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Modelling the Transfers of Training Effects on Performance in Elite Triathletes

Abstract

This study investigated the effects of 40-weeks training in swimming, cycling and running on performances in swimming, running and triathlon competitions in four elite triathletes. The training stimulus was calculated using the exercise heart rate. The level of performance was measured in running by a submaximal 30 min run, in swimming by a 5 × 400 m all-out test and subjectively in triathlon competitions. A mathematical model using one to three first order transfer functions linked actual and modelled performances by minimizing the residual sum of squares between them. The relationships between training and performances were significant in running ($\tau_1 = 20$; $\tau_2 = 10$; $r = 0.74$; $p < 0.001$) and in swimming ($\tau_1 = 31$; $r = 0.37$; $p = 0.03$), supporting the principle of specificity of the training loads. Cross-transfer training effects were identified between cycling and running ($\tau_1 = 42$; $r = 0.56$; $p < 0.001$), but not with swimming performances. In addition, the training loads completed in running were shown to have a major effect on performances in triathlon competition ($\tau_1 = 52$; $\tau_2 = 4$; $r = 0.52$; $p < 0.001$), indicating that running training is an essential part of triathlon performance. Swimming appears to be a highly specific activity, which does not gain nor provide benefits from/to other activities (i. e. cycling and running). The present study shows that cross-transfer training effects occur between cycling training and running performance in elite triathletes. A similar cross-training effect does not seem to occur for swimming performance.

Key Words
Heart rate · cross-training · specificity · training amount

Introduction

Multi-sports activities (i. e. triathlon, duathlon) have gained in popularity over the last 20 years and official recognition of this has been the inclusion of triathlon as the opening sport at the Olympic Games in Sydney 2000. The development of several multi-sports (triathlon; surf life saving; aquathlon; winter triathlon; duathlon) has generated new questions on the benefits of cross-training.

Cross-training can be defined as 1) the participation in an alternative training mode exclusive to the one normally used in competition [20]; 2) combined alternative training modes with sport-specific regime [20,41]; 3) cross-transfer of training effects from one sport to the other one [28,31,37,41].

A variety of cross-training methods can induce an improvement in general fitness for the recreational athletes [11,20,28,37,41]. However, cross-training effects have been shown to be lower than sport-specific effects in well-trained athletes [33,41]. The exercise needs to be specific [24,38] for the single-sport elite athlete. More generally, cross-transfers have been studied with recreational athletes, but the additional beneficial effects of cross-training for the elite athletes are still questionable and

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Table **1** Selected characteristics of the subjects

Variables	*Subjects*				
	S1	***S2***	***S3***	***S4***	***Mean ± SD***
Gender	Female	Female	Female	Male	
Age (yr)	33	27	33	36	32.3 ± 3.8
Height (cm)	151	165	174	175	166.3 ± 11.1
Mass (kg)	50	59	65	68	60.5 ± 7.9
HR_{max} (bpm)	190	196	175	188	187.3 ± 8.8
$\dot{V}O_2max$ ($ml \times kg^{-1} \times min^{-1}$)	74	68	66	76	71.0 ± 4.8
DT (yr)	9	8	10	10	9.3 ± 1.0
French champion title (n)	3	2	2	2	2.3 ± 0.5
European or World Championships top-3 individual position (n)	1	2	2	0	1.3 ± 1.0

HR_{max} = maximal heart rate; $\dot{V}O_2max$ = maximal oxygen uptake; DT = duration of training for triathlon

controversial [41]. The lack of results based on this population are due to the difficulty of accessing and redesigning their training programs. This is an important limitation in understanding the effects of cross-training in elite athletes.

Modelling the effects of training on performance has been applied on various endurance athletes, including runners [2,3,29] and swimmers [30]. The original model [2,3,5,29] based on estimation of modelled fatigue and fitness has been adjusted recently [6]. In triathlon, quantification of training amounts specific to the three disciplines has never been distinguished. Banister et al. [1] related the global training amount performed in swimming, cycling and running to running performances in order to assess the effectiveness of two tapering methods, but not to identify the different disciplines training effects and simulate the cross-training influences. Thus, the purpose of the present study was to evaluate, by modelling the training effects on performance, the transfers of the training influences in swimming, cycling and running on the performances in these disciplines and on the overall triathlon. The training effects will be also evaluated on the performance in the overall triathlon.

