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Research article

Identifying Optimal Overload and Taper in Elite Swimmers over Time

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Abstract

The aim of this exploratory study was to identify the most influential training designs during the final six weeks of training (F6T) before a major swimming event, taking into account athletes' evolution over several seasons. Fifteen female and 17 male elite swimmers were followed for one to nine F6T periods. The F6T was divided into two sub-periods of a three-week overload period (OP) and a three-week taper period (TP). The final time trial performance was recorded for each swimmer in his or her specialty at the end of both OP and TP. The change in performances (ΔP) between OP and TP was recorded. Training variables were derived from the weekly training volume at several intensity levels as a percentage of the individual maximal volume measured at each intensity level, and the individual total training load (TTL) was considered to be the mean of the loads at these seven intensity levels. Also, training patterns were identified from TTL in the three weeks of both OP and TP by cluster analysis. Mixed-model was used to analyse the longitudinal data. The training pattern during OP that was associated with the greatest improvement in performance was a training load peak followed by a linear slow decay (84 ± 17, 81 ± 22, and 80 ± 19 % of the maximal training load measured throughout the F6T period for each subject, Mean±SD) ($p < 0.05$). During TP, a training load peak in the 1st week associated with a slow decay design (57 ± 26, 45 ± 24 and 38 ± 14%) led to higher ΔP ($p < 0.05$). From the 1st to 3rd season, the best results were characterized by maintenance of a medium training load from OP to TP. Progressively from the 4th season, high training loads during OP followed by a sharp decrease during TP were associated with higher ΔP.

Key words: Repeated measures; random-effects methodology; monitoring training; pre-taper and taper; elite swimmers; periodization.

Introduction

Optimal training load periodization is a key factor in achieving maximal performance during the major event of the sports season (Avalos et al., 2003; Bosquet et al. 2007; Fry et al., 1992; Mujika et al., 1995; 1996a). The most usual program is two to four weeks of overload training followed by one to three weeks of training with a decreased load, known as taper (Houmard and Johns, 1994; Kenitzer, 1998; Mujika et al., 1995; 1996a; 1996b; 2002; Mujika and Padilla, 2003; Thomas and Busso, 2005; Thomas et al., 2008).

By consensus, the optimal strategy is assumed to consist of maintaining the training intensity while reducing the training volume (up to 60-90%), and maintaining or only slightly reducing the training frequency (no more than 20%) (Bosquet et al., 2007; Mujika and Padilla, 2003; Pyne et al., 2009). Concerning the pattern for reducing the training load, progressive non-linear tapers have been described as more beneficial to performance improvement compared with step tapers (Banister et al., 1999; Bosquet et al., 2007; Mujika and Padilla, 2003).

Most research has emphasized the importance of the overload training period preceding the taper, during which the increase in both training volume and intensity delays the stimulation of biological adaptations via an overcompensation process (Avalos et al., 2003; Bosquet et al., 2007; Fry et al., 1992; Thomas and Busso, 2005; Thomas et al., 2008). Moreover, overload volume and/or intensity training leads to a set of acute physiological and psychological disturbances that can limit short-term performance capacity (e.g., glycogen depletion, neuromuscular fatigue, decrements in red cell volume and hemoglobin, imbalance in anabolic and catabolic tissue activities, disturbance in the athlete's psychological status) (Mujika and Padilla, 2003). Consequently, to ultimately improve performance, the major challenge during the taper period is to maintain or further enhance the physiological adaptations while allowing the psychological and biological stresses of the overload periods to resolve (Bosquet et al., 2007; Houmard and Johns, 1994; Kenitzer, 1998; Mujika and Padilla, 2003; Thomas and Busso, 2005; Thomas et al., 2008).

Few studies have investigated the training load dynamics of the overload and taper periods before a major event (Avalos et al., 2003; Busso et al., 2002; Busso, 2003; Thomas and Busso, 2005; Thomas et al., 2008). Using mathematical models, these authors suggested interaction effects between training adaptation and fatigue dissipation over time. For instance, a greater training volume and/or intensity before the taper was shown to result in higher performance gains, but this required a greater reduction in the training load over a longer period (Avalos et al., 2003; Busso et al., 2002; Thomas and Busso, 2005; Thomas et al., 2008).

To ensure maximal performance improvement, the scheduling and durations of both the overload and taper periods need to be individually tailored to each athlete,

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taking into account the individual training profile and capacity to recover from the stress of the high daily training (Avalos et al., 2003; Hellard et al., 2005; Mujika et al., 1996a; 1996b). Previous research (Mujika et al., 1995; 1996b) has distinguished two major profiles of training response. The first is characterized by a temporary decline in performance level (as a consequence of training load-induced fatigue) followed by a long delay in the enhancement of performance via the overcompensation process (long delay in eliminating accumulated fatigue and in further enhancement or maintenance of physiological adaptations). The second profile is fast physiological adaptation to the training load without temporary performance decline (fast decay of fatigue concomitant with a continuous increase in physiological adaptations). Avalos et al. (2003) suggested longer recovery periods for older male sprint swimmers (late responders) than for young female middle-distance swimmers (early responders).

The adaptation of training load designs according to age, stroke specialty and swim standard is fundamental to ensure performance improvement throughout the athlete's career (Avalos et al., 2003; Stewart and Hopkins, 2000a; 2000b). Although several studies have pointed out changes in training response over time (Avalos et al., 2003; Busso et al., 1997; 2002), no study to our knowledge has yet analyzed these changes in response to the overload training period and taper (for some swimmers throughout their entire careers) (Pyne et al., 2009).

