing	12 days	Daily (detailed in the original paper)	Daily session performed in the heat. Detailed description of the training content in the original paper.	4 min TT on rowing ergometer	NS	10 min @95% of pre-intervention 30 min TT power output on rowing ergometer	"Average value"	Borg's RPE scale	15 (1)	14 (1)	*NS*	
	6					*Control group*. Same training but sessions not performed in a heat environment.						13 (2)	15 (1)	*NS*	
Matomäki *et al.* (Matomäki et al., 2023)	16	Sedentary and recreationally active men and women	Cycling	10 weeks	6.8 hours / week	Low intensity exercises (full details in the article).	Incremental step test *Weighted mean of the last 3 min of the test*	⇧	3-h cycling at 48% of pretraining maximal oxygen uptake.	Pooled Δ pre - post	Borg's CR-scale	Effect size = 1.09 95% Confidence interval = 0.33 – 1.86		⇩	
	19				1.6 hours / week	High intensity exercises (full details in the article).		⇧				Effect size = 0.85 95% Confidence interval = 0.17 – 1.53		⇩	

Chapter 2 - Metrology for rating the perception of effort: *back to science*

Preamble: Having dealt with the rating of perceived exertion for years, I had to measure this subjective variable for my research interests. Skilled in metrology, I analysed the traditional techniques used to determine which method has been employed in my context of investigation.

A pure chance made me realize that this area of psychometry was not rational. I noticed various fundamental, but not less important, scientific mistakes in the commonly used psychometrics for rating perceived exertion. I did not review the tens of thousands of scientific articles measuring the rating of perceived exertion. However, among the hundreds I came across, as I will demonstrate in this article, I can cite only few examples (Kilbom et al., 1983; Lloyd and Claskey, 1971) who measure and analyse this subjective variable scientifically.

This focused my attention on delving deeply into this field and proposing a comprehensive metrological article for individuals involved in rating perceived exertion. Due to its relevance in various fields, my sole mission in writing this piece is to return it to the path of science.

I. Introduction

Effort or exertion are synonymous terms (Samuele Maria Marcora, 2010) defined as the available resources invested over a given time frame to perform a task (Halperin and Vigotsky, 2023). *In this document, we talk about the effort on his psychological meaning not his physics.* In physical activities, the actual absolute effort is characterized as the one “required to achieve a particular task demand or set of tasks demands, and which is determined by the current task demands relative to capacity to meet those demands, though cannot exceed that current capacity” (Steele, 2020). “In physically demanding work, an individual’s physical capabilities and his or her psychological perceptions interact at all levels of task performance” (Fleishman et al., 1984, p. 947).

The construct of effort exists only subjectively. Hence, it can mean that it either "refers to something inside the organism that is not **directly** observable, or it may mean simply "judged" or "reported" (Attneave, 1962, p. 627). However, "in general judgement is a conclusive or decisive process, not a productive one, that brings a thoughtful episode to an end" (Johnson, 1955, p. 282). In the context of effort, research to date has dealt with the perception of effort (PE) and a difference exist between judgment and perception. This difference has been highlighted by Johnson (1955, p. 285): "as confidence approaches a maximum and time of response approaches the reaction time, judgment is minimized and the act approaches direct perception. Hollingworth's (1925) differentiation of perception and judgment depends on this quantitative difference". Hence, traditionally a familiarization to the construct of PE is necessary for observers to not simply give a judgement of their effort but to perceive it. For this reason, its important the subject strive to be spontaneous and "naive," adopting an introspective approach rather than one focused on external stimuli (Borg, 1998, p. 45). Considering these remarks, the PE has the subjective characteristics to be not directly observable and a variable reported.

For the experimenter, perception cannot be directly observed, but can be inferred from behavioural cues or from judgments or rating made under controlled conditions for greater accuracy. In psychophysical experiments, the experimenter records the subject's response, such as saying whether something feels heavier or lighter or making a mark in a designed box, as a means of communicating their underlying perceptual process. The goal of these experiments is to control or balance out idiosyncrasies of the rating process, so that the communicative responses can be reliably linked to the perceptual processes being studied (Johnson, 1955).

The "perception is relative to the memory of the perceiving system. Perception is relative intellego in nature: intellego as it chooses among alternative and relative in that it depends on the state of the perceiving system" (Norwich, 1993, p. 13). "Someone who is interested in the study of perception is interested in our conscious experience of objects and objects relationships (Coren and Ward, 1989, p. 9). So if we understand what is meant by consciousness we can infer the meaning of perception" (Norwich, 1993, p. 11).

Dealing with the rating of perceived exertion (RPE) has no direct relation with psychophysics and sensation measurement. However, because of the similarity of measuring a subjective construct and of the tremendous work on the measurement process in the topic, we present and use this field of research as a root for our methodological part.

One common error in the development of methodology to deal with the measurement of PE is using psychophysics principles considering the RPE as a psychophysical measurement (Borg, 1998; Noble and Robertson, 1996). However, “psychophysics has been used traditionally to designate the science associated with the study of human perception [to stimuli]” (Noble and Robertson, 1996) translating the “relationships between the physical world and the language processes of the observer” (Attneave, 1962, p. 627) or the study of “the relationships between sensation and stimulus when both are measured as quantities (Marks, 1974)”. As we will expand later, RPE is not a psychophysical measurement. It is an active perception according to Norwich’s criteria which means it comes from an internal “production” (Norwich, 1993, fig. 16,1). Consequently, “there is no direct "outer" criterion to which the subjective responses [PE] can be correlated ” (Borg, 1998, p. 34) because “subjective symptoms […] is a privately experienced event made public only when the experience is reported to an observer” (Kinsman and Weiser, 1976, p. 336). ***It is not necessary for there to be a direct correlation between the intensity of a stimulus and the intensity of perception.***

In the area of physical activity, investigators are interested in the measurement of the individual RPE. For this purpose, the development of a specific psychometry has been a productive field of research for four decades. When we talk about psychometrics (i.e., measurement theories and method (Borg, 1998, p. 13), we mention “primarily a device which enables us to use the laws of arithmetic to solve problems relating to phenomenal events.” (British Association for the Advancement of Science, 1938, pp. 296–297). This translates to the action of assigning numerals by rules to represent properties of objects or events (Campbell, 1920; Gescheider, 1997). For every measurement method, rules to assignment of numerals, mathematical properties of the scale, and statistical operations applicable to measurements made, must be explicit (Stevens, 1946, p. 677).

The application to rate the PE is tricky and complex. PE pertains to an individual’s inner state, and the level of intensity it holds within the individual’s own frame of reference. These perceptions are not “generated” in an impartial or unoccupied space, but are influenced by a cognitive context of memories, beliefs, and emotions that interact with other perceptions or sensations within a unique network (Borg, 1998). The process of recoding a subjective observation of a stimulus independently of irrelevant context's influences has been theorized under the signal detection theory (Rollman, 1977). Perception enters into our experience directly and, due to factors such as adaptation, fatigue, or other causes, the same stimulus may elicit perceptions of vastly different intensities on separate occasions (British Association for the Advancement of Science, 1938).

To answer the comments that could arise regarding the "real" entity of perceived exertion, we quote the mathematician R. Thom, who said (2009, p. 103): « I always say to my neurophysiological friends: why would you want me to believe more in the reality of neurons and synapses if you deny me the reality of this pen?".

Over the last decades, various definition of perceived exertion has been proposed with the most used being: "The perception of exertion is defined as the subjective intensity of effort, strain, discomfort, and/or fatigue that is experienced during physical exercise" (Noble and Robertson, 1996; Robertson et al., 1998; Robertson and Noble, 1997, p. 407). Borg on his part defines perceived exertion as "… the feeling of how heavy and strenuous a physical task is" (Borg, 1998, p. 8) or stated that "the perception of exertion depends mainly on the strain and fatigue in your muscles and on your feeling of breathlessness or aches in the chest" (Borg, 1998, p. 47). However, these definitions refers to the concept of perceived intensity (PI) or sense of effort like described in psychophysical experiments (Gescheider, 1997) and not to the original construct of perceived exertion introduce by Borg in 1962 as "The subjective rating being an expression of the individual's total physical and cognitive reaction to exertion during work" (Borg, 1962, p. 38). This issue will be expanded in the next part. To date, the closest and most explicit definition to the concept of PE published by researchers in the field has been proposed by Marcora (2010, p. 380): "Perception of effort, also known as perceived exertion or sense of effort, refers to the conscious sensation of how hard, heavy, and strenuous a physical task is".

To clarify this definition, when the author says, "how hard […] a physical task is", he is referring to the effort mobilize to perform the task as an entity and not a specific component (e.g., psychological, or physical effort). The strength and relevance of RPE is in the fact that it merges both motivational factors and physiological cues in a single construct.

Due to semantic and conceptual confusions, this definition is unfortunately not satisfying to work with the PE. It is however perfect for PI (see Perceived exertion or Perceived intensity: problems come from psychophysics misuse for details). The perception of effort is a subjective construct that people perceive and not felt or experienced (i.e., perception is experienced but it does not originate from a subjective experience) as I could have been proposed and published. Hence, in line with the definition of effort brought previously, we propose PE being defined as the:

"Subjective evaluation of the available resources invested over a given time frame to perform a task."

Across this text, some statements can be transferred & applied to other subjective measurements but are not the aim of this contribution and we let to the reader the responsibility to verify by himself the correct application to another field.

II. Perceived exertion or Perceived intensity: problems come from psychophysics misuse

The basic psychophysical problem this becomes: How does sensations output depend on stimulus input? Psychophysics determines the relationship between physical stimuli and perceptual output (Noble and Robertson, 1996). A former view is that we don't measure the subjective intensity of our sensation, but we are estimating the objective intensity (e.g. on loudness) (British Association for the Advancement of Science, 1938). But **PE is a perception and not a sensation**. Hence these definitions do not apply to PE and this reject the use of the term "sense of effort".

However, to date the majority of studies have focused on the "strong empirical evidence that perceived exertion is a positively accelerated function of the workload. Although there are inevitable interindividual differences, on the average, the exponent of the function will fall within a limited range (1,5 – 1,9) irrespective of the type of work performance or the muscle groups involved" (Gamberale, 1985, p. 301).

We could speculate that this confusion comes from Borg in regard to his influence in the field. He was spreading PE based on the original concept that : “The subjective rating being an expression of the individual’s total physical and cognitive reaction to exertion during work” (Borg, 1962, p. 38). “The test subject must understand that it is not the physical difficulty (e.g., what the weight is or how warm it is) that counts, but the inner feeling of exertion, strain, and fatigue” (Borg, 1998, p. 46). Thereupon, the following question rise: Why does he provide to the construct of PE a posteriori a different meaning in most of his studies? Actually, in the majority of his works, up to his last main book on the topic in 1998 (Borg, 1998, p. 21, 1961, p. 6, 1973; Borg and Dahlström, 1960, p. 7; Neely, 1995), he was using different definitions and instructions depending on the context (Borg, 1986, p. 4, 1962, p. 11,56). Instead of the PE, he was measuring and reporting the rating of perceived intensity (RPI) or perceived workload. This comes from the desire to make PE a psychophysical measures and stick to Stevens accelerating function of sense of physical workload (Marks et al., 1983).

Here we have to mention for the reader that G. Borg did an exploratory work on a different concept called “perceived difficulty”, that he was defining to the subjects in his experimental subjects with the same meaning of the original concept of PE (Borg, 1962)*.*

1) Can we differentiate them?

No clear evidence exist on the ability of subjects (i.e., observer) to discriminate the perception of effort and the perception of force or intensity perceptions (Jones, 1995). Nonetheless, some experimental data tend to demonstrate this as possible. The difficulty resides in the non-steady state of subjective appraisals and the proximity of kinetic of these two variables in many situations. It’s therefore complicated to observe experimentally that people are able to make this differentiation. However, until contradictory evidence emerge, the ability to differentiate PE from PI is supported by specific intervention (Roland and Ladegaard-Pedersen, 1977) or with subject experienced to deal with the subjective modalities of interest (Jones, 1995). It’s accepted that if an observer want or is asked to give objective estimation of physical stimuli (Teghtsoonian, 1965), they can (Gescheider, 1997; Steele, 2020). Consequently, PE is a subjective measure and not a misjudgement of the physical stimulus.

III. Requirements and assumptions for RPE measurement

Borg wanted to develop a scale that satisfied the psychophysical requisites of ratio scaling but, at the same time, was capable of providing interindividual comparisons.

1) Psychometrical requirements to deal with RPE

The reason we are writing this document is mainly because of the discrepancy between the variable to be measured, the psychometrics used, and the methodological errors. This divergence leads, with a few exceptions, to wrong outcomes because of the presence of scientific mistakes we will expand in next parts.

Among previous works on psychometrics, all authors concurred that the most effective approach to study how variations in stimulus intensity affect subjective sensations in a physical task is through the utilization of a ratio-scaling method (Gamberale, 1985; Stevens, 1946).

Borg detailed the main criteria required for the psychometric of RPE (Borg, 1998):

- Enable to compare the level of perceived exertion between different conditions,
- Rate the PE relative to a known reference with a secondary purpose to compare between individuals’ responses.

In addition to these criteria, when investigating the kinetic response of PE, the psychometric tool used for assessing RPE should aim to meet the following requirements:

- Consider the naturalistic decision-making (Klein, 2008) process and report what is perceived per se, as it is, without prior or post beliefs or inferences.
- Enable the highest precision possible in the rating process; that means, tend to the just noticeable difference of stimulus intensity (JNDs) at any intensity level (i.e., how much increase in PE is needed to be reported in the RPE).
- Provide clear instruction on scale properties (e.g., rank ordering, intervals, etc.)
- Two psychometric techniques with the same aim and discrepant outcomes means one is necessarily wrong. There is no in-between or trade off.

2) Assumptions to measure RPE

In order to investigate the RPE, some assumptions has been stated these past decades (Borg, 1990, 1961).*These points are not subject to debate in this article and we acknowledge them.* They are as follows:

1. **Frame of reference** : ”The perceptual range from a minimal to a maximal subjective intensity is the same for all individuals in spite of the fact that the stimulus range may vary considerable” (Gunnar Borg, 1982, p. 28).

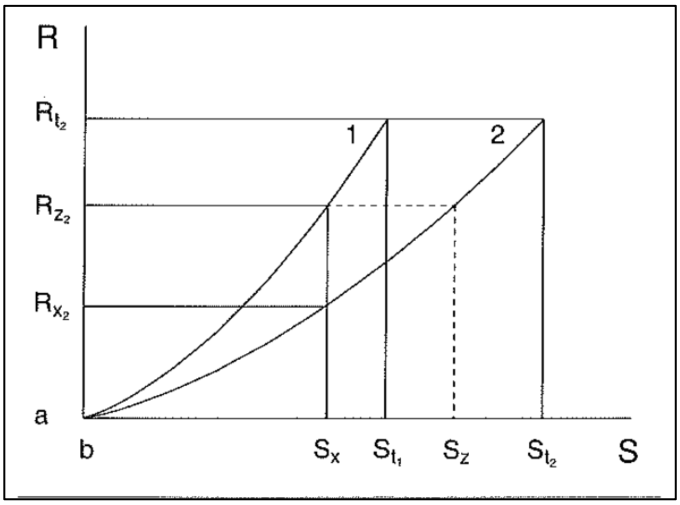


Figure 2: The psychophysical functions for two subjects (1 and 2). S is the physical intensity (e.g., weight in kilograms), R is the perceptual intensity, and R_i is the terminal subjective intensity (e.g., the heaviest weight a person can lift), which is set equal for both subjects according to the range theory.

2. The **intensity of a perception** is determined by its position in the perceptual range (see Figure 2).
3. **Maximum perceptual intensity** : perceptual intensities are approximately equal for different people at each individual's subjective maximal exertion (Borg, 1978; Marks, 1986). This is true and independent of the stimuli intensities related to this perceptual response.

This notion has been expanded recently to discern between the absolute maximal PE and maximal sustainable PE (Malleron et al., 2023) in line with the impact of motivation intensity theory (Brehm and Self, 1989; Wright, 2008a). *In the following sections, we will consider the maximum effort as defined by Borg, that is the maximal effort people are capable to produce in the context of investigation.* “It is certainly true that during an extreme performance an athlete may, in general, experience a more intense perception of exertion than a less- motivated person” (Borg, 1998, p. 28). However, for both of them, it’s their **maximal perceived exertion in the given context.**

4. The “**relations** between intensities of perception can be **assessed mathematically**” (Borg, 1962). As explained previously, perceptions are considered as an entity (they have an existence). The only warning is to use the appropriate analytical tools to deal with the scale properties and data collected (see below).
5. PE **transitivity** (i.e., equality) among subject: for instance, 50% of maximal effort is the same for all individuals in subjective terms.

IV. Theoretical psychometric framework for the RPE

“Sensation [and perception] is called a construct because it is a notion that we put together from observations made in laboratory experiments. […] The main difference between the constructs of physics and those of psychophysics is that psychophysical constructs pertain to people […] and therefore said to be subjective” (Stevens, 1975, p. 52). Compared to many construct measured in psychometry, PE has the particularity that “it is possible to determine a maximal perceptual intensity” (Borg, 1990, p. 441). This particularity is not valid for all sensations or perceptions. It’s the main reason for the non-transferability of the scale used for RPE to a wide range of contexts.

1) Epistemology of the metrology of RPE measurement

All our reactions and thoughts come from reaction to stimuli arising from the world. So, because we think only by what we received from the world, we don’t think the world, it’s the world in us who think itself (Delavier, 2018).

Why aren’t we able to perceive the world exactly as it is presented to us physically? In other words, why do we perceived linearly presented physical stimuli in a positively or negatively accelerating fashion? Perceptions are not exact imprints of the physical world.

In any measurement method, there are certain requirements that must be considered to ensure accurate and reliable results. The range of application of a measurement method depends on various factors, including the rate of application of the stimulus, the degree of expertise of the subject, and the knowledge of the (in)accuracy of the subject’s own reaction. Moreover, the state of application of the peripheral organs and the central nervous system mechanism are concerned as part of the context. The variation in subjective measure depends on the initial stimulus and the variation in stimulus observed as: $\Delta S = I + \Delta I$, where I = intensity of the stimulus, and S = subjective measurement.

The accuracy of the rating procedure is influenced by the intent, discrimination, and expectation of the experimenter. Therefore, altering the distribution of stimuli can change the outcome of the subjective measure, as noted by Stevens and Galanter (1957). On the other hand, measurement methods that have ratio properties are less susceptible to these issues (Price, 1988; Stevens, 1956).

From this perspective, the "RPE is an individualized measure of relative strain rather than absolute stress" (Borg, 1998, p. 36). For details on the chronology and process of Borg's scale development, readers are referred to Robertson & Noble (1997, p. 409). To our knowledge, the first scale developed to measure RPE was a 21 graded rating scale with verbal anchors (Borg and Dahlstrom, 1962). However, factually, the authors were measuring PI. As a consequence, to our knowledge the first scale to really measure the RPE was a 1-to-5-point scale defined linearly to subject (Lloyd and Claskey, 1971).

2) Psychometrics settings

The purpose of adjusting psychometric settings is to find the best compromise between the arithmetical constraints to get the most out of it, and the psychobiological entity of RPE. To explain this in details, "there is no a priori relation between phenomenal structure and number and that to make a connection we must artificially associate a phenomenal criterion with numerical equality and a phenomenal operation with numerical addition" (British Association for the Advancement of Science, 1938, pp. 297–298).

Continuity: In principle no scale of measurement can be continuous because it involves an association with number, which is essentially discontinuous. A scale of measurement can only define and identify a discrete series of quantities (British Association for the Advancement of Science, 1938). *Depending on the purpose of the measurement, the scale used can be more or less distant from continuity.*

Unity: No need to use the number 1 as a reference of quantity. The only necessity is that this number is uniquely associated with some quantity or intensity (British Association for the Advancement of Science, 1938).

Meaningless parameter: Do not overlook parameters because in some scenarios or circumstances, their impact is negligible (e.g., N/1; the 1 should not be overlooked, it can have his importance) (British Association for the Advancement of Science, 1938). *The application to RPE is the cause of the confusion between PI and PE. In most situation, these two measures are closely related. They can even behave similarly. This does not mean however that PI can substitute for PE, because they can be distinguished and then discriminated in some situations as explained previously.*

Relation of perceptions' ratings: This relationship is based on the principle of **ratio invariance**. This principle presupposed that the subjective measures also called **observation** (O) is a **measurable magnitude** by a **practical criterion of equality** and a **practical operation of addition** (British Association for the Advancement of Science, 1938). A fundamental concept in psychometry is *sameness* (or similarity) and the principle of *equal settings*, that is, the adjustment of a variable stimulus so that it is equally strong as a standard (or target) stimulus (Borg, 1998).

Ratio invariance is proposed "to apply to all the sensory systems" with a table proposed by Stevens (1974, p. 368) summarizing the exponential relations between sensory stimulus and perception or sensations.

This interpretation comes from the idea that senses are quite accurate in general (evolution perspective), their interpretation however can lead to false conclusions. "For the origin of the ratio invariance [in a given context] in the response of a sensory system, we may perhaps seek cues in the evolutionary history of the organism. In perceiving and reacting to the world, it is advantageous to an animal if the perceived relations among stimuli do not depend too strongly on the absolute magnitudes of the stimuli" (Stevens, 1974, p. 369).

Few authors dealing with psychometrics contradicts the preceding arguments and more importantly, this proposition influence the purpose for psychometric tools later on in the field of RPE (Borg, 1998; Noble and Robertson, 1996). Sadly, the stimuli to construct these relations were characterize only by the absolute intensity without considering the time of exposure, even after its influence being observed (Borg, 1962; Kilbom et al., 1983).

This omission is one among others that makes the proposal of ratio invariance between an objective intensity and its associated perception wrong if we do not specify that the result apply only in the context of experimentation. The **context** influences the relation between stimuli and observations. “The exponent of this function was shown to depend on the type of work investigated as well as on its intensity” (Gamberale, 1985, p. 301). Additionally, another problem has been detailed on inference based on **average** response leading often to a distortion in the shape of the subjects’ response (Pradhan and Hoffman, 1963).

As it was proposed and published, it seems irrelevant to look for a general stimulus-observation (S-O) relationship.

3) Scales used

The three criteria of a scale are: 1) the rules to assignment of numerals, 2) mathematical properties of the scale, 3) and consequently statistical operations applicable to measurements.

“Numerical assignment and scales are two different entities”. To describe a scale, “we need to know both an empirical relation system and a full numerical relational system” (Suppes and Zinnes, 1963, p. 22).

Fundamental scales relevant for understanding RPE measurement are presented in Table 2. The columns listing the basic operations and permissible statistics are cumulative: information listed opposite a particular scale must be added to all those information preceding it (in the rows above) (Stevens, 1946). Readers are referred to Suppes & Zinnes (1963) & Stevens (1946) for complementary information and extensive description of scales characteristics and properties.

As suggested by R. Thom (2009, p. 82), it’s “easier to conceive the idea of making the discrete from the continuous than the continuous from the discrete”. In line with this remark, ratio can be transformed to interval but not the opposite; or from ratio, we can retrieve an interval scale but from interval properties, ratio scale cannot be obtained (Stevens, 1974, 1971).

In the next part, we present the main methods to investigate RPE and the associated type of scales traditionally or necessarily used.

4) Methods to investigate psychological responses during exercise

A (non-exhaustive) list of traditional methods used in the literature to measure PI (the closest, and applicable for RPE measurement) will be presented briefly, ordered and regrouped by the minimum level of scales required to record data. Each method can be translated in whether estimation (i.e., observer has to rate their perceived exertion in a given context) or production (i.e., observer has to adjust the stress, strain, workload, etc. in order to perceive a required level of perceived exertion) approach (Borg, 1962, p. 31).

Table 2: Main types of scales in psychometrics and their fundamentals characteristics

Scale	Description	Basic empirical operations	Statistics permitted
Nominal	Permits no transformation other than identity (Marks, 1974; Suppes and Zinnes, 1963, p. 17).	•Determination of equality (classification)	• Number of cases • Mode • Contingency correlation
Specific case: Absolute			
Ordinal	Described by monotone transformation function. Can be increasing or decreasing but usually for RPE, only increasing is considered in practice.	• Rank-ordering: determination of greater or less	• Median • Percentiles
Specific case: Hyperordinal	“Characterized by transformations (called hypermonotone) which preserve first differences. More formally, a function is a hypermonotone (increasing) transformation if and only if the function is a monotone transformation. Every linear transformation is a hypermonotone increasing transformation by the opposite is not true.” $x - y < u - v$ then $f(x) - f(y) < f(u) - f(v)$ (Suppes and Zinnes, 1963)		
Interval	Have specified neither the unit, not the origin.	• Determination of equality of intervals or differences	• Mean • Standard deviation • Rank-order correlation • Product-moment correlation
Specific case: Logarithmic interval			
Ratio	Ratio scales are defined as follows. Let <B, R, g> be a derived scale. Then it is a ratio scale in the narrow sense if for any other scale <B, R, g’>, g and g’ are related by similarity transformation. With B an empirical relational system, R a full numerical relational system and f a function which maps B homomorphically onto a subsystem of R (Suppes and Zinnes, 1963).	• Determination of equality of ratios	• Coefficient of variation • Inter-individual comparisons

Mixing estimation & Production methods:

The relationship between estimation and production measurement differs depending on whether the scale used is discrete or continuous, as well as its application.

On one hand, the results obtained with these two methods have been compared in different context initiating in loudness sensation (Hellman and Zwislocki, 1968). It has later been investigated in exercise condition using the RPE-scale and workload (i.e., running speed) where both methods provide outcomes that are not different (Smutok et al., 1980; Van Den Burg and Ceci, 1986).

On the other hand, some authors had proposed to compare these two methods as a validation criterion of subjective scales (Gescheider, 1997), while some results contradicting this statement exist (Stevens and Greenbaum, 1966). Appealing at first glance, the influence of context, reflected by the discrepancy of the results obtained between these two methods, raises some questions. Authors suggested that the typical response could be considered to be in-between of the result obtained using these two methodologies (Stevens, 1971).

Previous studies comparing these two approaches used scales with numerals, and when measured as estimation the memory effect transform the measure from a magnitude characteristic to a threshold identification at the opposite to the production method because in this second situation the absolute intensity level is not known by observer.

1. Methods adapted at best with a nominal scale

a. Method of adjustment

This method allows to determine the difference threshold, define as the amount of change in the stimulus necessary to produce a JNDs (Noble and Robertson, 1996, p. 46). *This notion will be expanded in a following part.* The subject is asked to manipulate a stimulus in order to match his PE to a standard PE determined upstream. This procedure can be performed multiple times to get an average response because the JNDs is context dependent hence the context has to be detailed explicitly for a proper utilisation with the RPE. This method has been mainly used with psychophysical subjective measures.

b. Method of constant stimuli

Experimenter presents a succession of random stimuli. The subject is asked to report according to the purpose whether the stimuli is perceived, or perceived to be different from a pre-determined standard stimulus. *In the context of RPE, the stimuli are traditionally thought to be workload but can be another intervention known to influence PE (e.g., caffeine ingestion, placebo ingestion, psychological interventions). For instance, when exercising in a similar context (i.e., with the same workload), ingesting caffeine is considered to be the stimulus and the method of constant stimuli will be used to determine whether the observer's perception is different or not*. Over again, the uniformity of the context is primordial to limit the biases in the interpretation.

c. Method of Equal-Appearing intervals

The method of equal-appearing intervals is a technique used where all the stimuli are presented at once to the participant. The observer is required to categorize the stimuli into groups, with each stimulus being evaluated six times for instance. It may or may not be predetermined how many categories the stimuli should be divided into (Noble and Robertson, 1996). This method can be applied to RPE with different variants so to speak. The outcome will differ because of the inability to set a level of PE — *"Being a privately experienced event, [PE] can only be measured indirectly through the use of self-report techniques" (Gamberale, 1985, p. 299).* — PE is a complex phenomenon influenced by all structures under stress (psychological & physiological) during exercise. It can reflect all kind of interventions affecting (or not) the performance as demonstrated in earlier experimental investigations (Bigliassi et al., 2015; A. Blanchfield et al., 2014; Chow and Etnier, 2017; Van Cutsem et al., 2019). When investigating or reporting the RPE, we do not get the subjective response to a stimulus because to date, we are not able to measure objectively the effort (at the opposite of workload for instance). The outcome traditionally reported in research dealing with the RPE is nothing more than the relation between a perceptual measure and an objective marker of strain or stress for instance (Halperin and Vigotsky, 2023). Relating these two variables (i.e., perceptual measure and objective marker of strain) provide insights to characterize and interpret the psychophysiological observer's responses in different contexts: the strength of RPE.

2. *Methods adapted at best with an ordinal scale*

"Measurement is a process of establishing a relation not between properties and numerals, but properties and numbers" (Campbell, 1920, p. 275).

As for nominal scale, subjective data obtained from an ordinal scale (like nominal) are not considered as a measurement from a statistical and mathematical point of view. From that standpoint, ordinal scale is a discrimination procedure that provides comparison parameters. As an example, to illustrate these words, "according to Mohs' scale, the hardness of diamond is represented by 10, of ruby by 9 ..., of talc by 1" (Campbell, 1920, p. 274). Nonetheless, these data do not exhibit proportionality. It is plausible that the discrepancy in hardness between diamond and ruby is at least as substantial as the disparity between ruby and talc. Such an analogy would not be applied within the framework of a weight measurement scale for example.

The relation generating order is transitive and asymmetrical. A number of terms will form a series and will have a real order if there is a transitive asymmetrical relation such that every term has either this relation or its converse to every other term (Campbell, 1920).

a. Method of limits

The method of limits is one of the methods traditionally used to measure an absolute threshold, which involves presenting comparative stimulus values in ascending and descending order to determine the stimulus that is never perceived and the one always perceived. This method does not require a standard stimulus, making it useful for researchers interested in exploring different thresholds.

b. Method of rank or grades

Another method providing **data from an ordinal scale** is the method of rank, or grades. This method involves comparing every trial in pairs and assigning points to each comparison, leading to a final ranking (Brown and Thomson, 1921).

c. Method of rating

The data are reported using an ordinal scale, that is, "perceptual intensities are ranked" (Noble and Robertson, 1996, p. 51) **but this method can also be used with an interval or ratio scale.**

The method of rating involves the presentation of stimuli to the participant, who is then asked to categorize them according to scale properties. “The categories may be designated by a limited set of adjectives, such as large, medium, and small. Or the categories may be designated by a finite set of numbers, such as 1 to 6” (Stevens, 1971, p. 434). Or a combination of both. This type of method is of importance in RPE because it’s exemplified by the Borg’s scales characterized as **graphic rating scales** (Noble and Robertson, 1996).

Special case of category scaling

At the very least, category scales yield ordinal level data (Neely, 1995, p. 8). In the field of RPE (and to some extent in the field of psychology), this method of rating associated with category scales is overrepresented, yet it may be the least optimal in terms of accuracy and effectiveness to measure and interpret subjective magnitudes (Carterette and Friedman, 1974; Stevens, 1974, 1971). However, in areas where it’s required to detect and identify thresholds or determine boundaries between classes, it can be of high utility and relevance (Carterette and Friedman, 1974; Stevens, 1975, 1974, 1971).

The use of category scaling in psychophysical experiments has been criticized for its lack of precision and efficacy (Garner, 1953). When using categories in subjective measurement, the observation is a judgment expressing in which categories the perception falls. When subjects are asked to categorize, they are forced to divide the continuum into segments and their observation is constrained by the categories chosen by the experimenter (Stevens, 1975, 1971). At the opposite, when the perception is expressed on a continuous scale, there are no boundaries between categories and the phenomena of judgment that occur near category boundaries do not occur (Johnson, 1955, p. 284). By putting limits to measurement (e.g., category scale), outcome can be distorted (Gescheider, 1997) and less discrimination can be observed between stimuli at both extremes (minimum & maximum) (Stevens and Galanter, 1957). Despite some researchers advocating for the use of ratio scales, category scales (with ordinal properties) continue to be used in experiments (Stevens, 1971; Stevens and Galanter, 1957). To point out, there is still debate on the optimal number of categories to use. It was suggested seven as the maximum acceptable but in practice, it’s common to be around ten categories (Carterette and Friedman, 1974).

Stevens tried to create a “pure” category scale with an equiprobability in the utilisation of categories but this does not resolve the problem later expanded of scale-induced outcome distortion (Stevens, 1975). This has the consequence to distort the reality independently of whether numbers or adjectives are used (Carterette and Friedman, 1974; Stevens, 1974). This last criticism is dishonest in many situations as traditionally used category scales have ordinal properties and are not systematically intended to have the properties of interval or ratio scales. However, some category scales can have interval or ratio properties and in this specific case, this remark takes all its importance (Stevens, 1958, 1974). These issues will be expanded later on the part dealing with the Influence of context.

d. Method of ranking

In the method of ranking, the participant is presented with a series of stimuli that need to be sorted into categories based on their relative intensity compared to other stimuli. **The data are reported using an ordinal scale.**

e. Method of paired comparison

The method of paired comparison requires the observer to evaluate two stimuli presented simultaneously and select the one that they perceive as having a greater intensity. **The data are reported using an ordinal scale.**

3. *Methods adapted at best with a ratio scale*

Methods tailored for interval scale so are for ratio scales.

For studying how perceptions in a physical task are influenced by variations in stimulus intensity, the more complete method is by using a ratio-scaling technique. Furthermore, it has been suggested that other techniques are inadequate for obtaining a comprehensive understanding of the relationship between perceived and its associated stimulus (Gamberale, 1985; Stevens, 1946).

There are various ways to categorize the methods used in ratio scaling, but for our current needs, they can be grounded into two main categories. The first is (a) magnitude matching, which consists of magnitude estimation, and magnitude production. The second category is (b) ratio matching, which comprises ratio setting including both ratio estimation and ratio production. Additionally, cross-modality matching (CMM) is a method that can fall into these two categories for ratio scaling (Stevens, 1971).

Magnitude matching refers to the question of “how fell the stimulus or what stimulus produce this subjective state” while for ratio matching the measurement is made in regard to a standard or reference criteria (stimulus or subjective condition (Gamberale, 1985). For this second method, the influence of reference point in measurement could lead to biased outcomes if the characteristics of JNDs measurement are not well appraised.

a. Ratio matching

The “ratio matching methods” include procedures such as fractionation, multiplication, constant-sum, magnitude estimation, etc. (Ferguson et al., 1940). Merkel (1888) is credited with devising the earliest form of ratio matching, which he used to determine what he referred to as the "doubled stimulus".

Ratio setting: Ratio estimation & Ratio production

A simple method of scaling with a high degree of intersubjectivity is *ratio setting*, such as halving or doubling. The stimulus-response relationship can be studied and demonstrated in such a simple way. There are two main methods of ratio scaling: production where subjects are asked to produce a physical work matching with a subjective intensity (Stevens, 1971), and the estimation method where subjects are asked to provide their subjective estimation of an imposed working intensity (Ham and Parkinson, 1932).

Method of Equal sense distances (equisection)

The method of equal sense distances ask the subject to divide a continuum into two (bisection) or more (equisection) equal parts (Garner, 1954). A famous example of its implementation include Plateau’s shades of grey experiment (Plateau, 1872).

To note, this method has demonstrated internal inconsistency in the past with auditory and visual sensations (Gage, 1934a, 1934b). This is partly explained by the variability of JNDs according to the initial value.

Method of fractionation

The method of fractionation presents the subject with a standard stimulus, followed by a series of comparative stimuli. The subject must identify the comparative stimulus that is a given fraction of the standard and may be required to produce the required fraction as well. **The data are reported with an interval or a ratio scale depending on the characteristics and properties of the scale.**

b. Magnitude matching

Magnitude estimation (or Absolute judgment) & production

In *(free) magnitude estimation* the subject is first presented with a stimulus and asked to provide a number to represent the perception it procures.

This method has undergone various changes of name. Originally referred to as absolute judgment, later as numerical estimation, and eventually as magnitude estimation (Stevens, 1971). ***To note, the majority of research dealing with this method used a ratio scaling approach.***

The method of magnitude estimation involves presenting stimuli to the subject and requesting that they assign a numerical value to the perceived magnitude of each stimulus. The subject is asked to assign numbers to the following stimuli in such a way that if the stimulus is twice as the first one, the number should the double of the first selected number (Borg, 1998; Gamberale, 1985; Neely, 1995). As mentioned previously, “this procedure [ME] is actually a form of cross-modality matching in which numbers are matched to stimuli” (Stevens, 1971, p. 428). This method can be used with or without a standard or anchor stimulus, and the starting point of the scale does not need necessarily to be zero. In magnitude production, at the opposite, subject is presented with different subjective intensities and is asked to produce a stimulus eliciting this perceptual response.

c. Method of cross-modality matching (CMM)

CMM refers to the ability to recognize and match information across different subjective modalities and can falls into magnitude and ratio matching depending on the context. For instance, a special case is, if the responses are numbers the method is called “magnitude estimation”.

Stevens (1959) observed that the approach of CMM can been expanded to cover a diverse range of continuums, and it can be an effective tool for gauging subjective variables. Production-estimation matching of a specific method of investigation is another special case of CMM (Stevens, 1975).

The key advantage of CMM is that it usually provides unlimited or very large response ranges, which make it less sensitive to biases compared to other scaling methods (Gracely, 1979; Pradhan and Hoffman, 1963).