Methods

Subjects

Four elite triathletes provided written informed consent to participate in this study. The four triathletes were full-time professional members of the French national squad and had won international medals and French elite titles. Selected characteristics of the subjects are outlined in Table **1**. Three of the athletes were members of the winning team at the long-distance World Championship Day 237 (Fig. **1**).

Period

The period studied was 40 weeks from the beginning of training early November following a six weeks break until the last important competition early September. In preparation for the World Championship, all the athletes participated in two altitude-training camps during the weeks 10 – 12 and 19 – 20.

Quantification of training amount

Based on the method described by Banister et al. [2], the training stimulus (W) is calculated separately for each discipline (swimming, cycling, running) and for miscellaneous training (i.e. cross-country skiing, weight training). The total training amount is the sum of the swimming, cycling, running and miscellaneous training amount:

$$W = \sum_{j=1}^{j=T} X_j \times d \times k$$

Where $X_j = (HR_j - HR_{rest}) \times (HR_{max} - HR_{rest})^{-1}$, j = time varying between 0 and the end of the session (T), d = 5 s (time elapsed between two samples in the heart rate monitor), HR_j is the exercise heart rate at j, HR_{rest} is the resting HR value, HR_{max} is maximum heart rate and k is a coefficient used to enhance the value of training amounts completed at high intensity.

$k = 0.86\ x_j\ e^{1.67 x_j}$ for women, $k = 0.64\ x_j\ e^{1.92 x_j}$ for men [2].

In addition, when the mean HR of the session was higher than 120 bpm, we calculated the average intensity I, expressed in arbitrary units (a.u.):

$I = W \times T^{-1}$

The athletes recorded their HR during every swimming, cycling and running sessions with a HR monitor (Sport-tester PE4000®, Polar Electro, Finland) and downloaded the data to a laptop computer after each session. When data were not available due to recording problems, the intensities at the different parts of the session were assessed, to calculate the training amount, according to the initial method of Banister and Hamilton [3]. HR_{rest} was self-measured every day when the athletes first awoke and remained in a supine position. HR_{max} was measured separately in the three disciplines once every quarter with a standardised set of 3 x 1 min all out with 30 s recovery [22].

