Regulation of Energy Expenditure during Prolonged Athletic Competition

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ABSTRACT

FOSTER, C., J. HOYOS, C. EARNEST, and A. LUCIA. Regulation of Energy Expenditure during Prolonged Athletic Competition. *Med. Sci. Sports Exerc.*, Vol. 37, No. 4, pp. 670–675, 2005. **Background:** Athletic competitions, such as the Tour de France, demand both momentary bursts of very high power output and the ability to provide high levels of energy expenditure for several weeks. As such, they provide a model of the ability for sustained muscular activity, which is important in terms of how humans are understood, not only as athletes, but also within an evolutionary context. **Methods**: Laboratory correlated HR responses were made of elite professional cyclists ($N = 7$) during successive competitions in one of the three grand tours in cycling in successive years, with the intent of evaluating the magnitude and pattern of energy expenditure. HR recordings were normalized into a training impulse (TRIMP) score, summating the intensity and duration of each race, and tracked over the duration of successive tours. **Results**: Although the day-by-day pattern of HR responses in exercise intensity zones associated with exercise intensities below the first ventilatory threshold, between the first and second ventilatory thresholds, and above the second ventilatory threshold varied in response to the course and competitive situation, the net accumulation of both time in each of the HR zones and TRIMP was remarkably constant from one tour to the next, both within the group at large as well as within individual athletes. The magnitude of accumulation of TRIMP was similar to that of previous reports on elite tour cyclists. **Conclusions**: We interpret these results as evidence that humans adopt a pacing strategy designed to optimally distribute energy reserves over the duration of each tour. **Key Words:** EXERCISE, TRIMP, CYCLING

The physical accomplishments of athletes are remarkable as examples of the limits of human adaptability, and instructive regarding the locomotor capabilities of the species. Scientific studies have focused on the anatomic and physiologic characteristics of elite athletes (1,2,4,18,23) on correlative studies comparing physiologic capabilities and performance (4,5,16,23), on responses during prolonged training (6,15,18,22,26) and competition (7,19–22), and on a global understanding of the "performance picture" (16). Recent studies have focused on the pattern of energy expenditure during competition (e.g., pacing) (8,12,13). These studies are of interest in light of the recently proposed teleoanticipation hypothesis (24), which proposes that humans monitor the magnitude of metabolic disturbance during exercise with the intent of preventing homeostatic disturbances that might cause injury. In this regard, the classic 3-wk bicycle tour races (Giro de Italia, Tour de France, Vuelta a España) represent a unique model of prolonged, high-intensity exercise during which each day of competition presents energy expenditure equal to or greater than any other single-day athletic competition (e.g., Olympic marathon or cycling road race), but repeated for about 21 d (21,25). Studies performed with athletes capable of completing such events have demonstrated remarkable physiologic capabilities (21), challenges to the balance of energy metabolism (3,25), and profound hormonal/metabolic disturbances (7,20). Lucia et al. (20) have used HR monitors during such competitions to estimate the metabolic requirements of these events. Analysis of HR records from the grand bicycle tours have demonstrated that shorter tours (Vuelta a España) are completed at higher intensities than longer tours (Tour de France), such that the summated HR "score" or training impulse (TRIMP) is similar (22). This suggests that there might be an upper limit to the sustainable rate of relative energy expenditure that is revealed in these athletic events. As such, this information may be useful in terms of understanding the limits of human energy expenditure.

In this study, we sought to evaluate the exercise responses to repetitions of the same tour in successive years by the same athlete, with the intent of determining whether there is a "pacing strategy" used by the athlete to regulate energy expenditure over the duration of the tour.

METHODS

The subjects for this study were elite professional cyclists ($N = 7$). Their anthropometric and physiologic characteristics were similar to those reported previously (21) (Table 1). The subjects provided informed consent before testing, in

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TABLE 1. Characteristics of the subjects.