CMM allows for proper ratings (Stevens and Guirao, 1963) and inter-individual comparisons if the subjective continuum used as reference is a finite continuum with a minimum and a maximum for a given context. For instance, PE has an objective minimum (null) and a maximum value compared to pain sensation where a null value can be considered but an "absolute maximal pain" does not exist.

Besides, CMM has been shown to be robust under constrains because interventions generally modify the intercept but not the slope of linear regressions, and labelling the first stimulus in a series can account for a ten-fold change in modulus without altering the log slope (Gracely, 1979). The use of CMM does not influence (modify) the outcome, and the ratio of the relation between the intensity and stimulus remains unaffected.

5) Methodological considerations in psychometric

The experience or more commonly called familiarization is not required for the process or recording per se (Stevens, 1971). However, as explained in the introduction, if the subject is not familiar with the concept of PE, this is mandatory in order for him to rate his perception of effort and not a judgment of his exertion (Johnson, 1955).

1. How perception become a measured entity

Perceptions (and sensations) are measurement of category A as defined by the British committee of science (1938). *"A" measurement is something measured directly, and "B" is an indirect (e.g., speed = D/T).*

Subjective entities have been divided in two categories of continuum: metathetic and prothetic (Stevens, 1974). "On metathetic continua the absolute variability is constant; on prothetic continua the relative variability is constant" (Stevens, 1974, p. 379).

Metathetic continua refer to subjective continua where differences between the stimuli are perceived by the subject in a qualitative manner. In other words, the subject perceives the differences between the stimuli as a change in quality of the perception rather than as a change in quantity. An example of a metathetic continuum is the difference between colours, where the difference between shades of red is perceived qualitatively.

Prothetic continua, on the other hand, refer to perceptive continua where the differences between stimuli are perceived by the subject in a quantitative manner. In other words, the subject perceives the differences between the stimuli as a change in quantity rather than a change in quality of the perception. An example of a prothetic continuum is exertion or loudness, where the difference between two sounds can be perceived as a change in quantity, such as increase of decrease in volume.

Consequently, only scales with nominal or ordinal properties will fit with metathetic continua. However, at the contrary to suggestion from previous reports on the topic, prothetic continua can fit with partition (or category) scaling. For instance, if the aim of the investigation is to determine thresholds in the continuum of a stimulus, a scale with ordinal properties can be a better fit than an interval or ratio scale, even though ordinal characteristics can still be extracted from the latter. It's not always better to do more when it's not necessary (Gamberale, 1985).

2. Scale validity

"The outcome is always a function of method in science" (Stevens, 1956, p. 24). We agree on this quote however, the ensuing argument by psychophysicists is that we can't obtain valid measurement without external criteria of comparison (Borg, 1998; Stevens, 1956). We reject this statement as some methods are able to report subjective measures without any of the bias detailed later (e.g., ME with well-defined boundaries for a single measurement). Even methodologies considered as biased (i.e., without interval properties) can provide valid measures if not overinterpreted.

When talking about scale validity, does it really exist? Are there valid or invalid scales? The validity criterion has been introduced in psychometrics' research because of the common misuse of scales. In the field of PE, there are two reasons: the confusion of PE and PI, and from this confusion, the desire that subjective and objective should have a defined relationship (Robertson et al., 1998; Stevens and Galanter, 1957) independently of the scale used. However, "for any individual act of perception to provide information absolutely consistent with this synthetic whole would require a uniqueness of relation between stimulus and response only obtainable from a mechanism of absolutely constant properties deliberately designed and constructed for the purpose" (British Association for the Advancement of Science, 1938, pp. 322–323). For details on this issue, readers are referred to Method of Equal-Appearing intervals.

The invariance of a scale is also limited because the outcome depends on the context in which it is applied (for more details, see Influence of context) (Stevens, 1959). Additionally, the reliability can be an appealing measure of validity but it may be influenced by factors leading to confusion (e.g., Fig 4D of Stevens and Galanter (1957). These two issues make the comparison of production versus estimation or the evaluation of scale transitivity approaches not fool proof (Gescheider, 1997, p. 271), even though they appear to be the closest to what could be considered scale validation (Gescheider, 1997).

While test-retest reliability face the same problem of seeking for scale invariance (Johnson, 1955; Robertson and Noble, 1997), the verification process is limited by the ability to divide the magnitude of subjective measurement. Ratings are an interpretation of the subjective experience and this last is unknown, leading the comparison to be impossible (Stevens, 1936).

Inter-day variability has been observed among subjects in subjective records on many research investigations. Some experimenters did it performing cross-modality matching experiments (Stevens, 1959). On another occasion, the standard deviations or variabilities exhibited by the observers when setting values on three continua were as follows: 1.0 for length, 2.1 for largeness, and 4.0 decilogs for loudness (Stevens, 1971). To correct the fact that repeatability of answer is not a criteria of validity based on previous remarks, in the field of PE retest correlation of responses ranges from 0.37 to 0.75 for lightest to highest load, respectively (Komi and Karppi, 1977). "Experiments should not be rejected because they make the averages less accordant. The results of experiment depend on accommodation to the conditions of experiment as well as on differences in senses or faculties, and these factors should be separately studied" (Fullerton and Cattell, 1892, p. 152).

3. Relation between the perception and stimuli eliciting it

For this issue, the uniformity of context is primordial in RPE. As mentioned before, inter-relation of sensory attributes (e.g., Broca phenomenon) demonstrated that no point-to-point correspondence can be claimed between psychological qualities of perceptions and their physical correlates. The relation is neither linear nor constant, it's "unpredictable" because it's specific to each individuals and context (British Association for the Advancement of Science, 1938).

"To establish quantitative relation between two entities both entities must be measured each in terms of some unit appropriate to itself". As a consequence, the physical stimulus is measured in physical units sensation in sensation units (British Association for the Advancement of Science, 1938, pp. 332–333).

Perceptual unit definition comes from Borg's model (Borg, 1961). It was used to measure effort and exertion in physical work and employed a unit of measurement that corresponded to a percentage of each person's perceived intensity during maximum performance. This approach facilitated the comparison of subjective magnitudes across individuals, thereby enabling significant comparisons to be made.

An exponent of the relationship between the perceptual intensity and the physical stimulus(i) greater than 1.0 follows a positively accelerated pattern. On the opposite situation with an exponent lower that 1.0, the pattern describing the relation is a negatively accelerated function (Borg, 1998; Gamberale, 1985). As a useful criterion to deal with this issue, if the midpoint of the bisected interval is positioned at the geometric mean of the endpoints that define it, the logarithmic function (i.e., exponent below 1.0) is suggested. Conversely, if the midpoint is located above the geometric mean, as was apparently the case in Plateau's experiment, a power function is suggested (Stevens, 1971).

Regarding PE, empirical evidence suggests that it increases at a faster rate in proportion to workload. Although there may be individual variations, on average, an exponent ranging from 1.6 to 1.9 has been proposed, regardless of the type of work or muscle groups involved (Ljungberg et al., 1982). However, this ratio has only been verified for cycling and running in specific contexts (e.g., duration), whereas for instance for walking, the positively accelerating function is closer to an exponent of 3 (Borg, 1978). A tremendous mistake comes from the nature of these studies reporting PI and not PE, so these observations are not valuable for our interest in RPE.

While using estimation and production to balance out the results can be a good starting point, if we have a genuine interest in determining the power function for a specific individual, we will not settle for just magnitude estimation and production. Instead, we should aim to obtain information from a wide range of cross-modality matching tasks to achieve a well-rounded and balanced understanding, as the more tasks we perform, the better our results will be (Stevens, 1971).

Noteworthy, when using different types of scales with a prothetic stimulus, the relation between the stimuli and the perception tend to be convex with a magnitude scale, while it tend to be concave when a category scale is used (both scales have ratio properties) (Stevens and Galanter, 1957).

a. Weber's Law

Weber's law proposes that the perceived change in a stimulus is proportional to the magnitude of the original stimulus.

b. Fechner's Law

In contrast to Weber's theory, Fechner suggested that the ratio increases with the logarithm of the stimulus. Weber and Fechner employed indirect methods of psychophysics, which did not involve direct measurement of the response. It was thought that direct measurement of perception was either meaningless or unattainable. The debate on the direct observability of subjective reality dates to the early stages of psychophysical measurement, as mentioned previously.

c. Stevens's Power Law – Power function

As the intensity of the stimulus increases, the perception also intensifies, and this relationship is determined by a distinct power function for each dimension of the stimulus. Stevens (1957) also suggested that the subjective ratios are directly proportional to the ratios of the stimuli, meaning that equal ratios of stimuli lead to equal ratios of perceptions.

A radical procedure was used to demonstrate that individual subjects produce power functions and that the power function is not an artifact of averaging using free production method (Stevens and Guirao, 1964). The slope relating the logarithm of the perceptual response to the logarithm of the objective (stimulus) value was linear (slope = exponent of the power function). This was observed with different methodological approach (i.e., fractionation, constant sum, ratio estimation, magnitude estimation methods) and dealing with tenth of subjective continuum (Bernyer, 1959; Stevens, 1959; Stevens and Galanter, 1957).

The debate about psychophysical measurement being mainly represented by power function is a matter of debate and we will not try to argue for one or the other side. We only mention here that there are controversies on this topic, primarily stemming from the argument that this observation applies only to group average data. Therefore, using a power function to describe the psychophysical function is not considered correct (Estes, 1956; Pradhan and Hoffman, 1963).

4. Importance of the scale

For the reasons we will expand in this part, it's necessary to report explicitly what scale has been used and the related instructions (e.g., discriminate PI instead of PE based on instruction). For instance, "RPE was determined with the Borg RPE scale (Borg 1970b or Borg 1985), and the instruction given by Borg (Borg 1985)" (Borg, 1998, p. 48).

As demonstrated, minor changes may alter the behaviour of a scale and should therefore be avoided (Scott and Huskisson, 1976) because even if some scales' outcomes might have been shown to be correlated, the data have not been obtained under conditions that permit an exact comparison (Johnson, 1955, p. 340). For this purpose, we will provide few examples available coming from the literature highlighting the importance of scale utilisation, mainly by reporting discrepancies of outcomes when using different scales for the same purpose.

Ex 1: 9 different category-scales were used to measure the same stimuli and they all gave a different result for brightness perception (Marks, 1968).

Ex 2: In this instance, researchers compared CR10 & CR100 outcomes. Even for two different scales constructed with the same purpose regarding stimulus-subjective relation, the results obtained were different (0.1 exponent gap) (Borg and Kaijser, 2006).

Ex 3: In this study, Borg & colleagues demonstrated the importance of using a correct measurement method by observing that CR10 (log-spaced, different from the "official" one) & magnitude estimation as described by Stevens (1974) gave different results while, according to the authors, they were expected to give similar outcomes (Marks et al., 1983).

Ex 4: Again, another study has demonstrated the importance of the measurement method as we have as many different outcomes as we have methods available (i.e., CR10, visual analogue scale (VAS), category-partitioning (CP), CR20) (Neely, 1995).

Ex5: The measurement method has been shown to change the kinetic of the outcome from convex to concave (1st Borg scale vs. Magnitude estimation) (Morgan, 1973).

Ex5: In RPE, a correlation coefficient between CR10 & magnitude estimation methods of 0.178 has been reported (Marks et al., 1983).

5. Scale distortion resulting from instructions

The situation and context influence the *set* (Johnson, 1955, p. 80) and as a consequence the "judgment of any stimulus object is influenced by the context of that object. [...] Anchoring instructions introduce new material into the context" (Johnson, 1955, p. 367). It is, therefore, important to include these settings in every report, and this is even more essential in psychometrics, as failing to do so may lead people to anchor their PE on other perceptions (Steele, 2020).

*"A **set** may be defined, in the usual way, as a readiness to make a specified response to a specified stimulus. [...] The term readiness in the definition means that the stimulus – response coordination is prepared in advance, so that when the stimulus is perceived, the response follows with little delay" (Johnson, 1955, p. 65).*

In the field of **RPE studies, instructions have been problematic** from the outset due to their lack of clarity. For instance, the concept of PE is often define in a general and vague manner for subjects such as "how laborious it feels" (Borg, 1962, p. 35), or their misuse as expanded previously regarding the differentiation between PI & PE. This could explain the so-called difficulty described by Borg (1998, p. 15) for some adults to understand the instruction of the Borg's RPE scale.

The **importance of instruction** has been demonstrated by Teghtsoonian (1965) in experiments where he observed that when subjects are asked "how the stimulus is", or "how the stimulus looks", their answers are completely different. The exponent describing the relation between the stimulus and the observation were 1.07 & 0.76 respectively (Teghtsoonian, 1965, p. 394). More recently in RPE, from a different perspective, a graphic rating scale was used with numerals from 0 to 10 and instructions of their respective correspondence to minimum and maximum effort. However, no instructions were provided to the observers about the characteristics of the scale whether it was numerals or numbers with linear relation with traditionally known interval properties (or logarithmic). This omission prevents from giving interval or ratio properties to the scale but restrained it to ordinal properties (Malleron et al., 2023). The potential wealth of the outcome is similarly impacted.

Example of instruction provided to participants in former studies:

PE instruction: "During the test we want you to rate your perception of exertion (or pain, etc.) because your own perception is an important complement to the physiological measurements we are going to take " (Borg, 1998, p. 44).

ME instruction: "You can use any number – decimal, fraction, or whole number – the only restriction being that the number you use should be proportional to the felt heaviness […] Do not try to be consistent. Make your judgments independent of what you have done in the past. Every time compare the given weight with the standard only" (Pradhan and Hoffman, 1963, p. 535).

6. Distortion problem

In the estimation method of investigation, category scales (even without verbal anchors) will give results of ordinal properties. The subject is compelled to categorize the perception and lacks the freedom to provide a rating on a continuous basis, resulting in observations with ordinal properties. Examples of studies assessing the responses from a category scale (aiming to reproduce the result of a continuous-magnitude scale) against those obtain with a magnitude scale observed that the category scale is closely matched by a logarithmic transformation of the magnitude scale (Ekman and Künnapas, 1962). To gather observations from a category scale with interval properties, a production method must be adopted in a first glance, but this condition is not sufficient. Indeed, the production of the stimulus must not be restricted and must have a continuous nature. This statement stems from the observed influence by the items of the category scale and / or the space or interval between stimuli, on the perceived response (Stevens and Galanter, 1957, fig. 4D).

a. Verbal Anchor (VA)

For our interest, in PE studies we can categorize the VA into two main categories: VAs with quantitative properties that provide criteria of equality and addition such as “half”, “quarter”, etc., that enable comparisons. On the other hand, VAs with qualitative properties, describe subjective qualities or characteristics, such as “weak” or “strong”, evoking subjective opinions rather than (precise) measurements. Quantitatively speaking in the perceptual range presented before, hard has not the same position in the perceptual range for everyone while “half” is “half” quantitatively. One is quantitative, the other is not! The first allows the scales to have interval or ratio properties, the second gives to the scale an ordinal or nominal property depending on the characteristics of the scale.

Verbal anchoring is the main misunderstood issue in psychometric still nowadays. The primary reason is the consideration of qualitative words (VA) as measurable quantities. It’s in general worthless to use two different anchors on an ordinal scale when the aim is to play with numerals. They do not become numbers, but the opposite effect can be produced. This procedure can transform numbers into numerals.

A debate has been held on inter-individual comparisons based on scale using qualitative VAs. We can use VA for inter-individual comparisons, but the individual relationship between perceptual magnitude & the different VAs need to be established beforehand. The magnitude order between VAs is individual and unknown beforehand. For instance, the magnitude between “light” and “hard” can correspond to 40% of PE’s frame of reference for one individual and 60% for another. This VA – perceptual magnitude relationship needs to be determined previously if VA’s outcomes want to be treated as intervals or ratio, otherwise observations are ordinals. Such an example on how to contradict former observations in psychophysics from a misunderstanding of VA has been published by Borg and Linderholm (1967). They obtained fairly linear relation between stimuli and observation, in contradiction to earlier observations.

Additionally, the use of VA implements few specificities to scales that need to be described in order to be controlled:

1) One of the consequence to the use of VA is the **reduction in the variability of response** at and near the anchoring (stimulus) (Borg and Kaijser, 2006, p. 65; Johnson, 1955, pp. 364–365; Rogers et al., 1947). A practical illustration in the field of PE has been reported by Borg and Kaijser (2006) where subjects utilisation of VA were 34% with the CR10 and 25 % for CR100 scales where theoretically, the numbers of responses are unlimited.

2) By setting VA, subjects can observe almost anything and make almost any response depending on experimenter's willingness if the observations are not treated correctly as being ordinal (Gescheider, 1997, p. 224; Gracely, 1979, p. 819; Johnson, 1955, p. 67). However, the remark that **outcome's kinetic** is decided or at least **influenced** by experimenter is pointless (at the exception when VA are representing quantities). Indeed, they considered a scale with ordinal properties as a scale with interval or ratio properties. Without this mistake, this remark has not the same relevance because there is no response's kinetic in ordinal outcomes.

It was an error Borg did as well. As Gamberale (1985) stated, Borg was able to achieve linearity "by a careful choice of verbal categories" (Noble and Robertson, 1996, p. 63) but the VAs used are not reflecting quantities. Consequently, the combination of numerals with qualitative VA produces solely an ordinal scale. The subjective aspect of magnitude order relating VAs to each other is based from experiments done in a controlled situation. Nonetheless, results are not systematically transferable to all contexts and situations (British Association for the Advancement of Science, 1938), as demonstrated every time this assumption was tested.

Interestingly, Borg sold his two main scales (CR10 & RPE-scale) boasting their interval and ratio properties while he pointed himself the issues we just mentioned related to the use of VA (Borg, 1998, p. 30; G. Borg, 1982; Borg and Lindblad, 1976).

3) The utilisation of a scale based entirely on VA in psychometrics has the consequence of **limiting possibilities** for the observer and can result in a failed attempt to grasp nuances in the outcome (Aitken, 1969, p. 989; Stevens, 1971, p. 434).

4) **The settings for the utilisation of VA** are important, and some important consideration from previous psychometrics studies must be kept in mind when using them knowingly:

1. The concept of natural anchor: “The ends of most series of stimuli presented for judgment are not so salient as a definite zero point, but end anchoring is always a possibility when the end stimuli are easily identified as such” (Johnson, 1955, p. 363).
2. Small space between the stimuli: Having a small range corresponding of 2 to 3 JNDs doesn’t change the response of category scale to lifted weight estimation (Wever and Zener, 1928). While this can be wrong in some contexts, in general the curve remains concave and the different intensities can be discriminated.

5) **Non-quantitative VA**, even when combined to numerals are not reflecting quantities (Neely, 1995, p. 2; Noble and Robertson, 1996, pp. 71–73). Actually, it produces the opposite effect, the numerals most of the time arrange as numbers in scales cannot be considered quantitatively anymore.

b. Memory

From the nature of our sensory machinery, exactly similar psychological relation structures doesn’t lead to the same phenomenal relation structure on each occasions and conditions (Klein, 2008). The repetition of experiences will create a norm that will be interpreted as the perceived objective structure. (British Association for the Advancement of Science, 1938).

Errors of habituation are common in psychophysical measurement. These errors occur when a subject “has made the same response a number of times in a row and continues to make that response even when it is no longer applicable” (Manning and Rosenstock, 1968). The flip side of errors of habituation are the ***errors of anticipation***.

The investigation of a single stimulus in psychometry is traditionally said to be judge compared to memorized experiences. However, we explained previously the difference between judgement and perception. In the context of PE, if instructions are rigorous, subjects will rate a perception and the influence of memory in the process of judgement loses its relevance.

Next, we will detail the concerns observed in research on the influence of intra- and inter-day psychometric measures.

Intraday:

"The observer should not know the results of preceding experiments nor the objective relations of the stimuli" (Fullerton and Cattell, 1892, p. 152).

In order to avoid any interference with a preceding rating in the same measurement session, the scale proposed should avoid incorporating any items that could be easily used as an (momorized) anchor by the subject. The implementation of visual anchors will add to the scale's instruction the influence of feedback from the previous rating. Hence, the observer's response will have the subsidiary interrogation: "Is my current perception different from the previous I had?", and not anymore: "how is my current perception?". *The same remark worth for any subjective measurement.* When feedback is used (or available to the observer), the rating is qualified as a threshold measurement because subject is (indirectly) asked to rate if the intensity is different from the current one and eventually by how much depending on the nature of the scale. Hence, every graphic scale using number has this property.

A common remarks in the field of PE is the necessity to consider the order of appearance of stimuli (Bernyer, 1959), the characteristic of the previous stimuli presented (Garner, 1953), or the duration between two observations (Borg, 1962; Noble and Robertson, 1996, p. 55); in other words, the context. According to the authors aforementioned, this requirement is because of an alteration of the outcome; this means an "incorrect" observation. As explained previously, this interpretation is not based on any rational arguments. Nevertheless, these influences in observer's measures have to be considered and reported as a part of the general context of investigation and not as a mistake in the rating.

Inter-days:

In the condition, *ceteris paribus stantibus*, that the context is identical, the "magnitude observed on separate occasions will result in the same as if it is measure simultaneously because the **only** bias in both case is memory" (British Association for the Advancement of Science, 1938, p. 321).

c. Numbers issues

Difference must be made between numbers and numerals. A numeral is a material or quasi-material symbol. The usual order of the numerals arises from pure convention. The advantages are: 1) that the convention enables the order to be remembered very easily; 2) that the list of things ordered can be indefinitely extended and yet the order of them remains perfectly definite; 3) that interpolation to any desired extent can be carried out without changing the order already established (Campbell, 1920). However, "there is nothing inherently numerical in these [perceptual] relations: in order to establish a connection we must arbitrarily associate some unique symmetrical transition phenomenal relation from among those which may have perceptual significance with the arithmetical relation of EQUALITY; and further, we must associate some suitable experimental operation with the arithmetical operation of addition" (British Association for the Advancement of Science, 1938, p. 297).

At the opposite, a number is "a unit that forms part of the system of counting and calculating" (Cambridge dictionary). It is important to differentiate in order to avoid misinterpreting numerals as quantities.

Memory

As stated by Borg (1998, p. 34), when using numerals (like any anchors) "subjects may remember what ratings they have given before". This creates an issue in analysis, especially for retest correlation (Carterette and Friedman, 1974, p. 232) that can "cause a spuriously high coefficient".

Numbers & Numerals

In regard to this dichotomy, the numbers of nonsense related in the "scientific" literature is mind-blowing… As an example, Borg didn't hesitate to infringe the logical laws. He discredited Stevens' psychometric propositions, saying his "(ratio scales) do not give perfect ratio scales in an absolute mathematical sense, since the numbers used by [hu]man are not equal to true mathematical concepts but are subjective numerical conceptions" (Gunnar Borg, 1982, p. 25). However, when *selling* his own scales with numerals and qualitative VAs, not even using numbers, he had the audacity to claim that they possess interval and/or ratio properties (Borg, 1998). Unfortunately, as pseudoscience has developed in this field, the majority of researchers believe in it and use it without verifying the validity of the underlying theory. The reader will be able to observe later that a large part of research in PE metrology is blaming the others of mistakes you make yourself.

The individual relation of observers with numbers has been an argument to reject the practice of interindividual comparisons when using numbers (Stevens, 1975). "Observer may respond a number but is it really a number that can be averaged [or is it a numeral]?" (Stevens, 1975, p. 109). The debate on the ability of observers to interpret numerals as numbers when experimenters ask them explicitly to do so, should not be rationally challenged as explained and demonstrated previously (Attneave, 1962; Marks, 1974, p. 272; McGill, 1974).

Noteworthy fact, Zwislocki (1983) proposed to use CMM to correct for potential bias in estimation of numbers relation, however the heterogeneity of relations between numbers and different subjective estimates (Stevens and Galanter, 1957) makes it an unreliable method; indeed, which numbers – perceptual relation should be used as reference...

7. Influence of context

The preparation for the rating of a perception followed three steps:

1) The observer is alerted, prepared for action at the appropriate time.

2) The stimulus objects, data, or materials to be perceived are specified. I.e., the observer is sensitized to, or set for, some aspects of the environment or of memory rather than others.

3) Third, the form of the response or the alternative response categories is specified (Johnson, 1955, p. 286).

Perceptions are not isolated experiences but are influenced by memories, ideas, and emotions that interact with other perceptions in a complex network (Borg, 1998, pp. 24–25). "Factors in the environment, such as music, heat, and social context, may distract subjects or cause them to attend to special cues" (Borg, 1998, p. 38). As a consequence, finding simple patterns or invariances in sensory experiences is challenging because every experiment and measurement is inevitably influenced by its context (Stevens, 1971, p. 446).

This context has been historically conceptualized as a “frame of reference” defined as “the background of stimulation which influences our behaviour in a particular situation” (Buxton, 1942, p. 17). *Since the term 'frame of reference' is already used to mean something else, when referring to this concept, we will use the word 'context' instead.* “The word background implies that something is in the foreground, obviously the object of perception or judgment, the stimulus pattern to which the organism is set to respond. The frame of reference exerts its influence by supplying background for the object of perception or judgment” (Johnson, 1955, p. 314).

“It is not only the object [to be perceived] which determines the final decision, but also the background pattern or context within which the object is [perceived]” (Johnson, 1955, p. 314).

a. Subject influences

Individual differences’ assessment in perception are: perceptual abilities, perceptual sets, perceptual references (Johnson, 1955, pp. 111–113). In some context of experiments (especially when using category scaling), subjects can have expectations of stimuli to be perceived and adjust their rating accordingly. Stevens & Galanter (1957) proposed the utilisation of “pure” category scaling mentioned previously to overcome this issue.

b. Time – intensity effect

An increase in the duration or intensity of the physical stimulus to which the observer is exposed influence the PE & PI in the same way (i.e., increase) but with a different magnitude of effect (Borg, 1962; Stevens and Cain, 1970). These magnitudes are, except for specific context created on purpose, non-linearly related to the quantity of workload performed. Kilbom *et al.* (1983) have asked subjects to perform an endurance task until exhaustion (TTE) at a fixed absolute intensity to record their individual performance. On consecutive days, subjects perform the same exercise with the same workload but are stopped at predefined duration corresponding to a given percentage of the maximal observed on the first maximal evaluation. Briefly, subjects tended to overestimate the effort expended as related to time spent on the task when linearly compared to the duration sustained during the initial TTE. This overestimation was statistically significant for each condition corresponding to 50, 60, 70, 80% of the maximal duration. To recap, the findings indicated that subjects tended to underestimate their maximum static endurance capacity during the task.

In a different area of application, they demonstrated that the timing of RPE recording is important and needs to be standardized. The average RPE of an exercise session has been demonstrated to be influence by this factor (Rodríguez-Marroyo et al., 2022).

c. Virtual exponent

Virtual exponent is the "as if" exponent obtained through incomplete investigation of a stimulus-response relationship, a small part of the stimulus-response range (Marks, 1974), or through a method not adapted to assess this relation as when using a partition scale (Stevens, 1971, p. 431). On the contrary, the **functional exponent** is obtained through a comprehensive examination of the stimulus-response relationship. It's important to remember that this relation is context-dependent and not universal.

8. *Threshold measurements*

These notions are important in psychophysics and in particular in the field of PE because there are related with the majority of old studies in this area of research. As explained earlier, the majority of methods used previously employ intermediate anchoring, which gives them the property of measuring thresholds.

Methodologically, "the underlying experimental operation for determining any kind of threshold always involves a procedure of matching either stimulus to category or category to stimulus" (Stevens, 1971, p. 435).

In psychophysics, "the threshold cannot be defined as the stimulus value below which detection never occurs and above which detection always occurs. […] Since reactions to stimuli are variable, the threshold must be specified as a statistical value. Typically, the threshold has been defined as the stimulus value which is perceptible in 50% of the trials." (Gescheider, 1997, p. 45)

a. The J(ust) N(oticeable) D(ifference) of s(timulus intensity): a special case of threshold measurement

The JNDs (or just perceptible difference of stimulus intensity), defined as the smallest difference between two stimuli that a person can detect, is not a constant parameter

(British Association for the Advancement of Science, 1938, p. 308). The JNDs is condition (time) and observer dependent. It cannot be regarded as a fixed unit fit for measuring the intensity of subjective measures. Hence, an absolute JNDs at a given intensity is not transferable to another intensity of stimulus (Weber's law) (Fullerton and Cattell, 1892). An important remark to make: During an experiment where observer is asked whether his subjective rating of a stimuli is higher, similar, or lower, if a difference is perceived, it merely a difference that can be perceived but not necessarily the JNDs. An assessment with incremental stimuli must be performed to obtain the JNDs.

An important observation on the properties of JNDs is regarding its relationship with the intensity of stimuli. Back in the days, Fullerton & Cattell (1892, pp. 25–26) noticed that "the error of observation tends to increase as the square root of the magnitude [of the stimuli], the increase being subject to variation whose amount and cause must be determined for each special case" (Fullerton and Cattell, 1892, pp. 25–26). One century later, Borg (1998, p. 21) declared the following point: "at a strenuous exercise intensity a small increase in physical performance is perceived as requiring a larger subjective effort than the same increase at a lower exercise intensity". These points are coherent. Rationally, a greater value will result in a higher absolute variability in the measurement.

The JNDs is a special case of threshold measurement, and similarly is a comparative stimulus value that is identified 50% of the time. This concept was central at the start of psychophysics (British Association for the Advancement of Science, 1938) but was gradually abandoned afterwards. To explain this change in the context of research, the goal of modelling an objective-subjective relationship has gradually become central. If you have been following along from the beginning, you'll understand that measurement tools suitable for threshold identification are less suited for subjective kinetics, and vice versa.

According to us, the method of bisection has played a major role in this evolution. In this production design, one pair of stimuli is presented to the observer and he is asked to produce a stimulus that appear to lie subjectively equally between the two reference stimuli. Next, the two ranges obtained are bisected to give two new stimuli that are presented to the subject that he needs to bisect in order to obtain a second produced stimulus. The outcomes of these experiments demonstrated an internal inconsistency in the subjective appraisal (i.e., the discrepancy between the two stimuli produced were outside of the experimental error). The author's conclusion was even that a scale of sensation cannot be built up; a scale on which the subjective measurements would be proportional to the objective stimuli (Gage, 1934a, 1934b, p. 19; Plateau, 1872). While questioning the relevance of the research outcomes of objective-subjective relation, the point highlighted in these scientific observations is important but not excluding for the study of human's perceptions (or subjective response).

9. Analysis & Influence of analysis on interpretation

Measurement exists in a variety of forms and scales of measurement fall into certain definite classes with empirical operations and formal mathematical properties for each scale. The statistical manipulations that can be legitimately applied to empirical data depend on the type of scale and ordering of data (Stevens, 1946). It is important in this issue to make the distinction between numbers and numerals. Readers are referred to Numbers issues' part for more details.

As already mentioned since a long time ago, transforming data mathematically can reveals relation existing between variables (i.e., intensity & stimulus) (Ferguson et al., 1940, p. 349; Sheel et al., 2020). However, this practice often used, as shown previously, is not acceptable in psychometry and must be banned when the aim is to observe a response's kinetic.

The relation generating order is transitive and asymmetrical. A number of terms will form a series and will have a real order if there is a transitive asymmetrical relation such that every term has either this relation or its converse to every other term.

a. Statistics remarks applied to psychometric

1) Mean and standard deviation (and other quantitative statistics) applied to an ordinal scale (i.e., the majority of current scales used) are an error because the successive intervals on the scale are unequal in size (Stevens, 1946).

In regard to the current use of statistics, we feel appropriate to remember that the standard deviation computation (technically called the root mean square deviation) is not an appropriate metric to represent the variations in a dataset and the computation of mean absolute deviation is more appropriate to this end (Taleb, 2019b, pp. 49–50).

2) Type of data and statistical distribution to analyse are to be considered. The choice between median (traditionally used for ordinal data), arithmetic mean, and geometric mean (better for lognormal distribution) is an example of metrics that fit to different data (Stevens, 1975).

3) Regarding the mean (average), Stevens (1975) has made the remark that in psychometric, the arithmetic mean should never be used because of nearly universal tendency of error to be relative, nor absolute. Indeed, for instance "the log-log slope (exponent) determined by the geometric means is not affected by the fact that each observer uses a different unit of modulus" (Stevens, 1971, p. 428). This point applies especially for the method Stevens investigated (i.e., *free* magnitude estimation).

b. Average

A major "effect produced by averaging is in changing the degree of skewness in the mean curve. […] The mean curve differs definitely from the individuals in this characteristic. […] It is therefore not possible to ascribe the degree of asymmetry observed in a series of averaged measurement to the growth of an individual organism." (Merrell, 1931, p. 69)

To illustrate potential influences on inferences from averaging, for instance "Stevens (1956, p. 13) concluded that 'the spacing of the variable stimuli seems to play only a negligible part in determining the estimate made in these experiments'. But such conclusions appear unwarranted, since the two psychophysical curves were group curves. The individual-spacing interactions would tend to cancel out in the process of averaging" (Pradhan and Hoffman, 1963, p. 534).

Problem of inferring from curves based on group data

It's not because the group has a descriptive function that each individual will have a similar function. The opposite is true, but in this way, some parameters have to be verified (Pradhan and Hoffman, 1963). The fault lies **in our customary interpretations of the results.**

The form of the growth curve obtained from the average of a series of individual growth curves cannot be assumed to be characteristic of the growth of the individual (Estes, 1956, p. 134). "The mean curve does not provide the information necessary to make statements concerning the function for the individual" (Sidman, 1952, p. 268). The extent of the differences hinge on the variability of the individuals (Merrell, 1931).

“We can no longer expect averaged data to yield any direct answer to the question ‘what is the form of the individual function?’ *We can, however, replace this question with one which can be answered namely,* ‘Is the form of the mean empirical curve in accord with the assumption that the individual functions are of a given form, say y=f(x, a, b, …)?’ […] if the function obtained for the individual organism is y=f(x, a, b, …), then the function describing the mean curve for a group of organisms should be y=f(x, $\bar{a}$, $\bar{b}$, …), i.e., a curve of the same form with parameters equal to the means of the corresponding individual parameters. *The assumption is not generally true*” (Estes, 1956, p. 135). More details are available in the original paper of Estes (1956) for the particularity of different functions when averaging.

c. Inter-individual comparisons

One of the main works of Borg in the field of PE was to shed light on the benefits of assessing interindividual differences during physical exercise. It all started from his former publications (Borg, 1961). The assumptions detailed previously (i.e., frame of reference, maximal perceptual intensity, etc.), are fundamental for this purpose (c.f., Assumptions to measure RPE part) (Borg, 1990; Noble and Robertson, 1996).

The significance placed on interindividual comparisons has, to some extent, marginalized the use of magnitude estimation and ratio setting methods in the field of RPE (an area strongly influenced by Borg’s perspectives). This is due to the requirement of accepting the assumptions outlined earlier.

V. Actual methods: what’s wrong with them

1) General considerations

Borg’s scales (i.e., CR10, RPE scale, CR100) (Haile et al., 2015) are best described by the concept of **threshold measurement** (Carterette and Friedman, 1974; Stevens, 1975, 1974, 1971). This feature makes these scales particularly interesting in some contexts. “The RPE-scale is constructed to aid a person in estimating and regulating exercise intensity in most kind of activity” (Borg, 1986, p. 6). It can be as it has been described “very useful […] in many practical situations” (Gunnar Borg, 1982, p. 26).

Because of the **greater constraints** coming from the use of anchors, as explained previously, the observations collected with Borg’s scales have been reported to have a smaller standard deviation (SD) than when collected with an interval or ratio scale following the method of magnitude estimation (Marks et al., 1983).

The method used to construct Borg's scales (1962) was:

1. Introduce semantic on scales,
2. Report the stimuli intensity corresponding,
3. Observe the relationship between the subjective record and an objective variable
4. Adjust the semantics on the scale until a desired outcome is obtain.
5. If point 4 is not satisfied, restart the loop.

An important consideration to have in mind is the **context-dependence** of the "validity" claims for the Borg's scales. Indeed, Borg used short-duration (<1 min) effort to limit the influence of metabolism with the aim to restrict to the muscle capacities to produce force (Borg, 1962). To overcome this issue and potential critics, he stated himself that "for long-term exercise of a steady-state character […] it is difficult to get good intra-test reliability estimations since the test has to be spread over time with several trials on different days to avoid fatigue effects or memories of previously given ratings for identified workloads" (Borg, 1998, p. 32). These problems are present for experiments performed during the same day and in a single experiment too (see Methodological considerations in psychometric for more details).

Information to be noticed, Borg voluntarily omit the settings related to JNDs, absolute threshold, and discrimination threshold to concentrate on the subjective range (Borg, 1998, p. 18).

To obtain a linear **relationship between the RPE and workload or a physiological variable responding linearly to workload** was in fact one of the objectives in the construction and development of the RPE scale (Borg, 1998). Therefore, rationally, studies using Borg's scales don't demonstrate the kinetic of RPE (e.g., how RPE increases with workload), as the RPE scale was designed to exhibit a specific relationship between the workload and the RPE (Borg and Johansson, 1986, p. 47).

The RPE or CR10 scales were supposed to have the advantage over previous scales to fulfil the demands of absolute identification of levels of intensity (*not really true for the CR10 scale because of the free choice of the value assigned to the maximum PE*). According to Borg, the characteristic he created (on purpose) is one of the main advantages of the RPE scale. Id Est, “the given ratings grow linearly with exercise intensity, heart rate (HR), and VO_2” (Borg, 1998, p. 15).