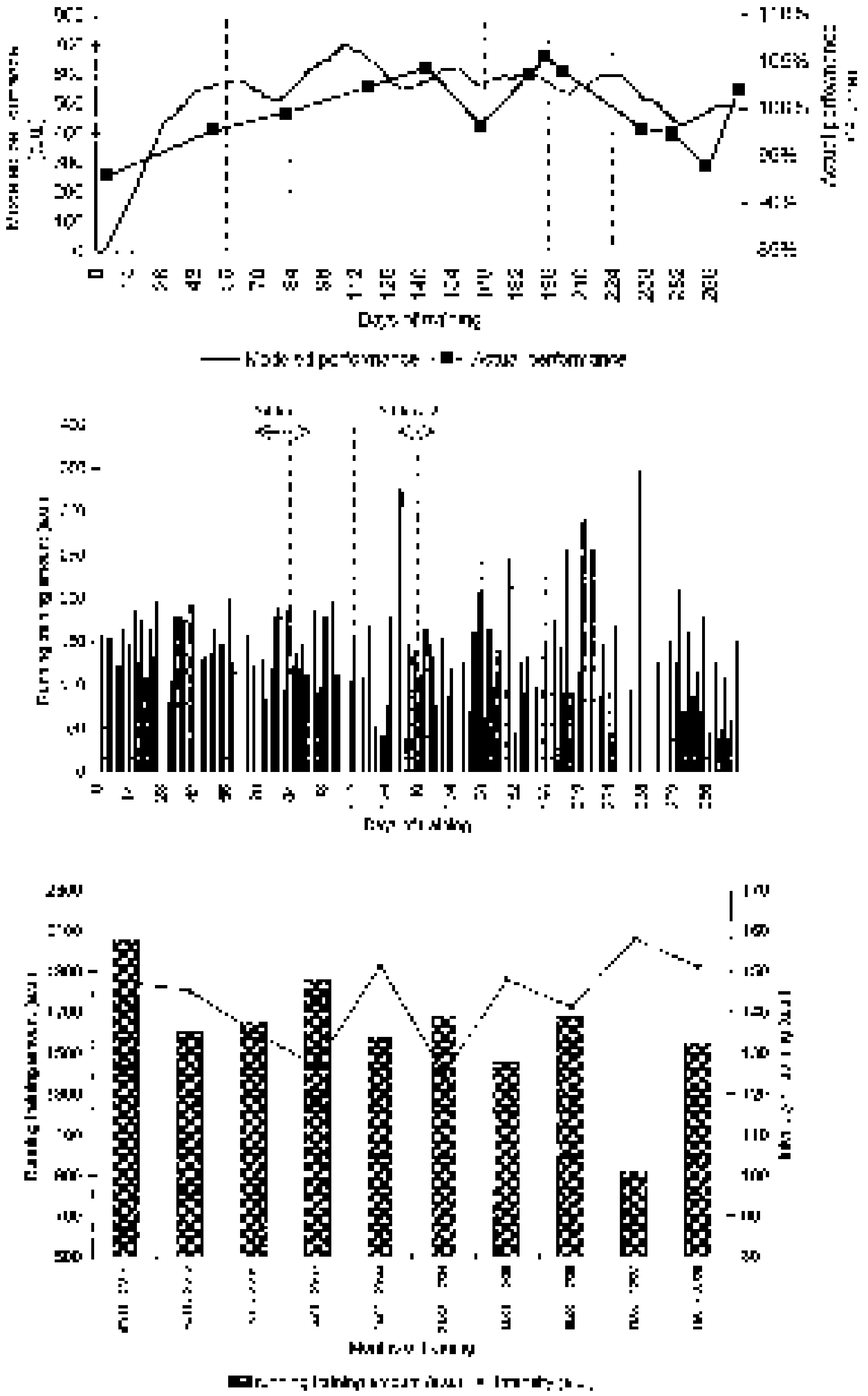

Fig. **1** Example of Subject 1. Below: running training amounts (a. u.) and average running intensity per month; Middle: running training amounts (a. u.) per day. The altitude camps are presented at days 70 – 90 and 133 – 147; Top: modelled and actual performances in running. The actual performances (n = 13) are the performances measured and expressed as a percentage of the mean speed achieved by the athlete during the tests over the period studied.

Quantification of performance

The level of performance was measured in running, swimming and triathlon. Overall, 52 swimming, 50 running and 36 triathlon performances were measured over the period studied. In running, it was expressed as the mean speed achieved by each athlete in a submaximal 30-min test run in a 5 bpm HR zone around the individual lactate threshold. It has been shown that the velocity at the lactate threshold explains a large part of the variability in running performance [13]. The test was always performed early morning on the same flat road to minimise the influence of temperature and circadian variation. The triathlete recorded HR and stabilised his/her pace in order to stay within the defined HR zone. The distance was measured with less than 50 m error margin (i. e. < 0.1 km × h^{-1}). Fig. **1** shows an example of the running performances changes during the season for subject 1. In swimming, the test consisted of a self-paced but all-out 5 × 400 m workout with 30 s recovery. This test set was chosen as the average velocity was very close (i. e. 103 % ± 2 %) to the velocity sustained over the 1500 m (without wetsuit) during the triathlon competition. The performance was expressed as the time achieved by each triathlete over the test set. No criteria of performance in cycling were obtained due to the potential confounding influence of the environmental/external parameters. The performance during the triathlon competition was subjectively assessed through a scale rate from 0 (worst feeling) to 10 (best feeling). Both the triathlete and the coach assessed the per-

Table **2** Characteristics of the training of the subjects during the 280-days period