Thus, the aim of this exploratory observational study was to identify the most influential training designs during the final six weeks of training before a major swimming event, taking into account athletes' changes in training response over several seasons.

Methods

Subjects

Fifteen female and 17 male elite swimmers were followed for one to nine consecutive years. Their mean age, body mass and height at study inclusion was 18 ± 2 years, 59 ± 4 kg, and 1.68 ± 0.05 m for females, and 21 ± 3 years, 73 ± 5 kg and 1.84 ± 0.06 m for males. Eight females specialized in the 50-m and 100-m events, while the other seven swam middle-distance races: the 200-m and 400-m events. Six males specialized in the 50-m and 100-m events, six in middle-distance races: the 200-m and 400-m, while the other five were specialists in a long-distance event: the 1500-m. The study was reviewed and approved by the local University Committee on Human Research and written informed consent was obtained from each participant. The swimmers trained according to the program prescribed by their coaches, and the characteristics of the training regimens and competition schedules were not modified by the present study. Values and changes in annual number of kilometers and in the best annual performances for all subjects over the ten seasons studied are indicated in Tables 1 and 2.

Table 1. Annual number of kilometers swum for the 32 subjects over the follow up period.

S	G	Sp	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
1	W	200-F								1600	1780	1571
2	W	100-B									1400	1100
3	W	400-F										1976
4	W	400-F					1595	1827	1777			
5	W	100-B										1890
6	W	200-F		1980	1924	1621	2065	2278	1107	1801	1764	1961
7	W	200-B	1550	1046	1177		2086					
8	W	100-F										1271
9	W	100-Br							1546	1634		
10	W	100-B				1650	1590	1345	1475	1816		
11	W	100-F				1830	1404	1040	1152	1258	1020	
12	W	200-Ba	1832	1572		1558						
13	W	100-B				1957						
14	W	100-Ba									1566	
15	W	200-Fr						1400	1700	1654		
16	M	100-Fr				2250	1933	1700	1626	1679		
17	M	200-B	1721	1726								
18	M	1500-Fr								1864	2186	2900
19	M	1500-Fr	2082									
20	M	50-Fr					1523	1104	1157			
21	M	200-M								1800	1620	1819
22	M	100-Br	1230	594								
23	M	1500-Fr										2172
24	M	200-Br									1800	1460
25	M	200-M		1930	1409	2215	1812					
26	M	100-Ba	690	696								
27	M	400-Fr			2600	2700	2055					
28	M	1500-Fr								2230	2280	
29	M	100-Br				2118	1583					
30	M	1500-Fr									2632	2700
31	M	200-M										1540
32	M	100-Br					1343	970				

S: subject, G: gender, Sp: Specialty, B: butterfly, Ba: backstroke, Br: breaststroke, Fr: freestyle.

Table 2. **Best annual performances expressed in minutes:seconds.hundredths of seconds for the 32 subjects over the follow up period.**

S	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
1								2:06.4	2:05.3	2:06.4
2									1:06.4	1:05.6
3										4:21.2
4					4:16.1	4:20.8	4:16.1			
5										2 :33.1
6		2:01.5	2:00.7	2:04.4	2:01.2	1:59.6	2:00.1	1:59.6	1:59.9	1:58.3
7	2:12.9	2:14.7	2:13.4		2:10.7					
8										1:00.5
9							1:12.5	1:12.1		
10				0:55.2	0:54.7	0:55.2	0:54.6	0:53.7		
11				0:57.9	0:57.3	0:57.3	0:56.9	0:56.8	0:57.2	
12	2:14.2	2:16.3		2:14.6						
13				1:04.6						
14									1:02.5	
15						2:06.3	2:04.1	2:05.1		
16				0:51.5	0:51.6	0:51.9	0:52.1	0:51.9		
17	2:06.7	2:06.6								
18								15:45.0	15:51.0	15:37.0
19	16:11.0									
20					0:23.1	0:22.5	0:23.6			
21								2:03.1	2:04.8	2:02.7
22	1:02.3	1:04.0								
23										15:51.0
24									2:17.9	2:20.5
25		2:01.1	2:01.6	2:02.6	2:01.8					
26	0:57.8	0:57.5								
27			3:59.8	3:57.4	3:54.8					
28								15:58.0	15:47.0	
29				1:04.9	1:05.4					
30									15:49.0	15:40.0
31										2:08.9
32					1:03.1	1:03.6				

S: subject.

Studied periods and performance-related measures

The final six weeks of training (F6T) preceding the national championships, held in May each year, were studied from 1996 to 2004. Two distinct periods composed F6T: the overload training period (OP) covered the first three weeks and the taper period (TP) covered the last three weeks.

Three performance standards were considered: national, European and Olympic (i.e., participation in national, European, and Olympic or World Championships). Athletes' performances were measured in real competition (final events only), in the stroke and distance of each swimmer's main event. Performances were expressed as a percentage of the world record for the same stroke, distance and sex, in order to scale values for different swimming events (P). The performance change (ΔP) between mid- and post- F6T was calculated, i.e., the difference between the performance following OP, recorded during preparatory events, and the performance following TP, recorded during major events such as the national championships. A positive value indicated improved performance (faster performance after TP than OP).