Characteristic	Mean	SD
Age (yr)	27	1
Height (cm)	180.0	5.2
Body mass (kg)	68.1	6.2
Peak power output (W)	504	51
$\dot{V}O_2$ peak (mL·min^{-1}·kg^{-1})	75.9	6.5
Professional cycling experience (yr)	5	1

accordance with the protocol at the European University of Madrid. Each subject completed one of the classic 3-wk cycle tour races in each of two different racing seasons. Although the specific course changes slightly from year to year, and the tours differ somewhat from each other (22), the general format, number of stages, total distance, and number of rest days within each tour are remarkably similar from year to year (21). The tours completed by each subject included S1 (Vuelta 1998 and 1999), S2 (Vuelta 1997 and 1998), S3 (Vuelta 2000 and 2001), S4 (Vuelta 1997 and 1998), S5 (Vuelta 2000 and 2001), S6 (Vuelta 2000 and 2001), and S7 (TdF 2001 and 2002).

Before each tour, the subjects underwent physiologic testing, which allowed matching of HR to the relative metabolic state (19,22) and identification of three metabolic zones corresponding to less than the ventilatory threshold (VT1) (zone 1, low intensity), between VT1 and the respiratory compensation threshold (VT2) (zone 2, medium intensity), and above VT2 (zone 3, high intensity), as in previous studies (19). During each tour, each subject wore a telemetric HR monitor that recorded HR every 15 s throughout each exercise stage, including warm-up. The relative energy requirement of each stage was computed by multiplying the duration of exercise within each HR-defined metabolic zone by a multiplier for that intensity zone (zone 1 = 1, zone 2 = 2, zone 3 = 3) (11). Summation of the zone-adjusted HR records allowed computation of the TRIMP across the duration of different tours performed by the same athlete. This allowed us to compare time in each zone on a day-by-day basis, accumulated time in each HR-defined zone, as well as TRIMP on a day-by-day and accumulated basis. The monotony (mean/SD) for TRIMP, an index predictive of negative responses during training (9), was calculated for the entire tour.

Because each race was performed on a different course, and the timing of rest days was slightly different from race to race, we only performed statistical comparisons at the end of each week of paired races in successive years using repeated measures ANOVA. Further, because a given TRIMP could be achieved by different combinations of intensity and duration, we compared the week-by-week time in each metabolic zone using repeated measures ANOVA.

RESULTS

On a day-by-day basis, the pattern of accumulation of time in each of the HR-defined intensity zones, as well as the pattern of accumulation of TRIMP, varied in accordance with the plan of the race within each year (Figs. 1–4). Nevertheless, the overall pattern was substantially similar

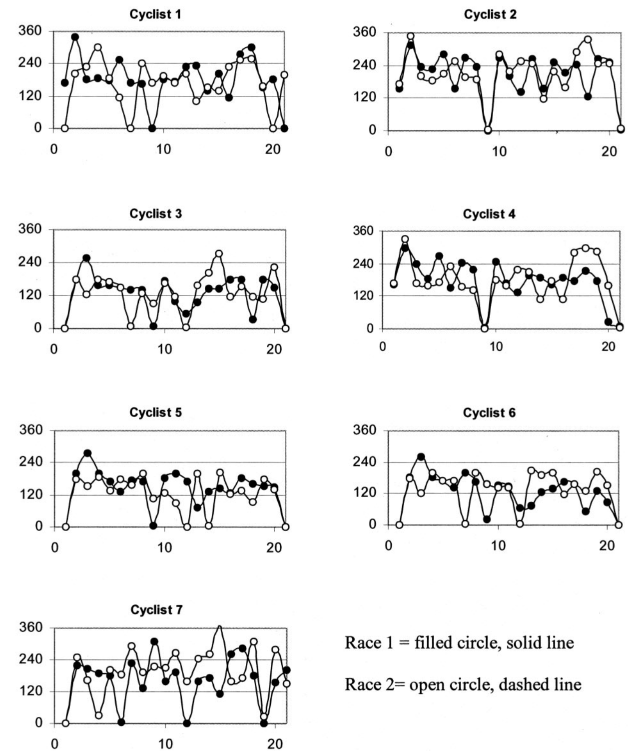

FIGURE 1—Day-to-day variation in zone 1 time.