Variables			***Subjects***		
	S1	***S2***	***S3***	***S4***	***Mean*** ± ***SD***
Swimming hours (h)	216	196	136	233	195 ± 42
Swimming distance (km)	639.3	562.9	444.7	689.2	584.0 ± 106.4
Swimming amount (a. u.)	21 846	20 171	12 056	22 464	19 134 ± 4 817
Swimming intensity (a. u.)	122	115	125	119	120 ± 4
Cycling hours (h)	320	286	294	389	322 ± 47
Cycling distance (km)	8 865	8 049	7 992	11 352	9 065 ± 1 576
Cycling amount (a. u.)	26 787	22 476	19 439	22 148	22 713 ± 3 038
Cycling intensity (a. u.)	103	108	107	93	103 ± 7
Running hours (h)	125	140	119	141	132 ± 11
Running distance (km)	1 518	1 691	1 393	1 958	1 640 ± 245
Running amount (a. u.)	16 018	17 666	12 971	15 160	15 454 ± 1 955
Running intensity (a. u.)	142	132	141	121	134 ± 10
Miscell. Hours (h)	43	65	45	32	46 ± 13
Miscell. Amount (a. u.)	2 880	6 043	2 681	2 371	3 494 ± 1 712
Miscell. Intensity (a. u.)	80	96	75	83	83 ± 9
Rest days (n)	36	22	49	23	32 ± 13
Triathlons (n)	10	11	14	10	11 ± 2
Total hours	705	686	594	795	695 ± 82
Total amount (a. u.)	67 531	66 356	47 147	62 143	60 794 ± 9 388

Miscell. = Other activities than swimming, cycling or running, i. e. cross-country skiing; a. u. = arbitrary unit

formance. The average mark was retained. All performances were expressed as a percentage, 100% being the average of the individual performances along the 40 weeks studied.

Modelling the effects of training

The relation between training and performance is described by a system where the input is the training load W(t) and the output is the performance p(t), both of which are functions of time t. A first-order system is described mathematically by $g(t) = k\ e^{-t/\tau}$ where τ is the decay time constant and k a positive or negative factor inducing respectively an increase or a decrease in performance.

The first studies [2,3] applied a two-components model with two antagonistic systems models ascribed as the fitness (positive function) and fatigue (negative function) responses. However, as shown by Busso et al. [4], the performance can be described by the convolution product of the training loads w(t) with the impulse responses of each system $g_r(t)$ with r varying from 1 to R.

$$p(t) = p^* + w(t) \times g_1(t) + w(t) \times g_2(t) + w(t) \times g_R(t)$$

Therefore the performance on day n is estimated by:

$$\hat{P}_n = p^* + \sum_{r=1}^{r=R} STR_r\ (n)$$

$$\text{where } STR_r\ (n) = k_r \sum_{i=1}^{n-i} w^i e^{-(n-1)/\tau_R} + k_p e^{-n/\tau_R}$$

R is the number of components of the system, $\hat{P}_n$ is the predicted performance in running, swimming or triathlon at day n, K_r is the multiplying factor, τ_R the decay time constant for each of the transfer functions retained, expressed in days. The term p*, the initial decrease of performance due to the previous training amount prior to the period analysed, was neglected as the follow-up period started after 6-weeks of recovery and the residual effects of the previous season were assumed to be very low.

The set of model parameters is determined by minimizing the residual sum of squares (RSS) between predicted and real performances:

$$RSS(N) = \sum_n (\hat{p}_n - p_n)^2$$

With n taking the N values, being the day when the actual performance is measured. The statistical significance was tested by an F ratio on the mean RSS between the predicted and measured performances. The addition of a first-order function was accepted only when it improved the explanation of the performance variations. As described previously by Busso et al. [5,6], the use of the F ratio is possible even for few athletes, if there is a sufficient number of performances and if the two preliminary conditions (normality; homogeneity of variance) are achieved.

The model has been tested for a set of decay time constants τ between 0 and 100 days, a set of number of components between 1 and 3. The model used in the present study related mathematically the resulting swimming (P_{swim}), running (P_{run}) and triathlon (P_{tri}) performances to the amount of training calculated in swimming (T_{swim}), cycling (T_{cyc}), running (T_{run}) and overall (T_{tot}).

The four subjects were homogeneous with regard to their initial level (French national long-distance team), their training program (same coach, same preparation leading to the World Championship, including regular training camps) (Table **2**). The aim of the present investigation was not to study the individual responses to training, but the difference in the training effects among the three disciplines. Thus, the global responses of the squad were analysed instead of the classical method based on individual responses. Thus, the overall analysis has been conducted over 4 × 40 weeks.

Statistical analysis

Mean and standard deviations were calculated for all the variables. The normality of the distribution of the variables was tested and accepted by drawing the histograms of the frequencies of the predicted and measured performances. The homogeneity of variance was tested and accepted by the test of Cochran. Correlations coefficients between the modelled and actual performances were also determined. The P value of 0.05 was accepted as the level of statistical significance.