Training-related measures

Intensity levels for swim workouts were determined as proposed by Mujika et al. (1996a) and detailed in Avalos et al. (2003). An incremental test to exhaustion was performed at the beginning of each season (repeated and adjusted 4 times per season) to determine the relationship between blood lactate concentration and swimming speed. Each subject swam 6 x 200-m at progressively higher percentages of their personal best competition time over this distance, until exhaustion. Lactate concentration was measured in blood samples collected from the fingertip during the 1-min recovery periods separating the 200-m swims. All swimming sessions were divided into five intensity levels according to the individual results obtained during this test: swimming speeds 1) below ~ 2 mmol·l^{-1}; 2) at ~ 4 mmol·l^{-1}, the onset of blood lactate accumulation; 3) just above ~ 6 mmol·l^{-1}; 4) at ~10 mmol·l^{-1}; and 5) at maximal swimming. Workouts in the water were quantified in meters per week covered at each intensity level. Strength training included 6) dryland workouts and 7) general conditioning (workouts involving activities like cycling, running, cross-country skiing, and collective sports) and was quantified in minutes of active exercise (Hellard et al., 2005; 2007). To scale the intensity values, the weekly training volume at each intensity level was expressed as a percentage of the maximal volume measured at the same intensity level throughout the F6T period for each subject (see Avalos et al., 2003; Hellard et al., 2005; 2007, for a full explanation of this method).

These intensity measures were synthesized as follows: the low-intensity training load, w_t^{LIT}, was the mean

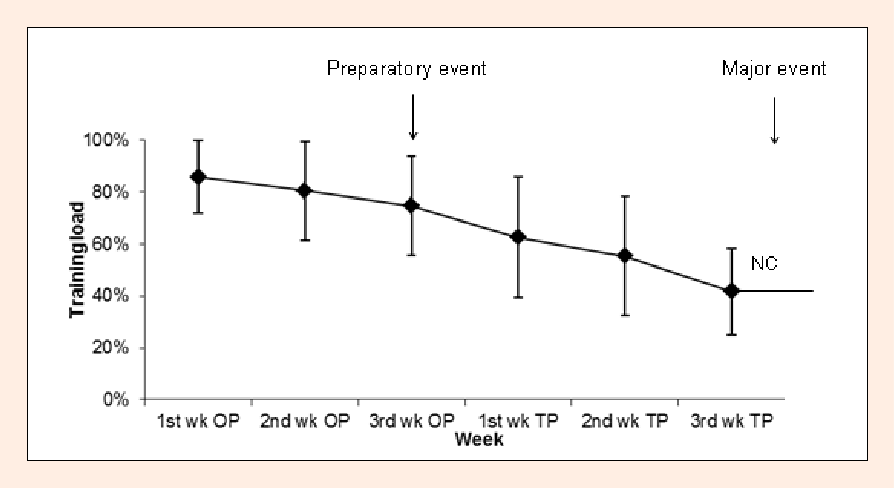

Figure 1. Change in total training load for the entire group of subjects and for the 85 OPs and TPs included in the study during the final six weeks preceding the national championships. The preparatory and major events are indicated on the figure. NC indicates National Championships. Values are mean±SD.

weekly training volume expressed in percentage terms of intensity levels 1 to 3 at the t^{th} week; the high-intensity training load w_t^{HIT} , was the mean weekly training volume expressed in percentage terms at intensity levels 4 and 5 at the t^{th} week; strength training w_t^{ST} , was the mean weekly training volume expressed in percentage terms of dryland workouts and general conditioning sessions at the t^{th} week; and the total weekly training load, w_t^{TTL} , representing the total physiological stress produced by the different workout sessions, was the mean weekly stimulus for each training intensity at the t^{th} week. Figure 1 shows the weekly training load for the entire group of swimmers during F6T. Last, the total mileage swum, w_t^{D} was the total volume of swim training at the t^{th} week, expressed in kilometers.

Statistical analysis

Overload and taper periods were grouped based on the similarities between the total weekly training loads using k-means cluster analysis.

We used mixed-model analysis (Proc Mixed of SAS version 9.1; SAS Institute, Cary, NC, USA) to explore the association of training-related measures (recorded at OP as the mean of the three OP weeks: low-intensity training $w^{LIT}{}_{OP,}$ high-intensity training $w^{HIT}{}_{OP}$,strength training $w^{ST}{}_{OP,}$ total training load $w^{TTL}{}_{OP,}$ total mileage swum $w^{D}{}_{OP;}$ and at TP as the mean of the three TP weeks: $w^{LIT}{}_{TP,}$ $w^{HIT}{}_{TP,}$ $w^{ST}{}_{TP,}$ $w^{TTL}{}_{TP,}$ $w^{D}{}_{TP}$) and training patterns in OP and TP (clusters were coded into dummy variables), with performance change (ΔP). Adjustment variables (gender, age, performance standard and swimming specialty) were forced into the models as fixed effects to control for their potential confounding effect. The season for each performance and the season interaction with training variables were included as numeric linear fixed effects, to account for athletes' changes in training response over seasons. All models included random intercept and random slope terms to account/test for potential inter-individual variability in baseline ΔP and rate of change, respectively. Statistical significance was tested at $p < 0.05$. Verbeke et al. (2000) and Ugrinowitsch et al. (2004) provided a comprehensive description of the use of linear mixed-effects models, and Avalos et al. (2003) applied this methodology to model elite swimming data.