for each athlete. The mean (±SD) values for time in zone for race 1 and race 2 were: zone 1, 1581 ± 223 and 1464 ± 284 min; zone 2, 1227 ± 180 and 1213 ± 228 min; and zone 3, 97 ± 33 and 84 ± 52 min. The mean (±SD) value for

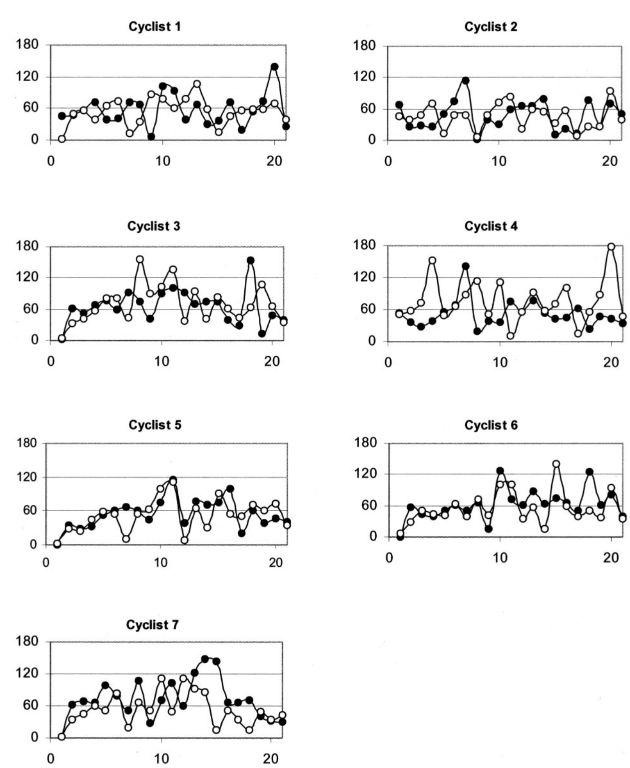

FIGURE 2—Day-to-day variation in zone 2 time.

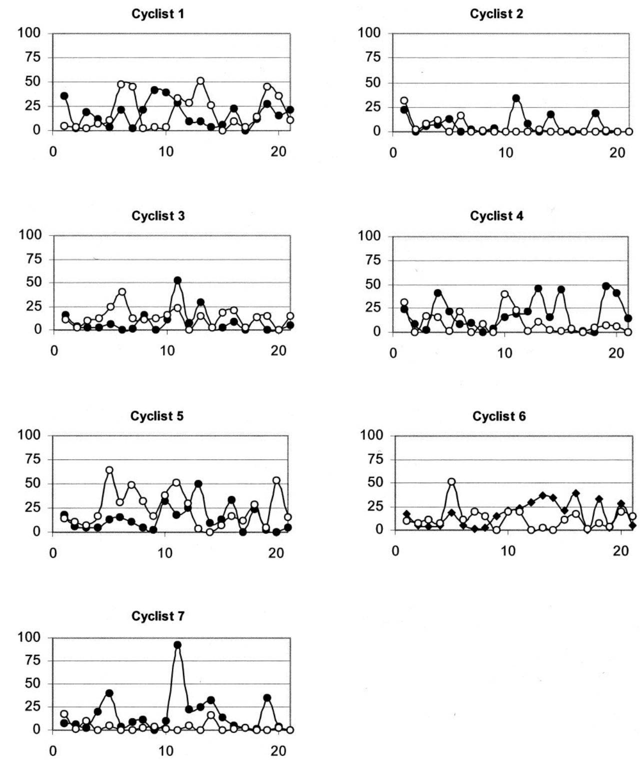

FIGURE 3—Day-to-day variation in zone 3 time.

