Quantification of Training and Competition Loads in Endurance Sports: Methods and Applications

Iñigo Mujika

Training quantification is basic to evaluate an endurance athlete's responses to training loads, ensure adequate stress/recovery balance, and determine the relationship between training and performance. Quantifying both external and internal workload is important, because external workload does not measure the biological stress imposed by the exercise sessions. Generally used quantification methods include retrospective questionnaires, diaries, direct observation, and physiological monitoring, often based on the measurement of oxygen uptake, heart rate, and blood lactate concentration. Other methods in use in endurance sports include speed measurement and the measurement of power output, made possible by recent technological advances such as power meters in cycling and triathlon. Among subjective methods of quantification, rating of perceived exertion stands out because of its wide use. Concurrent assessments of the various quantification methods allow researchers and practitioners to evaluate stress/recovery balance, adjust individual training programs, and determine the relationships between external load, internal load, and athletes' performance. This brief review summarizes the most relevant external- and internal-workload-quantification methods in endurance sports and provides practical examples of their implementation to adjust the training programs of elite athletes in accordance with their individualized stress/recovery balance.

Keywords: external load, internal load, intensity, monitoring, training adaptation

Training is a process whereby athletes are exposed to systematic and repetitive exercise stimuli with the goal of inducing adaptations matched to a desirable function, such as delaying the onset of fatigue, increasing power output, refining motor coordination, or reducing the risk of injury. Coaches and trainers generally consider that the outcome of the training process depends on the type and amount of the stimulus, and understanding this cause-and-effect relationship between training dose and response is crucial to prescribe exercise training accordingly.¹

Nevertheless, to analyze and establish causal relationships between the training performed and the resultant physiological and performance adaptations, accurate and reliable quantification of the training load undertaken by the athlete is a *sine qua non*. It is simply not possible to identify the effects of training without a precise quantification of the training load.² This is the reason why several sport-science experts have previously underlined the importance of proper training quantification. For instance, Pollock³ highlighted that many investigators reported their results without quantifying their training procedures, and with no mention of energy cost, heart-rate intensity, miles covered, and so on. Along the same lines, Hopkins⁴ indicated that with the links between training and outcomes such as performance and injury being so strong, it is surprising that the methodology of measurement of training has not been a focus of attention in the sport-science literature. He considered it to be a blind spot that some papers reporting the effects of training neglect to describe or state the method by which the measures of training were obtained. Similarly, Foster et al⁵ underlined that the ability to

monitor training is critical to the process of quantitating training periodization plans.

More recently, Borresen and Lambert⁶ and Lambert⁷ thoroughly described the methods available for coaches and researchers to quantify the training loads undertaken by athletes, and made recommendations regarding their practical use both in sports and research. Halson⁸ also highlighted the importance of monitoring the training load to determine whether an athlete is adapting to the training program and to minimize the risk of nonfunctional overreaching (fatigue lasting weeks to months), injury, and illness and summarized the potential quantifying and monitoring tools available. Saw et al⁹ systematically reviewed objective and subjective measures of athlete well-being to guide training and to detect any progression toward negative health outcomes and associated poor performance.

Whatever the quantification methods used, they can be defined as quantifying either external or internal training load.^{7,8} The external training load is an objective measure of the work that an athlete completes during either training or competition and is measured independently of the internal workload. This is in contrast with the internal workload, which assesses the biological stress imposed by the training session and is defined by the disturbance in homeostasis of the physiological and metabolic processes during the exercise training session.⁷ It is important to emphasize that the external training load does not measure the biological stress imposed by a given training session. In fact, 2 athletes may undertake an identical external training load but experience quite different internal loads, depending on their fitness, training background, and genetic characteristics.⁷

In view of the importance sport scientists and coaches attribute to external and internal training load quantification, most especially in endurance sports, this brief review aims to summarize the most relevant workload quantification methods in long-duration, cyclic sports (eg, running, cycling, rowing), and provide practical examples of their applications to adjust the training programs of elite athletes in accordance to their individualized stress/recovery balance.

The author is with the Dept of Physiology, University of the Basque Country, Leioa, Basque Country, and the School of Kinesiology, Finis Terrae University, Santiago, Chile. Address author correspondence to inigo.mujika@inigomujika.com.