Results

Descriptive analysis

A total of 85 F6Ts were available (from 1 to 9 seasons per subject). The overall performance change between mid- and post-F6T (OP and TP, respectively) was 1.7 ± 1.7%. A total of 76 of the 85 observations (belonging to 30 subjects out of 32) were faster after TP and nine (belonging to 8 subjects) were slower. The performance change in males was 1.9 ± 1.7%, with a total of 41 of the 47 observations (belonging to 14 males out of 17) being faster after taper. The performance change in females was 1.4 ± 1.6%, with a total of 35 of the 38 observations (belonging to 15 females out of 15) being faster after taper. The performance change in the national, European and Olympic standards was 2.2 ± 1.7%, 1.3 ± 1.6% and 1.7 ± 1.4%, respectively, with a total of 29 out of 32, 29 out of 35 and 18 out of 18, respectively, being faster after taper. The differences between genders and performance standards were not however, significant (p = 0.056 for the latter).

Training patterns

In OP, four clusters were distinguished. Cluster 1 comprised 32 of the 85 OPs and revealed a high training load peak during the 1st week associated with a linear fast decay training load design (HP, FD). Training load as a percentage of the maximal individual training load was 91 ± 13, 82 ± 18 and 76 ± 20% of the mean total training load (TTL) during the 1st, 2nd and 3rd weeks of OP, respectively. Cluster 2, comprising 26 periods, consisted of a medium training load peak during the 1st week associated with a linear slow decay training load design, (MP, SD). Training load in this cluster was 84 ± 17, 81 ± 22 and 80 ± 19% mean TTL. Cluster 3, comprising nine periods, revealed a medium training load peak during the 1st week

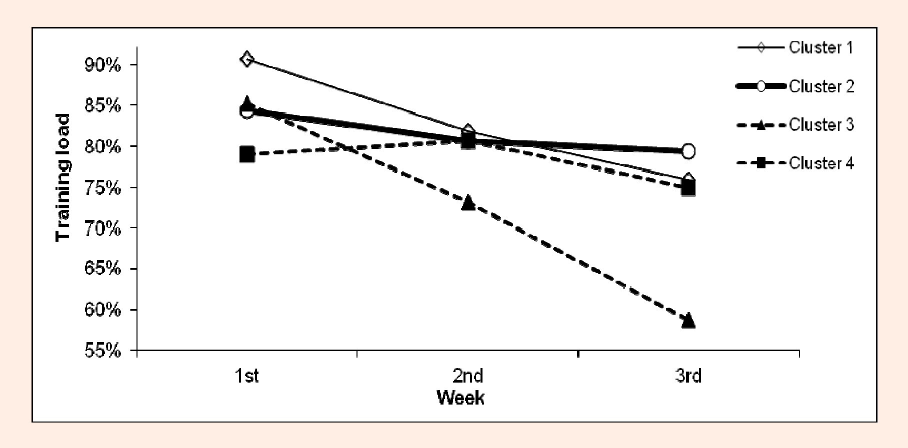

Figure 2. Change in total training load in the four clusters during the overload training period. Cluster 1 (continuous line with white diamond shapes, 32 periods) indicates a high training load peak during the 1st week associated with a linear fast decay training load design. Cluster 2 (continuous line with white circles, 26 periods) indicates a medium training load peak during the 1st week associated with a linear slow decay training load design. Cluster 3 (broken line with black triangles, 9 periods) revealed a medium training load peak during the 1st week associated with a fast decay logarithmic design. Cluster 4 (broken line with black squares, 18 periods) shows a low training load peak during the 1st week, followed by an increase and then a decrease in the training load design. ΔP for design 2 (MP, SD) was significantly higher than ΔP for design 4 (LP, ID).

associated with a fast decay logarithmic design (MP, FD). Training load in this cluster was 85 ± 17, 73 ± 29, 58 ± 25% mean TTL. Last, cluster 4, with 18 periods, was characterized by a low training load peak during the 1st week, followed by an increase and then a decrease in the training load design (LP, ID). Training load in this cluster was 79 ± 26, 81 ± 22, 75 ± 19% mean TTL. The four training load patterns during OP are outlined in Figure 2.

In TP, four clusters were identified, all of which were consistent with previously defined taper types (Mujika and Padilla, 2003). Cluster 1 comprised three of the 85 taper periods and was characterized by a low training load peak during the 1st week of TP associated with a slow decay logarithmic pattern (LP, SD). Training load as a percentage of the maximal individual training load was 51 ± 23, 46 ± 10 and 37 ± 4% mean TTL during the 1st, 2nd and 3rd weeks of TP, respectively. Cluster 2, comprising 33 periods, was characterized by a high training load peak during the 1st week associated with a fast decay logarithmic pattern (HP, FD). Training load in this cluster was 71 ± 21, 61 ± 22 and 42 ± 15% mean TTL. Cluster 3, with 34 periods, showed a medium training load peak during the 1st week associated with a low decay logarithmic pattern (MP, LD). Training load in this cluster was 58 ± 23, 56 ± 23 and 44 ± 20 % mean TTL. Last, cluster 4, comprising 15 periods, displayed. Training load in this cluster was 57 ± 26, 45 ± 24, and 38 ± 14% mean TTL. The four patterns during TP are outlined in Figure 3.