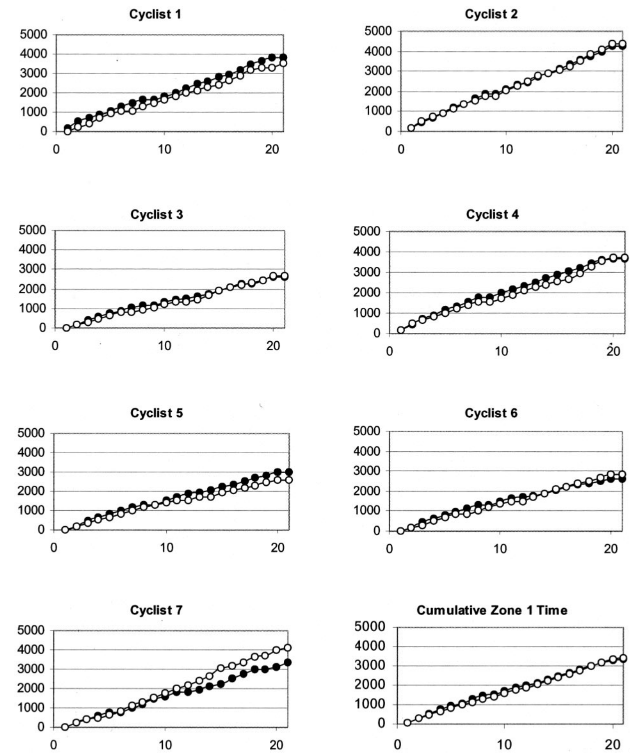

FIGURE 5—Cumulative zone 1 time.

TRIMP was 6634 ± 960 and 6284 ± 1343. The monotony (mean/SD) for TRIMP was 2.98 ± 0.29 and 2.87 ± 0.42.

The net accumulation of time in zones 1–3 and of TRIMP is presented in Figures 5–8). There was a remarkable similarity, both for the entire group and for individual athletes, of all exercise intensity markers, but particularly for TRIMP. With minor exceptions, the upper limit of TRIMP was on the order of 2000 TRIMP units per week (Fig. 8).

At the end of each week, there were no significant ($P < 0.05$) differences in the accumulation of time in any of the

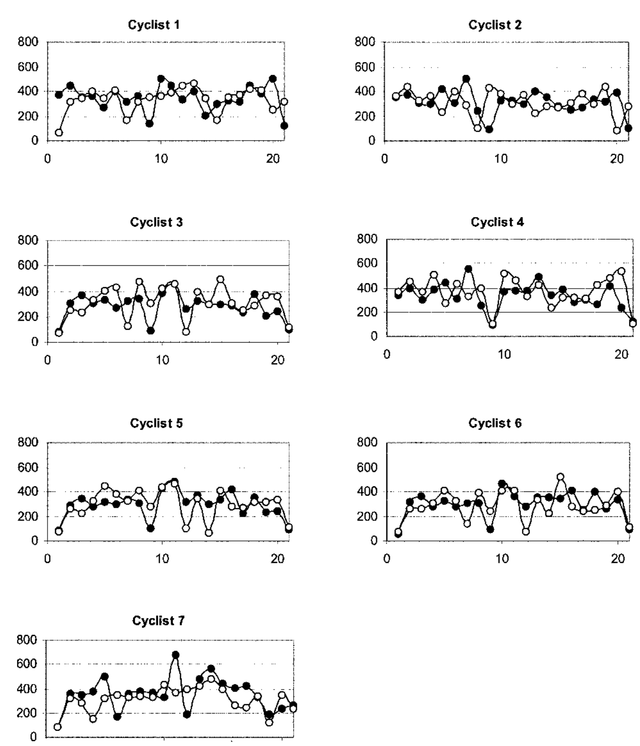

FIGURE 4—Day-to-day variation in training impulse score.