Results

Training distance, duration, amount and intensity in each discipline are presented in Table **2**. The relationship between training amount and performance was significant in running (fitness function: $\tau_1 = 20$; fatigue function: $\tau_2 = 10$; $r = 0.74$; $p < 0.001$) and in swimming (fitness function: $\tau_1 = 31$; $r = 0.37$; $p = 0.03$). A significant relationship was identified between the training amounts in cycling and the performances in running (fitness function: $\tau_1 = 42$; $r = 0.56$; $p < 0.001$). There was no significant relationship between the training amounts in cycling or running and the performances in swimming. The evaluated performances in triathlon are related to the running training amounts (fitness function: $\tau_1 = 52$; fatigue function: $\tau_2 = 4$; $r = 0.52$; $p < 0.001$). All the parameters of the model describing the training influences in swimming, cycling, running, on the swimming, running and triathlon performances are shown in Table **3**.

Table **3** Parameters of the model describing the training influences in swimming, cycling, running, on the swimming, running and triathlon performances

Training	*Parameters*	*Performances*		
		Swimming	*Running*	*Triathlon*
Swimming	Functions (n)	One-		
	τ_1 (days)	31		
	K_1	0.0018		
	P(F)	0.03	NS	NS
	r	0.37		
Cycling	Functions (n)		One-	
	τ_1 (days)		42	
	K_1		0.0016	
	P(F)	NS	< 0.001	NS
	r		0.56	
Running	Functions (n)		Two-	Two-
	τ_1 (days)		20	52
	K_1		0.002	0.004
	τ_2 (days)		10	4
	K_2		−0.0004	−0.001
	P(F)	NS	< 0.001	< 0.001
	r		0.74	0.52

Model based on 52 swimming, 50 running and 36 triathlon performances. τ_1 and τ_2 are the decay time constant; K_1 and K_2 are the multiplying factors for the positive and negative transfer functions. P(F) is the level of significance of the F-test estimating the fit of the relationship between training responses and performances. r is the correlation coefficient between the training responses (the modelled performances) and the actual performances.

The one-component model was retained both in swimming and cycling and no further significant improvement of the residual sum of square could be obtained. The two-components model was retained in running. One example of the training amounts, modelled and actual performances for the subject 1 is presented in Fig. **1**.

The model was also tested with the amount of miscellaneous training. But no significant influence of miscellaneous activities, which is only a small part (5.7% ± 2.4%) of the triathletes' regimen, was found.

Discussion

The most important finding of the present study is, besides the specific effect of running and swimming training on the performances in these two disciplines, a significant cross-training effect observed between cycling training and running performance.

For the first time, this mathematical method was applied in triathlon to test the cross-transfer of training effects from one discipline to another. In line with previous studies [4 – 6], the addition of a third component in the model was not associated with a significant improvement of RSS. Moreover, the one-component model was retained in swimming and cycling. The lack of negative effects derived from swimming and cycling could be explained by the lack of precision in the quantification of both the training and performance, and by the smaller fatigue induced in those disciplines compared to running, where the two-components model was retained. The values of 31, 42 and 52 days for the positive time constant decay, τ_1, for respectively the $T_{swim} - P_{swim}$, $T_{cyc} - P_{run}$ and $T_{run} - P_{tri}$ relationships were close to those obtained in endurance conditioned athletes [30]. The values of 10 and 4 days for the negative time constant decay, τ_2, for respectively the $T_{run} - P_{run}$ and $T_{run} - P_{tri}$ relationships were in line with previous studies [1,3,29,30].

One could argue that there are not cycling performance measurements and that the training effects from the other disciplines to cycling could not be assessed. Although the laboratory tests have been shown as a reliable method of assessing or predicting performance in cycling [16], it is reasonable to assume that there are some differences between the physiological responses in the field and the laboratory tests; i.e. Palmer et al. [32] showed that road race times were on average 8% slower over 40 km cycling time trial than when measured on a Kingcycle ergometer. Moreover, the lack of performance in cycling does not modify the relationships between swimming, cycling and running training amounts and the performances in swimming, running and triathlon.