Association of training patterns with performance change

In OP, the mean ΔP changes for clusters 2 (MP, SD), 3 (MP, FD), 1 (HP, FD), and 4 (LP, ID) were 2.4±1.6, 1.7 ±1.5, 1.5 ± 1.6, 1.2 ± 1.7%, respectively, whereas during

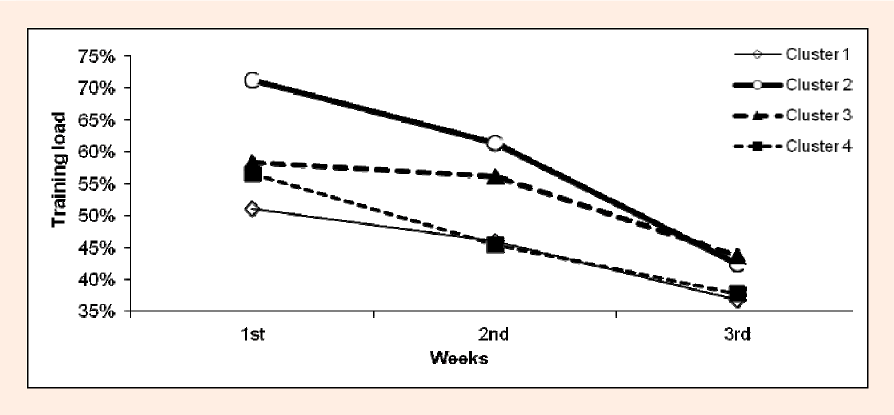

Figure 3. Change in total training load in the four clusters during the taper training period. Cluster 1 (continuous line with white diamonds shaped, 3 periods) shows a low training load peak during the 1st week of TP associated with a slow decay logarithmic pattern. Cluster 2 (continuous line with white circles, 33 periods) was characterized by a high training load peak during the 1st week associated with a fast decay logarithmic pattern. Cluster 3 (broken line with black triangles, 34 periods) showed a medium training load peak during the 1st week associated with a low decay logarithmic pattern. Cluster 4 (broken line with black squares, 15 periods) is associated with a medium training load peak during the 1st week associated with a slow decay exponential design. ΔP for designs 2 (HP, FD) and 3 (MP, LD) was significantly lower than ΔP for design 4 (MP, SD).

Table 3. Fixed effects estimates and p-values for the random effects for training patterns identified by clustering at OP and TP.

Variable	Fixed effect	Parameter (se)	p-value	Random-effect variance p-value
Patterns in OP	**Intercept**	.012 (.004)	.011	.042
	Global effect of patterns		.033	
	cluster 1	.004 (.004)	.404	
	cluster 2	.012 (.004)	.006	
	cluster 3	.006 (.006)	.341	
	cluster 4	reference		
Patterns in TP	**Intercept**	.016 (.004)	.011	.105
	Global effect of patterns		.026	
	cluster 1	.002 (.009)	.874	
	cluster 2	-.012 (.006)	.047	
	cluster 3	-.015 (.005)	.007	
	cluster 4	reference		

TP, the mean ΔP for design 1 (LP, SD), 4 (MP, SD), 2 (HP, FD), and 3 (MP, LD) was 2.8 ± 1.7, 2.1 ± 1.6, 1.8 ± 1.7, and 1.4 ± 1.5%. The global effect of training patterns on ΔP was significant (Table 3). In particular, ΔP for design 2 (MP, SD) was significantly higher than ΔP for design 4 (LP, ID) at OP; and ΔP for designs 2 (HP, FD) and 3 (MP, LD) was significantly lower than ΔP for design 4 (MP, SD) at TP. The relationship between ΔP and training patterns in OP was particular to each subject (p = 0.042).

Association of training-related measures with performance change

Total mileage swum in OP, high-intensity training in OP, and total weekly training in TP showed significant associations with performance change (Table 4). Season and season interactions with these training variables showed significant effects. The random intercept was significant or of borderline significance. Total mileage swum in OP showed a negative association with ΔP that gradually weakened from the 1st to 3rd season (the higher the values for these variables, the lower the difference was between the major event and preparatory-event performances), while a progressive inverse trend was observed from the 4th season (Table 4). Conversely, high-intensity training in OP had a positive effect on ΔP that gradually weakened from the 1st to 2nd season, while a progressively intensified negative effect was observed from the 3rd season. Figure 4 shows the relationships between w^{D}_{OP} (A) and w^{HIT}_{OP} (B) and ΔP, taking into account the evolution over seasons and season interaction with training variables. Total weekly training in TP had a negative effect on ΔP from the 2nd season, which was gradually strengthened. Figure 4 also shows the relationship between w^{TTL}_{TP} (C) and w^{D}_{V} (D) and ΔP, taking into account evolution over time and the interaction time by variable effect on ΔP.

Discussion

The main results were the following: During the overload training period, a medium training load peak in the first week followed by an exponential slow decay training load design (84 ± 17, 81 ± 22, 80 ± 19% mean TTL) was linked to higher performance improvement. During the taper period, the training load design that was characterized by a medium training load peak during the 1st week associated with a slow decay (57 ± 26, 45 ± 24, 38 ± 14% mean TTL) led to higher ΔP. At the beginning of the athlete's career, high ΔP was characterized by medium training load maintenance from OP to TP, whereas high training loads during OP followed with a sharp decrease during TP gradually became associated over the seasons with high ΔP.

Influence of training variables on performance improvement

The mean performance gain (1.7 ± 1.7%) was lower than the gains reported by Mujika et al. (2002) (2.2 ± 1.5%) during the final three weeks of training before the Sydney 2000 Olympic Games and by Hellard et al. (2007) (2.2 ± 1.2%) in Olympic swimmers, but equivalent to those recorded by Bonifazi et al. (2000) (1.5% and 2.1%) in male 100-m to 400-m specialist swimmers. A literature search on taper in swimming (Avalos et al., 2003;

Table 4. Fixed effects estimates and p-values for the random effects for training-related measures at OP and TP.