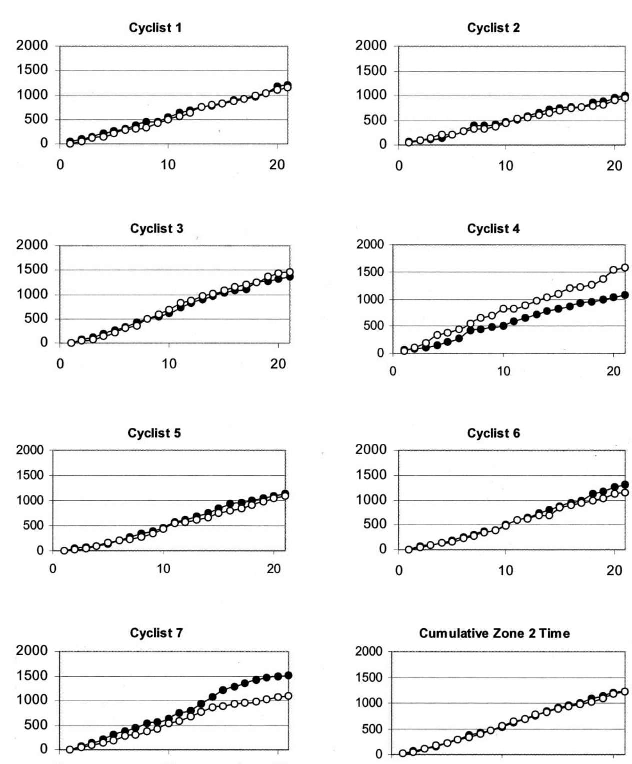

FIGURE 6—Cumulative zone 2 time.

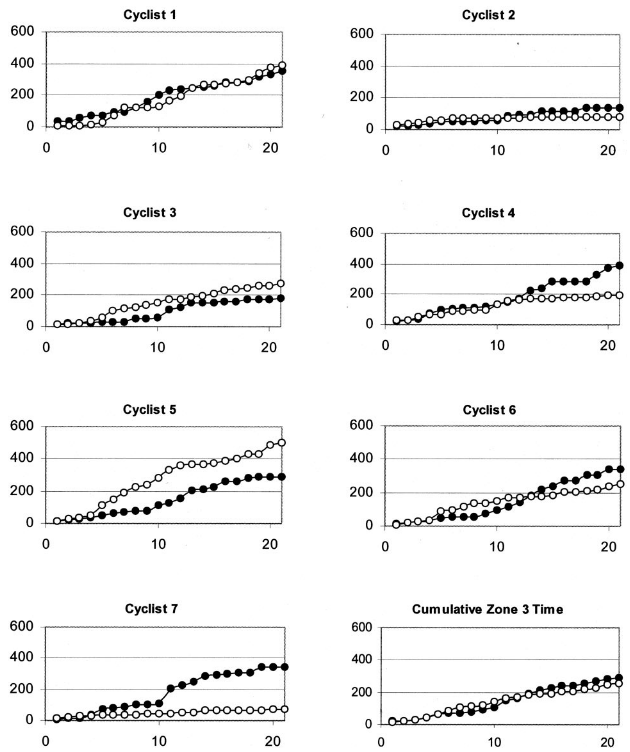

FIGURE 7—Cumulative zone 3 time.

three HR-defined zones or in the accumulation of TRIMP between races completed in different years, despite different courses and different competitive situations from year to year (Table 2).