“One strong proof, in my mind, is the very high correspondence between psychophysical functions and relevant physiological ones” (Borg, 1998, p. 20). There is no place for beliefs in science but this idea and the associated confusion could arise from the consideration of the “rating of perceived exertion [as] a physiologically valid and easily applied measure for assessing functional aerobic power” (Robertson et al., 1998, p. 190). *We haven’t followed at which moment the PE became a physiological measure. As a reminder, PE is a psychophysiological measure.*

In fact, because of the amount of stimuli influencing directly or indirectly PE during exercise (Marcora, 2019) “the subjective perception of effort or exertion is sometimes a better indicator of the degree of physical strain than is the objective heart rate” (Borg, 1978, p. 333). However, it has been experimentally demonstrated that heart rate doesn’t reflect effort, as it can be dissociated from the RPE using autonomic blocking drugs (Ekblom and Golobarg, 1971; Sjöberg et al., 1979) or environmental manipulation like temperature (Pandolf et al., 1972). **This calls into question the method used to validate the Borg’s RPE scale and the CR10 scale** (Borg, 1998).

1. Problem with linearity:

Borg observed a “very high correlation between HR & RPE” (or RPI to be precise) while in these conditions (i.e., intermittent exercise with incremental intensity), HR increases linearly and RPI kinetic is convex with increase of the workload data (from psychophysics magnitude investigation). Combined with the claim that CR10, RPE-scale & HR correlate highly among them (Borg, 1998, p. 41), there is a scientific error somewhere. Because the CR10 scale has been constructed to behave exponentially and RPE-scale linearly, this claim is mathematically wrong. Linear functions cannot be correlated with exponential functions because linearity between variables is a prerequisite for assessing the relationship between variables through correlation analysis.

Other remark is the proposed transformation of Borg to convert the RPE-scale result into the frame of CR10. The 20 is convert to 12, but CR10 can go over 12, consequently modifying all the framework. It’s whether a non-sense, whether the scale was constructed to be used up to the numeral 12 but we would support the first option as Borg clearly said: “instruction encouraged ratings […] above 10 such as 11 or 12 or even higher” (Borg, 1998, p. 41).

2. Critics of ratio methods

Borg decided to move from traditional ratio scaling methods because they did not satisfy his needs. First, according to him “magnitude estimation methods instruct **people to use** any **numbers** they choose **according to their own feelings** and conceptions of numbers without any restrictions to a common response scale” (Borg, 1998, p. 23). These methods are, for him, only “valid for general descriptions of growth functions, but not for differential use and direct estimations of intensity levels” (Borg, 1998, p. 13) or in other words because of the inability to infer on the “strength of the perception in an “absolute” sense” (Borg, 1998, p. 25, 1978, p. 341).

However, his scales produce the same issue by using qualitative verbal anchors. When Borg stated that this issue was resolved using his scales, he didn’t figure out the problem of validating the verbal anchors multiplicative characteristics with indirect stimuli of a subjective observation. Additionally, by allowing a “free” maximum in the CR10 scale, the assumption of the intensity of perception based on the frame of reference is not respected and can’t be used anymore.

The last point to mention regarding the actual methodologies used to report RPE is the assertion that “there is no major difference between different CR scales” (Borg, 1998, p. 41). However, this affirmation is contradicted by experimental data (Neely, 1995)…

3. RPE relation to physiological variables

First of all, we need to warn about the erroneous results that can be obtained when using a parametric method instead of non-parametric one. Nevertheless, even if we consider the results as correct, based on the data reported in the literature, we can conclude that when a high correlation was obtained, it was often a result of a spurious, context-dependent correlation, meaning it occurred in situations where all influences, except for workload, were diminished. Nonetheless, this could also be explained because the workload is one of the main input influencing PE during physical task.

"Perception of effort is not consistently or necessarily associated with proxies of effort, such as heart rate and force. This is due to the influence of various factors and their interactions, which can modify the strength of these associations" (Halperin and Vigotsky, 2023, p. 7). If someone is interested in objective physiological or physical variable: measure it! Please refrain from causing any inconvenience or disruption with investigations of the perception of effort. You can study their relation but do not use it as validity criterions.

So where is the real benefit of the scales? Even setting aside the methodological errors, they distort the outcome for no real benefits; These scales just seems to be the result of an overfitting created during earlier experiment in a specific context to meet specific needs of a model and goals.

As we have emphasized throughout this paper, context is key (Johnson, 1955). The HR – RPE relation is highly dependent upon the type of physical task involved (Gamberale, 1985, p. 305) and differs even from walking to running (G. Borg, 1982, p. 379). Moreover, in the 3 traditional modes of locomotion (i.e., swimming, running, cycling), the RPE – workload (measured as %$\dot{V}O_2$max) relationship is different (Noble et al., 1986).

The relation between HR and RPE (most of the time measured as RPI which promotes a stronger link) has been assessed through correlation analysis. To note, the reported outcomes demonstrate low correlation (Borg and Dahlstrom, 1962, p. 24; Borg, 1973; Chen et al., 2002). For instance, Borg measured subject's RPE during different constant load exercises at different intensities and reported the correlation between HR and RPE. The correlation reported for the different submaximal intensities was very low (p=0,40). However, due to the subadditivity property of correlation (Taleb, 2019a), when these intensities were grouped together, the correlation increased (p=0,85). This findings align with a previous investigation (p=0.83) although it lacks specific details regarding the submaximal intensities. Unfortunately, the only outcome used to draw conclusions and interpretations was when computed over all the data together (Borg, 1962, p. 40). This was done without providing any explanations. In another example, using a similar design with a different population Borg stated that "the correlation between RPE & HR was high in the two healthy group but not in the myocardial infarction patients" (Borg, 1978, p. 349). However, when examining the correlation values, they were 0.589, 0.692, and 0.400 for the 3 respective groups (Turkulin et al., 1985, p. 361); far from containing a high mutual information. Additionally, we have no information or scatter plot available to confirm the linearity of the dataset but the average response is displayed and it is not linear. This is another incorrect methodology for correlation analysis (Taleb, 2019a).

We are sad to say that majority of the RPE research field fall in the category of the "psychological researches [that] have but little value because the author has rejected experiments and series which seemed wrong to him. Under such circumstances even the most conscientious observer may obtain results conforming better to his theory than to the truth" (Fullerton and Cattell, 1892, p. 29).

2) Borg's RPE scale

"Starting with 6 (instead of 0) shows that the scale is not a ratio scale with an absolute 0". The "number 20 on the scale refers to a kind of "absolute maximum," an intensity that most people never will have reached previously in their lives " (Borg, 1998, p. 30). The RPE-scale does not allow for the use of decimals, an issue that increase the constraint applied to the observer. Borg figured out this problem and tried to overcome it in its CR10 (see later).

"The construction of the RPE scale is unique, and the scale may be considered an equidistant interval scale" (Borg, 1998, p. 30). Borg classify the scale in the category of interval scales *but a statement does not worth an observation*. There is no evidence for such affirmation. Gamberale (1985) was one of the first to point out that the RPE-scale was not a scale with interval but an ordinal properties.

The "reason" why RPE-scale is classified as an "interval scale" is because, during exercise, heart rate is regarded as an interval scale, ranging from resting to maximum. Perceptual ratings were reported to have a linear relationship with heart rate, which supposed to support this classification. However, as explained earlier, physiological variables or workload are not criteria for establishing intervals in RPE.

3) The Category-ration scale (CR10)

How Borg came to a point to "call" his CR10 scale a "ratio-scale"?

The CR10 scale was presented in a congress in 1980 and published in 1982. Four main considerations were employed to construct the CR10 scale (Neely, 1995; Noble and Robertson, 1996):

1. The acceptance of the ratio scaling techniques as the best for general descriptions of perceptual variation,
2. A method to make valid interindividual comparisons,
3. Adjectives and adverbs may function as multiplicative constants (and allow to manipulate the scale according to a will and objective),
4. The fourth consideration was the relationship between category rating and ratio scale rating of perceived exertion.

Because "in some situations, it is of interest to use a ratio scaling method" (Borg, 1998, p. 39), Borg tried to correlate the RPE collected using the CR10 scale with HR and the results obtained were low (0,290 ≤ r ≤ 0.750) (Marks et al., 1983). However, this is not a surprise scientifically. An exponential function or presented as so (CR10 – Workload) cannot be correlated to a linear function (HR – Workload).

Across the years, this scale has been the most widespread over various fields of application and countries but also the most modified. We must recall to users here what Borg himself stated about his scale: "A very bad distortion of the CR10 scale is when the dot (.) above 10 and outside the range of numbers on the scale is changed to 10+, which simply means something more than 10. The dot means absolute maximum, and numbers higher than 10 should be possible. To avoid the "ceiling effect," there should not be a fixed endpoint" (Borg, 1998, p. 15). However, nowadays, we encounter numerous scales labelled as CR10, which reference Borg's studies as a criterion for "validity", even as we observe alterations in the scale's design (e.g., colours, position of the VA, etc.) or the omission of the dot (Van Der Zwaard et al., 2023a).

The utilisation of a dot, or in other words not having an absolute maximum is nonetheless problematic (Neely, 1995). Using an individual maximum instead of a set value means that no interindividual comparisons are possible. Not because of the different number affected to the maximum RPE, but because of the use of qualitative VAs. They have interindividual variability in their meaning. The use of this methodology (i.e., free maximum anchor) without instruction in the relation between the numerals allows only for comparisons on an individual basis (Neely et al., 1992).

Statements are beautiful. Borg declared the following remark: “CR10 scale makes it possible to determine growth functions for different modes, to compare them with physiological growth functions, and to make direct estimates of intensity levels for interindividual comparisons. The CR10 scale is a general intensity scale that can be used to estimate most kinds of perceptual intensities” (Borg, 1998, p. 15). **However, the requirements to support these statements are not present in the data provided by his team (Neely et al., 1992) and it lacks any psychometric basis.**

A

Goals

1

Correlate the outcomes of Borg's scales with physiological variable(s) and workload. This mistake is still published in recent reviews on the topic (De Souza et al., 2023) and have to be addressed quickly as a consequence.

2

Inter-individual comparisons based on a frame of reference.

B

How it was achieved?

1

"By a careful choice of verbal categories" (Noble and Robertson, 1996, p. 63).

2

Setting a maximum and intermediate reference points to allow interindividual comparison (Gunnar Borg, 1982).

C

Resulting problems

1

Result obtained with a CR10 is supposed to be exponential and RPE-scale to be linear in relation to an increase in workload (Borg, 1998). Borg aimed to correlate both scales with HR and stated that they are (Borg, 1982). Secondly, in context of non-linearities, the correlation coefficient is uninformative (Taleb, 2019). For the non-sense of comparing RPE and physiological variables as a validation criteria to construct a scale, we explained previously why this is an aberration. **This is 2 mistakes in one statement, a bit too much for communications claiming to be scientific; more common in research...**

Borg's methodology adds a third issue related to this goal of linking RPE with physiological variables. His statements are built on an unstable base. Borg's RPE scale and CR10 scale are specifically **designed to produce a specific response on bicycle ergometer & in a specific context** (Borg, 1962). His efforts to "validate" his scales are therefore limited in their applicability, asides from other problem

D

Psychometric mistakes

1

Rationally, this cannot be an aim. However, from an interpretive perspective, it holds high relevance (Henriksson et al., 1972).

2

The frame of reference is a great step forward in the field of RPE but in this case, the method to determine the intensity of perception in the scales is not correct. Inter-individual variability exists when using qualitative verbal anchors and as explain before the argument "it correlates with x" is false and is not authoritative. *For instance "hard" has not the same meaning for everyone but half" is "half" for everyone.*

Summary of the general considerations of Borg's scales.

A

Goals

1

“To obtain a linear relationship between the RPE and workload was in fact one of the objectives in the construction and development of the scale” (Gamberale, 1985, p. 304).
Specific aim of the RPE-scale: Borg desired to construct a scale that grows linearly with intensity traditionally measured in mechanical terms (i.e., watts; kpm/min) or with the heart rate (Borg, 1982).

B

How it was achieved

1

“By a careful choice of verbal categories” (Gamberale, 1985, p. 304; Noble and Robertson, 1996, p. 63).

C

Resulting problems

1

The aim of a subjective measure is not to reflect an objective measure that is not its direct stimulus.
A potential explanation for this mistake is the recurrent confusion between PI & PE.

D

Psychometric mistakes

1

Considering ordinal as interval: Additionally, to the problem of using qualitative VAs, the way the scale is built distorts the outcome. This “validation” is context dependent.
This mistake can be explained by the fact that when reading the instructions of the author, the perception measured is the intensity and not the effort (see Perceived exertion or Perceived intensity: problems come from psychophysics misuse).

Summary of the general considerations of Borg's RPE-scale.

A

Goals

1

Obtain a scale with ratio properties. “A category-ratio scale (that is, a combination of a category scale for direct level determinations and a ratio scale for determinations of scale tests and growth functions)” (Borg, 1998, p. 40) and correlates with non-linear physiological parameters during subjective assessment of increment intensities (Marks et al., 1983).

2

To diminish the ceiling effect (Gunnar Borg, 1982, p. 31).

B

How there were achieved

1

Modify the correspondence of numerals and verbal anchors to match a ratio function between RPE and a desired variable (e.g., HR, Blood lactate, etc.) (Neely, 1995).

2

“A person may experience a pain stronger than he or she has ever experienced before. People must therefore be able to respond with a number higher than expected according to previous experiences” (Borg, 1998, p. 40). “In the final version of the scale maximal intensity was there placed outside the scale” (Gunnar Borg, 1982, p. 31) and ““instruction encouraged ratings [...] above 10 such as 11 or 12 or even higher” (Borg, 1998, p. 41).

C

Resulting problems

1

Decrease precision for lower perception level (see, Neely, 1995, Fig. 7 & Studies 2 & 3) because of the limited number of categories.

2

This reasoning cannot be applied to effort because this last is a conscious individual production, not a response to stimuli. As a consequence, there is an identifiable maximum. *Marcora (2019) effectively addressed this issue. During a physical task performed until exhaustion, when clear instructions are provided “in conditions of high potential motivations, people decide to stop endurance exercise when effort is perceived as maximal and sustaining the required velocity/power seems impossible”. In conditions of low potential motivation, what we can theoretically refer to as “absolute effort”, the effort level at the point of exhaustion is submaximal. However, within the context of interest, the effort remains maximal and is perceived as such.* This characteristic is what enable to infer the effect of an intervention based on the RPE – workload relation (Nicolò et al., 2019).

D

Psychometric mistakes

1

Utilisation of qualitative VAs does not enable to create a scale with ratio properties.
“Partitioning operations can produce at best an interval scale, not a ratio scale” (Stevens, 1974, p. 373, 1971, p. 430).

2

There is no errors at the condition to interpret the outcomes correctly; that means as ordinal data.

Summary of the general considerations of Borg's CR10 scale

VI. How the rating of perceived exertion has to be measured?

Previous assertions (Borg, 1998; Gescheider, 1997) regarding one (category of) scale being superior in an absolute or general sense must be prohibited. The choice of scales is context dependent, and each type of scale have their strengths and weaknesses. The most important is using the best scale in regard to the aim of the measurement.

As a rule of thumb, we recommend using a finite scale for finite measurements & an infinite scale for infinite measurements.

In this part, we will present the most effective solution, based on our current knowledge, for measuring the RPE as accurately and objectively as possible. This solution incorporates ratio properties to facilitate inter-individual comparisons (*aligning with the original intent of Borg).* It also seeks to mitigate the various influences that have been discussed previously, which might otherwise interfere with this objective. To this end, using a proper psychometric device is primordial or it would be like measuring distance linearly using a tape measure with logarithmic marks.

We will detail why, to our knowledge, the most appropriate measurement method to fit with this aim is a visual analogue scale individualized with cross-modality matching for line length perception (IVAS) (Collins and Gescheider, 1989; Gescheider, 1997) and explain its methodology.

Borg's group introduced VAS as a measurement tool in the field of PE but later rejected it [without considering individual variability in length perception] based on correlational results with HR as a criterion of validity (Borg, 1973; Neely et al., 1992)*. However it's to note that even if few studies have measured RPE using a VAS, no problem in its applicability have been demonstrated* (Bian et al., 2023; Rodríguez-Marroyo et al., 2022)*. An information to raise for the readers considering the technology available nowadays is that a digital version of a VAS can be used interchangeably with a traditional paper-based VAS* (Delgado et al., 2018)*.*

1) Rationale of using IVAS

VAS produce similar results in production & estimation methods; hence both approach can be used, interchanged, and compared (Price, 1988, pp. 31–33).

- There are no intermediate anchors to **avoid outcome distortion** described previously. Only **anchors locating the minimum and maximum** are used because they don't bias the outcome (Price, 1988) and allow for interindividual comparisons by **setting the perceptual range** (i.e., the frame of reference).

How did we come to this choice: *When comparing two scales under the same condition, if one scale (with verbal anchors) results in less variability, we can infer that these anchors tend to influence the rating of the subjects. This observation has been consistent across all studies investigating this issue.*

- VAS allows more sensitive and uniform responses (Huskisson, 1974; Scott and Huskisson, 1976), especially compared to graphic rating and category scales (Huskisson, 1974; Scott and Huskisson, 1976; Turk and Melzack, 2011, p. 20). *The sensitivity of a measurement is defined as the minimum change in stimulus intensity required to be detected by the measuring instrument* and is a key feature of the precision of a scale in psychometry.

2) Methodology:

1. A VAS is provided to the observer with written anchors at both extremities of the scale (i.e., “No effort” and “Maximum effort”). **For every measurement (or cross-modality matching) realized, the scale presented must not have any information related to previous measurements; feedbacks never have to be available**.

The length of the scale has been shown to be of no influence in the outcomes, hence experimenters are free to use what they prefer. As a general piece of advice, using a 10-20 cm VAS is more common and practical.

2. The VAS is **individualized by cross-modality matching**. Before every session (Pradhan and Hoffman, 1963), we ask the observers to determine subjectively on the scale different percentages (the more, the better) of the objective total line length in order to adjust the subsequent outcomes based on individual line length perceptions. The results are then extrapolated to interpret the individual outcomes obtained from the subjective modality we are interested in (Johnson, 1955). This step is necessary to eliminate a significant known bias: inter-individual comparisons. *Knowing the inter-individual differences in line perceptions exponent, this procedure is essential to merge and / or compare the*

outcomes between individual during an experiment. Unlike previous statements about number and line length being proportional (Gescheider, 1997, p. 270; Stevens, 1975)*, this can be true when data are averaged* (Stevens, 1974, 1971; Teghtsoonian, 1965) *but not always (seldom) when considering individual cases* (Krueger, 1970).

To confirm this necessity, we ran a pilot study on 4 subjects. They had to rate ¼, ½, and ¾ of line length on a VAS anchored as detailed previously. The average median of measurement was 9.7 (ranging from 9.2 to 10.3) and the mean absolute deviation was of 0.6 (ranging from 0.2 to 1.2). This simple little observation illustrates the necessity for this step in the measurement with VAS to enable future interindividual comparisons.

3. Clear instructions are presented to the observer about the nature of the line in front of them (VAS**). This part is primordial in order for the outcomes to have ratio properties** (Gracely, 1979; Stevens, 1946).

"Rate how you perceive your actual exertion on this (visual analogue) scale anchored at the extremities by the verbal of the same significance "no effort" and "maximal effort". As a rule of thumb, when your perception of the effort doubles, the distance of your answer from zero has to double, and the centre of the scale represents an effort perceived as being equal to half of (what you perceive as) your maximal effort.

We want you to rate your perception of effort, that is, your s*ubjective evaluation of the (available) resources invested over a given time frame to perform a task."*

4. The last part involves **computing the RPE** values from the measure of the VAS and the CMM of line length perception.

3) Alternatives

In specific context, this methodology might not applicable (e.g., running on a track). Here we propose an alternative, that in specific context can allow experimenter to measure the RPE using the same principles. This method introduces issues related to the use of numbers (memory effect, etc.), which is why we don't propose this measurement as the preferred one. However, in contexts where observer do not have the possibility to put a mark on a VAS (or indicate where to place it), this becomes one of the few and acceptable alternative available to meet our aim.

This method is based on the free magnitude estimation as described by Stevens *et al*. in their works on psychophysics. That means, observer is asked to give numbers that best represent the intensity of their RPE. Starting point (i.e., number) is arbitrarily and freely chosen by the observer knowing "zero" means no exertion and respecting the ratio rule; that is when intensity of RPE double, the assigned number used to rate the perception is double in consequences. At the end, subjects are asked to provide the number they would have verbalized in a situation of maximal exertion, whether this situation occurred during the experiment or not.

This method of investigation, while limiting the bias introduced by various methodological settings (as described previously), provides ratio properties based on the subjective range (i.e., the frame of reference) and the position of the observer's ratings (i.e., the intensity of perception). It provides all we need to measure the RPE and perform inter-individual comparisons.

VII. Proposed directions to improve RPE measurement

Improvements are necessary to optimize the IVAS. Future research can be performed regarding the best way to set the scale. Answering the following questions appears important to optimize its practical utilisation:

1. How many data points and what is the best (or the least bad) option for the purpose of decreasing the number of measure while maintaining the same quality of CMM.
2. Which extrapolation method enable the better fit with the subjective outcomes to individualize the scale (e.g., linear, polynomial, etc.)?
3. Does this extrapolation have to be individual or could be similar for all observers?

These are in our view some valuable improvements that could be supplied to this method of measurement.

VIII. Conclusion

Metrology in psychometry can be complex and challenging. Throughout this text, we aim to guide readers, whether practitioners or researchers, towards a comprehensive understanding of how to measure the rating of perceived exertion accurately. We explained the errors regarding the current methods used in research and their associated mistaken publication. Even though we suggest the method of IVAS to measure the RPE, this is regarding a specific (i.e., the most common) aim. We want to emphasize that no specific scales are inherently better, nor should they be used simply out of conformity. We hope the theoretical constructive criticism we provide gives an idea of how to understand the topic, so the readers can make informed choices regarding the best (or least problematic) method to use in their context of intervention.

To spread misinformation is easy, but to demonstrate its invalidity, the amount of work required is exponentially greater. Please try to be honest and do your job correctly. Our article is just an example. Minor mistakes can invalidate and discredit decades of research on a topic.

Chapter 3 - Perceived exertion's kinetic, and relation with ventilatory control during incremental running exercise

I. Introduction

The ventilatory response is among the most important variables recorded during incremental test until exhaustion (INC). Through ventilatory kinetics, it's possible to obtain the first and second ventilatory threshold, which are considered as markers of endurance capacity and body health. Consequently, the INC is the widespread exercise protocol used in both clinical and sports field. Whilst there are several approaches to identify the thresholds, how this ventilatory changes happened remains unclear.

The INC is the widespread evaluation in sport science and health area to assess people's fitness, and this in many kinds of exercise modalities. The major part of these studies has been done during cycling for the easiness to record the different physiological variables. According to traditional model of endurance performance, the heart rate (HR), lactate concentration [La] and oxygen uptake ($\dot{V}O_2$) are the major ones to describe the subject's responses to exercise (Joyner and Coyle, 2008a). The responses of these variable during a INC are established as follows: 1) Blood [La] increases only gradually, if at all, in response progressively increasing intensity until the first ventilatory threshold (VT1) (Pallarés et al., 2016; Wasserman and McIlroy, 1964). The buffering of [H^+] induces an increment of CO_2 and then an increment in minute ventilation (V_E) leading to an increase in the ventilatory equivalent in oxygen (relationship between $\dot{V}_E$ and $\dot{V}O_2$) used as an indicator to identify VT1 (Green et al., 1983). Beyond VT1 frequently observed between 50 and 80% of $\dot{V}O_{2max}$, blood [La] increases in a nonlinear fashion (Dennis et al., 1992; Joyner and Coyle, 2008b). 2) Heart rate (HR) increases immediately at the onset of exercise and then, it shows a linear increment in accord to the change in workload until exhaustion where a plateau is usually observed. The first response of HR is due to a fall of the parasympathetic nervous system mediated mainly by the action of central command (CM) and baroreflex; the two main drivers decreasing the vagal activity to the heart with a high frequency of response (0,15 – 0,4 Hz)) (Bishop, 2004). The visual (recorded) increase after this drop of the parasympathetic system is then delayed from 7 to 25 seconds to the signal (workload) by the low-frequency of the sympathetic nervous system (0,04 – 0,15 Hz) (Christensen and Galbo, 1983; Freeman et al., 2006). It important to note that the starting point of INC is generally preceded by a constant workload (very low exercise intensity). Therefore, the response of HR observed at the onset of exercise recorded is virtually abolished. 3) O_2 uptake increases up to maximum value ($\dot{V}O_{2max}$) as a linear function of work rate during a progressive increase of intensity (Gaesser and Brooks, 1975; Hughes et al., 1982; Poole and Jones, 2012).

This last parameter has been the main one to describe the endurance performance capacity until the end of the 90's (Fitts, 1994; Mitchell et al., 1958; Mitchell and Blomqvist, 1971; Taylor et al., 1955) and is the principal explanation for the reductionist approach of studies aiming to predict endurance performance. From an applied point of view, the ability to predict the endurance performance is of interest for different aim ranging from monitoring to evaluation, etc. In the last 30 years, psychophysiological model rose up and the central governor model in the beginning of the 2000' was a turning point (Noakes, 2000). Briefly, the central governor theory is proposed as a mechanism of central nervous system that take as input information on energy needs, current physiological states and various motivations to regulate physical effort and protect the body from homeostatic failures during exercises (St Clair Gibson et al., 2004). However, Marcora showed this model as unnecessary, incomplete and/or failing in the explanation of many phenomenon of physical effort regulation (Marcora, 2008b, 2007). Thereby, Marcora (2009b) proposed a psychobiological model of endurance performance regulation. According to many previous models, people terminate exercise when perceived effort is so intense that can no longer be tolerated. Instead, the psychobiological model adopted a different explanation provided by motivational intensity theory (Brehm, 1989; Wright, 2008b). People terminate exercise (i.e. disengage from the task) when the perceived effort exceeds the maximum effort they are willing to exert in order to succeed in the task. This model has been experimentally verified in the last decade with experiments showing the decrease in performance following previous mental fatigue intervention (Marcora et al., 2009b) and moreover during exercise to exhaustion where peak power output (PPO) is recorded immediately after exhaustion. This last design has provided strong evidences against the fact that people terminate exercise when they are not more able to produce the PPO required, and this whether during time to exhaustion at constant workload (Marcora and Staiano, 2010b) or during INC (Hodgson et al., 2018).

For this reason, we will measure concurrently the RPE in order to determine if it can potentially be a discriminant variable able to respond differently in regard to the variation in workload. This investigation is made possible by the rejection of current psychometric doctrine and the utilisation of ratio scale to measure the RPE as explained in the chapter 2.

To deepen the understanding of this theoretical framework, this research group emphasized the importance of re-afferent corollary discharge (Bigliassi, 2015) in the conscious awareness of the central motor command sent to active muscle to "create" the perception of effort (H. M. De Morree et al., 2014; H. M. D. E. Morree et al., 2012). This is of importance in the understanding of psychobiological responses to INC and more for our interest regarding ventilatory control during INC. Indeed, recently, the correlation of one physiological variable (i.e. breathing frequency (f_R)) with the RPE has been emphasized (Nicolò et al., 2015). This is of interest as ventilation and especially f_R could be used as an objective marker of effort during exercise (Nicolò et al., 2017e).

The control of ventilation during exercise has been submitted to numerous reports providing different hypothesis regarding the regulation of V_E and its two components: f_R, and tidal volume (V_T). ME results in a proportional increase of V_E with work rate (Gallagher et al., 1987) until the VT2 as a respiratory compensation point for lactic acidosis (Wasserman et al., 1973) and then in an exponential way (Dennis et al., 1992). In subjects with normal respiratory control, it has been shown that a greater degree of metabolic acidosis will result in higher ventilation (Koyal et al., 1976) and reduced endurance time (Jones et al., 1977). However, looking the behaviour of V_E could cover and reduce the information extracted by

V_E itself. Indeed, V_E is the product of f_R and V_T, the two variables directly regulated. Hence, during INC, its established that V_E initially increases through increases in both V_T and f_R (Gallagher et al., 1987), while at high work rates further increases in V_E are due, largely, if not exclusively, to increases in f_R with V_T remaining constant or showing little change (Hey et al., 1966; Martin and Weil, 1979).

The recent advances in the field of ventilatory control under different stressors (Tipton et al., 2017) led to a new model of ventilatory control during exercise, which is based on two main pillars: 1) The differential control of f_R and V_T; 2) The unbalanced interdependence between f_R and V_T. Differential control means that central command appears to be a major regulator of f_R during high-intensity, but not low-intensity exercise. f_R is also driven by afferent feedback, but its contribution to f_R regulation decreases with the increase in the magnitude of central command while metabolic stimuli hasn't any effect on f_R. On his side, V_T appears to be affected by metabolic inputs (allostatic response) (Nicolò et al., 2017b). The unbalanced interdependence phenomenon stipulate that while f_R seems not to be substantially influenced by the levels of V_T, at least until critical V_T levels are reached, V_T appears to be constantly influenced by f_R in order to guarantee that V_E is matched to carbon dioxide output ($\dot{V}CO_2$), irrespective of the specific value of f_R (Nicolò et al., 2018b).

In this scientific study, our focus lies on exploring the specificity of ventilatory variables and the rating of perceived exertion as discriminators of exercise intensity. We delve into detailed comparisons of the last minute of the maximal exercise across different time intervals: 90-60 seconds, 60-30 seconds, and 30-0 seconds. Specifically, we examine the variations in breathing frequency (f_R), oxygen consumption (VO2), respiratory exchange ratio (RER), total breath duration (Ttot), tidal volume (V_T), and the rating of perceived exertion (RPE). Additionally, our investigation extends to the mutual information between ventilatory variables and RPE, aiming to uncover potential relationships and dependencies.

The study also delves into the kinetic aspects of the rating of perceived exertion during specific incremental running. However, caution is advised in the interpretation of these findings due to the inherent rigidity of the exercise protocol. Despite the satisfactory volume of data, it is emphasized that further data collection in diverse contexts is essential to generalize and validate these observations. Our analysis includes a careful examination of the kinetics of key ventilatory variables such as fR, Ttot, VT, and RPE, shedding light on the dynamic interplay between respiratory parameters and perceived exertion during incremental running. This comprehensive exploration contributes to the scientific understanding of the intricate relationships between ventilatory variables and RPE, providing valuable insights for future research and practical applications in exercise physiology.

This is even more important, because as we explained in the chapter 2 of this thesis, this is the first time the RPE kinetic is reported per se during exercise with variation in workload.

II. Method

1) Participants

Ten young competitive runners (2 men and 8 women; average age: 17 years) participated in this study. Participants performed a minimum of 2 training sessions per week during the 3 months preceding the visit. They were asked to refrain from strenuous exercise, consumption of alcohol and caffeine for at least 24 h before each test. Smokers, people with a cardiopulmonary disease history, injuries and illnesses were excluded.

2) Experimental overview

Participants were instructed they have to complete a running INC on an approved 400m outdoor athletics track. All around the track, markers were placed at a distance of 20m from each other in order for subjects to regulate their pace. Running velocity was set at 8 km/h for 1 min and then increased by 0.5 km/h every minute until volitional termination of the exercise. The experimenter helped the subject to regulate their pace with a whistle blow every time runners had to pass through a marker on the ground.

3) Variables measurements

Throughout the test, the volume of oxygen consumption ($\dot{V}O_2$), volume of carbon dioxide utilization ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$), total breath duration (Ttot), tidal volume (V_T), end-tidal carbon dioxide pressure ($PetCO_2$), end-tidal oxygen pressure ($PetO_2$) were measured continuously breath-by-breath using a metabolic cart (K42b, Cosmed, Italy). The device was calibrated carefully before each test following the manufacturer's instructions.

The RPE was recorded every lap. Observers had to give numbers (decimals were allowed) that best represent the intensity of their RPE knowing 0 means "no effort" and 10, their "maximum effort". A ratio rule had to be respected, that's to say, when intensity of RPE double, the assigned number used to rate the perception is double in consequences. The following instructions was provided to subjects before the test in regard to the RPE measurement:

"Each lap, you will be asked to rate how you perceive your effort from zero to ten, meaning respectively "no effort" and "maximal effort". The intensity of your perceived effort is defined as your subjective evaluation of the available resources you invest over a given time frame to perform the task. As a rule of thumb, when your perception of the effort doubles, your answer has to double too, and a RPE of 5 represent an effort perceived as being equal to half of (what you perceive as) your maximal effort."

4) Data processing and analysis

Data processing and analysis were performed using Rstudio software running the programming language R version 4.2.2 (R Core Team, 2022) and the following packages: "xlsx" version 0.6.5 (Dragulescu and Arendt, 2020), "ggplot2" version 3.3.0 (Wickham, 2016), "lubridate" version 1.9.2 (Grolemund and Wickham, 2011), "ggmap" version 3.0.2 (Kahle and Wickham, 2013), "gridExtra" version 2.3 (Auguie, 2017), "pracma" version 2.4.2 (Borchers, 2022), "Hmisc" version 5.1.0 (Jr, 2023), "infotheo" version 1.2.0.1 (Meyer, 2022), "msu" version 0.0.1 (Sosa, 2017), "data.table" version 1.14.8 (Dowle and Srinivasan, 2023), "ggpubr" version 0.3.0 (Kassambara, 2020), "grid" version 4.2.2 (R Core Team, 2022), "reshape2" version 1.4.4 (Wickham, 2007).

1. Breath-by-breath data were filtered for errant breaths (i.e., values resulting from sighs, swallows, coughs, etc.) by deleting values greater than 3 standard deviations from the local mean (Lamarra et al., 1987).
2. Data were extrapolated linearly every seconds.
3. Data were then smoothed computing a simple moving average with a window of 10 s.
4. Average of the epoch from 90 seconds to 60 seconds before the total duration of exercise preceding the exhaustion (T), from 60 seconds to 30 seconds before T, and from 30 seconds before T to T were computed for the VO_2, RPE, respiratory exchange ratio (RER

= $\dot{V}CO_2$ / $\dot{V}O_2$), breathing frequency (f_R), V_T, and Ttot. In order to normalize the result, these three windows of time for each variable were individually divided by the maximum of each variable, except for Ttot which has been divided by the delta between the maximum and minimum value recorded during the test for rationale reasons.

5. The mutual information (MI) between the RPE and f_R, RER, $\dot{V}O_2$, and V_T were computed respectively according to the entropy of the empirical probability distribution to investigate the relation and influence of ventilatory variables on the RPE. Afterwards, the results in nats were converted in bits.

5) Statistical analysis

1. The average of the different periods was compared for each variable among each other using an unpaired T-test.
2. The results and responses of the variables during the INC are expressed as mean ± mean absolute deviation (MAD).
3. The effect of time on each variable is determined using a one-way repeated measures ANOVA. Considering that the exercise (INC) has an increment in intensity over time, the effect of time can also be considered to be the effect of intensity and we cannot discriminate these two independent variables. As a consequence, when we mention the effect of time in the rest of this chapter (for easier communication), this incorporates the effect of intensity too.

In the context of statistical significance within our study, the notation * denotes a p-value lower than 0.05, ** indicates a p-value lower than 0.01, *** signifies a p-value lower than 0.001, **** signifies a p-value lower than 0.0001, and "ns" indicates a p-value higher than 0.05.

III. Result

The average (MAD) response on the last part of the INC over the defined duration (i.e., 90s-60s, 60s-30s, 30s-T) were respectively 95.8% (2.3%), 95.6% (2.1%), 95.6% (2.9%) for the $\dot{V}O_2$; 5.3% (3.6%), 4.5% (3.9%), 3% (2.4%) for the Ttot; 94.1% (3.9%), 95.2% (3.6%), 94.2% (3.7%) for the RER; 94.3% (3%), 95.2% (3.6%), 96.8% (1.7%) for the f_R; 91.6% (4.3%), 93% (4.4%), 91.3% (5.2%) for the V_T; 97.8% (2%), 99.4% (0.9%), 99.8% (0.3%), for the RPE.

Representation and comparison between the different durations for each variable are available in Figure 3.

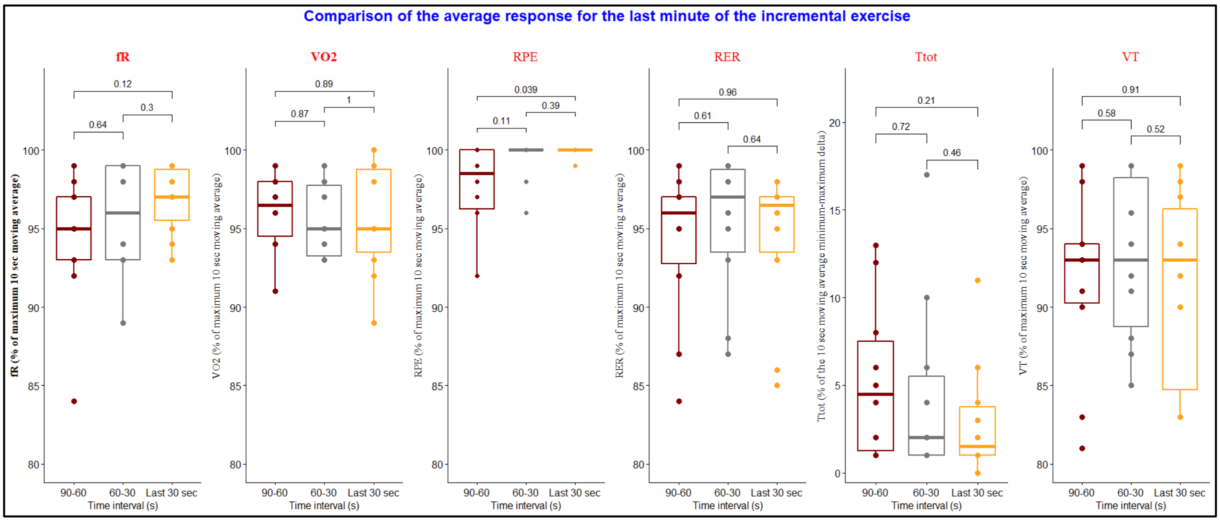


Figure 3: Statistical comparison using an unpaired T-test of the average response for the last 90 sec of the maximal incremental exercise for the different psychophysiological variables of interest. Data are normalized in percentage of their maximum except for Ttot, which is in percentage of the delta between the maximum and minimum value in order to normalize the analysis and interpretation because the derivative of the response's kinetic is negative.