Variable	Fixed effect	Parameter (se)	p-value	Random-effect variance p-value
Total mileage swum in OP	**Intercept**	.059 (.014)	<.001	.058
	w^{D}_{OP}	-.063 (.023)	.007	
	Season	-.011 (.005)	.033	
	Season x w^{D}_{OP}	.016 (.008)	.041	
High-intensity training in OP	**Intercept**	.004 (.008)	.615	.050
	w^{HIT}_{OP}	.053 (.021)	.017	
	Season	.006 (.003)	.036	
	Season x w^{HIT}_{OP}	-.022 (.008)	.007	
Total weekly training in TP	**Intercept**	.010 (.007)	.142	.031
	w^{TTL}_{TP}	.068 (.032)	.039	
	Season	.006 (.003)	.035	
	Season x w^{TTL}_{TP}	-.046 (.016)	.007	

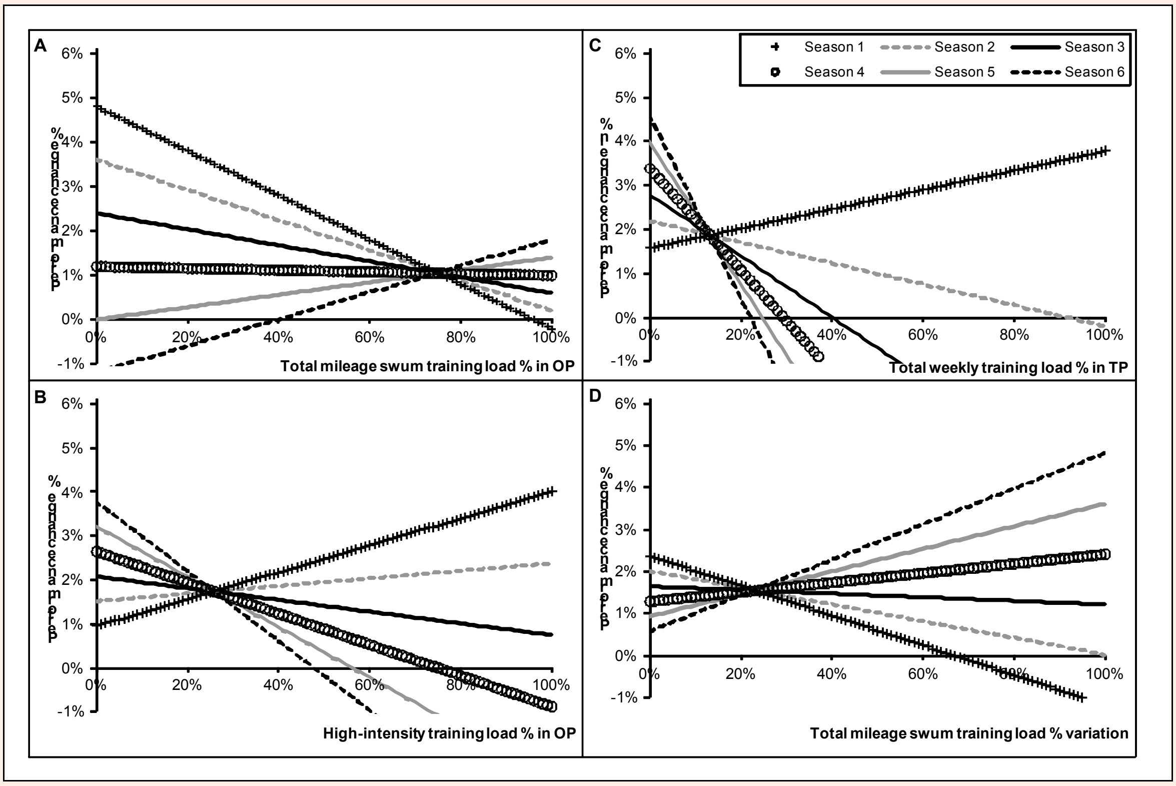

Figure 4. **Mean effect of (A) total mileage swum training load in OP (B) high-intensity training load in OP, (C) total weekly training load in TP, and (D) total mileage swum training load variation on the performance change from 1st to 6th season.**

Bonifazi et al., 2000; Hellard et al., 2007; Houmard and Johns, 1994; Kenitzer, 1998; Mujika et al., 1995; 1996a; Mujika and Padilla, 2003; Pyne et al., 2009) suggested average improvement to be about 2%, marked improvement to be about 3%, and small improvement to be about 1%.