The Basics of Training-Load Quantification in Endurance Sports

Performance in most endurance events is determined to a great extent by the maximal sustained power production for a given competition distance and the energy cost of maintaining a given racing speed. In shorter endurance events and during accelerations, establishing breakaways, and sprint situations, anaerobic capacity and maximal speed may also contribute to endurance performance and competition outcomes.¹⁰ This implies that both low- to moderate- and high-intensity training are important for endurance athletes to optimize adaptive signaling and technical mastery at an acceptable level of stress,^{11–13} and thus training-load-quantification methods should cover the entire range of training intensities, in addition to other training variables, such as volume and frequency, and a range of training modalities used by endurance athletes (Table 1).¹⁴

Data relating to training loads and to athletes’ responses and adaptations can be of interest to athletes, coaches and sport scientists. According to Hopkins,⁴ training-related data can have a motivational impact on the athlete by heightening his/her awareness of time and effort investment, promoting a pride in achievement and encouraging a more systematic and goal-oriented approach to training. In addition, physiological monitoring may be motivational per se, by making the athlete feel part of a select group receiving sport-science support, while direct observation may be motivating because athletes perceive that other sport specialists around them are taking keen interest in their training and competition activities. A systematic approach to training quantification also facilitates training prescription and assessment of compliance, and sport scientists can and should rely on training and competition quantification to

carry out descriptive and experimental studies on training effects, performance prediction and enhancement, recovery, injury prevention, and so on. Mujika² considers the information about training (ie, training quantification) the most important information for a study on training manipulation, and the lack of a precise description of the training contents, in terms of volume, intensity, and frequency before and during a training intervention a fatal limitation of many sport-science studies, rendering them basically useless. Therefore, precise information about training quantification is absolutely necessary as manipulation of a training program is the basis of many studies in our field.

In this respect, coaches and sport-science researchers should always bear in mind that there are 3 distinct external training loads that may vary significantly in a training program: the load planned before the season (or study) starts, the load prescribed on a daily basis, and the actual load completed by each individual athlete. The latter is the load that should be quantified and reported for both sports training and research purposes.² Given that no absolute gold-standard method exists that defines the training load that is applicable to all endurance sports under all circumstances, factors like accessibility, feasibility, degree of labor intensity, cost-efficiency, validity, and reliability need to be considered when a decision is made about which method should be used to quantify training and competition load. Practitioners need to understand and accept that all methods present advantages and limitations, variable levels of accuracy and suitability for specific sports and training or competition situations.⁷ In his 1991 review on methods and applications of training quantification, Hopkins⁴ classified quantification methods into 4 major groups: retrospective questionnaires, diaries, physiological monitoring and direct observation. Retrospective questionnaires and diaries obtain data recalled from the athlete’s memory after training, and can yield information on any aspect related to training. On the positive side, they are cheap and easy to administer, and they do not interfere with the training program; on the negative side, they rely on an athlete’s memory and subjectivity, so the information gathered may be intentionally or unintentionally distorted or forgotten. In addition, diaries may present problems of compliance and also management and interpretation of the huge volume of data they can generate. More objective training measures can be obtained by physiological monitoring and direct observation. Oxygen consumption (VO₂), heart rate (HR), and blood lactate concentration ([La]_{blood}) have all been extensively used to objectively determine the intensity of training, but each of these methods presents its own limitations (eg, VO₂ is not a suitable method to quantify supramaximal training bouts, field HR values may be affected by environmental conditions, and [La]_{blood} may not be a suitable measure of intensity above the lactate threshold, which in addition can be calculated by different methods yielding variable results). Direct observation can also provide objective measures of most aspects of training, but is time-consuming and may introduce a subjective error for each observer. All in all, although physiological monitoring and direct observation can provide valid and reliable measures of training intensity, they may be too expensive and impractical for continuous long-term use for practitioners with limited access to technical and/or financial resources.⁴

To gain an understanding of the external training load and its effect on the athlete (ie, internal load), a number of potential markers are available for use,⁸ in addition to those already mentioned herein. These include power output, speed, and acceleration; critical power; time–motion analysis relying on various technologies such as video-based analysis systems, semiautomatic multiple-camera

Table 1 Training Variables Quantified Daily and Individually for an Entire Season in a Group of National- and International-Level Swimmers^{14,37}