Specificity of training

In theory, the body adapts to adequately cope with the specific forms of exercise stress applied. The adaptive process does not include any capacity that extends beyond the specific training stress [24]. In addition, the training stimulus needs to induce fatigue that results in performance decrement, then positive adaptation with recovery in a particular quality. In the present study, the relationships between training and performances both in running and swimming support the principle of specificity. These results are in line with several previous studies, which displayed the specificity concept [8,21,23,33]. Specificity of training is highlighted when peripheral (muscular) adaptations occur without significant concomitant central (cardiovascular) adaptations. It can be 1) When a small muscle mass is trained, i.e. the arms only; or 2) When the total demand is insufficient to cause significant central cardiovascular enhancement, i.e. the absolute intensity is not high enough [19].

These results are in line with the conclusions of a previous review, showing that there are no or little training transfers between dissimilar (i.e., using primarily different muscle groups) exercise modes [20]. It highlights the specificity of the swim training. It is particularly true for the triathletes, who have a less efficient swim technique than swimmers of the same level of performance. Triathletes display 21%-29% higher energy cost compared to swimmers of the same level, mainly due to a lower propulsive efficiency [7]. Stroke frequencies are similar, but swimmers have a longer stroke length; i.e. 1.09 vs 0.98 m [7].

From a physiological perspective, the question of the efficiency of cycling or running training to improve swim performances has been raised. Positive transfers appear to be easier from lower limbs to upper limbs than *vice versa* [17]. For example, eight weeks of cycling has been shown to induce improvement in $\dot{V}O_2$max during arm cranking activity (+9% vs +13% for leg trained), despite a decrease in mitochondrial volume densities (-17%) and a decreased fibre size in the M. deltoideus. Clausen et al. [8] also reported a +17% and +10% for leg- and arm-$\dot{V}O_2$max, respectively. Thus, in theory, running or cycling could elicit cardio-vascular adaptations beneficial for swimmers [23]. Nevertheless, improvement in swimming needs specific skill practice, and performance improvements for triathletes will be related largely to technical improvements. Moreover, for swimmers, cross-training activities could result in a higher injury risk, particularly if traumatic or plyometric activities of the lower limbs are not introduced gradually [25].

Peak HR and oxygen uptake are training mode specific [14]. During cycling or running exercise at 50–85% $\dot{V}O_2$max and involving a large muscle mass, HR is a good indicator of the appropriate stimulus for cardiovascular adaptations. Under some conditions (i.e., hydration, altitude, temperature, duration of training etc.), the relationship between HR and $\dot{V}O_2$ is modified. HR increases for a given $\dot{V}O_2$, but the metabolic stress experienced by the athlete increases, too. HR represents a biological marker that integrates the stress generated by the change in the environmental conditions. Therefore, despite a small inaccuracy, HR remains the best and most common way to assess the intensity of the training stimulus and so was used in most of the previous studies modelling the training responses [1–3,29].

During swimming, peak HR and $\dot{V}O_2$peak are lower than that obtained during running or cycling [14,15,21,23] due to 1) a smaller muscle mass, 2) an altered hemodynamics associated with a horizontal body position, 3) a reduced effect of gravity and 4) reflex bradycardia. Hauber et al. [14] showed that exercise at a given submaximal $\dot{V}O_2$ would elicit a similar HR, regardless of the mode. However, the recovery HR slopes are different in swimming and running, suggesting that exercise adjustments have to be different. In the present study, the swimming and running intensities were very similar (120 ± 4 vs 134 ± 10 a.u., Table **2**); nevertheless, the running training effects on swimming were not statistically proven. The lack of relationship between swimming training and running performances are in line with previous studies where the swimming training mode seems especially specific and provide few benefits in other disciplines [12,21]. Magel et al. [21] showed that recreational swimmers improved their tethered swim $\dot{V}O_2$max by 11% but did not change their treadmill running $\dot{V}O_2$max after a swimming program. Gergley et al. [12] noted also only a 1% treadmill running $\dot{V}O_2$max improvement after a 10 weeks block of swimming training in good swimmers. However, for unfit or sedentary athletes, swimming training, like any other aerobic activity, can improve the general fitness and therefore be beneficial in the other disciplines. Lieber et al. [19] showed that sedentary males ($\dot{V}O_2$max = 42.6 ml × kg^{-1} × min^{-1}) demonstrated a similar significant running $\dot{V}O_2$max increase after 11.5 weeks of either running (+28.4%) or swimming (+25.0%) training at a similar absolute intensity. Combined run-swim training vs running-only training among recreational runners elicited a similar improvement on running performance [11]. Cross-training could improve running performance, but less however, than with increased running-only training. In summary, it seems that swim training is highly specific and may only have a training effects transfer to another activity in recreational athletes.