Most effective training patterns during OP

The most effective training design (cluster 2) during OP (mean improvement of 2.38 ± 1.63%) showed a high training load peak six weeks before competition associated with a small load decrease during the following two weeks. This agrees with the findings of previous research, which concluded that a training load peak situated five to eight weeks before the main competitive event is a key factor in optimizing performance (Avalos et al., 2003; Busso et al., 2002; Fitz-Clarck et al., 1991; Fry et al., 1992; Pyne et al., 2009). Regarding the training volume trend, Mujika et al. (2002) observed the weekly training mileage for a typical Australian swimmer in the 16-week preparation for the Sydney 2000 Olympic Games and indicated a peak associated with 80-, 65-, and 35-km volume decreases during the 5th, 4th and 3rd weeks prior to the Olympic Games. For the same training period and concerning the global training load, Hellard et al. (2007) similarly indicated a peak followed by an exponential training-load decrease for a female 200-m freestyle world champion. Thomas et al. (2005; 2008) conducted mathematical simulations and found that an overload training period resulting in a 20% step increase in training over 28 days followed by a longer and more sharply decreasing taper led to greater performance enhancement than a shorter period with smaller load reduction. Using the influence curve simulations from the Banister model, Fitz-Clarke et al. (1991) indicated that the period of greatest influence (maximum benefit) occurs from weeks 12 to 4 prior to competition, with the maximum at about week 6. Avalos et al. (2003) used a linear mixed model and reported that high training loads imposed six to seven weeks before competitive events improved performance in ten out of 13 elite swimmers in the study. The results of these studies concord with the findings of the present study in emphasizing the importance of maintaining a high training load during the 6th to 3rd weeks prior to competition. This period constitutes a specific block that has been described as permitting the development of event-specific energetic mechanisms and motor skills linked to the competitive speed (Avalos et al., 2003; Hellard et al., 2005; Issurin, 2010). In OP, training patterns 1 (high peak, fast decay) and 4 (low peak, increased and decreased training load) were linked to lower performance improvement. Cluster 1 presented the highest training load design during the first two weeks (91 ± 13, 82 ± 18, 76 ± 20% mean TTL). A concentration of such high training loads five weeks before competition may perhaps exceed swimmers' ability to adapt. Indeed, several studies have shown that the impact of training loads on performance has an upper limit above which training does not elicit further adaptation (Busso, 2003; Hellard et al., 2005; Mader, 1988; Thomas and Busso, 2005; Thomas et al., 2008). If the training stimulus is too intense, protein degradation exceeds synthesis, leading to catabolic processes (Mader, 1988), excessive and damaging immune system response, chronic tissue disruption, and subsequent muscular atrophy and degradation of physical capacities (Fry et al., 1992). Other reports have emphasized the importance of maintaining the intensity and duration of the training stimulus below the overtraining limit in order to obtain an optimal development of physical capacities (Hellard et al., 2005; Mader, 1988; Morton, 1997). Busso (2003) suggested that the relationship between daily amounts of training and performance would be stronger if defined by an inverted-U-shape. One could argue that for the high training load design (cluster 1) greater performance would be obtained with longer taper associated to a smaller load reduction, as recommended by Thomas et al. (Thomas and Busso, 2005; Thomas et al., 2008).

Cluster 4 was associated with the lowest improvement in performance and showed the weakest training load during the 6th week preceding the performance (78.9% mean TTL). The lack of a sufficient training load peak six weeks before the competitive event would probably reduce the stimulation of biological adaptations via the overcompensatory process (Bosquet et al., 2007; Hellard et al., 2005; Mujika and Padilla, 2000; Thomas and Busso, 2005; Thomas et al., 2008). Moreover, a training load reduction during OP could induce an insufficient training stimulus, leading to rapid short-term detraining due to a partial loss of training-induced physiological adaptations (e.g., decreases in VO_{2max} and muscular strength, reduction in capillary density and oxidative enzymes, increased reliance on carbohydrate metabolism during exercise) (Bosquet et al., 2007; Hellard et al., 2005; Mujika and Padilla, 2000; Thomas and Busso, 2005; Thomas et al., 2008).

Most effective training patterns during TP

Cluster 4 (medium peak, slow decay) was significantly associated with the highest performance improvement. In cluster 4, the total training load was reduced from 55% of the most efficient cluster in OP (cluster 2 OP, 84 ± 17; 81 ± 22, 80 ± 19% mean TTL). This 55% training load decrement is in accordance with the 40-60% values generally suggested in the literature (Bosquet et al., 2007, Houmard and Johns, 1994; Johns et al., 1992; Mujika et al., 1996a; 1996b). Swimming economy has been reported to improve as a result of training load reduction in taper (D’Acquisto et al., 1992). Other studies have also shown that increases in maximal heart rate (Houmard and Johns, 1994), hemoglobin and hematocrit values (Yamamoto et al., 1988), and muscular power (Costill et al., 1985; 1991; Johns et al., 1992) are positively related to reduced training volume during taper.

In the most efficient pattern during TP (cluster 4, medium peak, slow decay), the 55% reduction in the total training load of pre-taper values was achieved through a 37% decrease in low-intensity training (training below the lactic threshold), a 49% decrease in high-intensity training (above the lactic threshold), and a 95% decrease in strength training. The 37% decrease in low-intensity training was less than the usual decline recommended in taper studies, which suggest performance improvement for a 60% decrement in low-intensity training (Bosquet et al., 2007; Mujika and Padilla, 2003; Pyne et al., 2009).

The 49% decrease in high-intensity training (above the lactic threshold) in the most effective training pattern (cluster 4) is in line with most earlier studies, which demonstrated the paramount importance of training intensity in maintaining the training-induced adaptations during periods of reduced training (Bosquet et al., 2007; Houmard and Johns, 1994; Mujika and Padilla, 2003; Pyne et al., 2009). These studies showed that intensity training had a fundamental role in preserving the physiological adaptations obtained during earlier periods of intensity training. However, the relationship between performance improvement and the decreases in training intensity during TP in the present study agrees with other reports suggesting the importance of decreasing training intensity during the final weeks preceding major events (Hellard et al., 2005; Mujika et al., 1996a; Van Handel et al., 1988). For instance, Van Handel and co-workers (1988) studied physiological and performance changes in elite swimmers performing 20 days of taper, with training volume dropping from 10,000-12,000 m to 2,000-3,000 $m \cdot day^{-1}$ while training intensity was held constant. They suggested that training intensity should also be reduced to further optimize the effects of taper, allowing adequate rest and recovery. Mujika et al. (1996a) reported a 2.94 ± 1.51% and 3.18 ± 1.70% improvement in performances during three taper periods lasting three and four weeks, respectively, in the course of which significant reductions were observed in the weekly distance swum in the high-intensity training zones. It has also been pointed out that excessive training at high intensity could lead to the deterioration of stroking parameters (particularly, stroke length) as stroke mechanics deteriorate at speeds above the anaerobic threshold as a consequence of local muscular fatigue (Dekerle et al., 2005; Toussaint et al., 2006). Therefore, it could be speculated that, in swimming, the amount of intensity training during taper needs to be optimized in order to maintain the training-induced adaptations acquired during the preceding overload training periods, while maintaining a high efficient swimming technique.