Training variable
Frequency (sessions/d)
Total volume (km)
Intensity I (km ≤2 mM blood lactate)
Intensity II (km 2–4 mM blood lactate)
Intensity III (km 4–6 mM blood lactate)
Intensity IV (km ≥6 mM blood lactate)
Intensity V (km sprint swimming)
50 m pool (km)
25 m pool (km)
Normal swim (km)
Arm pulling (km)
Kicking (km)
Front crawl (km)
Medley (km)
Own stroke (km)
Strength swim (increased resistance to advance, km or min)
Stroke rate (km to develop stroke frequency)
Distance per stroke (km to develop stroke distance)
Weight lifting (dry-land strength training, min)

systems, and commercially available global positioning systems; measures of neuromuscular function such as countermovement and/or squat jump, sprint performance, and isokinetic and isoinertial dynamometry; rating of perceived exertion (RPE)¹⁵; session RPE¹⁶; HR-to-RPE ratio; training impulse (TRIMP)^{17,18}; [La]_{blood}-to-RPE ratio; HR recovery^{19,20}; HR variability^{20,21}; summated HR-zone score²²; HR-running speed index,²³ biochemical, hormonal, and immunological assessments; psychomotor speed assessed using computer-based reaction time and rapid visual information-processing tasks; and sleep quality and quantity. A comprehensive review of all available methods and tools is beyond the scope of this brief review, and readers are referred to the thorough reviews by Borresen and Lambert,⁶ Lambert,⁷ Halson,⁸ and Saw et al.⁹

Lambert et al^{24,25} have previously discussed practical ways of gathering training and adaptation related information to monitor levels of fatigue in an athlete with the goal of continuously adjusting training prescription according to the symptoms that manifest in response to the training program. To that end, these authors consider that the information gathered needs to assist the coach to answer the following questions: How hard did the athlete find the session? How hard was the session? How did the athlete recover from the session? How is the athlete coping with the cumulative stress of training? In response to these questions, Lambert and Borresen²⁴ suggested using RPE in every session, TRIMP and/or session RPE in every session, Kenttä and Hassmén's²⁶ perceived and action recovery scales and a muscle-soreness scale on a daily basis, the Profile of Mood States (POMS) questionnaire²⁷ and the recovery heart-rate test²⁸ on a weekly basis, and the Daily Analysis of Life Demands for Athletes (DALDA)²⁹ on a daily basis. In line with these recommendations, Saw et al⁹ recently performed a systematic review to assess whether subjective measures accurately reflected changes in athlete well-being, as objectively measured by performance, physiological and biochemical indicators, and whether subjective measures were responsive to acute changes in training load and chronic training. Their findings indicated that subjective measures respond to training-induced changes in athlete well-being, which typically worsened with an acute increase in training load and with a chronic training load but improved with an acute decrease in training load. In addition, there was no consistent association between subjective and objective measures, leading the authors to recommend that athletes report their subjective well-being on a regular basis and alongside objective athlete-monitoring practices.

Both external and internal loads contribute to the quantification of an athlete's actual training load, and a combination of both may be the key for proper training monitorization.⁸ Monitoring daily training load might contribute to optimize athlete development, due to better training regulation and the possibility of detecting overtraining or injuries early on.³⁰ Assessing the relationship between external and internal loads, and between these and competition performance may aid in the evaluation of stress/recovery balance and the adjustment of individual training programs to optimize adaptation. A recent systematic review³⁰ suggested the combination of quantitative and qualitative data as the most promising approach to evaluate the training load and athletes' response to the training. It also indicated that validated questionnaires or RPE, combined with physiological parameters such as heart rate, are often used on a daily basis and seem to provide the most reliable training related information. From the coaches' perspective, training duration and mode, RPE, and personal remarks in the athletes' training diaries were considered essential information.