Cross-training

In the present study, the cycling training was significantly related to the running performances, supporting the concept of cross-training. The transfers of the training influences between different disciplines have been extensively studied (for a review: [20,41]) and more specifically between cycling and running [9,10,28,30,33–35,37], cycling and swimming [8,36] or running and swimming [11,14,15,19,23,25].

Several explanations have been proposed to support the cross-training principle. The peripheral limitations to $\dot{V}O_2$max may be related to mitochondrial and capillary densities [38]. Nevertheless, if sufficient muscle mass and exercise mode lead to sufficient central adaptation and, if tested in an exercise which elicits sufficient demands, the specificity of $\dot{V}O_2$max will not be demonstrated [19]. In addition, central cardiac improvement after endurance exercise may be used by untrained muscles to benefit from a higher blood flow [8,38]. A greater oxidation and clearance of lactate in the trained muscles could also explain partly the improvement in the non-trained muscles [36]. Non-active muscles are of established importance relative to the uptake of lactate during exercise.

Another possible explanation for the efficiency of cross-training is that it may evolve multi-sports athletes to train at a higher intensity in every discipline [11,20]. Thus, cross-training may be an advantage when incorporating frequent high-intensive intervals. The endurance athlete will use cross-training mainly to break the boredom of usual routine regime [41], as a preventive method to minimise the injuries due to a weight-bearing activity [28,41], to maintain a general fitness while the athlete has been forced to stop training in his primary activity because of injury [20,28,41] or even to limit overtraining during high-volume periods. However, the cross-training method requires redefining the overall training program, while addition of new exercises increases the risks of injuries [25] and overtraining [9,10,35].

This study is the first to show that, in elite triathletes, cycling training has a significant effect on running performance. Run and bike use major extensor muscles in the lower limbs. However, cycling will recruit predominantly the quadriceps and gastrocnemius muscles. In running activity, mainly the adductors, semitendinosus, biceps femoris and semimembranosus are used; except during uphill running, where the muscles most activated are the adductors, biceps femoris, gluteal group, gastrocnemius and vastus group [40]. Compared to running, cycling is associated with a lower $\dot{V}O_2max$ [33] due to a lower arteriovenous oxygen difference and/or a lower cardiac output. Moreover, some athletes who do not train in cycling cannot reach their $\dot{V}O_2max$ when tested on ergometer, due to the lack of strength in the lower limbs. This could also be an explanation for lower $\dot{V}O_2max$ in cycling. At the same heart rate, the cardiac output is lower in cycling due to a lower stroke volume. This is of primary importance for matching the intensity of the different running and cycling programs, and could be an explanation for the lower transfer effect from bike to run, than vice-versa, as reported in most of the studies [33,41]. Ruby et al. [37] showed that untrained females can benefit from a 10-week either run-only, either bike-only or either combined run-bike training to improve treadmill or cycle ergometer $\dot{V}O_2max$ and lactate threshold. It confirms that the aerobic adaptations for an untrained population do not have exercise mode specificity. Moroz and Houston [28] showed that 4 weeks of replacing running by cycling in moderately trained female runners did not have a detrimental effect on $\dot{V}O_2max$ or running performance. Moreover, after the cycling period, the athletes increased the strength of the knee extensors when tested in a concentric manner. It suggests that, over a short period, cycling is a good method of maintaining the aerobic fitness when moderately-fit runners are injured.

In cycling, intensity could be too low to induce beneficial adaptations for running. It is recommended to add interval-training cycling sessions to a running program [9]. In addition, there are no differences between run-only or combined run-cycle mode on any mood state, hormonal responses to overtraining [10], immunity status fluctuation [35], muscular subjective pain [10], or performance [34]. When comparing the two (specific vs combined) modes, running economy at sub-maximal pace is similarly modified in one study [9] and more altered in the combined mode in another study [34].