The average mutual information (MAD) between of the RPE with ventilatory variables are: 1.45 (0.21) bits with RER, 1.65 (0.29) bits with Ttot, 1.93 (0.2) bits with VO_2, and 1.33 (0.38) bits with V_T. Representation and assessment of the differences of pair of variables' MI are available in Figure 4.

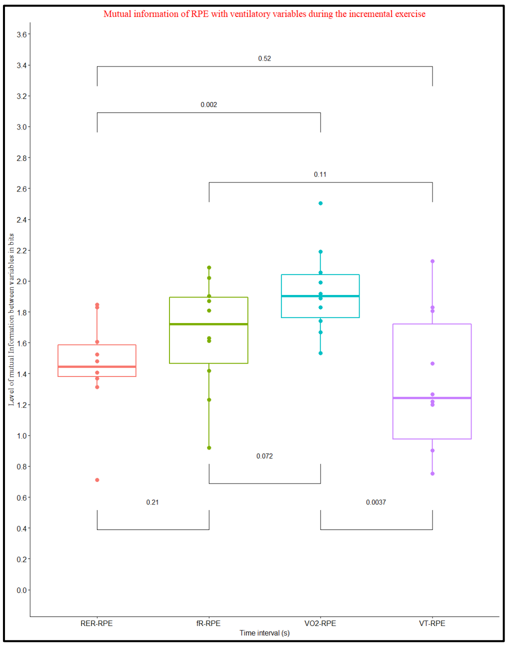


Figure 4: Mutual information between the RPE and the RER, the f_R, the VO_2, and the V_T respectively. Horizontal brackets displayed the results of independent samples t-test between each pair MI.

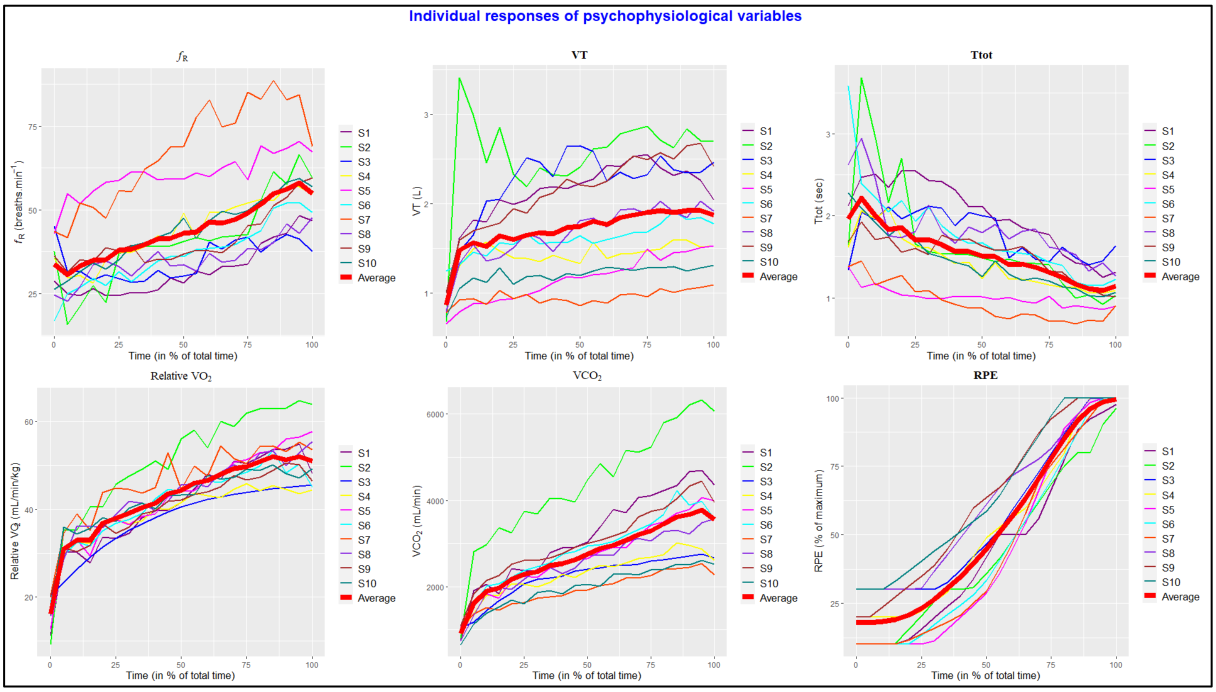


Figure 5: Individual psychophysiological responses during the INC.

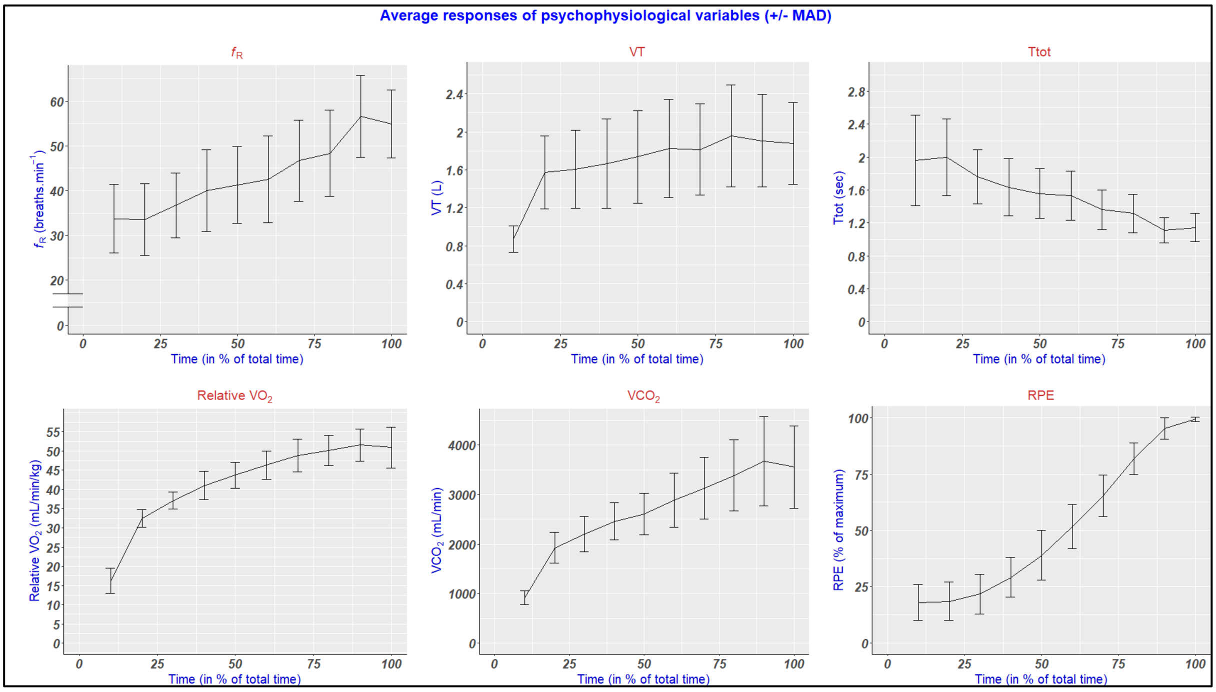


Figure 6: Average and MAD psychophysiological responses during the INC.

The median, median absolute deviation are presented in table 3 and normality assumption is checked by computing Shapiro-Wilk test for each time point along with the outliers and extreme outliers' detection calculated using the Tukey's fences method with a multiplier of 1.5 and 3 respectively.

Table 3: Median, median absolute deviation, and shapiro-wilk test results of the breathing frequency (f_R), total breath duration (Ttot), oxygen consumption (VO_2), carbon dioxide production (VCO_2), tidal volume (V_T), and RPE for each of the ten equal period of the INC. Outliers and extreme outliers calculated using the Tukey's fences method with a multiplier of 1.5 and 3 respectively are available on the two columns at the right of the table.

		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Outliers	Extreme outliers
ƒR	Median	30,1	31,3	35,4	37,5	37,5	39,2	40,8	43,9	52,3	57,1	10%-S5 | 20%-S7 | 30%-S5 | 30%-S7 | 40%-S5 | 40%-S7 | 50%-S5 | 50%-S7 | 60%-S7 | 70%-S7 | 80%-S7 | 90%-S7 | 100%-S7	20%-S5
	Median absolute deviation	7,32	5,41	6,74	7,44	8,74	8,97	9,96	10,2	11	10,6		
	Shapiro-Wilk's test (p-value)	0,075	0,016	0,056	0,081	0,1	0,061	0,092	0,069	0,126	0,522		
Ttot	Median	2,04	1,97	1,73	1,61	1,61	1,54	1,48	1,37	1,15	1,05	20%-S5	Ø
	Median absolute deviation	0,58	0,32	0,36	0,38	0,37	0,35	0,37	0,31	0,28	0,21		
	Shapiro-Wilk's test (p-value)	0,567	0,479	0,714	0,853	0,775	0,777	0,803	0,868	0,618	0,914		
VO2	Median	27,8	32,8	37	39,6	42,3	44,8	47,3	49,2	51,7	51,6	30%-S2 | 40%-S7 | 50%-S7 | 60%-S7 | 70%-S7 | 80%-S2 | 90%-S2 | 100%-S2	40%-S2 | 50%-S2 | 60%-S22 | 70%-S2
	Median absolute deviation	2,02	3,86	2,99	2,12	1,78	1,71	2,03	3,58	3,32	4,97		
	Shapiro-Wilk's test (p-value)	0,908	0,424	0,47	0,042	0,016	0,011	0,063	0,246	0,525	0,854		
VCO2	Median	1430	1914	2175	2418	2542	2758	2964	3256	3463	3677	10%-S2 | 30%-S2 | 40%-S2 |50%-S2 | 60%-S2 | 70%-S2 | 80%-S2 | 90%-S2	30%-S2
	Median absolute deviation	253	326	260	373	457	488	634	905	1031	1289		
	Shapiro-Wilk's test (p-value)	0,095	0,035	0,044	0,037	0,129	0,173	0,167	0,236	0,238	0,254		
VT	Median	1,24	1,49	1,57	1,6	1,63	1,7	1,77	1,82	1,85	1,9	10%-Z2 | 20%-S2	Ø
	Median absolute deviation	0,33	0,51	0,63	0,72	0,76	0,84	0,79	0,81	0,75	0,67		
	Shapiro-Wilk's test (p-value)	0,084	0,413	0,519	0,636	0,329	0,467	0,503	0,614	0,628	0,866		
RPE	Median	1,5	1,57	2,15	2,94	3,81	5,02	2,91	7,66	9,31	9,99	100%-S1	100%-S2
	Median absolute deviation	0,74	0,85	1,22	1,47	1,69	1,6	0,84	0,86	0,84	0,01		
	Shapiro-Wilk's test (p-value)	0,005	0,013	0,479	0,442	0,214	0,185	0,09	0,36	0,537	<0,001		

With the application of the Geisser-Greenhouse correction, the analysis of breathing frequency revealed a statistically significant difference across various time points, F(2.02, 18.22) = 45.3, p < 0.0001, generalized eta squared (eta2[g]) = 0.31 (see figure 7).

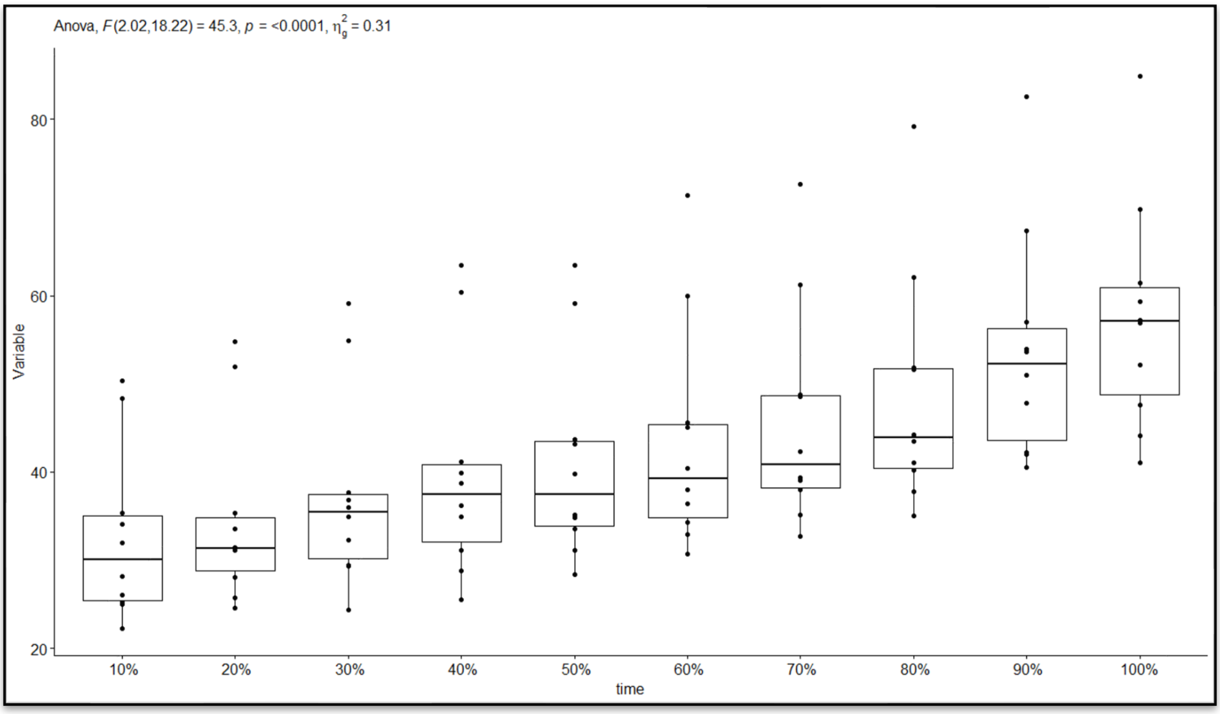


Figure 7: Boxplot grouping the devils of the breathing frequency during the INC.

Post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time revealed mixed results for the f_R during the INC (see table 4). P-values are adjusted using the Bonferroni multiple testing correction method.

Table 4: Results of the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC for the f_R. From the left to the right, the column represent: 1) the difference between the time point #1 and # 2; 2) the variable of interest; 3) the decile used as the time point #1 for comparison; 4) the decile used as the time point #2 for comparison; 5) the T-value; 6) the p-value of the t-test; 7-8) lower and upper bound of the confidence interval; 9) the adjusted p-value using the Bonferroni multiple testing correction method; 10) the significance level of the adjusted p-value.

Difference in means	Variable	Time point #1	Time point #2	T-value	P-value	Lower bound of the 95% confidence interval	Higher bound of the 95% confidence interval	Adjusted P-value	Adjusted P-value Significance
-2,09	*f*R	10%	20%	-2,21	0,054	-4,23	0,05	1	ns
-4,80	*f*R	10%	30%	-2,90	0,018	-8,56	-1,05	0,796	ns
-7,34	*f*R	10%	40%	-3,26	0,01	-12,44	-2,24	0,446	ns
-8,54	*f*R	10%	50%	-3,89	0,004	-13,51	-3,57	0,166	ns
-10,80	*f*R	10%	60%	-4,54	0,001	-16,18	-5,41	0,064	ns
-13,10	*f*R	10%	70%	-5,78	0,000265	-18,23	-7,98	0,012	*
-15,98	*f*R	10%	80%	-6,46	0,000117	-21,58	-10,38	0,005	**
-21,14	*f*R	10%	90%	-7,50	3,71E-05	-27,51	-14,76	0,002	**
-24,80	*f*R	10%	100%	-8,12	1,97E-05	-31,70	-17,89	0,000886	***
-2,71	*f*R	20%	30%	-2,46	0,036	-5,20	-0,22	1	ns
-5,25	*f*R	20%	40%	-3,13	0,012	-9,04	-1,45	0,549	ns
-6,45	*f*R	20%	50%	-3,64	0,005	-10,45	-2,45	0,242	ns
-8,71	*f*R	20%	60%	-4,37	0,002	-13,21	-4,20	0,081	ns
-11,01	*f*R	20%	70%	-5,43	0,000415	-15,59	-6,42	0,019	*
-13,89	*f*R	20%	80%	-6,30	0,000142	-18,88	-8,90	0,006	**
-19,04	*f*R	20%	90%	-7,67	3,10E-05	-24,66	-13,43	0,001	**
-22,70	*f*R	20%	100%	-8,40	1,50E-05	-28,82	-16,59	0,000675	***
-2,54	*f*R	30%	40%	-2,83	0,02	-4,56	-0,51	0,891	ns
-3,74	*f*R	30%	50%	-3,25	0,01	-6,33	-1,14	0,447	ns
-5,99	*f*R	30%	60%	-3,91	0,004	-9,46	-2,53	0,16	ns
-8,30	*f*R	30%	70%	-4,90	0,000846	-12,13	-4,47	0,038	*
-11,18	*f*R	30%	80%	-5,81	0,000255	-15,52	-6,83	0,011	*
-16,33	*f*R	30%	90%	-8,76	1,07E-05	-20,55	-12,11	0,000481	***
-19,99	*f*R	30%	100%	-9,56	5,22E-06	-24,72	-15,26	0,000235	***
-1,20	*f*R	40%	50%	-1,80	0,106	-2,71	0,31	1	ns
-3,46	*f*R	40%	60%	-3,92	0,004	-5,45	-1,46	0,158	ns
-5,76	*f*R	40%	70%	-4,81	0,000959	-8,47	-3,05	0,043	*
-8,64	*f*R	40%	80%	-6,29	0,000142	-11,75	-5,54	0,006	**
-13,80	*f*R	40%	90%	-10,39	2,61E-06	-16,80	-10,79	0,000117	***
-17,46	*f*R	40%	100%	-10,41	2,55E-06	-21,25	-13,67	0,000115	***
-2,26	*f*R	50%	60%	-3,29	0,009	-3,81	-0,71	0,422	ns
-4,56	*f*R	50%	70%	-5,65	0,000313	-6,38	-2,73	0,014	*
-7,44	*f*R	50%	80%	-6,30	0,000142	-10,11	-4,77	0,006	**
-12,59	*f*R	50%	90%	-10,38	2,62E-06	-15,34	-9,85	0,000118	***
-16,26	*f*R	50%	100%	-10,47	2,43E-06	-19,77	-12,74	0,000109	***
-2,30	*f*R	60%	70%	-4,04	0,003	-3,59	-1,01	0,131	ns
-5,18	*f*R	60%	80%	-8,55	1,29E-05	-6,55	-3,81	0,00058	***
-10,34	*f*R	60%	90%	-11,14	1,44E-06	-12,44	-8,24	6,48E-05	****
-14,00	*f*R	60%	100%	-10,33	2,74E-06	-17,07	-10,93	0,000123	***
-2,88	*f*R	70%	80%	-4,50	0,001	-4,33	-1,43	0,067	ns
-8,03	*f*R	70%	90%	-6,36	0,000132	-10,89	-5,18	0,006	**
-11,70	*f*R	70%	100%	-6,92	6,90E-05	-15,52	-7,87	0,003	**
-5,15	*f*R	80%	90%	-4,39	0,002	-7,81	-2,50	0,079	ns
-8,82	*f*R	80%	100%	-5,70	0,000295	-12,32	-5,32	0,013	*
-3,66	*f*R	90%	100%	-6,19	0,000161	-5,00	-2,32	0,007	**

With the application of the Geisser-Greenhouse correction, the analysis of total breath duration revealed a statistically significant difference across various time points, F(2.03, 18.24) = 27.27, $p < 0.0001$, generalized eta squared (eta2[g]) = 0.38 (see figure 8).

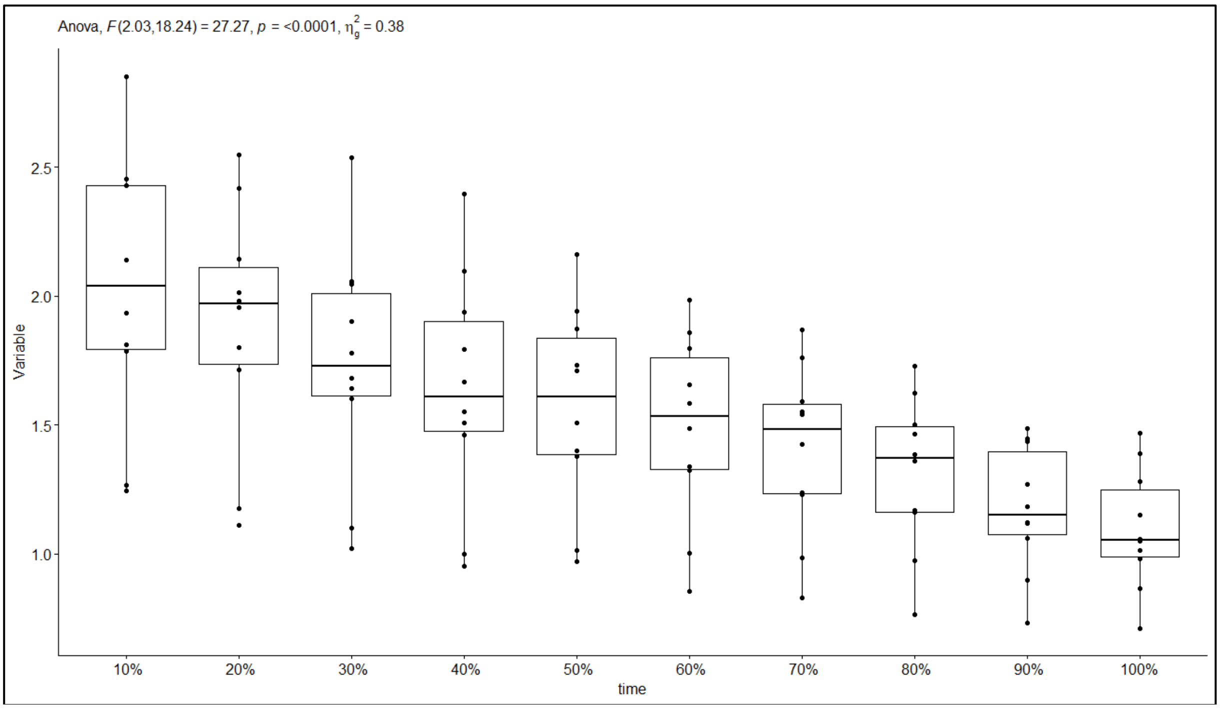


Figure 8: Boxplot grouping the devils of the Ttot during the INC.

Post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time revealed mixed results for the Ttot during the INC (see table 5). P-values are adjusted using the Bonferroni multiple testing correction method.

Table 5: Results of the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC for the Ttot. From the left to the right, the column represent: 1) the difference between the time point #1 and # 2; 2) the variable of interest; 3) the decile used as the time point #1 for comparison; 4) the decile used as the time point #2 for comparison; 5) the T-value; 6) the p-value of the t-test; 7-8) lower and upper bound of the confidence interval; 9) the adjusted p-value using the Bonferroni multiple testing correction method; 10) the significance level of the adjusted p-value.

Difference in means	Variable	Time point #1	Time point #2	T-value	P-value	Lower bound of the 95% confidence interval	Higher bound of the 95% confidence interval	Adjusted P-value	Adjusted P-value Significance
0,15	Ttot	10%	20%	2,49	0,034	0,01	0,28	1	ns
0,30	Ttot	10%	30%	2,60	0,029	0,04	0,56	1	ns
0,40	Ttot	10%	40%	2,91	0,017	0,09	0,71	0,774	ns
0,47	Ttot	10%	50%	3,51	0,007	0,17	0,77	0,299	ns
0,55	Ttot	10%	60%	4,37	0,002	0,26	0,83	0,081	ns
0,63	Ttot	10%	70%	5,26	0,000523	0,36	0,91	0,024	*
0,72	Ttot	10%	80%	6,24	0,000151	0,46	0,98	0,007	**
0,86	Ttot	10%	90%	6,16	0,000166	0,54	1,18	0,007	**
0,94	Ttot	10%	100%	6,37	0,000129	0,61	1,27	0,006	**
0,15	Ttot	20%	30%	1,96	0,082	-0,02	0,32	1	ns
0,25	Ttot	20%	40%	2,56	0,031	0,03	0,47	1	ns
0,32	Ttot	20%	50%	3,19	0,011	0,09	0,54	0,495	ns
0,40	Ttot	20%	60%	4,28	0,002	0,19	0,61	0,092	ns
0,48	Ttot	20%	70%	5,06	0,000679	0,27	0,70	0,031	*
0,57	Ttot	20%	80%	6,40	0,000126	0,37	0,78	0,006	**
0,71	Ttot	20%	90%	6,34	0,000134	0,46	0,97	0,006	**
0,79	Ttot	20%	100%	6,58	0,000102	0,52	1,06	0,005	**
0,10	Ttot	30%	40%	3,16	0,012	0,03	0,17	0,522	ns
0,17	Ttot	30%	50%	3,19	0,011	0,05	0,29	0,495	ns
0,25	Ttot	30%	60%	4,58	0,001	0,13	0,37	0,06	ns
0,33	Ttot	30%	70%	4,88	0,000873	0,18	0,49	0,039	*
0,42	Ttot	30%	80%	6,32	0,000138	0,27	0,58	0,006	**
0,56	Ttot	30%	90%	6,72	8,68E-05	0,37	0,75	0,004	**
0,64	Ttot	30%	100%	6,77	8,13E-05	0,43	0,85	0,004	**
0,07	Ttot	40%	50%	1,88	0,092	-0,01	0,15	1	ns
0,15	Ttot	40%	60%	3,55	0,006	0,05	0,24	0,279	ns
0,24	Ttot	40%	70%	3,77	0,004	0,09	0,38	0,199	ns
0,32	Ttot	40%	80%	5,04	0,000696	0,18	0,47	0,031	*
0,46	Ttot	40%	90%	5,99	0,000205	0,29	0,64	0,009	**
0,54	Ttot	40%	100%	6,14	0,00017	0,34	0,74	0,008	**
0,08	Ttot	50%	60%	4,83	0,000928	0,04	0,12	0,042	*
0,17	Ttot	50%	70%	5,10	0,000641	0,09	0,24	0,029	*
0,26	Ttot	50%	80%	6,30	0,000141	0,16	0,35	0,006	**
0,39	Ttot	50%	90%	7,09	5,72E-05	0,27	0,52	0,003	**
0,47	Ttot	50%	100%	7,06	5,92E-05	0,32	0,62	0,003	**
0,09	Ttot	60%	70%	3,06	0,014	0,02	0,15	0,608	ns
0,18	Ttot	60%	80%	5,98	0,000207	0,11	0,24	0,009	**
0,31	Ttot	60%	90%	6,90	7,10E-05	0,21	0,42	0,003	**
0,39	Ttot	60%	100%	6,91	7,00E-05	0,26	0,52	0,003	**
0,09	Ttot	70%	80%	4,39	0,002	0,04	0,14	0,078	ns
0,23	Ttot	70%	90%	4,94	0,000805	0,12	0,33	0,036	*
0,31	Ttot	70%	100%	5,23	0,000544	0,17	0,44	0,024	*
0,14	Ttot	80%	90%	3,89	0,004	0,06	0,22	0,165	ns
0,22	Ttot	80%	100%	4,63	0,001	0,11	0,32	0,056	ns
0,08	Ttot	90%	100%	5,15	0,000606	0,04	0,11	0,027	*

With the application of the Geisser-Greenhouse correction, the analysis of the oxygen consumption revealed a statistically significant difference across various time points, F(1.73, 15.57) = 161.75, $p < 0.0001$, generalized eta squared (eta2[g]) = 0.77 (see figure 9).

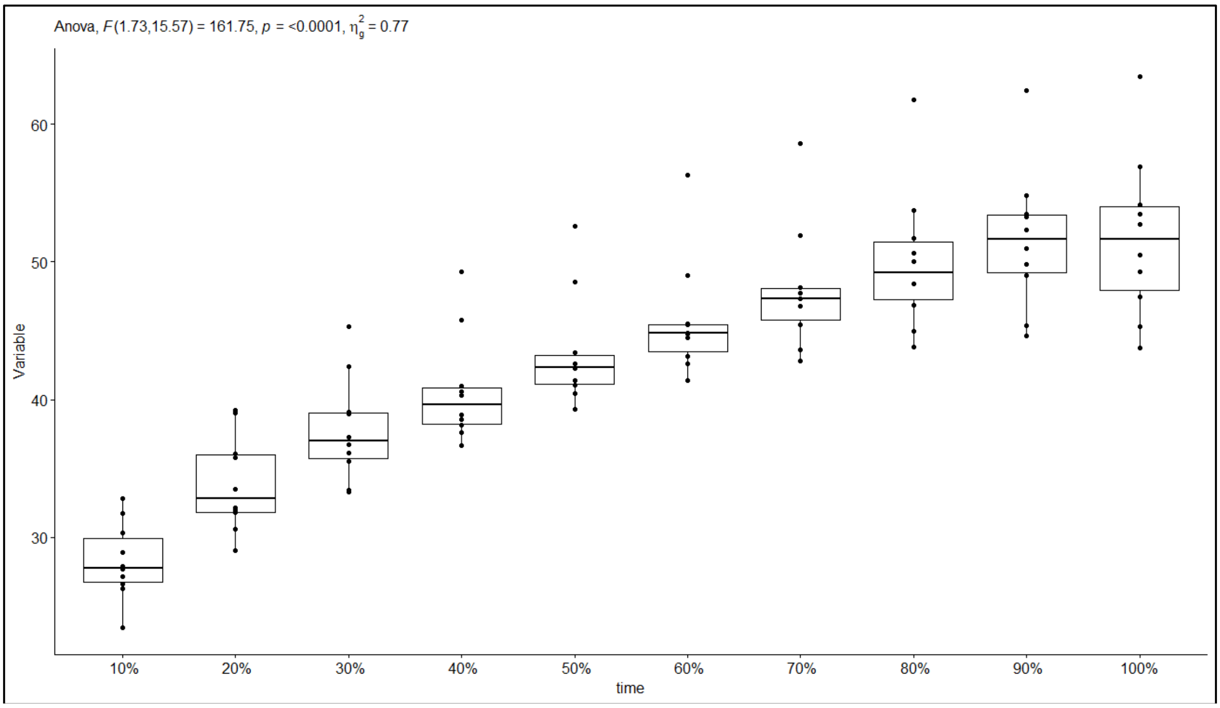


Figure 9: Boxplot grouping the devils of the VO₂ during the INC.

Post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time revealed mixed results for the VO_2 during the INC while the majority of pairwise comparison is significantly different (see table 6). Only few pairwise comparisons are not significantly different and concern the comparisons of the last parts of the INC. P-values are adjusted using the Bonferroni multiple testing correction method.

Table 6: Results of the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC for the $\dot{V}O_2$. From the left to the right, the column represent: 1) the difference between the time point #1 and # 2; 2) the variable of interest; 3) the decile used as the time point #1 for comparison; 4) the decile used as the time point #2 for comparison; 5) the T-value; 6) the p-value of the t-test; 7-8) lower and upper bound of the confidence interval; 9) the adjusted p-value using the Bonferroni multiple testing correction method; 10) the significance level of the adjusted p-value.

Difference in means	Variable	Time point #1	Time point #2	T-value	P-value	Lower bound of the 95% confidence interval	Higher bound of the 95% confidence interval	Adjusted P-value	Adjusted P-value Significance
-5,63	VO2	10%	20%	-9,03	8,31E-06	-7,04	-4,22	0,000374	***
-9,54	VO2	10%	30%	-12,07	7,32E-07	-11,33	-7,75	3,29E-05	****
-12,41	VO2	10%	40%	-13,64	2,56E-07	-14,47	-10,35	1,15E-05	****
-15,13	VO2	10%	50%	-15,92	6,72E-08	-17,28	-12,98	3,02E-06	****
-17,48	VO2	10%	60%	-16,03	6,33E-08	-19,95	-15,01	2,85E-06	****
-19,71	VO2	10%	70%	-17,75	2,60E-08	-22,22	-17,20	1,17E-06	****
-21,77	VO2	10%	80%	-16,40	5,18E-08	-24,77	-18,77	2,33E-06	****
-23,35	VO2	10%	90%	-17,58	2,82E-08	-26,35	-20,35	1,27E-06	****
-23,45	VO2	10%	100%	-14,09	1,94E-07	-27,21	-19,68	8,73E-06	****
-3,91	VO2	20%	30%	-11,18	1,40E-06	-4,70	-3,12	6,30E-05	****
-6,78	VO2	20%	40%	-12,23	6,55E-07	-8,03	-5,52	2,95E-05	****
-9,49	VO2	20%	50%	-13,86	2,23E-07	-11,04	-7,94	1,00E-05	****
-11,85	VO2	20%	60%	-14,35	1,66E-07	-13,71	-9,98	7,47E-06	****
-14,07	VO2	20%	70%	-16,12	6,02E-08	-16,05	-12,10	2,71E-06	****
-16,14	VO2	20%	80%	-14,35	1,66E-07	-18,68	-13,59	7,47E-06	****
-17,72	VO2	20%	90%	-14,80	1,27E-07	-20,42	-15,01	5,72E-06	****
-17,81	VO2	20%	100%	-11,33	1,25E-06	-21,37	-14,26	5,62E-05	****
-2,87	VO2	30%	40%	-9,18	7,28E-06	-3,58	-2,16	0,000328	***
-5,59	VO2	30%	50%	-12,71	4,72E-07	-6,58	-4,59	2,12E-05	****
-7,94	VO2	30%	60%	-12,89	4,19E-07	-9,33	-6,55	1,89E-05	****
-10,17	VO2	30%	70%	-14,28	1,73E-07	-11,78	-8,56	7,79E-06	****
-12,23	VO2	30%	80%	-12,35	6,02E-07	-14,47	-9,99	2,71E-05	****
-13,81	VO2	30%	90%	-12,65	4,90E-07	-16,28	-11,34	2,20E-05	****
-13,91	VO2	30%	100%	-9,41	5,92E-06	-17,25	-10,56	0,000266	***
-2,72	VO2	40%	50%	-14,39	1,62E-07	-3,14	-2,29	7,29E-06	****
-5,07	VO2	40%	60%	-13,27	3,26E-07	-5,93	-4,20	1,47E-05	****
-7,30	VO2	40%	70%	-15,26	9,72E-08	-8,38	-6,21	4,37E-06	****
-9,36	VO2	40%	80%	-11,93	8,10E-07	-11,13	-7,58	3,64E-05	****
-10,94	VO2	40%	90%	-12,20	6,70E-07	-12,97	-8,91	3,02E-05	****
-11,04	VO2	40%	100%	-8,51	1,35E-05	-13,97	-8,10	0,000608	***
-2,35	VO2	50%	60%	-6,99	6,39E-05	-3,11	-1,59	0,003	**
-4,58	VO2	50%	70%	-10,12	3,25E-06	-5,60	-3,56	0,000146	***
-6,64	VO2	50%	80%	-9,17	7,34E-06	-8,28	-5,00	0,00033	***
-8,22	VO2	50%	90%	-9,66	4,79E-06	-10,15	-6,30	0,000216	***
-8,32	VO2	50%	100%	-6,77	8,15E-05	-11,10	-5,54	0,004	**
-2,23	VO2	60%	70%	-10,37	2,65E-06	-2,71	-1,74	0,000119	***
-4,29	VO2	60%	80%	-8,75	1,07E-05	-5,40	-3,18	0,000481	***
-5,87	VO2	60%	90%	-9,47	5,60E-06	-7,27	-4,47	0,000252	***
-5,97	VO2	60%	100%	-5,82	0,000252	-8,29	-3,65	0,011	*
-2,06	VO2	70%	80%	-5,19	0,000573	-2,96	-1,16	0,026	*
-3,64	VO2	70%	90%	-7,38	4,18E-05	-4,76	-2,53	0,002	**
-3,74	VO2	70%	100%	-3,93	0,003	-5,89	-1,59	0,155	ns
-1,58	VO2	80%	90%	-6,07	0,000185	-2,17	-0,99	0,008	**
-1,68	VO2	80%	100%	-2,66	0,026	-3,10	-0,25	1	ns
-0,10	VO2	90%	100%	-0,18	0,862	-1,34	1,14	1	ns

With the application of the Geisser-Greenhouse correction, the analysis of $\dot{V}CO_2$ revealed a statistically significant difference across various time points, F(1.17, 10.51) = 61.17, $p < 0.0001$, generalized eta squared (eta2[g]) = 0.44 (see figure 10).