Relating External Load and Performance

Descriptive training studies can be used to characterize the training undertaken by athletes or examine relationships between training contents and variables directly or indirectly related to performance.⁴ We have recently followed this approach to simply describe the training behavior of a world-class female triathlete preparing to compete in the London 2012 Olympic Games (Figures 1, 2, and 3)³¹ and a long-distance world-champion male paratriathlete.³² Based also on daily quantification of training intensity, volume, and frequency during an entire season in high-level swimmers on one hand and repeated performance assessments in competition on the other, Mujika et al¹⁴ studied the relationships between training variables and performance variations over the season. This simple approach allowed them to describe a training-intensity distribution that matched what a decade later would be conceptualized as a polarized training-intensity distribution.³³ They also found that training intensity, rather than volume or frequency, was the key factor in producing a training effect leading to performance improvements during the season. In addition, they reported that previous detraining and the level of performance at the beginning of the season could jeopardize athletic success in spite of a good adaptation to training.¹⁴

In an attempt to identify optimal overload and tapering strategies in elite swimmers over time, Hellard et al³⁴ also used a mathematical modeling approach based on the quantification of the external training load and competition performances. Training variables were derived from the weekly training volume at several intensity levels. Training patterns were identified from total training loads during 3 weeks of overload training and 3 weeks of tapering by cluster analysis, and mixed modeling was used to analyze the longitudinal data. This approach allowed the authors to conclude that during the overload training period 6 to 4 weeks before major events, swimmers adopted an optimal training design consisting of 84%, 81%, and 80% of the mean total training load. During the first week of the taper, they maintained a medium training load, followed by a load decrease according to a slow decay logarithmic pattern in the following 2 weeks (58%, 56%, and 44% of the mean total training load). They also suggested that over the course of the swimmers' athletic careers, these schedules should change, with an increase in training load during the overload period followed by a sharper decrease in the taper period.

These studies are some examples of the scientific and applied interest of training load quantification, in conjunction with competition performance assessment. This type of approach, requiring no technological gadgets or expensive equipment, could yield quite interesting outcomes to understand the training-performance relationships, enhance training effectiveness, and optimize individual performances.

Relating External Load, Internal Load, and Performance

Both external and internal loads have merit for understanding an athlete's training load and training adaptations, and a combination of both may be important for training monitoring and performance prediction.^{7,8} Forty years ago, Banister et al¹⁷ proposed a systems model of the effects of training as a method to study an athlete's response to training. To understand the fluctuations of athletic performance during periods of heavy training separated by periods of relative rest or tapers, the mathematical model generated estimated fatigue and fitness profiles from a training impulse computed from

Figure 1 — Weekly training volume performed by the athlete over the 50-week training and competition season. Note that swim volumes are expressed in kilometers, whereas bike and run volumes are expressed in hours.³¹ Reprinted with permission from Mujika I. Olympic preparation of a world-class female triathlete. *Int J Sports Physiol Perform.* 2014;9:727–731. © Human Kinetics.

Figure 2 — Total training load, expressed in arbitrary units, over the 50-week training and competition season. The boxes over the horizontal axis indicate competitions, and the numbers within, competition placing. Empty boxes represent low-priority competitions not contributing to world rankings. Gray boxes represent high-priority races contributing to the world rankings. The black box represents the highest-priority race of the season: the London 2012 Olympic Games.³¹ Reprinted with permission from Mujika I. Olympic preparation of a world-class female triathlete. *Int J Sports Physiol Perform.* 2014;9:727–731. © Human Kinetics.

Figure 3 — Training-intensity distribution, expressed as a percentage of total training volume (including swim, bike, and run volumes), over the 50-week training and competition season. Black bars represent training intensities below the athlete's individual lactate threshold (ILT); white bars represent training intensities between the ILT and the onset of blood lactate accumulation (OBLA); gray bars represent training intensities above the OBLA.³¹ Reprinted with permission from Mujika I. Olympic preparation of a world-class female triathlete. *Int J Sports Physiol Perform.* 2014;9:727–731. © Human Kinetics.

training. According to this model, the level of performance of an athlete at any time of the training process can be estimated from the difference between a negative function (fatigue) and a positive function (fitness), resulting from each training bout and their accumulation. The training stimulus is quantified from the volume and the intensity of training. In a somewhat different approach, fatigue and fitness indicators have been estimated from the combination of the 2 opposite components of the model and described as the negative and positive influences of training on performance (NI and PI, respectively).³⁵ This approach was used by Mujika et al³⁶ to relate swimming training with performance and estimate individual profiles of NI and PI to study specific physiological reactions of the swimmers to a particular training stimulus. They also showed that 3- to 4-week progressive tapers resulted in ~3% improvements in the swimmers' competition times, attributed to a reduction in NI during the tapers. The PI did not improve with the tapers, but it was not compromised by them either.