Variance in running performances was more closely related to running than cycling training. The relationship between T_{cyc} and P_{run} ($r = 0.56$, $p < 0.001$) is lower than between T_{run} and P_{run} (0.74, $p < 0.001$). It suggests that cross-transfer, even using similar modes, cannot match the effects of mode-specific training. The concept of specificity is superior to the concept of cross-training [41]. It means that the benefits of training in the discipline where the athlete will be tested (by his results in competition or physiologically in a laboratory) would normally be greater than the benefits of training in a different one.

Many studies have investigated the use of cycling as a complement to running either on a combined exercise mode [9,10,26,28,31,34,35,37] or as a way to maintain fitness over a short period of time; i.e. for injured runners. Mikesell and Dudley [26] showed that, if the intensity is increased with a combined bike-run program, competitive distance runners did not change their running or cycling $\dot{V}O_2max$ but improved their 10 km time by 81 s. Mutton et al. [31] reported that 5 weeks of intensive run-only or combined run-bike training improved performances on one mile (21 vs 18 s), 5000 m (1.7 min for both groups) and $\dot{V}O_2max$ (5.2 % vs 5.9 %) in moderately-fit men. These findings suggest that run-cycle training is beneficial for the recreational athletes' running performances and that non-specific, but similar peripheral muscular training may contribute to enhanced running performance. However, the cross-training effects on $\dot{V}O_2max$ or performance did not exceed those induced by specific training. It highlights that the exercise intensity might be as important as the exercise mode itself [20,21].

Run training and performances in triathlon

Distances are standardised in triathlon, but because of the fluctuations in environmental conditions, i.e. waves during the swim, elevation or wind during the bike/run, the assessment of performances cannot be based on time. The method employed in the present study was based on subjective evaluation of the performance by both the athlete and the coach. Although prediction of triathlon performance from several laboratory tests in swimming, treadmill running and ergometer cycling has been shown as a valid method [39], the aim of this study was to relate the 'real world' triathlon performances with the training amounts in the three disciplines. Moreover, modelling the effects of training on performances requires an important number of performances. The triathletes do not perform triathlon events often (15 – 25 competitions per season) and elite athletes preparing for the World Championship cannot undergo 10 – 15 additional laboratory triathlons in addition to their competition regimen.

Indeed, the variances of performances in triathlon were only related to the running training amounts. It confirms that training in running might be more important than in the other disciplines for elite triathletes. Furthermore, since the modifications of triathlon rules to allow drafting during the cycling bout, running appears to be more important in the overall performance. Landers et al. [18] showed that running time variations among elite triathletes competing at the 1997 World Championship were larger than swimming or cycling time variations. More significant relationship between triathlon performances and $\dot{V}O_2max$, ventilatory threshold or economy [27] have been shown in running than in cycling. In addition, few relationships between triathlon performance and physiological variables measured in swimming have been identified. The "weight" of running is paramount in the triathlon training since firstly, it is the discipline which provides the larger transfer to the other disciplines [41]; and secondly, the running performance is more important in competition to the final outcome [18].

Practical considerations

Since the triathlete will train and compete in the three disciplines, examination of the cross-transfer issue leads to important practical implications. The training program of the elite triathletes should not consist of three separate training regimens and should be structured for each individual. Cross-transfers appear to be important for moderately-fit but very slight for most of the elite athletes, for whom specificity and intensity of exercise are paramount. The present results highlight that the swimming training has to be highly specific. Only technical improvements may have an impact for most triathletes. On the other hand, the swimming training does not provide beneficial adaptations for the other disciplines.

The present study confirms the idea of combined cycling-running training to improve the running performances, even in elite performers. It supports the usual training habits of the triathletes who train in cycling to improve their aerobic basis in a non weight-bearing activity in order to reduce the running mileage. Cycling is an excellent discipline to complement running. The literature suggests that an intensive training program including regular bike interval-training to reach “beneficial intensities” would be especially appropriate.

Conclusion

The specific effect of training on performance in running and swimming has been identified among elite triathletes. But the present study also showed that cross-transfer effects occur between cycling training and running performance. A similar cross-training effect does not seem to exist with swimming. The swimming training mode seems highly specific and provides few benefits in other disciplines. The main practical implication would be to combine cycling and running to improve the running performance, which is currently paramount in the overall triathlon outcome.

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