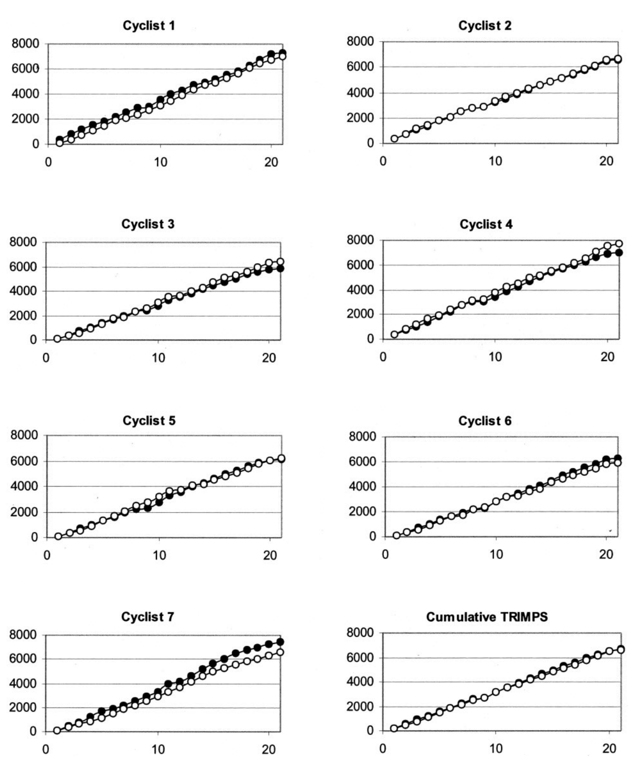

FIGURE 8—Cumulative training impulse score (TRIMPS).

DISCUSSION

The present data demonstrate that the rate and pattern of accumulation of relative exercise intensity and of the duration × relative intensity product (TRIMP) in professional cyclists, during some of the most demanding events in the world of sports, are remarkably consistent from year to year. As such, the data are consistent with the concept that these athletes are actively regulating their rate of energy expenditure. Just as athletes employ pacing patterns to optimize performance in competitions ranging from a few minutes to a few hours in duration (8,12,13), the present data suggest that qualitatively similar pacing patterns are employed in competitions of up to a 3-wk duration. This magnitude of energy expenditure, expressed using the HR-based TRIMP score (~2000 TRIMP units per week), is consistent with other studies on professional cyclists (19), and beyond comparable data collected during training in elite Kenyan runners (~800 TRIMP units per week) (2), subelite runners (~400 TRIMP units per week) (6), and elite junior Nordic skiers (~800 TRIMP units per week) (26). There are no directly comparable data during the training of professional cyclists, but reasonable estimates are 1000–1500 TRIMP units per week (21). It is remarkable that, in addition to the large value for TRIMP, the monotony of the exercise loading was also quite high (~2.9). Using a somewhat different approach to measuring exercise intensity, we have previously shown that monotony scores (a measure of the day-to-day variability of exertional effort) in excess of 2.0 contribute to the development of overtraining syndrome (10). Other studies, however, have shown that the session RPE and HR-based methods of evaluating exercise intensity are qualitatively similar (11). Both the total exercise load (TRIMP) and the monotony of exercise are predictive of maladaptations during training (9). Accordingly, it seems quite reasonable that athletes such as these professional cyclists frequently demonstrate abnormal hormonal responses during the grand tours (7,20), which mimic those observed in overtraining syndrome. In that regard, it is surprising that professional cyclists are very unwilling to take substantial rest on the designated rest days of the tours. For reasons that are beyond scientific explanation, it is

TABLE 2. Mean (± SD) accumulation of minutes in each of the heart rate–defined exercise intensity zones and TRIMPS during each week of race 1 and race 2.