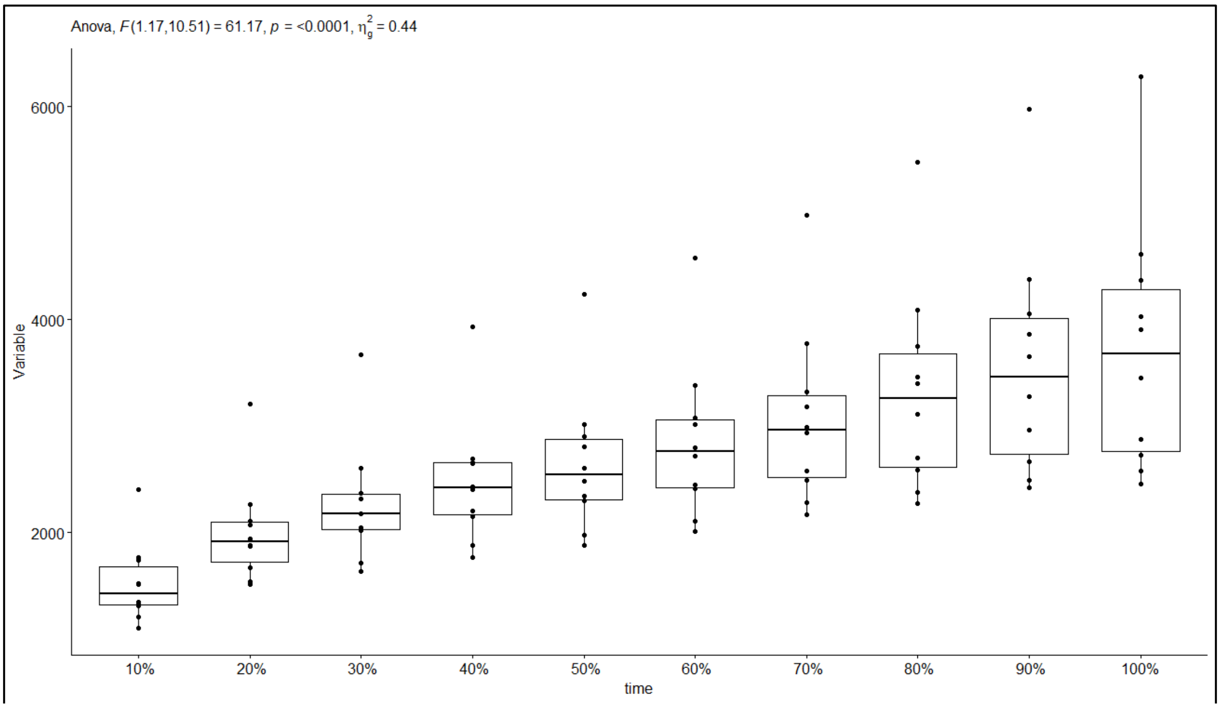


Figure 10: Boxplot grouping the devils of the V̇CO$_2$ during the INC.

Post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time revealed that all except one (90% vs 100%) comparisons are significantly different for the V̇CO$_2$ during the INC (see table 7). P-values are adjusted using the Bonferroni multiple testing correction method.

Table 7: Results of the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC for the VCO_2. From the left to the right, the column represent: 1) the difference between the time point #1 and # 2; 2) the variable of interest; 3) the decile used as the time point #1 for comparison; 4) the decile used as the time point #2 for comparison; 5) the T-value; 6) the p-value of the t-test; 7-8) lower and upper bound of the confidence interval; 9) the adjusted p-value using the Bonferroni multiple testing correction method; 10) the significance level of the adjusted p-value.

Difference in means	Variable	Time point #1	Time point #2	T-value	P-value	Lower bound of the 95% confidence interval	Higher bound of the 95% confidence interval	Adjusted P-value	Adjusted P-value Significance
-482,63	VCO2	10%	20%	-8,96	8,86E-06	-604,50	-360,77	0,000399	***
-749,70	VCO2	10%	30%	-9,42	5,87E-06	-929,73	-569,68	0,000264	***
-952,58	VCO2	10%	40%	-10,73	1,98E-06	-1153,36	-751,80	8,91E-05	****
-1129,50	VCO2	10%	50%	-10,80	1,87E-06	-1365,99	-893,01	8,42E-05	****
-1329,99	VCO2	10%	60%	-10,45	2,48E-06	-1617,92	-1042,07	0,000112	***
-1546,27	VCO2	10%	70%	-9,98	3,64E-06	-1896,73	-1195,81	0,000164	***
-1797,94	VCO2	10%	80%	-9,30	6,50E-06	-2235,12	-1360,76	0,000292	***
-2049,49	VCO2	10%	90%	-8,95	8,97E-06	-2567,76	-1531,22	0,000404	***
-2203,17	VCO2	10%	100%	-8,43	1,46E-05	-2794,52	-1611,82	0,000657	***
-267,07	VCO2	20%	30%	-7,90	2,45E-05	-343,55	-190,58	0,001	**
-469,94	VCO2	20%	40%	-9,87	3,99E-06	-577,66	-362,22	0,00018	***
-646,87	VCO2	20%	50%	-9,61	4,98E-06	-799,14	-494,59	0,000224	***
-847,36	VCO2	20%	60%	-9,16	7,42E-06	-1056,72	-638,00	0,000334	***
-1063,64	VCO2	20%	70%	-8,77	1,05E-05	-1337,91	-789,37	0,000472	***
-1315,31	VCO2	20%	80%	-8,12	1,96E-05	-1681,70	-948,91	0,000882	***
-1566,86	VCO2	20%	90%	-7,97	2,29E-05	-2011,79	-1121,92	0,001	**
-1720,54	VCO2	20%	100%	-7,42	4,00E-05	-2244,83	-1196,24	0,002	**
-202,88	VCO2	30%	40%	-6,78	8,04E-05	-270,52	-135,23	0,004	**
-379,80	VCO2	30%	50%	-7,97	2,28E-05	-487,59	-272,01	0,001	**
-580,29	VCO2	30%	60%	-7,72	2,95E-05	-750,40	-410,18	0,001	**
-796,57	VCO2	30%	70%	-7,50	3,70E-05	-1036,92	-556,21	0,002	**
-1048,24	VCO2	30%	80%	-7,30	4,55E-05	-1372,95	-723,53	0,002	**
-1299,79	VCO2	30%	90%	-7,31	4,52E-05	-1702,04	-897,53	0,002	**
-1453,47	VCO2	30%	100%	-6,86	7,39E-05	-1932,77	-974,17	0,003	**
-176,92	VCO2	40%	50%	-6,61	9,85E-05	-237,50	-116,34	0,004	**
-377,41	VCO2	40%	60%	-7,20	5,07E-05	-495,96	-258,87	0,002	**
-593,69	VCO2	40%	70%	-6,95	6,70E-05	-786,98	-400,40	0,003	**
-845,36	VCO2	40%	80%	-6,74	8,44E-05	-1129,02	-561,70	0,004	**
-1096,91	VCO2	40%	90%	-6,83	7,66E-05	-1460,32	-733,50	0,003	**
-1250,59	VCO2	40%	100%	-6,39	0,000127	-1693,22	-807,96	0,006	**
-200,49	VCO2	50%	60%	-6,87	7,34E-05	-266,55	-134,43	0,003	**
-416,77	VCO2	50%	70%	-6,58	0,000102	-560,12	-273,42	0,005	**
-668,44	VCO2	50%	80%	-6,56	0,000104	-898,86	-438,03	0,005	**
-919,99	VCO2	50%	90%	-6,69	8,97E-05	-1231,13	-608,85	0,004	**
-1073,67	VCO2	50%	100%	-6,20	0,000158	-1465,24	-682,10	0,007	**
-216,28	VCO2	60%	70%	-6,09	0,000182	-296,63	-135,93	0,008	**
-467,95	VCO2	60%	80%	-6,13	0,000173	-640,60	-295,30	0,008	**
-719,50	VCO2	60%	90%	-6,37	0,00013	-975,00	-463,99	0,006	**
-873,18	VCO2	60%	100%	-5,86	0,000242	-1210,44	-535,92	0,011	*
-251,67	VCO2	70%	80%	-4,84	0,000926	-369,39	-133,95	0,042	*
-503,22	VCO2	70%	90%	-5,70	0,000296	-703,09	-303,35	0,013	*
-656,90	VCO2	70%	100%	-5,26	0,000524	-939,64	-374,16	0,024	*
-251,55	VCO2	80%	90%	-5,99	0,000204	-346,49	-156,61	0,009	**
-405,23	VCO2	80%	100%	-5,48	0,00039	-572,49	-237,97	0,018	*
-153,68	VCO2	90%	100%	-3,21	0,011	-261,88	-45,48	0,477	ns

With the application of the Geisser-Greenhouse correction, the analysis of tidal volume revealed a statistically significant difference across various time points, F(2.23 20.11) = 16.43, $p < 0.0001$, generalized eta squared (eta2[g]) = 0.1 (see figure 11).

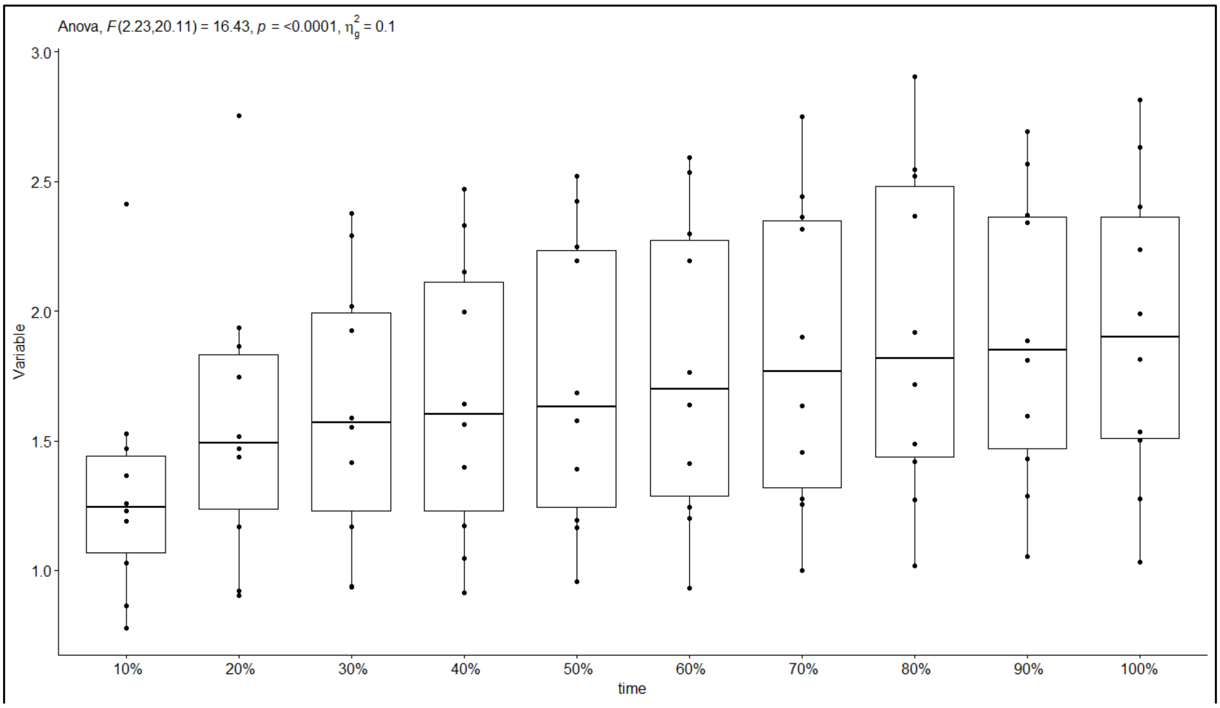


Figure 11: Boxplot grouping the devils of the V_T during the INC.

Post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time revealed mixed results for the V_T during the INC while the majority of pairs' differences are not significant (see table 8). P-values are adjusted using the Bonferroni multiple testing correction method.

Table 8: Results of the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC for the V_T. From the left to the right, the column represent: 1) the difference between the time point #1 and # 2; 2) the variable of interest; 3) the decile used as the time point #1 for comparison; 4) the decile used as the time point #2 for comparison; 5) the T-value; 6) the p-value of the t-test; 7-8) lower and upper bound of the confidence interval; 9) the adjusted p-value using the Bonferroni multiple testing correction method; 10) the significance level of the adjusted p-value.

Difference in means	Variable	Time point #1	Time point #2	T-value	P-value	Lower bound of the 95% confidence interval	Higher bound of the 95% confidence interval	Adjusted P-value	Adjusted P-value Significance
-0,26	VT	10%	20%	-5,59	0,000338	-0,36	-0,15	0,015	*
-0,31	VT	10%	30%	-3,58	0,006	-0,50	-0,11	0,269	ns
-0,36	VT	10%	40%	-3,33	0,009	-0,60	-0,11	0,393	ns
-0,42	VT	10%	50%	-3,77	0,004	-0,68	-0,17	0,198	ns
-0,47	VT	10%	60%	-4,37	0,002	-0,71	-0,23	0,081	ns
-0,53	VT	10%	70%	-5,43	0,000417	-0,75	-0,31	0,019	*
-0,60	VT	10%	80%	-5,72	0,000286	-0,84	-0,37	0,013	*
-0,59	VT	10%	90%	-5,94	0,000218	-0,82	-0,37	0,01	**
-0,61	VT	10%	100%	-5,85	0,000245	-0,85	-0,37	0,011	*
-0,05	VT	20%	30%	-0,82	0,434	-0,19	0,09	1	ns
-0,10	VT	20%	40%	-1,20	0,262	-0,28	0,09	1	ns
-0,16	VT	20%	50%	-1,86	0,095	-0,36	0,04	1	ns
-0,21	VT	20%	60%	-2,63	0,028	-0,39	-0,03	1	ns
-0,27	VT	20%	70%	-3,50	0,007	-0,44	-0,09	0,303	ns
-0,35	VT	20%	80%	-4,02	0,003	-0,54	-0,15	0,136	ns
-0,33	VT	20%	90%	-3,99	0,003	-0,52	-0,14	0,143	ns
-0,35	VT	20%	100%	-3,96	0,003	-0,55	-0,15	0,149	ns
-0,05	VT	30%	40%	-2,00	0,076	-0,10	0,01	1	ns
-0,11	VT	30%	50%	-3,01	0,015	-0,20	-0,03	0,661	ns
-0,16	VT	30%	60%	-4,34	0,002	-0,24	-0,08	0,084	ns
-0,22	VT	30%	70%	-3,95	0,003	-0,34	-0,09	0,151	ns
-0,30	VT	30%	80%	-4,18	0,002	-0,46	-0,14	0,107	ns
-0,28	VT	30%	90%	-4,99	0,000754	-0,41	-0,15	0,034	*
-0,30	VT	30%	100%	-4,37	0,002	-0,46	-0,15	0,081	ns
-0,07	VT	40%	50%	-2,48	0,035	-0,13	-0,01	1	ns
-0,11	VT	40%	60%	-3,91	0,004	-0,18	-0,05	0,161	ns
-0,17	VT	40%	70%	-2,94	0,017	-0,30	-0,04	0,747	ns
-0,25	VT	40%	80%	-3,47	0,007	-0,41	-0,09	0,317	ns
-0,23	VT	40%	90%	-4,04	0,003	-0,37	-0,10	0,131	ns
-0,26	VT	40%	100%	-3,56	0,006	-0,42	-0,09	0,273	ns
-0,05	VT	50%	60%	-2,31	0,046	-0,09	0,00	1	ns
-0,10	VT	50%	70%	-2,29	0,048	-0,21	0,00	1	ns
-0,18	VT	50%	80%	-3,27	0,01	-0,31	-0,06	0,436	ns
-0,17	VT	50%	90%	-3,95	0,003	-0,26	-0,07	0,15	ns
-0,19	VT	50%	100%	-3,52	0,006	-0,31	-0,07	0,292	ns
-0,06	VT	60%	70%	-1,60	0,145	-0,14	0,02	1	ns
-0,14	VT	60%	80%	-2,83	0,02	-0,24	-0,03	0,886	ns
-0,12	VT	60%	90%	-2,76	0,022	-0,22	-0,02	0,999	ns
-0,14	VT	60%	100%	-2,66	0,026	-0,26	-0,02	1	ns
-0,08	VT	70%	80%	-3,63	0,005	-0,13	-0,03	0,247	ns
-0,06	VT	70%	90%	-1,92	0,087	-0,14	0,01	1	ns
-0,08	VT	70%	100%	-1,98	0,078	-0,18	0,01	1	ns
0,01	VT	80%	90%	0,42	0,685	-0,06	0,09	1	ns
-0,01	VT	80%	100%	-0,18	0,863	-0,09	0,08	1	ns
-0,02	VT	90%	100%	-0,89	0,397	-0,07	0,03	1	ns

With the application of the Geisser-Greenhouse correction, the analysis of the rating of perceived exertion revealed a statistically significant difference across various time points, F(2.13, 19.14) = 383.94, p < 0.0001, generalized eta squared (eta2[g]) = 0.9 (see figure 12).

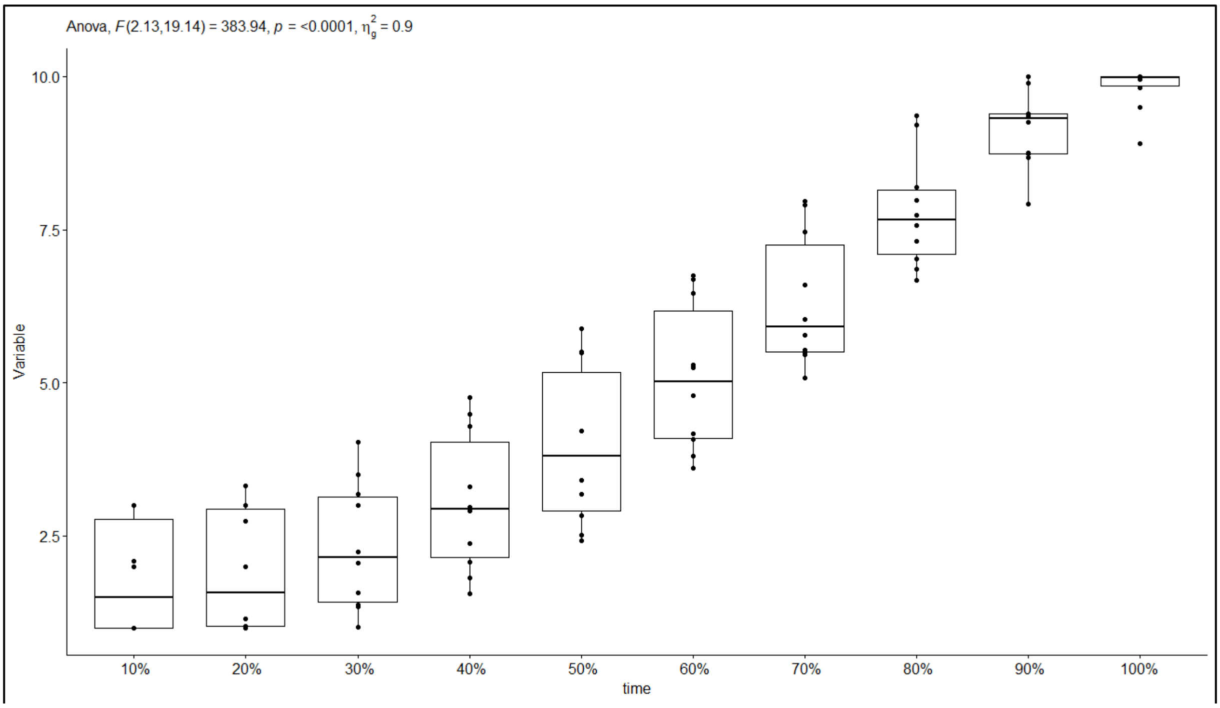


Figure 12: Boxplot grouping the devils of the RPE during the INC.

Post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time revealed that the majority of comparisons are significantly different for the RPE during the INC (see table 9). Only three comparisons close to the start of the INC are not significant. P-values are adjusted using the Bonferroni multiple testing correction method.

Table 9: Results of the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC for the RPE. From the left to the right, the column represent: 1) the difference between the time point #1 and # 2; 2) the variable of interest; 3) the decile used as the time point #1 for comparison; 4) the decile used as the time point #2 for comparison; 5) the T-value; 6) the p-value of the t-test; 7-8) lower and upper bound of the confidence interval; 9) the adjusted p-value using the Bonferroni multiple testing correction method; 10) the significance level of the adjusted p-value.

Difference in means	Variable	Time point #1	Time point #2	T-value	P-value	Lower bound of the 95% confidence interval	Higher bound of the 95% confidence interval	Adjusted P-value	Adjusted P-value Significance
-0,12	RPE	10%	20%	-1,70	0,124	-0,27	0,04	1	ns
-0,52	RPE	10%	30%	-3,41	0,008	-0,87	-0,18	0,346	ns
-1,25	RPE	10%	40%	-6,13	0,000172	-1,71	-0,79	0,008	**
-2,16	RPE	10%	50%	-9,21	7,09E-06	-2,69	-1,63	0,000319	***
-3,28	RPE	10%	60%	-15,20	1,01E-07	-3,77	-2,79	4,55E-06	****
-4,52	RPE	10%	70%	-23,54	2,15E-09	-4,96	-4,09	9,67E-08	****
-5,98	RPE	10%	80%	-26,60	7,25E-10	-6,49	-5,47	3,26E-08	****
-7,33	RPE	10%	90%	-35,08	6,15E-11	-7,80	-6,86	2,77E-09	****
-8,01	RPE	10%	100%	-31,50	1,61E-10	-8,58	-7,43	7,24E-09	****
-0,41	RPE	20%	30%	-4,08	0,003	-0,63	-0,18	0,124	ns
-1,13	RPE	20%	40%	-7,38	4,21E-05	-1,48	-0,78	0,002	**
-2,04	RPE	20%	50%	-11,15	1,43E-06	-2,46	-1,63	6,44E-05	****
-3,16	RPE	20%	60%	-18,18	2,10E-08	-3,56	-2,77	9,45E-07	****
-4,41	RPE	20%	70%	-31,69	1,53E-10	-4,72	-4,09	6,88E-09	****
-5,87	RPE	20%	80%	-30,83	1,95E-10	-6,30	-5,44	8,77E-09	****
-7,21	RPE	20%	90%	-34,15	7,82E-11	-7,69	-6,74	3,52E-09	****
-7,89	RPE	20%	100%	-28,38	4,08E-10	-8,52	-7,26	1,84E-08	****
-0,72	RPE	30%	40%	-9,49	5,54E-06	-0,90	-0,55	0,000249	***
-1,63	RPE	30%	50%	-11,04	1,57E-06	-1,97	-1,30	7,06E-05	****
-2,76	RPE	30%	60%	-18,32	1,96E-08	-3,10	-2,42	8,82E-07	****
-4,00	RPE	30%	70%	-31,28	1,71E-10	-4,29	-3,71	7,70E-09	****
-5,46	RPE	30%	80%	-27,84	4,83E-10	-5,90	-5,02	2,17E-08	****
-6,81	RPE	30%	90%	-27,20	5,95E-10	-7,37	-6,24	2,68E-08	****
-7,48	RPE	30%	100%	-23,60	2,10E-09	-8,20	-6,77	9,45E-08	****
-0,91	RPE	40%	50%	-8,78	1,04E-05	-1,14	-0,68	0,000468	***
-2,03	RPE	40%	60%	-18,04	2,25E-08	-2,29	-1,78	1,01E-06	****
-3,28	RPE	40%	70%	-23,15	2,49E-09	-3,60	-2,96	1,12E-07	****
-4,74	RPE	40%	80%	-20,38	7,70E-09	-5,26	-4,21	3,46E-07	****
-6,08	RPE	40%	90%	-21,01	5,87E-09	-6,74	-5,43	2,64E-07	****
-6,76	RPE	40%	100%	-19,05	1,40E-08	-7,56	-5,96	6,30E-07	****
-1,12	RPE	50%	60%	-21,68	4,45E-09	-1,24	-1,00	2,00E-07	****
-2,37	RPE	50%	70%	-14,55	1,47E-07	-2,73	-2,00	6,62E-06	****
-3,83	RPE	50%	80%	-14,49	1,52E-07	-4,42	-3,23	6,84E-06	****
-5,17	RPE	50%	90%	-16,72	4,37E-08	-5,87	-4,47	1,97E-06	****
-5,85	RPE	50%	100%	-15,17	1,02E-07	-6,72	-4,98	4,59E-06	****
-1,24	RPE	60%	70%	-7,62	3,26E-05	-1,61	-0,88	0,001	**
-2,70	RPE	60%	80%	-10,50	2,37E-06	-3,29	-2,12	0,000107	***
-4,05	RPE	60%	90%	-14,20	1,82E-07	-4,70	-3,41	8,19E-06	****
-4,73	RPE	60%	100%	-13,32	3,16E-07	-5,53	-3,92	1,42E-05	****
-1,46	RPE	70%	80%	-11,54	1,08E-06	-1,75	-1,17	4,86E-05	****
-2,81	RPE	70%	90%	-12,55	5,24E-07	-3,31	-2,30	2,36E-05	****
-3,48	RPE	70%	100%	-11,46	1,14E-06	-4,17	-2,80	5,13E-05	****
-1,35	RPE	80%	90%	-8,79	1,03E-05	-1,69	-1,00	0,000464	***
-2,02	RPE	80%	100%	-8,18	1,85E-05	-2,58	-1,46	0,000832	***
-0,68	RPE	90%	100%	-5,50	0,000379	-0,95	-0,40	0,017	*

IV. Discussion

The current study aimed to explore the intricate relationships between ventilatory variables and the rating of perceived exertion (RPE) during incremental running exercise until exhaustion. By examining the last 90 seconds of exercise across different time intervals and applying advanced statistical analyses, we aimed to shed light on the dynamics of ventilatory control and its interaction with perceived exertion at critical and decisive intensities for endurance performance (Leo et al., 2022).

1) Comparison of Time Intervals:

This investigation allowed us to identify nuanced changes in ventilatory variables and RPE as the exercise approached exhaustion. The observed variations in these intervals contribute to a comprehensive understanding of the dynamic interplay between physiological and perceptual responses during the final stages of incremental running. The main finding revealed that neither the f_R, the $\dot{V}O_2$, the RER, the Ttot, or the V_T changes significantly during this period of time at the end of the INC. Only the RPE shows a significant variation (increase) from the “90-60 secs” to the “last 30 secs” period compared to previous reports where other physiological variables were sensitive to increase in intensity close to exhaustion during an INC (Nicolò et al., 2019b).

2) Ventilatory Responses and Rating of Perceived Exertion:

Our report revealed significant variations in ventilatory variables and RPE during different time intervals of the incremental running exercise. The observed patterns in breathing frequency (f_R), total breath duration (Ttot), oxygen consumption ($\dot{V}O2$), carbon dioxide production ($\dot{V}CO2$), tidal volume (V_T), and RPE provide valuable insights into the physiological and perceptual aspects of exercise intensity.

We have observed a difference across the various time points for all the previously mentioned psychophysiological variables. A post-hoc analysis using a pairwise paired two-sided t-test between the levels of the within-subjects time helped to deepen the specificity of the responses for each variables. This detailed analysis revealed a less uniform time effect than a simple ANOVA could not highlight. The V_T revealed to have very few significant differences across the deciles of the INC revealing small differences at short term while an overall kinetic during the INC is displayed. In regard to the f_R (and Ttot), while the initial ANOVA indicates a significant overall difference in these ventilatory variables across various time points with a moderate to large effect size, the subsequent post-hoc analysis with Bonferroni correction reveals mixed results during the INC, emphasizing the importance of considering specific time point differences to avoid an over-interpretation. However, pertaining to the $\dot{V}CO_2$, the $\dot{V}O_2$, and the RPE, the post-hoc pairwise analysis confirmed the initial result of the ANOVA showing an effect of time on these variables during the INC as only one of the 45 pairwise difference is not significantly different for each variable; at the beginning for RPE and at the end of the INC for the $\dot{V}CO_2$ and $\dot{V}O_2$. As a consequence, these three variables appears to be the most relevant to discriminate the various variations in intensity encountered during the INC in running.

3) Mutual Information Analysis:

The mutual information (MI) analysis between RPE and ventilatory variables further emphasized the relationship between perceived exertion and ventilatory control. The MI values indicated meaningful information exchange between RPE and RER, Ttot, $\dot{V}O2$, and V_T. This supports the notion that perceptual cues, represented by RPE, are intricately linked to the underlying ventilatory responses during incremental running (Nicolò et al., 2015). The independent samples t-test reported in the figure 4 revealed some differences of MI for the different pair of variables but with no one being superior to all the others. However, based on our result, the couple $\dot{V}O2$-RPE is the one sharing the most information. This observation is rationale and coherent with the paired two-sided t-test between the levels of the within-subject deciles of the duration of the INC where $\dot{V}O2$ and RPE where among the variables having the most uniform response over the INC.

4) Limitations and Implications:

While our study provides valuable insights, several limitations should be acknowledged. The relatively small sample size and the homogeneity of the participant group may limit the generalizability of the findings. Additionally, the rigid nature of the exercise protocol should be considered when interpreting the results.

The implications of our study extend beyond the laboratory setting. Understanding the interdependence of ventilatory control and perceived exertion during incremental running has practical applications in exercise physiology, training prescription, and performance optimization. Trainers and athletes can benefit from this knowledge to tailor training programs and enhance endurance capacity.

V. Conclusion

In conclusion, this study delved into the dynamic interplay between ventilatory variables and the rating of perceived exertion (RPE) during incremental running. Examining critical intervals in the last 90 seconds, we observed significant increases in RPE, distinguishing it from other physiological variables. Ventilatory responses varied, with VCO2, VO2, and RPE emerging as crucial discriminators of intensity variations. Mutual information analysis highlighted a meaningful exchange between RPE and ventilatory variables, particularly emphasizing the informative relationship between VO2 and RPE. Despite limitations in sample size and protocol rigidity, this research contributes practical insights for exercise physiology, training prescription, and performance optimization.

Chapter 4 - Perceived Exertion in Individuals with Spinal Cord Injuries: A Comprehensive Analysis Across Incremental, Constant Workload, and Ultra-Endurance Events

I. Introduction

This chapter delves into the intricate realm of exercise psychophysiology, focusing on the application of the Rating of Perceived Exertion (RPE) during a maximal incremental test, a constant workload exercise and a competitive multi-discipline event (i.e., Ironman). Ironman triathlon is a long-distance sporting event that, in the past few years has become highly popular, with a rapid increase in the number of races and athletes' participation (Knechtle et al., 2019).

The primary objectives of this study encompass the observation of the kinetic response of the Rating of Perceived Exertion (RPE) during an incremental exercise protocol. Unlike previous investigations on this topic using constant workloads, our study aims to explore this dynamic in both incremental and constant workload settings.

Furthermore, the study seeks to demonstrate the application of the visual analogue scale individualized with cross-modality matching for line length perception (IVAS) in an experimental setting. To mitigate the impact of thermoregulation, short duration exercises will be employed, and environmental factors such as fans and air circulation were used to keep subjects well-refreshed.

This investigation aims to provide information on the differences in the RPE responses between SCI world-class athletes and previously studied able-bodied individuals. Additionally, in this chapter we will explore the reports obtained from participants in Ironman event examining the RPE, performance metrics, assessments of self-capabilities to complete the race, tympanic temperature, and blood lactate concentration. These diverse aims collectively contribute to a comprehensive understanding of the physiological aspects of exercise in SCI subjects and provide an exploratory study for the utilisation of the RPE in different contexts of exercise on the field.

II. Method

Subjects — Two male professional hand-cyclists (athlete 1: 30 yr, 57 kg, 1.74 m; athlete 2: 31 yr, 73 kg, 1.72 m) spinal-cord injured (SCI) (tetraplegia, S1; paraplegia, S2), paralympic &/or world championship podium medallists took part in the study.

Methodology — An observational case study design was used. Two days before the event, subjects performed a maximal incremental test (MIT) using a cycle ergometer (Cyclus2; RBM elektronik-automation GmbH, Leipzig, Germany) connected to their own race hand bikes. After one minute at 50 & 100 W respectively, power increased linearly by a rate of 5 W every 20 s until cadence dropped below 50 rpm or participants reached volitional exhaustion. The duration of the test was planned to last between 10 to 15 minutes to limit the threat of a heatstroke due to the characteristics of the task and the physiological impairments of the subjects. Pulmonary gas exchange was measured throughout the test (Cosmed K5; Cosmed Srl, Rome, Italy). During the test heart rate (HR) was measured using a band strapped around the chest (Garmin HRM-Dual; Garmin Ltd, Lenexa, KS, USA) and 10-μL samples of whole fresh blood were taken from the earlobe and analysed for lactate concentration [La$^-$] (Lactate Scout 4; EFK Diagnostics, SensLab GmbH, Leipzig, Germany) at the end of the MIT.

During the MIT, the rating of perceived exertion (RPE) was recorded every minute using two different methods. First, the French translation (Coquart et al., 2011) of the Borg's RPE-scale was used reproducing Borg's instructions (Borg, 1998, p. 47). On the other hand, a visual analogue scale individualized with cross-modality matching for line length perception (IVAS) printed on a white paper and with a length of 20-cm was used (see Chapter 2). The VAS was provided to the paracyclists with written anchors at both extremities of the scale (i.e., "No effort" and "Maximum effort"). For every measurement (or cross-modality matching) realized, a new sheet was used in order for the subject to not have any feedback on their previous measurements. Before the physical tasks, we ask the subjects to determine subjectively on the VAS 25, 50, and 75% of the objective total line length. The results were then used to adjust the RPE according to the individual line length perception. Subsequently, clear instructions were presented to the observer about the nature of the line in front of them: *"Rate how you perceive your actual exertion on this (visual analogue) scale anchored at the extremities by the verbal of the same significance "no effort" and "maximal effort". As a rule of thumb, when your perception of the effort doubles, the distance of your answer from zero has to double, and the centre of the scale represents an effort perceived as being equal to half of (what you perceive as) your maximal effort. We want you to rate your perception of effort, that is: your conscious sensation of how hard, heavy, and strenuous exercise is."*

In complement, a 6-min constant workload (CWL) exercise bout was performed at an intensity corresponding at 60% of the reported 20 min mean maximal power recorded during the running year. The same psychophysiological variables as during the MIT were recorded continuously, the RPE was measured every 2 min (i.e., at 2-, 4-, and 6-min) and the [La$^-$] at rest, 3rd and end of exercise. During these two exercises performed on the stationary bike, a fan was used, and a specific attention was taken in order to avoid an overheat of the athlete in regard to their impaired thermoregulatory capacities.

The event (IM) took place in September 2022 in Italy. An Ironman® triathlon competition, consisting of a single-loop 3.8 km swim in open waters, a transition phase (T1), a two-loop 180 km bike course, another transition (T2), and four laps of 10 km a final 200 m to the finish line. RPE was measured at the end of every part (i.e., during the transition and at the end) relating the average effort perceived of the previous part completed and at the end of the IM, relating the average effort across the overall race. For measuring the RPE during the IM, a magnitude estimation method anchored at the extreme with 0 & 10 representing respectively no effort perceived and the maximal perceived exertion was used. Decimals were allowed and subjects were instructed to use numerals as numbers with common criteria of equality and addition. 10µL samples of whole fresh blood were taken from the earlobe and analysed for lactate concentration (Lactate Scout 4; EFK Diagnostics, SensLab GmbH, Leipzig, Germany). Tympanic temperatures from the right ear were also measured (Braun Thermoscan 7 IRT6520; Braun GmbH, Germany). Self-capability was assessed asking the participants to rate their confidence to finish the race using a 7-point Likert scale (1 = Not confident at all; 7 = completely confident). A timeline of the study can be found in Figure 13.

Statistical Analysis— Due to the nature of an observational study with two subjects, no statistical analysis has been performed.

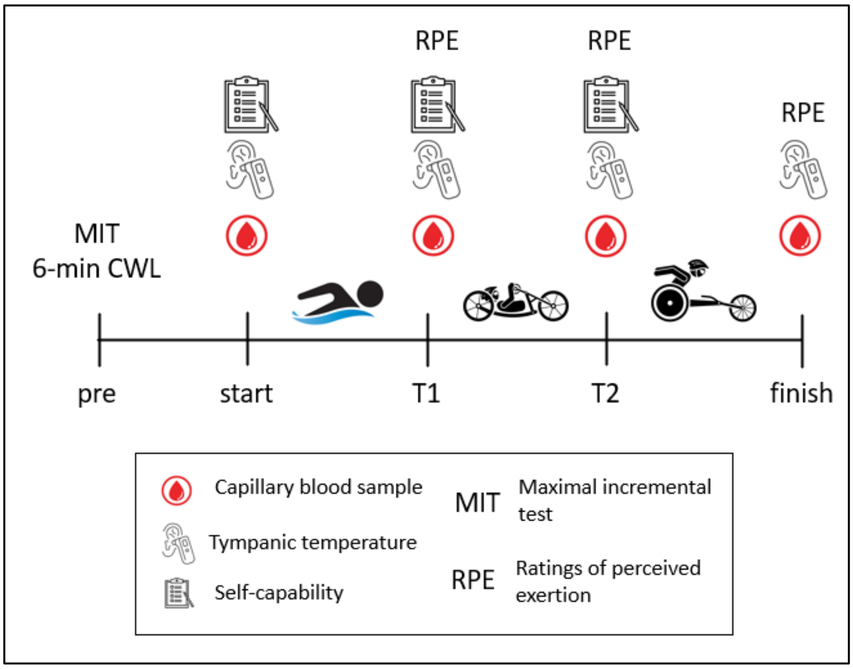


Figure 13: Timeline of the study

III. Results

We observed the kinetic of RPE during an MIT protocol (see Figure 14), which to our knowledge has never been performed before; the previous work on the topic using constant workloads (Kilbom et al., 1983). Additionally, this case study provides the psychophysiological response of world-class athletes with a SCI at different workload and until exhaustion, data very rare in the literature, that can serve as reference for different purposes.