Cluster 3 (medium training load, low decay), which showed the smallest decrease in the training load, was significantly associated with the poorest performance improvement during taper. An insufficient decrement in training load probably did not permit the biological and psychological stress of the overload training period to resolve (Bosquet et al., 2007; Mujika et al., 1996a, Mujika and Padilla, 2003; Thomas and Busso, 2005; Thomas et al., 2008).

A novel finding of this exploratory study on training periodization is that the optimal training design for the pre-taper and taper periods gradually changed over the course of the athletes’ careers. From the 1st to the 3rd season, higher performance improvements were associated with lower training loads during the overload training period (the greater the training distance, the smaller the difference was between the performances at the major and preparatory events). Furthermore, training-load maintenance during taper was associated with greater improvements during the first three competitive seasons (the lower the difference between the overload and taper periods in the amount of training at low intensity, the greater the improvement was in performance after taper). From the 4th competitive season, the training effects were progressively reversed. High training loads during the overload period followed by a sharp decrease in the above-mentioned variables, as well as in total training load during taper, led to greater performance improvement. These results suggest that training load responses depend on the years of exposure to intensive training (Avalos et al., 2003; Busso et al., 1997). In line with this suggestion, Avalos et al. (2003) modeled the training-performance response relationship in 13 elite swimmers over three seasons and demonstrated that reactions to mid- and long-term training were significantly modified between the 1st and 3rd season. The same training load for the three seasons led to a negligible decrease in the mid-term performance (2–3 weeks before the competition) and a decrease in the long-term training period (4–6 weeks before the competition). For the taper periods directly preceding major events, the results of the present study confirmed the results of Busso and co-workers (Busso et al., 1997, Busso et al., 2002), who reported an increase over time in the magnitude and duration of fatigue induced by a single training bout. First, in high-level athletes who have been training intensively for many years, further progress in physiological adaptations and performance assumes continued and progressive increases in training loads (Avalos et al., 2003; Gaskill et al., 1999; Mujika et al., 2002; Stewart and Hopkins, 2000b; Thomas et al., 2008). Nevertheless, these athletes require longer recovery times (Avalos et al., 2003; Gaskill et al., 1999; Mujika et al., 2002; Thomas and Busso, 2005; Thomas et al., 2008). Last, the present study suggests that at the beginning of intensive swimming practice, the optimal design for young swimmers should basically consist of a continued training load distribution. Conversely, after several years of athletic career, training volume should be increased during the overload training periods and decreased during the taper periods, with the total amount of high-intensity training also proportionately decreased (i.e., the relative amount of high-intensity training is maintained or increased).

Significant inter-individual variability, however, suggests that these general training recommendations should be adapted so that a personal model is constructed for each subject, as advocated in most studies of the training-performance relationship (Avalos et al., 2003; Hellard et al., 2005; Mujika et al., 1996a; 1996b; Stewart and Hopkins, 2000a; 2000b).

One limitation of this study was the three-week taper period, as the consensus is that this period should vary from one to four weeks, depending on age, sex, swimming specialty, and the type of overload training conducted during the preceding period (Avalos et al., 2003; Mujika et al., 1996; 2002; Thomas et al., 2008). However, in observational studies with many subjects followed over many years, it is not possible to experimentally vary the competition periods. Most countries program preparatory competitions three weeks before the major competitive events, as reported by Mujika and his team in 2002.

Another limitation of the study concerns the calculation of the change in performance. One could argue that the greatest improvement with the final reduction in training does not necessarily mean reaching the highest performance after the taper. For example, Thomas and his colleagues used computer simulations and showed that a greater overload before taper could lead to a greater decrement in performance before taper and thus enhance the increase with taper (Thomas et al., 2008). The results of the analyses of our observational data indicate that such cases are infrequent. Indeed, in the 85 periods we studied, 53 of the performances during the National Championships were the best performances during the winter period, which runs from September to the National Championships. Twenty-six of the best winter performances were during the preparatory competition three weeks earlier, suggesting that top form was reached too early. Last, for six of the periods, the performance reached during the preparatory period was very low, which may have reflected a training overload and/or a medical problem.

Conclusion

During the overload training period six to four weeks prior to major events, swimmers were shown to adopt an optimal training design consisting of 84 ± 17, 81 ± 22, 80 ± 19% mean TTL. During the taper period, they maintained a medium training-load peak during the 1st week followed by a load decrease according to a slow decay logarithmic pattern (58 ± 23, 56 ± 23 and 44 ± 20% mean TTL in weeks 3, 2 and 1 prior to competition). These exploratory findings suggest 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 observations need to be adapted according to the individual responses of each athlete.

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Key points

- During the overload training period, a medium training load peak in the first week followed by an exponential slow decay training load design was linked to highest performance improvement.
- During the taper period, a training load peak in the first week associated with a slow decay design led to higher performances.
- Over the course of the swimmers' athletic careers, better performances were obtained with an increase in training load during the overload period followed by a sharper decrease in the taper period.
- Training loads schedules during the final six weeks of training before a major swimming event and changes over time could be prescribed on the basis of the model results.

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