Expanding on the training and performance data collected on the swimmers mentioned herein, Mujika et al³⁷ proposed a method of individually evaluating the responses to the different swim-training components to enhance training effectiveness. They concluded that studying individual relationships between training content and performance by means of simple and stepwise regression analysis, along with the individual NI and PI profiles derived from the mathematical model of the effects of training on performance, could help coaches in assessing each swimmer's responses to training and individualizing training according to each swimmer's specific responses and reactions.

The relationships between external load, biological markers of internal load and competition performance have been used to assess training adaptation in highly trained swimmers. In a descriptive longitudinal study, Mujika et al³⁸⁻⁴⁰ quantified individual external training load during an entire season and tested the swimmers for hormonal, metabolic, immunological, and hematological markers of internal load on 3 occasions during a period of intensive training, immediately before and after a taper, during which training volume was progressively reduced but training intensity and frequency were maintained. To assess the effects of intensive training and tapering on performance, the swimmers participated in competitions held less than 1 week after each blood-sampling session. Contrary to their expectations, plasma hormones and metabolic indices previously identified as markers of training stress were unaltered by 12 weeks of intensive training and 4 weeks of tapering. However, the testosterone-to-cortisol ratio appeared to be an effective marker of the swimmers' performance capacity throughout the training season.³⁸ The external load induced no changes in blood leukocyte populations during intensive training, but significant changes were observed after the taper, and improvements in immunological markers seemed to correlate with desirable effects of tapering on competition performance.³⁹ The swimmers' hematological status improved during intensive training, suggesting a positive adaptation to the external load. Competition performance improvement was positively related with the red cell count at the end of taper. Furthermore, posttaper red cell count, hemoglobin, and hematocrit levels were higher in swimmers responding to the taper with more pronounced performance improvements.⁴⁰

In a description of the various types of sport-science studies relying on load quantification, Hopkins⁴ mentions studies of training characterization, which describe the training behavior of athletes in a given sport and/or compare training and competition behavior. Note that until the late 1990s sport scientists had neglected to characterize the competition behavior of professional

road cyclists, in terms of both external and internal load. In an attempt to fill such a knowledge gap, Padilla et al⁴¹⁻⁴⁵ published a series of studies in which they described exercise intensity and load during the major 3-week professional stage races (ie, Giro d'Italia, Tour de France, Vuelta a España). Recording distance, time, speed, and HR during racing, and based on individual HR-power output curves and exercise intensity thresholds previously determined in the laboratory, they estimated competition power outputs and quantified TRIMPs during short and long individual and team time trials⁴²; flat, semimountainous, and high-mountain stages⁴³; second, first, and off-category mountain passes⁴⁴; and assessed the physiological and performance capacities of professional road cyclists in relation to their morphotype-dependent specialty.^{41,45} The advent of portable power measuring devices allowed a direct determination of the external load during cycling racing (ie, power output),⁴⁶ and this type of measurement can conveniently be carried out in parallel with markers of internal load (eg, HR, RPE) to make fitness and fatigue assessments.⁸

Continuing on with their assessment of the relationships between external load, internal load and competition performance, Mujika et al^{47,48} carried out 2 consecutive experimental studies of potential performance enhancement by way of manipulating training variables during the taper in well-trained middle-distance runners. In the first study,⁴⁷ individual external load was quantified in terms of volume, frequency and intensity during 15 weeks of regular training, and the load was then manipulated during a 1-week taper by progressively reducing the training volume by either 50% or 75%. Blood samples were obtained and 800 m competition performance was determined before and after the taper. The taper-induced physiological changes were mainly hematological, and distinct physiological changes were elicited from low-intensity continuous training and high-intensity interval training during the taper. In a subsequent similar study,⁴⁸ the authors manipulated training frequency during the taper, randomly assigning the runners to a high frequency taper or a moderate frequency taper, consisting of training daily or resting every third day of the taper. Maintaining a daily training frequency during a 6-day taper was more appropriate for optimizing 800-m running performance than a moderate 33% reduction in training frequency. None of the analyzed blood markers of internal load could explain performance differences between the 2 tapering protocols, but tapering brought about increases in immunological, hematological, hormonal, and metabolic markers, indicating that high blood lactate concentrations and a hormonal milieu propitious to anabolic processes seemed to be necessary for optimal 800-m running performance.