	Race 1	Race 2
Week 1		
Zone 1	1286 ± 259	1106 ± 270
Zone 2	373 ± 60	327 ± 100
Zone 3	73 ± 29	106 ± 49
TRIMPS	2250 ± 346	2077 ± 361
Week 2		
Zone 1	2292 ± 437	2212 ± 471
Zone 2	838 ± 127	840 ± 175
Zone 3	206 ± 68	188 ± 104
TRIMPS	4599 ± 411	4457 ± 446
Week 3		
Zone 1	3278 ± 637	3242 ± 734
Zone 2	1190 ± 184	1192 ± 249
Zone 3	280 ± 101	242 ± 152
TRIMPS	6513 ± 558	6427 ± 593

TRIMPS, training impulse score.

normal for riders to train for ~2 h, including some high-intensity elements (~150 TRIMP units) on the so-called rest days. It would seem that an understanding of why the athletes feel compelled to avoid rest, which would reduce both the rate of TRIMP accumulation and decrease the monotony during the tours, would be most desirable. Certainly during periods of hard training, athletes routinely cycle their training through hard and easy days (1,6,10,26), and failure to take scheduled regeneration periods is widely regarded as a central feature in the development of overtraining syndrome (9). It can be argued that 2 h of mostly low-intensity training is, relatively speaking, a recovery day. Nevertheless, it still represents a very large amount of exercise.

Nutritional studies have suggested that one of the limiting factors during cycle tours is the ability to consume adequate amounts of carbohydrate to allow for recovery of muscle glycogen stores on a day-to-day basis (3,25). Various studies have suggested that the ability to perform high-intensity exercise (e.g., zones 2 and 3) at certain points within the race is the most important single factor critical to competitive success (21,25). Recent data, presented in defense of the teleoanticipation hypothesis, have demonstrated that when muscle glycogen stores are partially depleted before the beginning of cycle time trials, athletes spontaneously down-regulate their power output in a manner designed to preserve muscle glycogen until the end of the event (14). Our data may be interpreted in light of these findings as supporting the concept that humans can pace themselves over long periods of time. Lastly, although the present results may be interpreted as suggesting an upper limit for sustainable exercise of ~2000 TRIMP units per week, historical evidence (21) from the Tour de France suggests that during the early 20th century, the race was organized with much longer stages. While granting that the riders of this generation probably consumed less carbohydrate and accordingly spent relatively more time at low exercise intensities (e.g., zone 1), the total TRIMP scores may still have been on order of 3000–4000 TRIMP units per week (Fig. 9). However, the need to perform frequent high-intensity exercise to be competitive in contemporary tours may place a premium on the ability to consume carbohydrates to maintain muscle glycogen stores, and thus serve to limit the magnitude of effort.

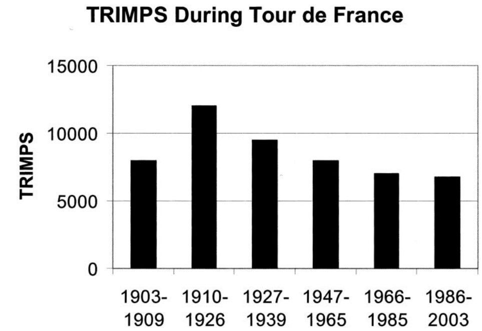

FIGURE 9—Training impulse score (TRIMPS) during Tour de France.

In conclusion, the results of this study provide evidence of a potential upper limit of the relative ability for high-intensity muscular effort over extended periods of time that is on the order of 2000 TRIMP units per week. The results suggest that there may be active pacing of effort across the duration of the tours, which supports the concept that humans are able to actively sense their relative energy reserves and distribute their energy reserves in a manner designed to optimize the competitive result. Although it may be argued that the simple requirements of just completing one of the grand tours is in the neighborhood of 2000 TRIMP units per week, the similarity of TRIMP accumulation on a day-to-day basis suggests to us that the simpler explanation is that athletes followed longer or harder stages with stages in which they rode in the peloton and conserved energy, such that the progressive rate of accumulation of TRIMP remained within a narrow range. The teleoanticipation hypothesis suggests that athletes regulate their energy expenditure on the basis of both experience and sensory feedback within an event. The results of this study suggest that this regulation of energy expenditure may continue, not only over the duration of a single race, but over periods of up to 3 wk.

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