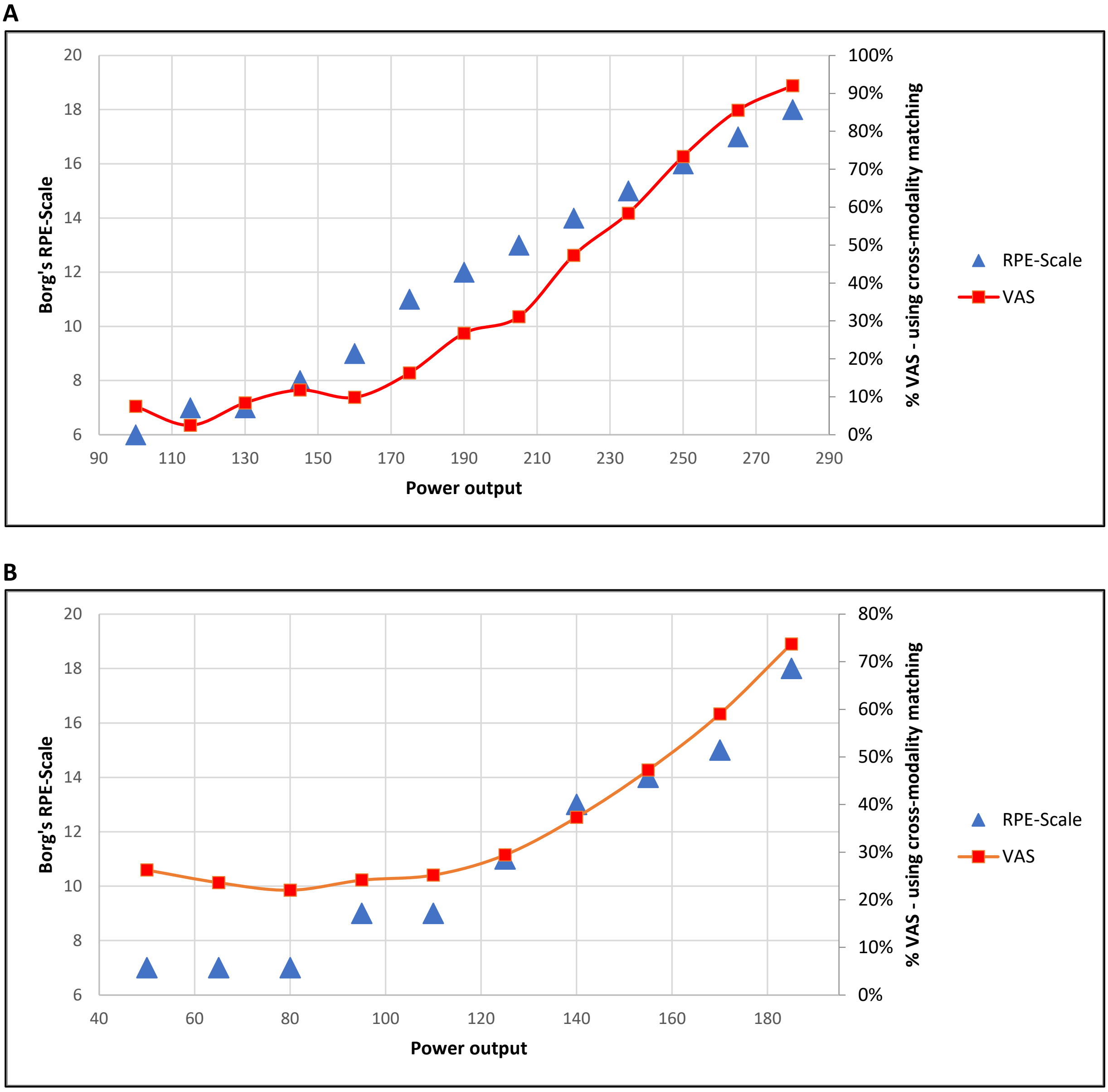


Figure 14: Kinetic of the RPE response during the MIT for the S1 (B) and S2 (A) using the IVAS and RPE-scale.

Subjects didn't reach a maximal perceived exertion during the MIT due to the inconfort for them to exercise with an ergometer.

During the MIT, the maximal [La$^-$] and heart rate (HR) recorded at exhaustion were 5.7 mmol.L^{-1} for S1 & 12.6 mmol.L^{-1} for S2 and 179 bpm for S1 and 197 bpm for S2 respectively.

Next, we observed the psychophysiological responses during a 6-min constant workload exercise on the ergometer. Results are presented in the Table 10 and Figure 15.

Table 10: Physiological responses to the exercise at constant workload performed at 60% of the athlete's best self-reported 20 min MMP. Data are epoched every 2 min and the average of the entire bout is presented in the last column. Table A contains the data of S1 and Table B, the data of S2. Variables of interest are: total breath duration (Ttot), Tidal volume (V_T), minute ventilation (V_E), oxygen consumption (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RQ), end-tidal O_2 ($PetO_2$), end-tidal CO_2 ($PetCO_2$), carbohydrate oxidation (CHO), Fat oxidation (FAT), inspiratory duration (Ti), expiratory duration (Te), gross efficiency (GE).

6 min CWL - S1				
	2 min	4 min	6 min	Avg
Ttot (sec)	1,17	0,99	0,93	1,03
VT (L)	1,18	1,09	1,06	1,11
VE (L/min)	61,5	68	68,4	66
VO2 (mL/min)	2452	2566	2295	2438
VCO2 (mL/min)	2103	2303	2227	2211
RQ	0,86	0,9	0,9	0,89
VE/VO2	23,6	24,8	26,0	24,8
VE/VCO2	27,4	27,6	28,7	27,9
HR (bpm)	130	150	160	147
PetO2 (mmHg)	103	104,3	107,2	104,8
PetCO2 (mmHg)	39,2	39	37,6	38,6
CHO (g/min)	1,67	2,2	2,22	2,03
FAT (g/min)	0,6	0,46	0,42	0,49
Ti (sec)	0,47	0,39	0,42	0,43
Te (sec)	0,7	0,6	0,52	0,61
VT/Ti (L/sec)	2,63	2,9	2,56	2,70
GE %	14,33	13,56	14,9	14,26

A

6 min CWL - S2				
	2 min	4 min	6 min	Avg
Ttot (sec)	2,19	1,53	1,17	1,63
VT (L)	2,4	1,91	1,64	1,98
VE (L/min)	66,2	72,7	83,2	74
VO2 (mL/min)	2852	2973	3178	3001
VCO2 (mL/min)	2328	2522	2695	2515
RQ	0,82	0,84	0,84	0,83
VE/VO2	22,6	23,5	24,8	23,6
VE/VCO2	27,6	27,9	29,5	28,3
HR (bpm)	152	158	160	157
PetO2 (mmHg)	103,9	106,1	107	105,7
PetCO2 (mmHg)	38	36,8	35,4	36,7
CHO (g/min)	1,49	1,87	2,03	1,80
FAT (g/min)	0,87	0,81	0,87	0,85
Ti (sec)	1,14	0,77	0,54	0,82
Te (sec)	1,1	0,75	0,63	0,83
VT/Ti (L/sec)	2,2	2,43	3,1	2,58
GE %	15,56	14,81	13,86	14,74

B

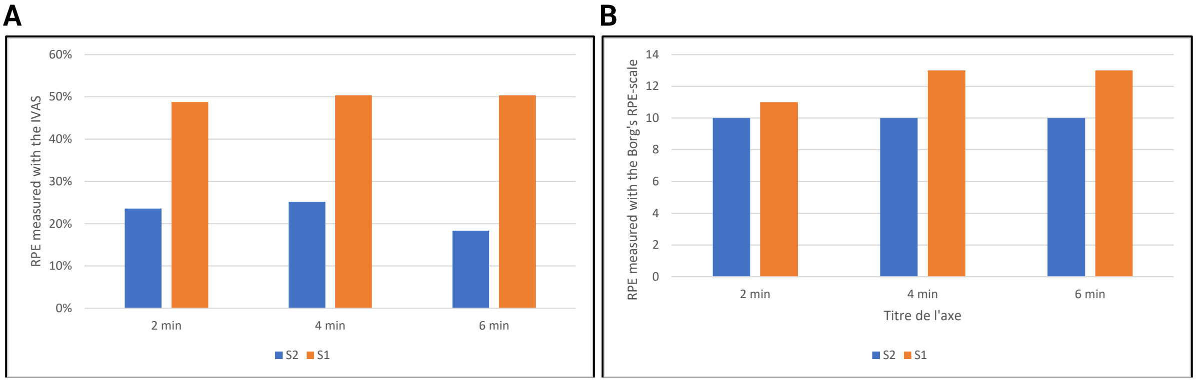


Figure 15: RPE at 2, 4, and 6 min during the CWL exercise measured with the Borg's RPE scale (A) and IVAS (B).

Finally, the psychophysiological responses of the subjects during the competitive ironman event are reported in Table 11 and 12.

Table 11: Psychobiological parameters during the event

	Blood lactate (mmol/L)			
	Start	T1	T2	Finish
Athlete 1	1.5	1.9	1.6	1.9

Athlete 2	1.0	2.0	5.1	1.1
	Tympanic temperature (°C)			
	Start	T1	T2	Finish
Athlete 1	35.1	35.9	35.9	36.1
Athlete 2	36.0	36.9	36.9	36.1
	RPE (0-10)			
	Start	T1	T2	Finish
Athlete 1	-	5	3	4
Athlete 2	-	4	2	3
	Self-capabilities (1-7)			
	Start	T1	T2	Finish
Athlete 1	7	5	5	-
Athlete 2	5	4	4	-

Table 12: Race times by split

	SWIM (3.8 KM)	T1	HAND BIKE (180 KM)	T2	WHEELCHAIR (42.2 KM)	TOTAL
ATHLETE 1	01:30:16	00:21:14	05:42:02	00:16:19	03:06:14	10:56:03
ATHLETE 2	01:13:36	00:37:54	05:30:37	00:26:24	02:58:00	10:46:29

IV. Discussion

Before starting the discussion of the results obtained during this investigation, we need to do a reminder. The kinetic of the RPE in this study is obtained using the IVAS. The results collected with the RPE-scale are ordinals and are interpreted as so. There is no point or aims of comparisons between these two outcomes. The results are not of the same nature. Readers are referred to the chapter two of this thesis for further information and explanation on this issue.

The RPE response during the MIT is different between both subjects (see Figure 14). We can visually observe the more linear response for S2 than for S1 for which the convexity of the RPE response is more pronounced. This discrepancy in the response of the perceived exertion (PE) can be explained by the difference in the level of the SCI. S1 being more severely injured has a lower active muscle mass. S1 is a world-class athlete with its associated tremendous training background, this leads to a disbalance between the "strength" of the cardiovascular system and the muscular or metabolic fitness of this athlete. It should be noted that the maximal HR recorded during the MIT for S1 was 179 bpm. This value indicates that his SCI lesion is incomplete, and his sympathetic nervous system (SNS) could not be intact but is at least not completely denervated and remains functional. At the opposite, the S2 has all the main motor muscle groups functionals to exercise on a handcycle. Consequently, his psychophysiological response can be expected to be closer to what we can observe in an able-bodied subject cycling on a bicycle with their legs. These remarks are illustrated by the $[La^-]$ reached at the end of the MIT.

The total breath duration (Ttot) decreases for both subjects between the start and end of the CWL exercise, with a greater magnitude for S2. This decrease is accompanied by a concurrent diminution of the tidal volume (V_T). Then, the minute ventilation ($\dot{V}_E$) increases during the 6-min physical exercise bout. Consequently, the intensity cannot be categorized as steady-state on a ventilatory standpoint. However, in regard to these observations, the same debate remain: is the unbalanced interdependence between breathing frequency and tidal volume driven by f_R (Nicolò et al., 2018a; Nicolò and Sacchetti, 2023) or V_T (Toffoli, 2020; Winning et al., 1985)?

The absolute intensities are, as desired, submaximal. This is illustrated by the RPE and the respiratory exchange ratio (RQ) below 1 indicating the utilization of fat as energy substrate and a stable level of $[La^-]$ (San-Millán and Brooks, 2018).

To note, the gross efficiency (GE) is around 14% for these subjects during the CW exercise bout. This is much lower than values reported in world-class cyclists exceeding 20 or even 25% (Lucía et al., 2002).

Finally, regarding the 6-min CWL, the RPE responses was relatively stable independently of the measure taken into account (see Figure 15) highlighting a steady effort as wanted when assigning the intensity. This observation coupled with the one of the ventilatory response is contradictory with previous published data showing a "strong correlation" between RPE & f_R (Nicolò et al., 2016).

Table 11 provides unique descriptive data regarding the psychophysiological response of world-class athlete with a SCI performing an IM. We can note that after the swimming part, their level of confidence to finish the race decreased. This is illustrated by the reduction of the self-capability ratings. The bicycle part, stabilized this drop in the rating of self-capabilities, and was rated to be perceived as the less effortful. The fact that these two athletes are professional handcyclists can in part explain this response due to their better familiarization to this locomotion mode.

V. Conclusion

This study provided an in-depth exploration of the perceived exertion in individuals with SCI across various exercise modalities, including incremental and constant workload protocols, and an Ironman event involving three different modes of locomotion (i.e., swimming, handbike, wheelchair). The results highlighted the kinetic response of RPE during an incremental protocol for the first time, yielding valuable psychophysiological data from world-class athletes with SCI. Additionally, the study showed that the RPE response during a CWL exercise was relatively stable at submaximal intensity during short duration task (i.e., 6 minutes). The psychophysiological responses of the subjects during the Ironman event, a scarce descriptive resource in the literature, highlighted dynamic self-confidence fluctuations and perceived lower effort during handcycling. These findings, though limited by sample size and study design, contribute significantly to improve our understanding of the psychophysiological responses in SCI individuals and on the kinetic of the RPE response, very rare data, as explained in the chapter 2.

Chapter 5: Altitude Acclimation in World Class Paracyclists with Spinal Cord Injury: Exploring and Unravelling the Role of Rating of Perceived Exertion (RPE)

I. Introduction

The pursuit of athletic excellence among individuals with spinal cord injury (SCI), particularly paraplegia, has seen remarkable advancements in recent years (Antunes et al., 2022; Gee et al., 2021; Hodgkiss et al., 2023; Hopman et al., 1998; Linde et al., 2023; Minder et al., 2023; Palladino et al., 2023; Valent et al., 2009). The increasing interest and development of paralympic games are the strong arms supporting this trend. For the same reason as cycling for able-bodied, handcycling is a popular mode of locomotion for research purposes in the case of people with SCI. Consequently, the psychophysiological response of people exercising on a handbike has been well described over the recent years in research in different population (Abel et al., 2006, 2003; Antunes et al., 2022; Arnet et al., 2014, 2013, 2012b, 2012a; Azizpour et al., 2018; De Groot et al., 2023; Faupin and Gorce, 2008; Fischer et al., 2020, 2014; Goosey-Tolfrey et al., 2008; Gordon et al., 2024; Groen et al., 2010; Hoekstra et al., 2017; Krämer et al., 2009a, 2009b; Litzenberger et al., 2016; Lovell et al., 2012; Maki et al., 1995; Mason et al., 2021; Meyer et al., 2009; Muchaxo et al., 2021, 2023; Nevin et al., 2022; Quittmann et al., 2020a, 2020b, 2019, 2018; Simmelink et al., 2015; Stangier et al., 2019; Stephenson et al., 2020; Stone et al., 2020, 2019b, 2019a, 2019c; Umar et al., 2023; Van Drongelen et al., 2013, 2011; Verellen et al., 2012b, 2012a).

In the process of optimizing their performance, professional paracyclists are increasingly using exposure to chronic hypoxia (e.g., altitude sojourn) to trigger some specific adaptations, beneficial in endurance sport to improve their performance. Among the myriad challenges faced by elite paracyclists, the adaptation to high-altitude environments stands out as a critical factor influencing performance and overall physiological well-being. Altitude acclimation, a process characterized by the body's adjustment to reduced oxygen availability at elevated altitudes, has been extensively studied in able-bodied athletes. However, the unique physiological responses of paracyclists with SCI to altitude exposure remain a relatively unexplored frontier.

This case study delves into the altitude acclimation of a world-class paracyclist with SCI, with a specific emphasis on the crucial role of Rating of Perceived Exertion (RPE) in monitoring and optimizing the process of adaptation. Individuals with paraplegia encounter distinctive challenges, such as altered autonomic function, thermoregulation, and cardiovascular responses, which can significantly impact their ability to acclimate to altitude. Understanding the physiological adjustments within this population is paramount for enhancing training protocols and performance outcomes.

The integration of RPE as a key monitoring parameter in altitude acclimation studies for paracyclists adds a novel dimension to the investigation. RPE serves as a subjective measure reflecting an athlete's perception of exertion, providing valuable insights into the psychophysiological responses during exercise. As paracyclists navigate the multifaceted terrain of altitude adaptation, RPE emerges as a dynamic tool for quantifying the perceived strain and tailoring training intensities to optimize the acclimation process.

This chapter observes a two-week period of altitude acclimation in a world-class paracyclist with a thoracic SCI and report for the first time, to our knowledge, the RPE quantitatively as a monitoring variable.

II. Method

1) Participant

A paraplegic male paracyclist was observed over a 14 days hypoxic acclimation period (i.e., 2500m simulated altitude). At the start of the data collection period, the participant's age was 32 years, VO2max was 55 mL·kg−1·min−1, and body mass was 72 kg.

2) Procedures

The athlete spent 14 days at 2500m of simulated altitude in a hypoxic chamber and trained outside on the field at low altitude between 700m and 1200m above sea level. Training sessions were assigned daily in the build-up to the paracycling world championship.

Athlete's recovery status was monitored with nocturnal heart rate (HR) and oxygen saturation (SaO_2) recording, and morning recording of supine heart rate variability (HRV), urine density, and pH. Additionally, the subject answered daily after waking up to the Hooper and Spiegel questionnaires.

During every training session, HR (Garmin HRM-Dual; Garmin Ltd, Lenexa, KS, USA) was recorded. Cadence, moment of force and power output (PO) were recorded with a mobile power meter mounted on his recumbent bike (SRM Professional Training systems, Schoberer Rad Messtechnik, Jülich, Germany). The subject was instructed on the use of the Garmin edge 520 plus (bike computer) and informed of the importance of performing the zero offset frequency procedure to obtain accurate PO data. Data were sampled at 1 Hz. After every session, the paracyclists returned through a questionnaire his average rating of perceived exertion (RPE) during the session and the level of fatigue he perceived at the end of the training session. For these two subjective rating, a magnitude estimation method anchored at the extreme with 0 & 10 representing respectively no effort perceived and the maximal perceived exertion was used. Decimals were allowed and subjects were instructed to use numerals as numbers with common criteria of equality and addition. A score that multiplies RPE with duration of training is computed as a general metric of strain of the training sessions (sRPE). We use a linear multiplication by convention. However, the “ideal” multiplicative process (e.g., exponential, logarithmic, etc.) would depend on the aspect of the sRPE we want to highlight, whether its impact on the acute performance decrement (Kesisoglou, 2020), subsequent training adaptation, etc.

The content of the training session regarding the power output and the heart rate will be presented as proposed recently by Van der Zwaard *et al.* (2023b) using 2-dimensional kernel-density estimation (2D-KDE).

3) Statistical Analyses

Data are reported using descriptive statistics. Changes observed within the data-collection period are reported as the percentage change compared with the first recorded measurement.

III. Results

The monitoring of the recovery status of the athlete is presented in the figure 16 with the values of the different physiological metrics recorded daily. When data are missing, the cause is a problem in the process of recording with a bad quality of raw data.

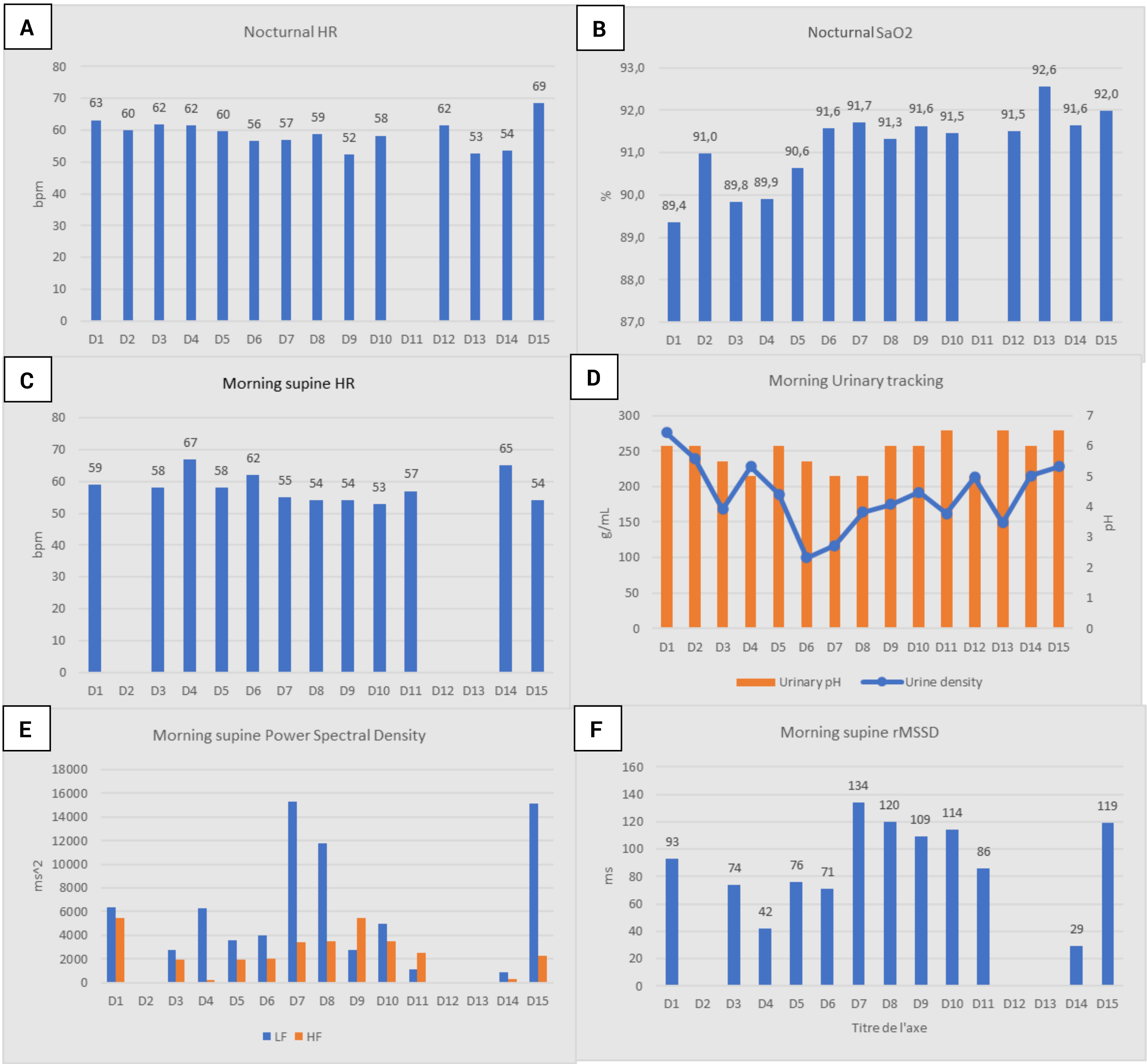


Figure 16: Daily measures of the recovering status. A: Daily nocturnal heart rate; B: Daily nocturnal SaO$_2$; C: Morning supine heart rate; D: Morning urinary pH and density; E: Morning supine heart rate low and high frequency power; F: Morning supine rMSSD

following figures. The overall content of the training camp in regard to the power output and heart rate is displayed in the figure 17. The figure 18 is composed of individual visualizations for every single training session performed during the study period.

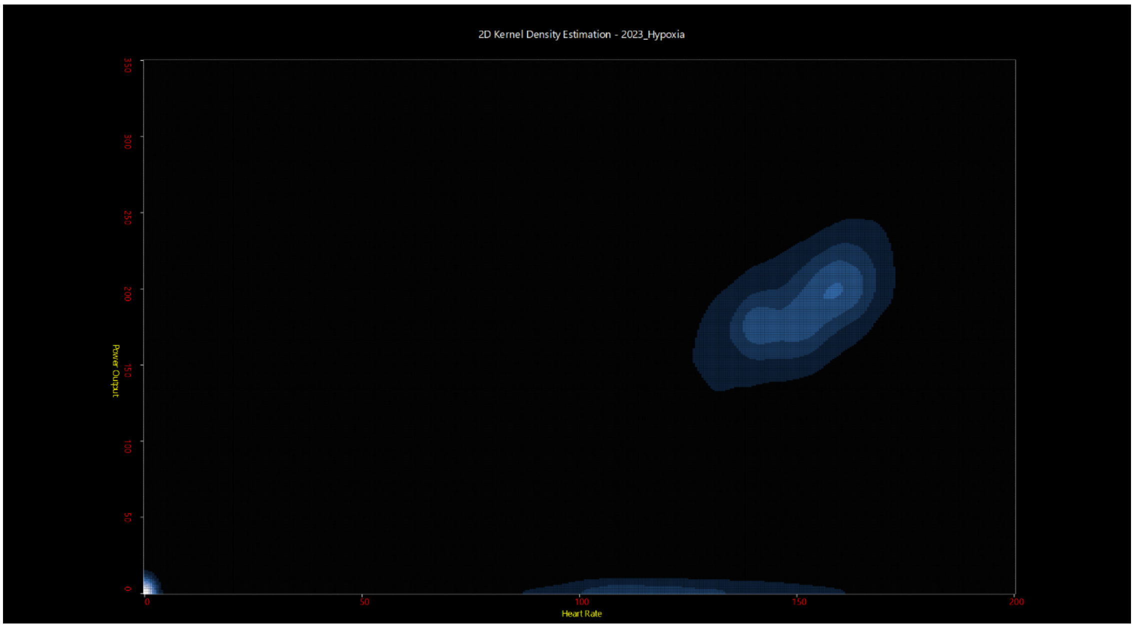


Figure 17: 2D-KDE visualization of the overall training content during the duration of the study.

To expand the detailed analysis and improve the interpretation of the objective variables recorded during every second of every training session, daily mean maximal power output (MMP) is provided in table 13. Additionally, visualizations of the relative power and heart rate distribution recorded for the entire period of the study have been computed in figures 19 and 20 respectively.

Supplementary metrics regarding the content and response to the training sessions and hypoxia exposure are reported in the figure 7 including the distance covered, the work achieved, the power to heart rate ratio, the average (non-zero) power for every session and the average speed.

Daily subjective measurements across the study are reported in the figure 21 and 22.

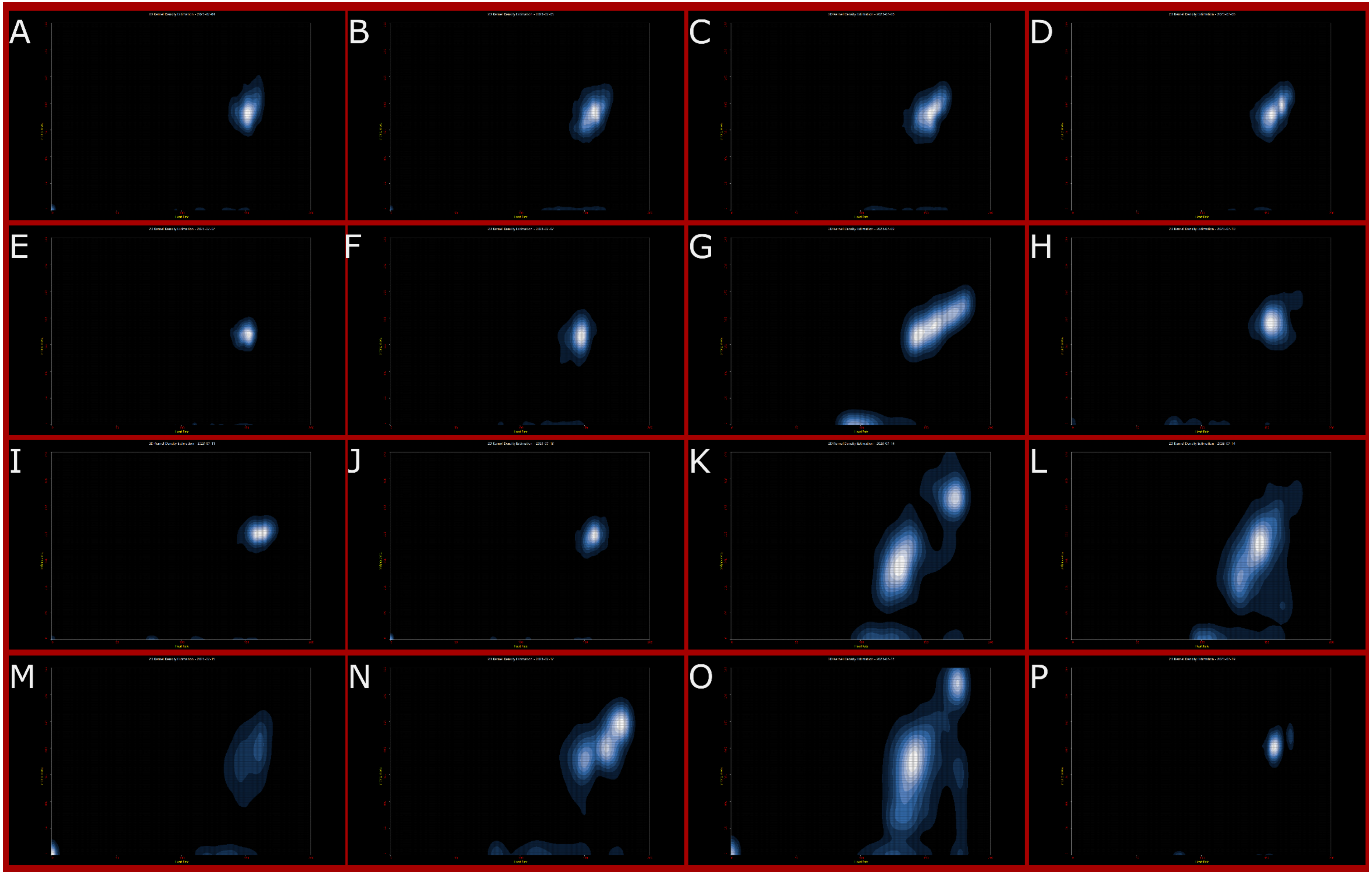


Figure 18: Training content visualization using 2D kernel-density-estimate plots based on heart rate and power output for every training session in chronological order across the acclimation period from A to P.

Table 13: *MMP of the sessions performed during the acclimation period. The 4 bests power for every duration are highlighted.*

2023_Hypoxia groupé par jour

Date	1 sec	5 sec	30 sec	1 min	2 min	3 min	4 min	5 min	10 min	20 min	30 min	45 min	1-H	2-H	Peak 3 hour Power	Pic 4 heure Puissance
	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	(watts)	
juil. 04 2023	392	369	275	240	230	215	208	204	202	190	186	170	166	0.0	0	0.0
juil. 05 2023	344	266	235	228	223	206	209	198	187	181	179	178	176	167.6	160	0.0
juil. 06 2023	358	333	240	235	231	207	204	200	187	183	178	174	172	166.8	0	0.0
juil. 07 2023	574	554	260	223	219	197	187	180	174	164	164	156	155	0.0	0	0.0
juil. 09 2023	303	281	245	239	235	233	231	230	217	193	189	170	169	151.2	0	0.0
juil. 10 2023	423	409	345	273	224	212	212	209	200	193	186	185	179	167.7	156	0.0
juil. 11 2023	382	361	311	281	242	235	230	225	222	207	201	192	189	178.7	169	0.0
juil. 13 2023	585	407	353	280	243	229	221	219	216	209	205	199	197	184.4	170	0.0
juil. 14 2023	606	567	346	285	272	268	264	260	228	204	190	175	174	0.0	0	0.0
juil. 15 2023	456	440	281	251	245	229	226	215	197	194	180	164	155	141.4	134	134.2
juil. 17 2023	451	425	341	275	248	247	246	246	244	222	217	194	191	0.0	0	0.0
juil. 18 2023	456	419	342	320	287	261	262	263	223	197	179	180	170	154.6	0	0.0
juil. 19 2023	398	312	301	287	260	247	244	240	227	221	217	208	194	192.6	0	0.0

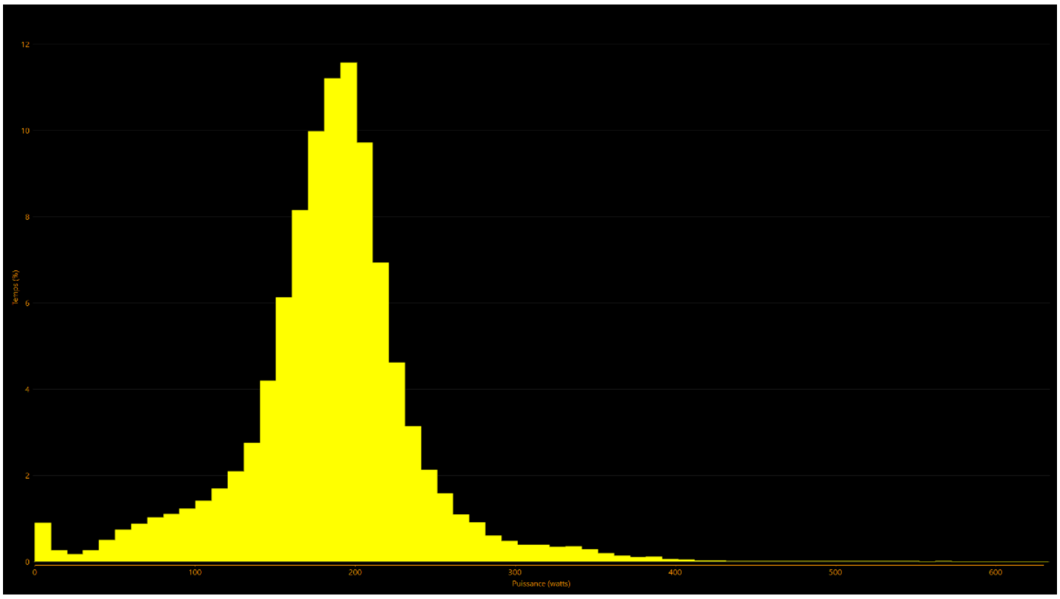


Figure 19: *Relative (in %) power distribution recorded for the entire period of the study grouped by range of 10 W.*