It is quite clear that the assessment of the relationships between external load, internal load, and performance can help sport scientists, coaches and other practitioners to examine the dose-response relationship and make a meaningful impact on training prescription and competition performance.

Concluding Remarks

There is no doubt that sport science has come a long way in the past few decades in the development and validation of methods and tools to quantify training and competition loads on the one hand, and the assessment of training adaptations on the other. Nevertheless, as previously indicated by Borresen and Lambert,⁶ we should keep in mind that no accurate quantitative means exists with which to prescribe the pattern, duration, and intensity of training required

to produce specific physiological adaptations, and that individual athletes adapt differently to identical training stimuli. Attempts have been made over the past 4 decades to describe training adaptations and predict competition performance by means of mathematical models that rely on training quantification and performance outcomes.^{17,35,36,49,50} Nevertheless, no single physiological marker has been identified that can accurately quantify the fitness and fatigue responses to training or predict competition performance. This implies that sport scientists probably need to direct their efforts toward the measurement of markers that reflect an athlete's global capacity to respond or adapt to training.⁶

Halson⁸ nicely summarized the key features of a sustainable athlete-monitoring system to ensure that data are effectively captured and reported, which include ease of use and intuitive design, efficient result reporting, ability to be used effectively remotely, possibility of data translation into simple outcomes such as effect sizes, flexibility and adaptability for different sports and athletes, simple and efficient identification of a meaningful change, assessment of cognitive function, and provision of both individual and group responses.

As highlighted by Coutts,⁵¹ an important role of sport scientists is to drive innovation in an attempt to gain a fair competitive advantage. However, a drive for innovation and integration of the most recent technologies into daily training quantification and monitoring practices should not take sport science away from effective industry practices, simplicity, validity, reliability, and integrity. In Coutts' own words, in the age of technology, Occam's razor still applies (ie, more things should not be used than are necessary, or it is futile to do with more things that which can be done with fewer). This scientific approach will allow sport scientists to integrate and benefit from technological advancements and hopefully have a positive impact on athletes' competition performance.⁵¹ Nevertheless, practitioners should not be led to the wrong conclusion that the most simple, noninvasive, less-expensive practical methods such as HR are the perfect solution to the training load quantification and athlete adaptation conundrum. For instance, Buchheit²⁰ recently emphasized that measures of HR cannot inform on all aspects of wellness, fatigue, and performance. Therefore, their use in combination with daily training logs, psychometric questionnaires, and noninvasive, cost-effective performance tests may offer a better solution to monitor training status in endurance athletes.

Expanding on the theme of embedding sport-science research into high-performance sports, Coutts⁵² recently presented a conceptual model for the complementary relationship between faster-thinking sport-science practitioners working directly with athletes and coaches, and slower-thinking applied researchers working in the background and not directly involved with the training process on a daily basis. According to this model, the sport scientist working at the sharp end of high-performance sport needs to provide coaches and athletes with innovative, efficient, and effective performance programs; deliver immediate feedback on individual athletes' training responses and adaptations; and feed data to the slower-thinking academic researcher. In turn, the latter should provide evidence base to the systems and methods used in the field, such as determining the signal-to-noise ratio in measurement tools, establishing the validity of new technologies, and providing the evidence to support the proof of concept for innovations and training methods.⁵² These concepts and ideas regarding a sound use of evidence based simple, valid and reliable innovations and technologies should be kept in mind by sport scientists, coaches and other sport practitioners when deciding on their quantification and monitoring methods and tools for endurance sport training and competition.

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This article is dedicated to the memory of Coach Juanxo González (1928–2017). In far-from-ideal material conditions (e.g., 2–3 lanes of a 25-m indoor public pool for dozens of swimmers per session) but with phenomenal passion and dedication, Juanxo managed to coach hundreds of local swimmers in Bilbao and Pamplona for almost 50 years. As he was a true pioneer of training quantification and individualization, all his swimmers were required to keep detailed training diaries that he would check one by one at the end of each month. My love for swimming and my fixation with training quantification grew from the seed he planted. *Agur t'erdi Juanxo!*

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