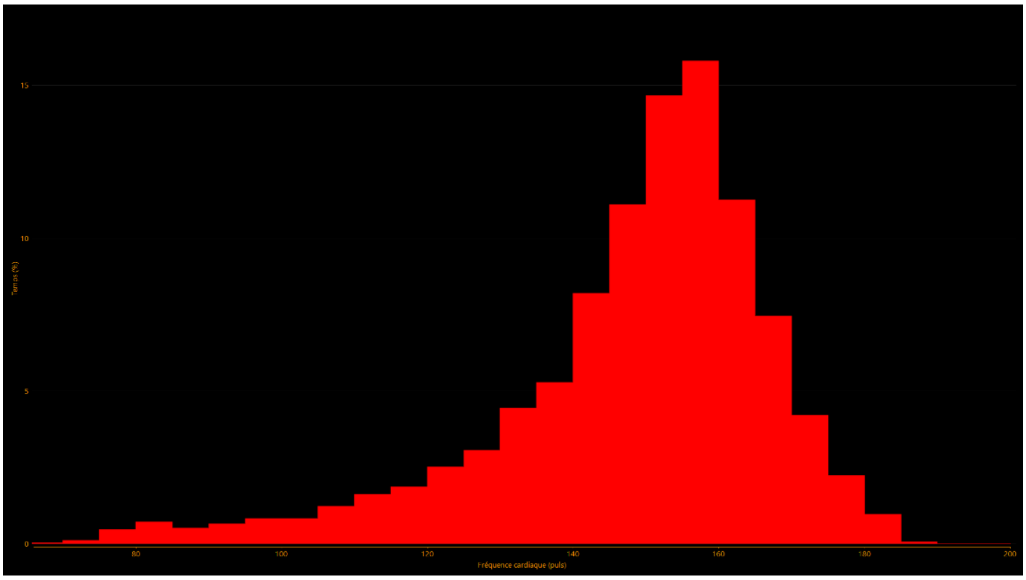
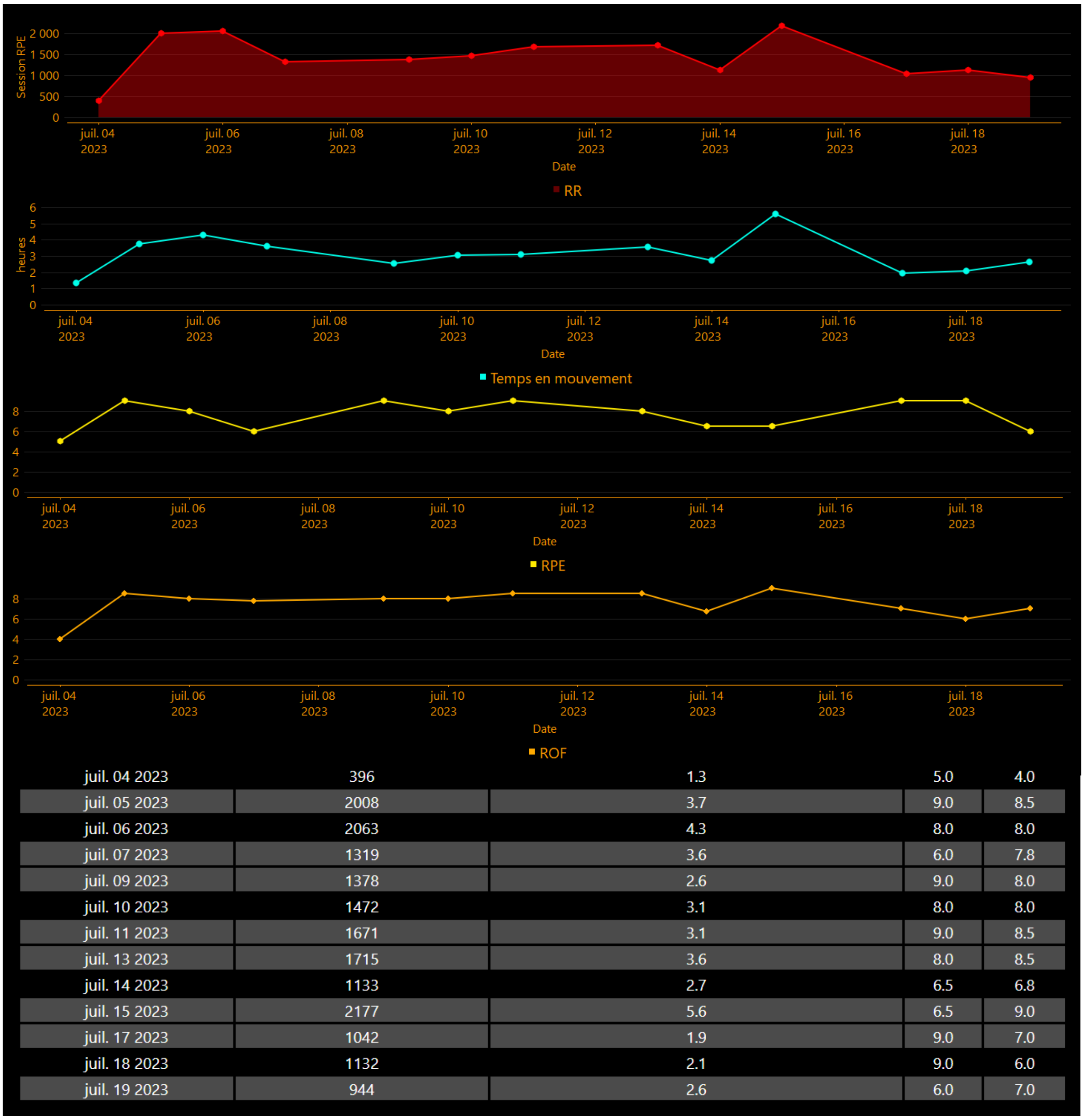
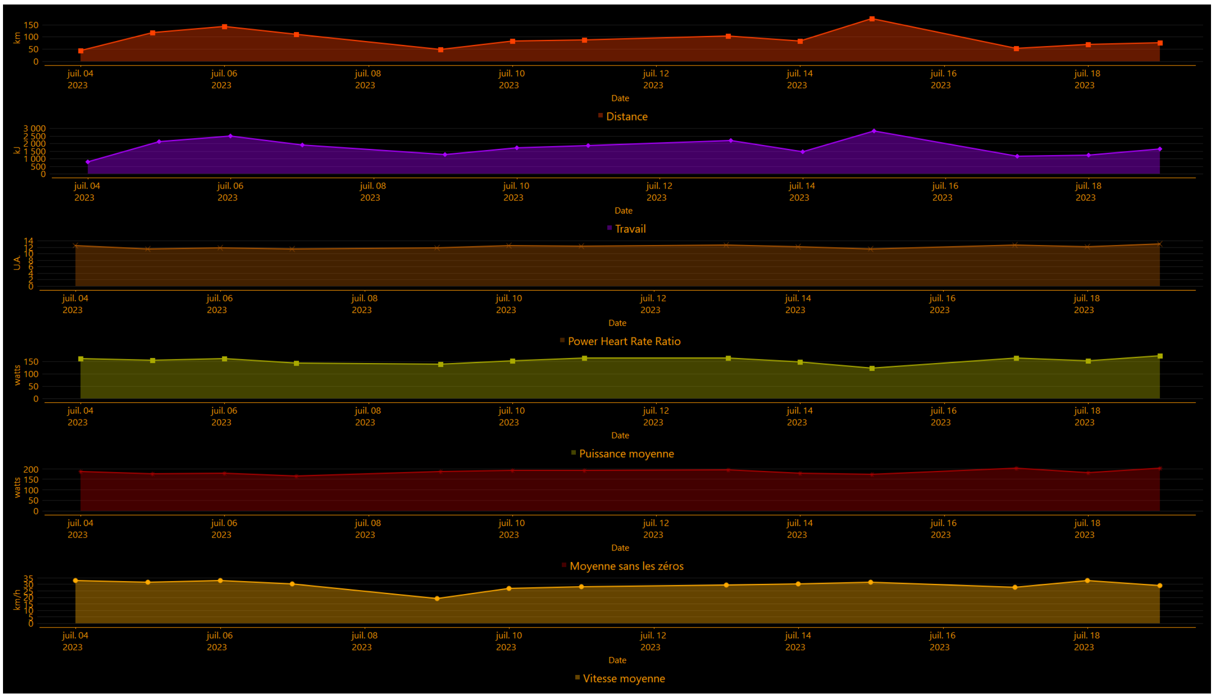


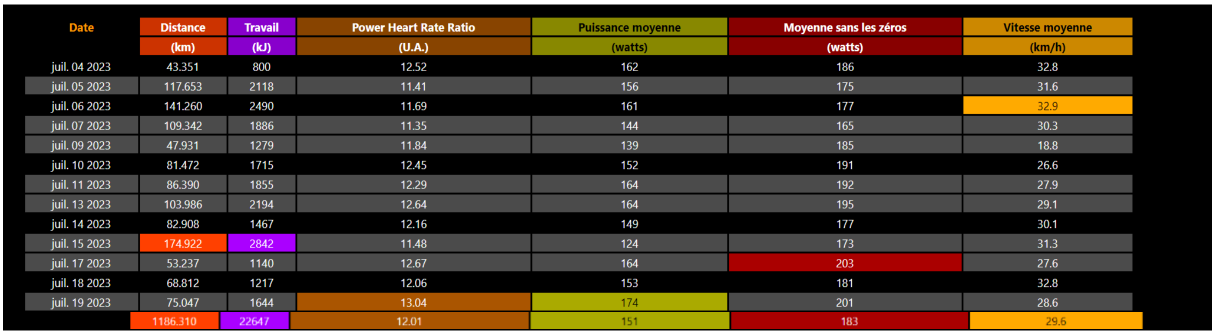
Figure 20: *Relative (in %) heart rate distribution recorded for the entire period of the study grouped by range of 5 beats.*



juil. 04 2023	396	1.3	5.0	4.0
juil. 05 2023	2008	3.7	9.0	8.5
juil. 06 2023	2063	4.3	8.0	8.0
juil. 07 2023	1319	3.6	6.0	7.8
juil. 09 2023	1378	2.6	9.0	8.0
juil. 10 2023	1472	3.1	8.0	8.0
juil. 11 2023	1671	3.1	9.0	8.5
juil. 13 2023	1715	3.6	8.0	8.5
juil. 14 2023	1133	2.7	6.5	6.8
juil. 15 2023	2177	5.6	6.5	9.0
juil. 17 2023	1042	1.9	9.0	7.0
juil. 18 2023	1132	2.1	9.0	6.0
juil. 19 2023	944	2.6	6.0	7.0

Figure 21: Daily training load from subjective measures. From top to bottom, the sRPE, duration of the training sessions, RPE, and rating of the perceived level fatigue (ROF). In the table are exposed the daily raw data in the same order as written from the left to the right column excepting the column containing the date.





Date	Distance (km)	Travail (kJ)	Power Heart Rate Ratio (U.A.)	Puissance moyenne (watts)	Moyenne sans les zéros (watts)	Vitesse moyenne (km/h)
juil. 04 2023	43.351	800	12.52	162	186	32.8
juil. 05 2023	117.653	2118	11.41	156	175	31.6
juil. 06 2023	141.260	2490	11.69	161	177	32.9
juil. 07 2023	109.342	1886	11.35	144	165	30.3
juil. 09 2023	47.931	1279	11.84	139	185	18.8
juil. 10 2023	81.472	1715	12.45	152	191	26.6
juil. 11 2023	86.390	1855	12.29	164	192	27.9
juil. 13 2023	103.986	2194	12.64	164	195	29.1
juil. 14 2023	82.908	1467	12.16	149	177	30.1
juil. 15 2023	174.922	2842	11.48	124	173	31.3
juil. 17 2023	53.237	1140	12.67	164	203	27.6
juil. 18 2023	68.812	1217	12.06	153	181	32.8
juil. 19 2023	75.047	1644	13.04	174	201	28.6
	1186.310	22647	12.01	151	183	29.6

Figure 21b: Daily training load metrics. From top to bottom, distance (in km), work (in kj), Power to heart rate ratio (U.A), average power (watts), average non-zero power (watts), and average speed (km/h).

The daily raw data are presented in the table. The highlighted data are the highest for each metric for the duration of the study, and the last line is the average or sum, depending on the nature of the data, of the different metrics for the entire duration of the intervention.

IV. Discussion

This case study aimed to quantify altitude training of live high train low (LHTL) training strategies prior to major international races for an elite paracyclist with a spinal cord injury. This deep investigation into the physiological response of a LHTL training period for an elite para-athlete with SCI provides valuable insight to better understand how SCI influence the responses and adaptations in the conditions aforementioned.

The races was performed 15 days (and during the week that followed) after 21 days of LHTL (Bonetti and Hopkins, 2009), and therefore, consistent with previous findings that post altitude performance benefits can be maintained for up to 4 weeks (McLean et al., 2013). The hypoxic dose (~1050 km·h) was also within the range typically required for performance improvement (Garvican-Lewis et al., 2016).

Simulated LHTL was implemented with the aim of increasing hypoxic dose and maintaining training intensity (Levine and Stray-Gundersen, 1997), as we can observe in the figure 21 through for instance the RPE and sRPE variables, to increase the potential for performance benefit (Saunders et al., 2019). In the current case study, the observed post altitude training response was positive as the athlete improved his result compared to the previous year with 4 podium finishes from as many races (i.e., World championships & European championships).

An observation we can raised is the slight increase in SaO_2 over the duration of the acclimation period demonstrating a good adaptation of the body. The HRV was suggested to be a good marker of acclimation to altitude in previous studies but in our report, we can question this point because we couldn't observe something similar. However, the autonomic response reflected by the HRV can be altered because of the SCI of the athlete.

V. Conclusion

In summary, this case study highlights the success of live high train low (LHTL) strategies in altitude acclimation for a top-tier paracyclist with a spinal cord injury, resulting in improved race performance. The utilization of Rating of Perceived Exertion (RPE) emerges as a crucial and dynamic parameter for monitoring and optimizing the acclimation process.

Chapter 6: Monitoring of the autonomic response in world class SCI athletes: Implementation of the RPE - A field case study

I. Introduction

Spinal Cord Injury (SCI) represents a complex and life-altering condition that not only affects mobility but also disrupts autonomic nervous system functioning.

The autonomic nervous system (ANS) plays a crucial role in regulating cardiovascular function and adapting to varying levels of physical activity. The function of the ANS for people with a SCI is complex as we described in the introduction of this thesis. SCI disrupts the normal communication between the brain and peripheral nerves, leading to altered autonomic control. Investigating HRV, a non-invasive marker of ANS activity, can provide valuable insights into the nuanced autonomic responses in individuals with SCI at rest. Additionally, monitoring blood pressure as a complement offers a holistic perspective on cardiovascular health, emphasizing the importance of understanding the dynamic relationship between HRV and blood pressure in this population.

Furthermore, assessing the Rating of Perceived Exertion (RPE) during daily exercise sessions is essential for understanding the subjective experience of effort during exercise and to observe the daily readiness to perform (see chapter 1).

This study aims to bridge the existing knowledge gap by employing a comprehensive approach, combining HRV analysis, blood pressure monitoring at rest, and RPE assessments combined with power output (i.e., an objective marker of the work performed) and heart rate (HR) during physical activities. By shedding light on the autonomic modulation and perceived exertion during daily exercise sessions in individuals with SCI, our findings may pave the way for tailored interventions that enhance cardiovascular health and overall well-being in this population. Ultimately, this research contributes to a deeper understanding of the physiological responses to exercise in individuals with SCI, offering valuable insights for optimizing rehabilitation strategies and promoting a healthier lifestyle in this unique cohort.

II. Method

Subjects — Two male professional hand-cyclists (athlete 1: 30 yr, 57 kg, 1.74 m; athlete 2: 31 yr, 73 kg, 1.72 m) spinal-cord injured (SCI) (tetraplegia, S1; paraplegia, S2), paralympic &/or world championship podium medallists took part in the study.

Morning Heart rate variability (HRV) recording — The record was realized every morning on the same condition, after waking up and miction, and before eating. Subjects lay down during 1 min in order to stabilize their heart rate. Then the recording was started using a Garmin HR band (Garmin HRM-Dual; Garmin Ltd, Lenexa, KS, USA) and the android app HRV logger to save the RR interval (time between two heartbeats in milliseconds). Subjects were instructed to breath every 6 sec to remove the effect of breathing on the recording of ANS activity. The supine record last one min and the blood pressure (BP) (i.e., systole and diastole) was measured at the end. Then, they were instructed to sit down and remain in this position for 5 min (Squair et al., 2018), while maintaining their breathing rate. Along these 5 minutes, the BP was recorded at 1, 3, and 5 minutes.

During every training session, HR (Garmin HRM-Dual; Garmin Ltd, Lenexa, KS, USA) was recorded. Cadence, moment of force and power output (PO) were recorded with a mobile power meter mounted on his recumbent bike (SRM Professional Training systems, Schoberer Rad Messtechnik, Jülich, Germany). The subjects were instructed on the use of the Garmin bike computer and informed of the importance of performing the zero offset frequency procedure to obtain accurate PO data. Data were sampled at 1 Hz. After every session, the paracyclists returned through a questionnaire his average rating of perceived exertion (RPE) during the session and the level of fatigue he perceived (ROF) at the end of the training session. For these two subjective rating, a magnitude estimation method anchored at the extreme with 0 & 10 representing respectively no effort perceived and the maximal perceived exertion was used. Decimals were allowed and subjects were instructed to use numerals as numbers with common criteria of equality and addition. A score that multiplies RPE with duration of training is computed as a general metric of strain of the training sessions (sRPE). We use a linear multiplication by convention. However, the “ideal” multiplicative process (e.g., exponential, logarithmic, etc.) would depend on the aspect of the sRPE we want to highlight, whether its impact on the acute performance decrement (Kesisoglou, 2020), subsequent training adaptation, etc.

The content of the training sessions in regard to the power output and the heart rate will be presented as proposed recently by Van der Zwaard *et al.* (2023b) using 2-dimensional kernel-density estimation (2D-KDE).

1) Data processing

HRV

The supine and seated data were analysed separately to compare them. The data are visually inspected for artifact removal and HRV metrics are computed using the RHRV package in R (Rodriguez-Linares et al., 2022). The following indices are extracted for each measurement:

- The square root of the mean squared differences of successive RR interval (rMSSD)
- The number of interval differences of successive RR intervals greater than 50 ms (SDNN)
- The average inter-beat interval in milliseconds (RR)
- Low- (LF) and high-frequency (HF) power in % of the total power of the heart rate signal though a Fourier transform and their ratio LF/HF to get an index of the ANS balance. Frequency bands used for LF and HF were 0.05 Hz to 0.15 Hz, and 0.15 Hz to 0.4 Hz respectively according to literature recommendations (Electrophysiology, 1996).
- The standard deviation of points perpendicular to the line-of-identity (SD1) on a Poincare plot, where RR are plotted with actual data in the x-axis and the data with a time lag of N+1 on the y-axis.
- Finally, two metrics computed with a non-linear analysis are observed alpha-1 (a1), and alpha-2 (a2). These indices are computed from a detrended fluctuation analysis (Goldberger et al., 2002) and the frequency bands delimited in order that alpha-1 represent the activity of the parasympathetic nervous system through its frequency bands and alpha-2 the frequency band of the sympathetic nervous system.

PO - HR ratio

A ratio was computed between the continuous recording of PO and the HR for every second and average for each session. To compute this metric, every second where the HR was equal to zero (pause in recording), and/or the PO was zero, were removed to reduce the bias in the subsequent interpretation. Indeed, PO can be reduced to zero while HR can't. As a consequence, this would add zero values in the raw ratio data and influence the average ratio of the sessions without any physiological meaning in the background. The reason why removing these data is better than keeping them. The average ratio has been arbitrarily multiplied by 10 to change the order of magnitude.

Optimal τ for the convolved pedal power (CPP)

The convolved pedal power (CPP), introduced by De Leeuw *et al.* (2023), "is a weighted average of the produced power in a specific time interval". From this CPP, then it's possible to model the HR response and a corresponding parameter τ (also called the recuperation time) that optimize this fit. To achieve this computation, several steps are required. We described thereafter the main ones to help the reader understand the transformation applied to the recorded raw data.

We combine the data of the last 7 rides containing HR and PO and we remove the couple of HR-PO data where whether the HR, whether the PO is equal to zero for the same reason explained previously regarding the PO – HR ratio. For a value τ, that we will define later, ranging from 1 to 120 we run the following steps:

1) Apply a convolution to time series to produce the convolved pedal power.

As suggested by the author, we use a time (t) for the convolution of 120 seconds. For this reason, 119 zeros are added at the beginning of the vector in order to start the computation from the first PO-HR couple of data. *We admit here an individualized period could be more appropriate but it's not the aim of this study and because of the high amount of resources required to run this computation, we don't optimize this parameter.* The convolution is computed as:

$$h(t) = e^{t/\tau}$$

$$h(t) = \frac{h(t)}{\sum_{i=1}^{w} h(t)}$$

$$CPP(i) = round(h * PO[i - 119: i])$$

where h is the kernel, a vector of 120 values, normalised such that the values of the CPP can be interpreted as weighted averages during the time window (w). The rounding is not set for the accuracy of the data *per se* even if regarding the accuracy of the power meter (+/- 1%), it's irrelevant to report PO with decimals. However, it's necessary for the next step in the computation of the optimal τ.

2) Apply a proportional under-sampling strategy on the data set.

Briefly, the frequency of each value of CPP in the dataset is determined and an under sampling is applied where the probability of a data point to be included in the sampled data set is inversely proportional to the frequency of each value. The reader is referred to the part 3.3.4 of the method in the original article (De Leeuw et al., 2023) for further explanations.

3) The training data set is split into 10 folds

4) The following steps are repeated 10 times (for *i* in 1 to 10):

We select the fold *i* as the test set and fit a cubic polynomial model on the remaining 9 folds to find optimal parameters $HR_0(t)$, *a*, *b*, and *c*. The model is set as:

$$HR(t) = HR_0(t) + a \cdot P_{conv}(t) + b \cdot [P_{conv}(t)]^2 + c \cdot [P_{conv}(t)]^3$$

The heart rate at time "t" is represented as HR(t), with HR0(t) indicating the intercept. Additionally, the linear, quadratic, and cubic dependencies between HR and CPP are characterized by the coefficients a, b, and c. Alongside optimizing the shape of the kernel, this approach involves optimizing four additional parameters.

Then, the explained variance of the model is determined on the test set with a simple computation of the squared correlation coefficient between the test set and the rest of the data set.

Finally, the explained variance for a given τ is averaged over the 10 folds and the recuperation time τ that optimizes the model fit is selected for a given session.

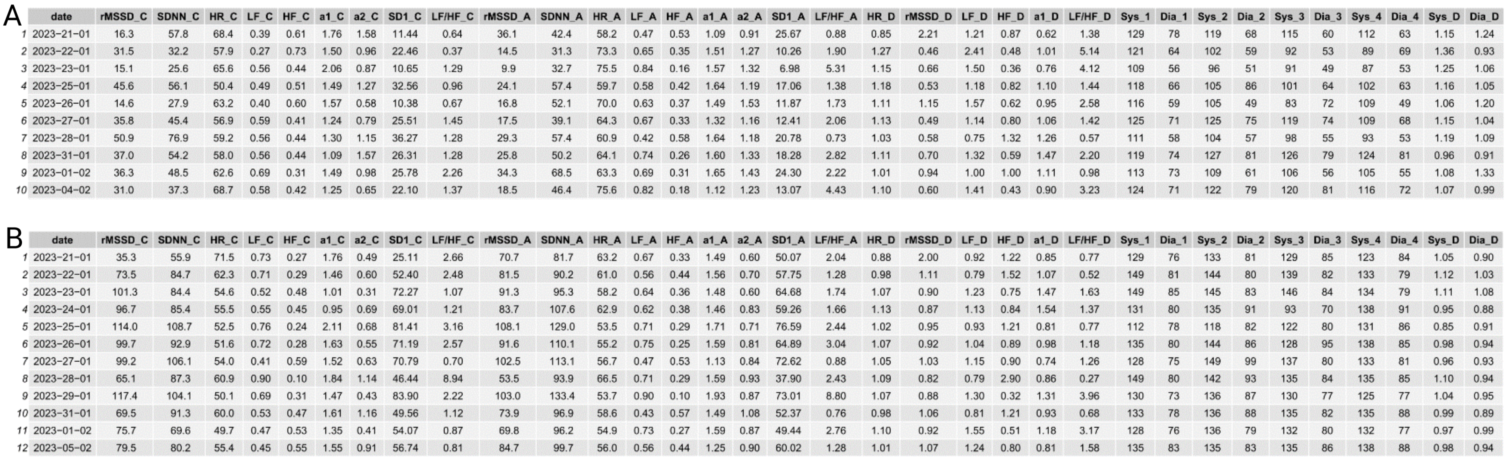
2) Statistical Analyses

Data are reported using descriptive statistics. Changes observed within the data-collection period are reported as the percentage change compared with the first recorded measurement.

III. Result

The daily HRV metrics and blood pressure response is reported in table 14.

Table 14: HRV and blood pressure records for subjects 1 (A) and 2 (B). The suffix "_C" indicates that the metrics are computed for the recumbent recording, the suffix "_A" conveys that the metrics are computed for the seated recording, and the suffix "_D" is the computation of the ratio between sit and supine records. For the blood pressure measure, the delta is computed between the supine position and the last measure of the seated position (at the 5th minute). The columns "Dia_x" are the diastole values (in mmHg) in the supine position, and at the 1st, 3rd, and 5th minute of the seated recording respectively for x=1, x=2, x=3, and x=4. The columns "Sys_x" are the systole values (in mmHg) in the supine position, and at the 1st, 3rd, and 5th minute of the seated recording respectively for x=1, x=2, x=3, and x=4.



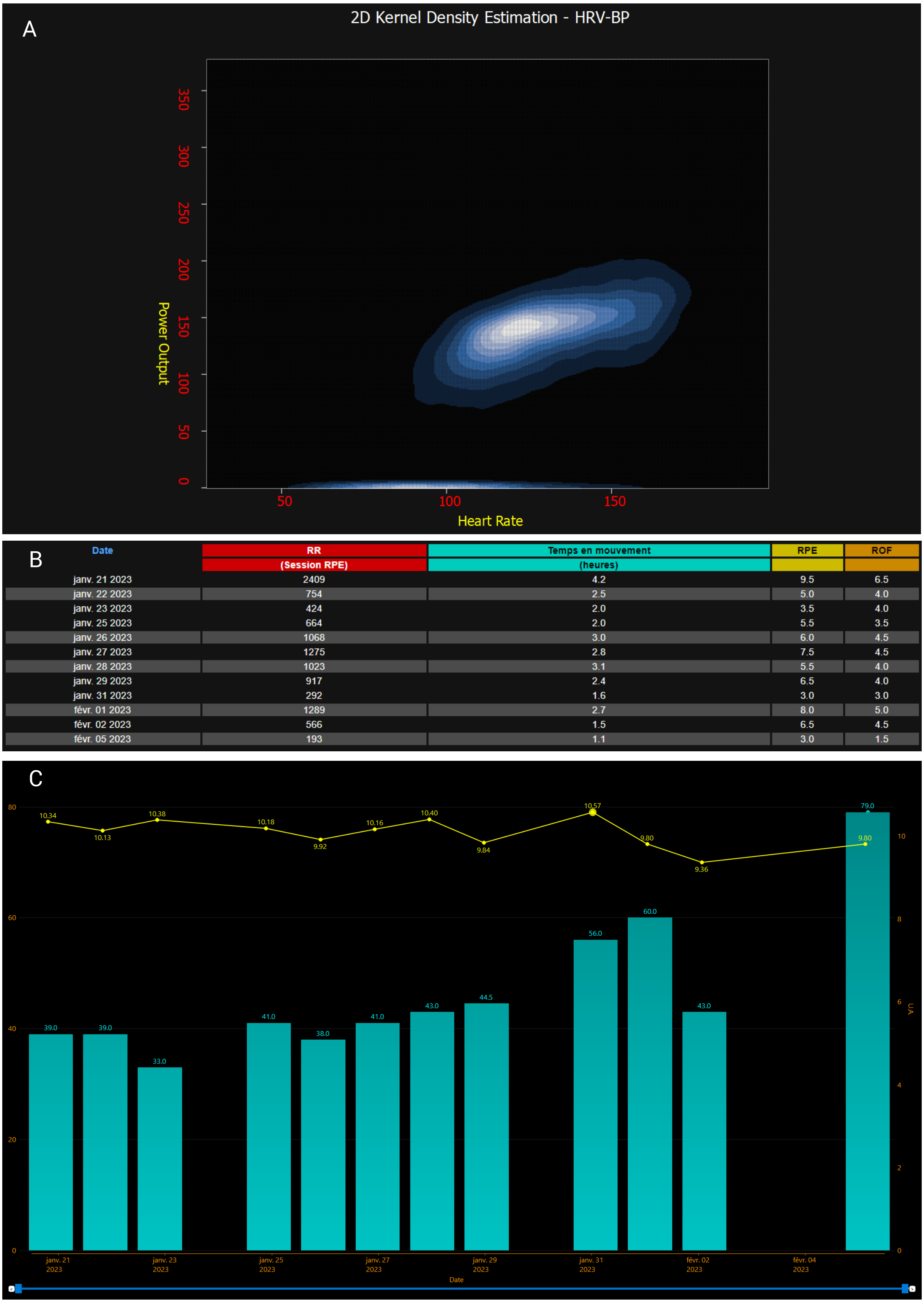
A

	date	rMSSD_C	SDNN_C	HR_C	LF_C	HF_C	a1_C	a2_C	SD1_C	LF/HF_C	rMSSD_A	SDNN_A	HR_A	LF_A	HF_A	a1_A	a2_A	SD1_A	LF/HF_A	HR_D	rMSSD_D	LF_D	HF_D	a1_D	LF/HF_D	Sys_1	Dia_1	Sys_2	Dia_2	Sys_3	Dia_3	Sys_4	Dia_4	Sys_D	Dia_D
1	2023-21-01	16.3	57.8	68.4	0.39	0.61	1.76	1.58	11.44	0.64	36.1	42.4	58.2	0.47	0.53	1.09	0.91	25.67	0.88	0.85	2.21	1.21	0.87	0.62	1.38	129	78	119	68	115	60	112	63	1.15	1.24
2	2023-22-01	31.5	32.2	57.9	0.27	0.73	1.50	0.96	22.46	0.37	14.5	31.3	73.3	0.65	0.35	1.51	1.27	10.26	1.90	1.27	0.46	2.41	0.48	1.01	5.14	121	64	102	59	92	53	89	69	1.36	0.93
3	2023-23-01	15.1	25.6	65.6	0.56	0.44	2.06	0.87	10.65	1.29	9.9	32.7	75.5	0.84	0.16	1.57	1.32	6.98	5.31	1.15	0.66	1.50	0.36	0.76	4.12	109	56	96	51	91	49	87	53	1.25	1.06
4	2023-25-01	45.6	56.1	50.4	0.49	0.51	1.49	1.27	32.56	0.96	24.1	57.4	59.7	0.58	0.42	1.64	1.19	17.06	1.38	1.18	0.53	1.18	0.82	1.10	1.44	118	66	105	86	101	64	102	63	1.16	1.05
5	2023-26-01	14.6	27.9	63.2	0.40	0.60	1.57	0.58	10.38	0.67	16.8	52.1	70.0	0.63	0.37	1.49	1.53	11.87	1.73	1.11	1.15	1.57	0.62	0.95	2.58	116	59	105	49	83	72	109	49	1.06	1.20
6	2023-27-01	35.8	45.4	56.9	0.59	0.41	1.24	0.79	25.51	1.45	17.5	39.1	64.3	0.67	0.33	1.32	1.16	12.41	2.06	1.13	0.49	1.14	0.80	1.06	1.42	125	71	125	75	119	74	109	68	1.15	1.04
7	2023-28-01	50.9	76.9	59.2	0.56	0.44	1.30	1.15	36.27	1.28	29.3	57.4	60.9	0.42	0.58	1.64	1.18	20.78	0.73	1.03	0.58	0.75	1.32	1.26	0.57	111	58	104	57	98	55	93	53	1.19	1.09
8	2023-31-01	37.0	54.2	58.0	0.56	0.44	1.09	1.57	26.31	1.28	25.8	50.2	64.1	0.74	0.26	1.60	1.33	18.28	2.82	1.11	0.70	1.32	0.59	1.47	2.20	119	74	127	81	126	79	124	81	0.96	0.91
9	2023-01-02	36.3	48.5	62.6	0.69	0.31	1.49	0.98	25.78	2.26	34.3	68.5	63.3	0.69	0.31	1.65	1.43	24.30	2.22	1.01	0.94	1.00	1.00	1.11	0.98	113	73	109	61	106	56	105	55	1.08	1.33
10	2023-04-02	31.0	37.3	68.7	0.58	0.42	1.25	0.65	22.10	1.37	18.5	46.4	75.6	0.82	0.18	1.12	1.23	13.07	4.43	1.10	0.60	1.41	0.43	0.90	3.23	124	71	122	79	120	81	116	72	1.07	0.99

B

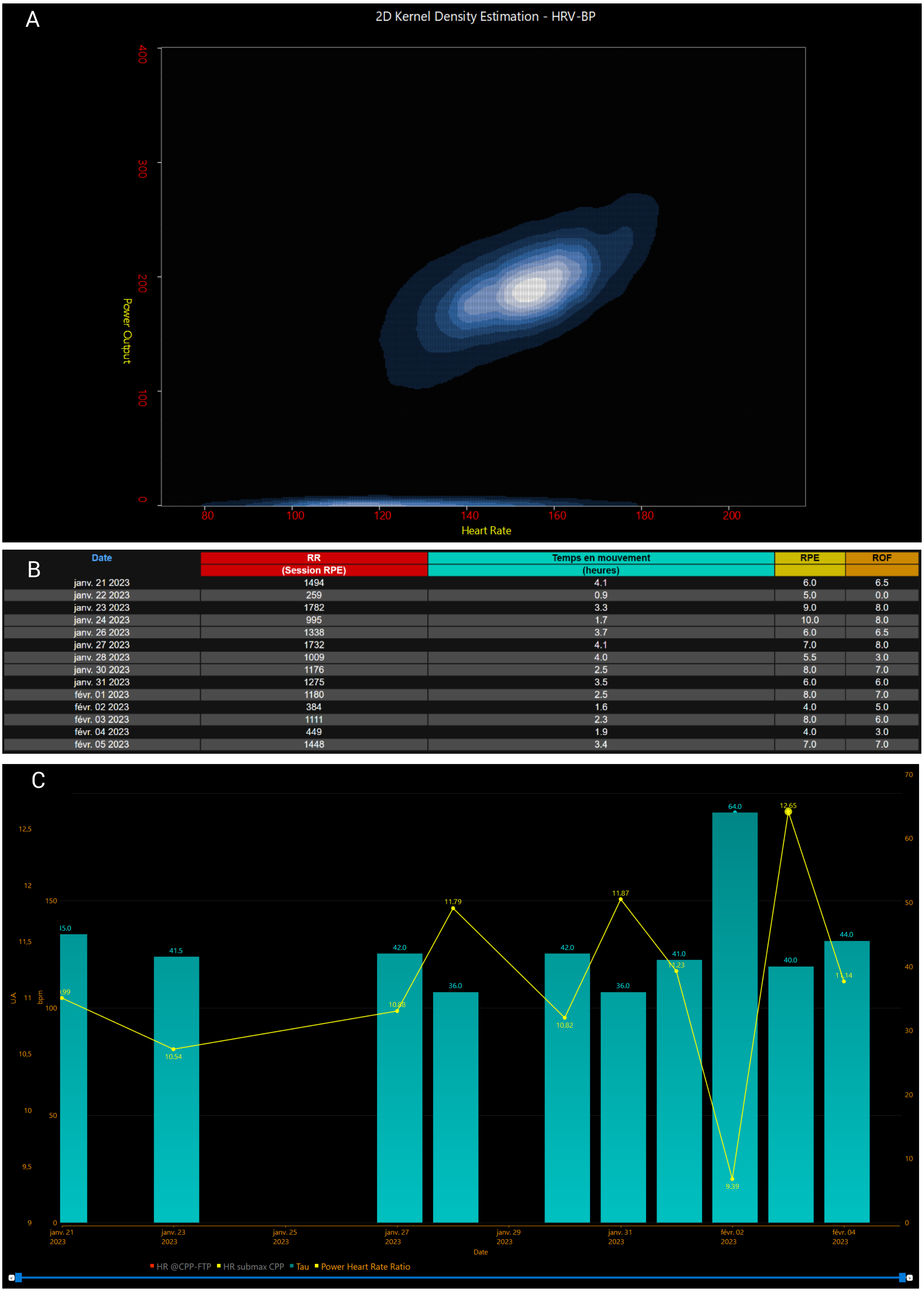
	date	rMSSD_C	SDNN_C	HR_C	LF_C	HF_C	a1_C	a2_C	SD1_C	LF/HF_C	rMSSD_A	SDNN_A	HR_A	LF_A	HF_A	a1_A	a2_A	SD1_A	LF/HF_A	HR_D	rMSSD_D	LF_D	HF_D	a1_D	LF/HF_D	Sys_1	Dia_1	Sys_2	Dia_2	Sys_3	Dia_3	Sys_4	Dia_4	Sys_D	Dia_D
1	2023-21-01	35.3	55.9	71.5	0.73	0.27	1.76	0.49	25.11	2.66	70.7	81.7	63.2	0.67	0.33	1.49	0.60	50.07	2.04	0.88	2.00	0.92	1.22	0.85	0.77	129	76	133	81	129	85	123	84	1.05	0.90
2	2023-22-01	73.5	84.7	62.3	0.71	0.29	1.46	0.60	52.40	2.48	81.5	90.2	61.0	0.56	0.44	1.56	0.70	57.75	1.28	0.98	1.11	0.79	1.52	1.07	0.52	149	81	144	80	139	82	133	79	1.12	1.03
3	2023-23-01	101.3	84.4	54.6	0.52	0.48	1.01	0.31	72.27	1.07	91.3	95.3	58.2	0.64	0.36	1.48	0.60	64.68	1.74	1.07	0.90	1.23	0.75	1.47	1.63	149	85	145	83	146	84	134	79	1.11	1.08
4	2023-24-01	96.7	85.4	55.5	0.55	0.45	0.95	0.69	69.01	1.21	83.7	107.6	62.9	0.62	0.38	1.46	0.83	59.26	1.66	1.13	0.87	1.13	0.84	1.54	1.37	131	80	135	91	93	70	138	91	0.95	0.88
5	2023-25-01	114.0	108.7	52.5	0.76	0.24	2.11	0.68	81.41	3.16	108.1	129.0	53.5	0.71	0.29	1.71	0.71	76.59	2.44	1.02	0.95	0.93	1.21	0.81	0.77	112	78	118	82	122	80	131	86	0.85	0.91
6	2023-26-01	99.7	92.9	51.6	0.72	0.28	1.63	0.55	71.19	2.57	91.6	110.1	55.2	0.75	0.25	1.59	0.81	64.89	3.04	1.07	0.92	1.04	0.89	0.98	1.18	135	80	144	86	128	95	138	85	0.98	0.94
7	2023-27-01	99.2	106.1	54.0	0.41	0.59	1.52	0.63	70.79	0.70	102.5	113.1	56.7	0.47	0.53	1.13	0.84	72.62	0.88	1.05	1.03	1.15	0.90	0.74	1.26	128	75	149	99	137	80	133	81	0.96	0.93
8	2023-28-01	65.1	87.3	60.9	0.90	0.10	1.84	1.14	46.44	8.94	53.5	93.9	66.5	0.71	0.29	1.59	0.93	37.90	2.43	1.09	0.82	0.79	2.90	0.86	0.27	149	80	142	93	135	84	135	85	1.10	0.94
9	2023-29-01	117.4	104.1	50.1	0.69	0.31	1.47	0.43	83.90	2.22	103.0	133.4	53.7	0.90	0.10	1.93	0.87	73.01	8.80	1.07	0.88	1.30	0.32	1.31	3.96	130	73	136	87	130	77	125	77	1.04	0.95
10	2023-31-01	69.5	91.3	60.0	0.53	0.47	1.61	1.16	49.56	1.12	73.9	96.9	58.6	0.43	0.57	1.49	1.08	52.37	0.76	0.98	1.06	0.81	1.21	0.93	0.68	133	78	136	88	135	82	135	88	0.99	0.89
11	2023-01-02	75.7	69.6	49.7	0.47	0.53	1.35	0.41	54.07	0.87	69.8	96.2	54.9	0.73	0.27	1.59	0.87	49.44	2.76	1.10	0.92	1.55	0.51	1.18	3.17	128	76	136	79	132	80	132	77	0.97	0.99
12	2023-05-02	79.5	80.2	55.4	0.45	0.55	1.55	0.91	56.74	0.81	84.7	99.7	56.0	0.56	0.44	1.25	0.90	60.02	1.28	1.01	1.07	1.24	0.80	0.81	1.58	135	83	135	83	135	86	138	88	0.98	0.94

The content of the training sessions in regard to the power output and the heart rate presented with the 2D-KDE can be visualize in the figure 22 and 23 for the subject 1 and 2 respectively, similarly to the daily sRPE, RPE, ROF, training volume (in hours), τ, and PO-HR ratio values.



Date	RR	Temps en mouvement	RPE	ROF
	(Session RPE)	(heures)		
janv. 21 2023	2409	4.2	9.5	6.5
janv. 22 2023	754	2.5	5.0	4.0
janv. 23 2023	424	2.0	3.5	4.0
janv. 25 2023	664	2.0	5.5	3.5
janv. 26 2023	1068	3.0	6.0	4.5
janv. 27 2023	1275	2.8	7.5	4.5
janv. 28 2023	1023	3.1	5.5	4.0
janv. 29 2023	917	2.4	6.5	4.0
janv. 31 2023	292	1.6	3.0	3.0
févr. 01 2023	1289	2.7	8.0	5.0
févr. 02 2023	566	1.5	6.5	4.5
févr. 05 2023	193	1.1	3.0	1.5

Figure 22: Description of the training content of the S1 during the period of the study with the power output and heart rate represented using a 2D-KDE (A), the daily sRPE, training volume in hours, RPE, and ROF on the panel B, and the daily τ and PO-HR ratio (C). Missing HR data are the reason for some missing metrics on the panel C.



B

Date	RR (Session RPE)	Temps en mouvement (heures)	RPE	ROF
janv. 21 2023	1494	4.1	6.0	6.5
janv. 22 2023	259	0.9	5.0	0.0
janv. 23 2023	1782	3.3	9.0	8.0
janv. 24 2023	995	1.7	10.0	8.0
janv. 26 2023	1338	3.7	6.0	6.5
janv. 27 2023	1732	4.1	7.0	8.0
janv. 28 2023	1009	4.0	5.5	3.0
janv. 30 2023	1176	2.5	8.0	7.0
janv. 31 2023	1275	3.5	6.0	6.0
févr. 01 2023	1180	2.5	8.0	7.0
févr. 02 2023	384	1.6	4.0	5.0
févr. 03 2023	1111	2.3	8.0	6.0
févr. 04 2023	449	1.9	4.0	3.0
févr. 05 2023	1448	3.4	7.0	7.0

Figure 23: Description of the training content of the S2 during the period of the study with the power output and heart rate represented using a 2D-KDE (A), the daily sRPE, training volume in hours, RPE, and ROF on the panel B, and the daily τ and PO-HR ratio (C). Missing HR data are the reason for some missing metrics on the panel C.

IV. Discussion

This study offers the opportunity to observe the theoretical basis of autonomic control in SCI subjects in practice and showed that between the theory and field conditions, there is a gap to close. The response is interindividual and generalities on this topic appears to be warranted from the results of our observation.

1) Autonomic nervous system

First of all, the first remark to note regarding the autonomic nervous system of the subject 1 is the presence of a clear activity of the sympathetic nervous system illustrated by a supine LF ranging between 0.27 and 0.69. This confirms the character incomplete of the spinal cord lesion. This note is confirmed by the figure 22A where we can clearly observe part of the training content were spent above 150 bpm while the intrinsic rate of the sinoatrial node is >100 electrical impulses per minute; therefore, parasympathetic withdrawal alone would elicit an HR in the range of 100–130 bpm (Sethi et al., 1984). This confirms what was observed by Currie *et al.* (2015, p. 1262) the “autonomic and neurological completeness of injury are not synonymous”.

At the exception of one day for S1 and three for S2, the HR response is higher in the seated than the supine position. At the same time, the blood pressure delta is slightly positive for both subjects. This suggests that there was a slight decrease in blood pressure from the supine position to the seated position.

Regarding the rMSSD, SDNN, and SD1, the inverse proportional response with HR reprobate from an interpretation knowing that the main explanation for the variation of this metric can be simply a change in HR (Boyett et al., 2019). However, we can observe that even if these two subjects are both professional athletes and performed relatively the same amount of volume in training, the rMSSD is lower for the S1 compared to S2 while their HR are in the same range.

An orthostatic hypertension have been observed only for three days for the S2 (i.e., 24/01; 25/01; 31/01) during the period of observation relating a possible withdrawal of vagal tone or hyperresponsiveness to sympathetic activation (Benowitz et al., 1996). On the contrary, the S1 have recorded an orthostatic hypotension every other day in average (i.e., 21/01; 22/01; 23/01; 26/01; 01/02).

The HRV metrics are fairly consistent between the different days. This suggests that subject 2's autonomic nervous system is relatively stable. The HRV metrics between seated and supine position is variable and in average over the days, they are evenly distributed whether higher or lower one from the other for the S2. On the contrary, for the S1 a biggest variability can be observed with no real trend or relation for example between the blood pressure and HRV metrics changes across the days.

It is important to note that this is just a preliminary assessment. To get a more complete picture and understanding of the ANS function of these subjects through the HRV and the orthostatic challenge assessment, it would be necessary to collect data over a longer period of time and compare it to established norms.

2) τ - Advanced model of the physiological response

In this approach, the initial step involves the creation of a HR model to link markers of internal and of external training loads. In this phase, regression techniques are utilized to identify correlations between HR and PO representing the external training load. In the subsequent part, a fitness-related information is derived about the cyclist by extracting features from the HR model. The first practical interpretation with τ, the centre of mass of the kernel, a lag of τ seconds is roughly introduced for the response of the HR to changing exercise intensity. Furthermore, the rate at which the HR diminishes post-exercise has been identified as a factor associated with physical fitness (Buchheit et al., 2007). In this approach, a fast HR recovery (HRR) signify that only efforts close to the time for which the HR is model are pertinent. In such instances, only a relatively small-time window for the CPP holds importance in modelling the HR. Conversely, extended windows are relevant for slower HRR. The parameter τ, which is obtained from the HR model, indirectly reflects the subject's HRR. A smaller value of τ indicates a faster HRR, suggesting better physical fitness. Conversely, a larger value of τ implies slower recovery and lower fitness. This parameter essentially serves as a rough indicator of the athlete's recuperation time and inversely correlates with their physical condition.

It's important to note that τ encapsulates the influence of various factors beyond power that impact HR. These factors include factors like altitude, weather conditions, and general wellness, including stress levels and sleep patterns. While it would be ideal to explicitly model each of these factors, this approach effectively captures their combined effect through a single parameter, τ. This simplified approach offers a more practical and efficient method for assessing fitness as compared to modelling each factor individually.

The figure 22C and 23C display the recuperating time monitoring. We can make a few observations about that. First, the S1 shows a clear trend of increase of his τ value suggesting a fatigue accumulation over this period of time, consistent with the loading period of training. At the contrary, the S2 shows a quite different response regarding his τ metric. His τ is more stable during the period of observation by with a high inter-day variability.

These repones are corroborated with the PO – HR ratio showing a very similar response in term of variability and trend over the period of the study. However, while attractive at first glance, the utilization of this metric is trickier than it might seem. Even if we can compute a ratio on these two continuous variables, their individual characteristics (e.g., limits, kinetic, etc.) are different and as a consequence, their relation is not linear. This is one of the reasons explaining the benefits of using a kernel to model the HR based on the PO; their relation is visually closer to a sigmoid than a linear slope. This makes their analysis and comparisons tricky. To avoid any over-interpretation, we need to compare what is comparable, so to speak either two ratios with whether a similar HR or a similar PO, either to weight the ratio with the optimal kernel.

3) RPE: a gestalt to monitor the training

The RPE and sRPE are good markers of the load of the session the athlete has achieved. However, unlike to what has often been published and explained, this should never be interpreted alone. At least, the objective difficulty of the session has to be measured but as we know, to date there is not a single marker to reflect objectively the difficulty of a bike session. The reason why RPE is so important is because it helps to measure the impact of a session without having to perform a maximal effort or something similar at some point as explained in the chapter 1 of this thesis. The main issue is when contradictory information arises from different markers of session load and body responses and/or adaptations for a given day. For instance, the theory from textbook and literature teaches us that HRV, through the parasympathetic tone (i.e., rMSSD), would increase when the body is "ready to work" and vice-versa when the HRV decreases. However, the body would theoretically be more ready to perform a physical task the day after an easy day than the day after a having performed a high quantity of work. Nevertheless, this phenomenon is not observed in our data. Considering this kind of observation have been observed and reported occasionally in regard to the HRV response, we advise practitioners to rely on the RPE and sRPE response to stimuli and monitor their kinetic over time as the most reliable metric for training supervision.

V. Conclusion

In conclusion, our study revealed distinct autonomic responses in spinal cord injury subjects, emphasizing the complexity of its regulation. The utilisation of a time constant (τ) provided insights into physiological responses to exercise and the exploratory utilisation of RPE and sRPE as quantitative variables emerged as valuable markers for training load monitoring. Contradictions between different markers of training stress and training load underscored the need for a multifaceted approach. Overall, our findings contribute to understanding autonomic control in SCI subjects and emphasize the importance of a comprehensive approach in training supervision.

Chapter 7: Multi-month training monitoring in cycling: Utilization of the rating of perceived exertion to track the training adaptation

I. Introduction

Within the domain of sport science, the intricate interplay between psychophysiological response and the adaptive processes induced by training remains a focal point of interest. We wanted to go deeper in the understanding of the adaptation of the RPE in line with the findings of the chapter 1 of this thesis highlighting the importance and relevance of the RPE in training monitoring. While RPE has been extensively studied in the context of acute exercise, its adaptation over prolonged training periods remains relatively unexplored. This study aims to bridge this gap by examining the long-term changes in RPE in response to systematic training interventions.

Prior research has primarily focused on short-term adaptations, often within weeks of training initiation. However, relevant physiological adaptations to endurance training for which we're interested in are observable and occurs over months and years, not weeks as most studies reported. As a consequence, we aimed to conduct a study that deviates from this trend of short intervention, rarely exceeding few months, by investigating the adaptation of RPE over a prolonged period, encompassing several months and years of training.

To gain a comprehensive understanding of RPE adaptation, we employed two distinct approaches. First, we assessed RPE during laboratory-based physiological evaluations, providing a controlled environment to isolate the effects of exercise intensity on RPE. Second, we continuously monitored RPE after training sessions measured as session RPE (sRPE), capturing the dynamic nature of RPE in real-world training scenarios during the periods between psychophysiological assessments. We expect the combination of these information help us better understand the pivotal role of RPE in endurance training adaptations to training and performance improvements.

The psychophysiological underpinnings of RPE necessitate further exploration. RPE is influenced by a complex interplay of factors, such as prior exercise experiences and physiological fitness. By considering the theoretical background of RPE expanded in the discussion of the chapter 1 of this thesis, we aim to unravel the mechanisms underlying its adaptation with training.

Moreover, we investigate the potential influence of RPE and its associated training load metric, the session RPE (sRPE), on the kinetics of adaptation of key psychophysiological parameters. We seek to elucidate the intricate relations between RPE and key psychophysiological parameters that characterize an athlete's performance and overall fitness level. By examining the relationship between RPE and these parameters, we seek to elucidate the role of RPE in regulating both immediate and long-term training adaptations

This study represents a multifaceted approach to understanding the adaptation of RPE with training. By encompassing long-term training periods, employing laboratory and field-based training monitoring, and considering the psychophysiological context of RPE, we aim to provide novel insights into the mechanisms and implications of RPE adaptation in athletes.

II. Methods

1) Participants

4 competitive cyclists (3 men and 1 women) were recruited to participate in this study. They were asked to refrain from strenuous exercise, consumption of alcohol and caffeine for at least 24 h before each test. Smokers, people with a cardiopulmonary disease history, injuries and illnesses were excluded.

2) Experimental overview

The training of the subjects was monitored during the extent of the study and they performed maximal incremental tests across the duration of the investigations with a maximum interval between two assessments of one year.

Subjects performed a maximal incremental test to exhaustion (INC) on a cycle ergometer riding their own bike with an initial intensity of 1 min @50w and then the ramp increment in intensity was 30w·min^{-1}. In the meantime, the RPE was measured using the Borg's RPE scale with the methodology proposed by Borg (1998). The RPE recorded at the 5th minute of the INC will be used as a marker of RPE adaptation to training considering the nature of the test. Peak power output (PPO) is defined as the highest 30 sec power output moving average. Additionally, the main physiological characteristics suggested previously to characterise training status will be reported (Toffoli et al., 2022). The readers are referred to the data processing instructions detailed in the chapter 3 for the methodology applied to the ventilatory variables. The $\dot{V}O_2$max is defined as the highest 30 seconds $\dot{V}O_2$ moving average. The gross efficiency is measured using the equation proposed by Brouwer (1957), and the macronutrient oxidation rate using the stochiometric equations proposed by Frayn (1983).

During every training session, HR (Garmin HRM-Dual; Garmin Ltd, Lenexa, KS, USA) was recorded. Cadence, moment of force and power output (PO) were recorded with a mobile power meter mounted on his recumbent bike (SRM Professional Training systems, Schoberer Rad Messtechnik, Jülich, Germany, and Power2max). Occasionally, during some sessions, the HR or PO was not recorded due to technical issues, however this issue only affects a paucity of sessions. The subjects were instructed on the use of the bike computer and informed of the importance of performing the zero offset frequency procedure to obtain accurate PO data. Data were sampled at 1 Hz. After every session, the subjects returned through a questionnaire their average rating of perceived exertion (RPE) during the session and the level of fatigue he perceived (ROF) at the end of the training session. For these two subjective rating, a magnitude estimation method anchored at the extreme with 0 & 10 representing respectively no effort perceived and the maximal perceived exertion was used. Decimals were allowed and subjects were instructed to use numerals as numbers with common criteria of equality and addition. A score that multiplies RPE with the duration (in minutes) of training is computed as a general metric of strain of the training sessions (sRPE). For this purpose, we used a linear multiplication by convention. However, the “ideal” multiplicative process (e.g., exponential, logarithmic, etc.) would depend on the aspect of the sRPE we want to highlight, whether its impact on the acute performance decrement (Kesisoglou, 2020), subsequent training adaptation, etc.

III. Results

The RPE recorded during the INC for each intensity (PO) at different points in time are reported in the figure 24. The table 15 reports the longitudinal evolution of the psychophysiological characteristics of each subject for every INC performed.

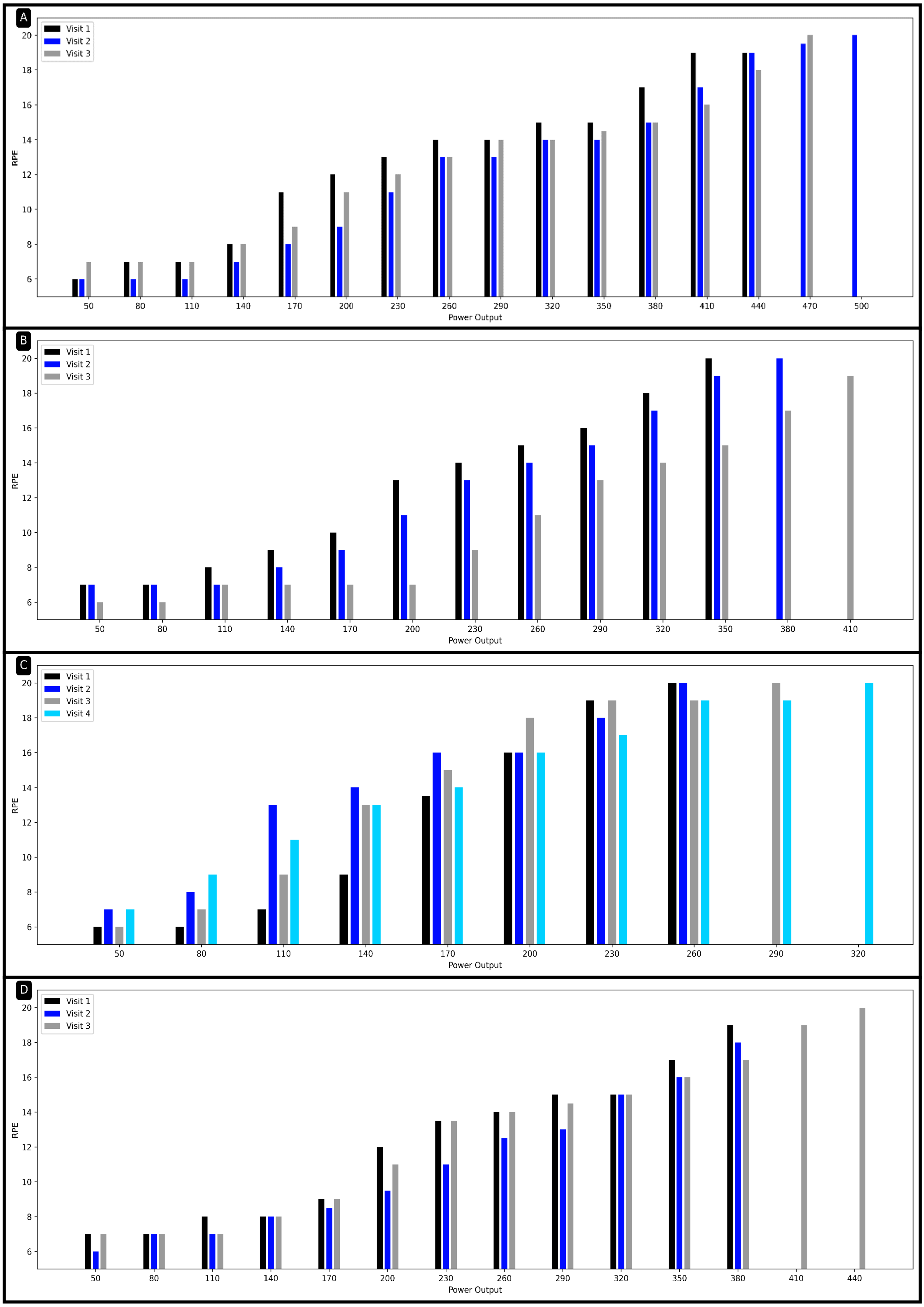
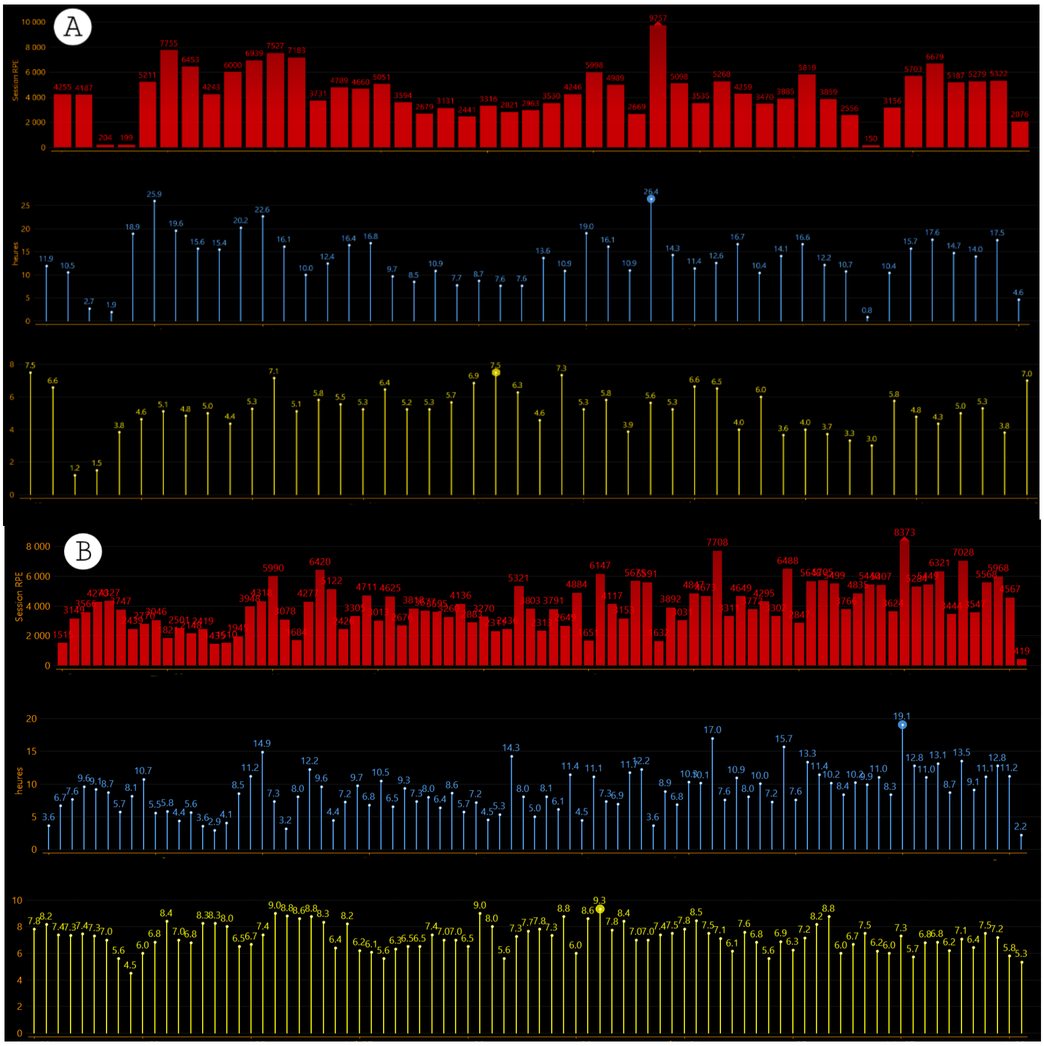


Figure 24: RPE recorded during the different INC for each subject (A, B, C, D), in chronological order from visit 1 to visit 3 or 4.

Table 15: RPE value at the 5th minute, PPO, absolute $VO2_{max}$, relative VO_{2max}, gross efficiency, Fatmax and power at Fatmax are reported in the table for each subject (S1 to S4), and for every INC performed.

	RPE value at the 5th minute (@ 170w)	PPO (W)	Absolute VO2max (mL/min)	Relative VO2max (mL/kg/min)	GE % (@ 50% PPO)	GE % (@ 150w)	Fatmax (g/min)	Power @Fat max
S1-Visit 1	12	461	5328	74	20,73	21,22	0,94	264
S1-Visit 2	9	498	5520	74,4	20,96	21,06	0,92	280
S1-Visit 3	11	481	5552	79,4	20,88	20,63	0,90	240
S2-Visit 1	13	350	3736	63,5	17,85	19,87	1,04	245
S2-Visit 2	11	364	4193	75,4	19,56	18,81	0,71	260
S2-Visit 3	7	412	4781	82,4	19,79	22,17	0,26	162
S3-Visit 1	16	262	2449	46	15,66	20,96	0,26	54
S3-Visit 2	16	270	3365	64,7	17,6	23,22	1,11	176
S3-Visit 3	18	297	3161	59,3	21,14	23,83	0,64	50
S3-Visit 4	16	319	3348	61,7	19,96	22,57	0,35	118
S4-Visit 1	12	461	4112	56,3	16,05	17,19	0,24	116
S4-Visit 2	9,5	406	5007	71,1	19,95	21,02	0,91	242
S4-Visit 3	11	457	5297	74,2	21,32	22,37	0,83	253



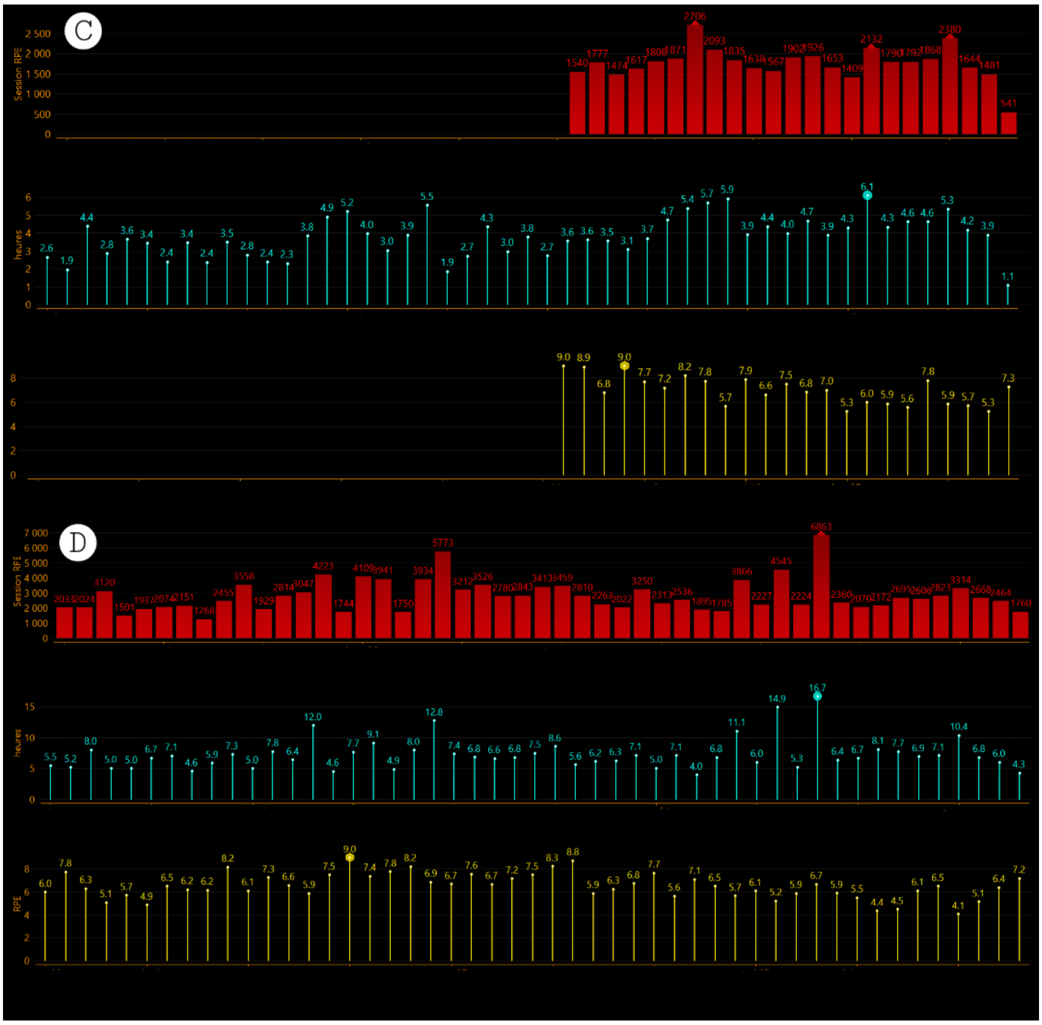


Figure 25: Training monitoring reports for subjects 1 to 4 (A to D respectively) with the sRPE at the top, the training volume (in hours), and the average RPE at the bottom. Each data are groups per weeks from the date of the first INC to the date of the last INC for each subject. Some subjective reports are missing for S3 due to logistic reasons.

IV. Discussion

This longitudinal study reports the response and adaptation of RPE to changes in fitness level and training volume and intensity (figure 25). One of the first things we can say is that the RPE tend to decrease during the INC test for a given PO over time with training as show in the figure 24. Moreover, this study provides unique exploratory data of training monitoring using RPE over such a long period of time, and foremost as a continuous variable like in previous chapters on which we can apply mathematical computations. On this point, we have to raise a remark for future studies aiming to measure sRPE.

The current standard method for calculating sRPE is simply to multiply the RPE score by the duration of the training session in minutes. This linear approach has been widely adopted due to its simplicity and intuitive interpretation. However, it has been suggested that other multiplicative processes, such as exponential or logarithmic functions, could better reflect the true strain of a training session and its impact on various aspects of performance and adaptation. The rationale for using non-linear multiplicative processes stems from the observation that the relationship between RPE and duration is not strictly linear. In other words, a longer training session with a constant RPE may not necessarily result in a proportional increase in strain. This is because the physiological and psychological stresses experienced during exercise accumulate gradually with time, and the effects of these stresses may not be linearly additive. An exponential multiplicative process, such as an exponential decay function, could potentially better capture the non-linear relationship between RPE and duration. An exponential decay function would suggest that the strain of a training session increases rapidly at first and then tapers off as the duration increases. This could reflect the fact that the body's ability to adapt to exercise stress is limited, and prolonged periods of high-intensity exercise can lead to overtraining or premature exercise cessation.

Through this study, one of the aim was to test experimentally the general conclusion of the review from the chapter 1 of this thesis that was in line with the theoretical background explained on this occasion. Our findings are divergent as our observations are both in line and at the opposite of the conclusion from the chapter 1. Let's expand it briefly. For the subject one, the submaximal RPE decrease with the marker of physical performance, the PPO, like for the subject 2. For the subject 3, the results are contrasted and opposite to what we expected from our theoretical explanations and outcomes of our systematic review. One explanation for these discrepancies can be the variations in emotional states of the subjects during the INC, that can influence strongly the outcomes, whether it is the submaximal RPE of the maximal performance (i.e., PPO). When related to a physiological marker of oxidative capacities, the VO_2max, the results are similarly contrasted but the VO_2max is not a measure of performance, and as a consequence is not opposed to the outcome of our review, just an observation highlighted here.

V. Conclusion

In conclusion, this longitudinal study delves into the intricate dynamics of psychophysiological responses, particularly focusing on the adaptation of the Rating of Perceived Exertion (RPE) over extended training periods. Our findings reveal a nuanced relationship between RPE, training volume, and intensity, with a notable decrease in RPE observed during incremental tests over time, a marker of training adaptation. The study also raises critical considerations for future investigations, urging a re-evaluation of the linear approach in calculating session RPE, proposing that non-linear multiplicative processes may better capture the complex interaction between RPE and training duration. Despite divergent observations for some subjects, our multifaceted approach contributes valuable insights into the mechanisms and implications of RPE adaptation in athletes, paving the way for further exploration in the field of sport science.

General Discussion

I. Main Findings

The primary thrust of this doctoral thesis lies in the meticulous exploration of the physiological and psychological intricacies governing the perception of effort, specifically in the context of endurance sports. A central revelation surfaced early in the journey - a critical methodological flaw at the metrological level affecting the measurement of perceived exertion. Chapter 2, devoted to this ascertainment, undertakes a profound metrological analysis, rectifying the error and establishing a foundation for the ensuing investigations.

The subsequent chapters apply this refined metrology in practical scenarios, unravelling the kinetic nuances of perceived exertion and its intricate relation with bodily (physiological) responses. A novel dimension is introduced by extending the study to high-level athletes grappling with spinal cord injuries, providing a unique lens into their psychophysiological responses during exercise and in context of longitudinal monitoring.

The overarching findings elucidate that the impact of endurance training on performance and perceived exertion is multifaceted. The specificity of training adaptation is intricately tied to the modality employed. The study uncovers that training can yield improvements in performance while concurrently diminishing perceived exertion, or conversely, impair performance and elevate perceived exertion. Additionally, there are instances where training induces no discernible alterations in either performance or perceived exertion.

Venturing into the dynamics of ventilatory variables during incremental running, the study reveals that critical intervals in the last 90 seconds distinctly influence perceived exertion. Ventilatory responses, particularly $\dot{V}CO_2$, $\dot{V}O_2$, and RPE, emerge as crucial discriminators of intensity variations. Mutual information analysis underscores a meaningful exchange between $\dot{V}O_2$ and RPE, offering practical insights for exercise physiology, training prescription, and performance optimization. Indeed, as it was reported episodically in previous research, RPE can be used as a marker of relative exercise intensity, that's to say, when we know the RPE necessary to elicit a given $\dot{V}O_2$ relative the

VO_2max, we can use the RPE as a proxy to regulate the exercise intensity based on relative physiological response. Physiological profiling is costly and not accessible regularly for majority of people, hence the results from the chapter 3 of this thesis reinforce the utility of RPE as a tool to prescribe exercise aiming to elicit a desired physiological response.

On another aspect, the investigation into individuals with spinal cord injuries across various exercise modalities and the success of live high train low (LHTL) strategies in altitude acclimation for paracyclists accentuates the applicability of perceived exertion as a dynamic parameter for monitoring and optimizing the acclimation process.

II. Limitations

Notwithstanding the significant contributions, it is imperative to acknowledge the limitations inherent in this research. The sample sizes and study designs, though meticulously executed, pose constraints on the generalizability of the findings. The intricacies of psychophysiological responses and the kinetic nuances of perceived exertion, while offering valuable insights, are tempered by the constrained scope of some protocols.

Methodologically, the reliance on specific scales, such as the IVAS method for RPE measurement, introduces a degree of specificity that warrants careful consideration. It is essential to underscore that no single scale is inherently superior to measure the RPE; rather, the choice should be context-dependent. Moreover, the linear approach in calculating session RPE, while extensively discussed, merits continued scrutiny, as the study proposes that non-linear multiplicative processes may better capture the complex interaction between RPE and training duration.

III. Perspectives

Looking forward, this comprehensive exploration opens avenues for further research and refinement. The refined metrology proposed in Chapter 2 lays the groundwork for future studies, encouraging researchers and practitioners to adopt a more scientifically rigorous approach in subjective measurements related to the perception of effort. The wide range of contexts investigated in the course of this thesis provides a solid starting point for future research whose aim is to measure the perception of effort.

The multifaceted nature of training adaptation and its impact on perceived exertion necessitate continued investigations into the underlying mechanisms. Longitudinal studies with larger and more diverse cohorts can contribute to a more nuanced understanding of the interplay between training, performance, and perceived exertion.

The insights gained from the intricate dynamics of ventilatory variables and their relationship with perceived exertion during incremental running provide a basis for future studies exploring the broader physiological markers influencing the perception of effort.

Moreover, the application of perceived exertion as a monitoring tool in unique populations, such as individuals with spinal cord injuries, presents a rich area for further exploration. Expanding the understanding of psychophysiological responses in these populations can inform tailored interventions and contribute to the broader discourse in sports science.

IV. Fitness monitoring: benefits to use the RPE

When we connect the results of our work from this thesis to the numerous studies relating to the monitoring of physical condition, this allows us to glimpse the creation of a theoretical framework allowing a more precise description of the psychological (PSY) & physiological (PHY) state of a person practicing a physical exercise of endurance.

This theoretical framework is based on the cross-interpretation of three variables which are the RPE, the HR, and an objective measurement of the energy produced. For the latter, we will take the example of cycling and use the PO.

Our model uses the combination of the ratio between RPE and HR (RPE:HR) and between RPE and PO (RPE: W). This creates the possibility of encountering 9 different observable situations which are presented in Table 16.

Table 16: Theoretical framework characterising the psychophysiological state of an individual performing an endurance physical task. The first columns represent the variation in the RPE : HR ratio, the second column represent the variation of the RPE : W ratio and the third column represent the interpretation to have for each line when facing a given combination of variation in both ratio. "PSY" is the abbreviation used for "psychological state" and "PHY" is the abbreviation used for "physiological state".

RPE : HR	RPE : W	Interpretation
=	=	-

⬆	=	⬇ PSY
⬇	=	⬆ PSY
=	⬆	⬇ PHY
=	⬇	⬆ PHY
⬆	⬆	⬇ PSY ⬇ PHY
⬆	⬇	⬆ PSY ⬆ ⬆ PHY
⬇	⬆	⬆ PSYCHO ⬇ ⬇ PHY
⬇	⬇	⬆ PSY ⬆ PHY

In regard to the computation of the two ratios, we have to remind the reader that these variables have different properties and as a consequence, to compare a ratio whether a weighting must be applied or one of the variable for each ratio has to be similar to the one it is compared to.

Using this framework, we solve the problem of the HR / PO ratio often proposed in literature but incomplete to draw an insightful description of subject's response to exercise. As an example of the limit of the HR / PO ratio, it can decrease in the case of physical fatigue (overtraining) but a similar response is observed in the case of an improvement of fitness. Our framework proposed in the table 16 however can discriminate both situations.

To provide another example, in the situation of someone exercise with a reduced carbohydrate storage, the 4th line of the table will be able to depict the origin of the situation, whether it is physiological or psychological (Heigenhauser et al., 1983).

Obviously, through our framework, we don't get a full detail of the cause of a variation in performance, but this is an additional step in this direction.

General Conclusion

In conclusion, this doctoral thesis not only advances our current understanding of perceived exertion but also sets the stage for continued inquiry. The rectified metrology, nuanced findings, and identified limitations collectively offer a springboard for future research, ensuring a progressive and informed trajectory in the exploration of the perception of effort in exercise science and sports performance.

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