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Modelling of optimal training load patterns during the 11 weeks preceding major competition in elite swimmers.

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Abstract

Periodization of swim training in the final training phases prior to competition and its effect on performance have been poorly described. **Purpose:** We modelled the relationships between the final 11 weeks of training and competition performance in 138 elite sprint, middle-distance and distance swimmers over 20 competitive seasons. **Methods:** Total training load (TTL), strength training (ST), low-to medium and high-intensity training variables were monitored. Training loads were scaled as a percentage of the maximal volume measured at each intensity level. Four training periods (meso-cycles) were defined: the taper (weeks 1 to 2 before competition), short-term (weeks 3 to 5), medium-term (weeks 6 to 8) and long-term (weeks 9 to 11). Mixed-effects models were used to analyze the association between training loads in each training meso-cycle and end-of-season major competition performance. **Results** For sprinters a 10% increase between ~20-70% of the TTL in medium and long-term meso-cycles was associated with 0.07-s and 0.20-s faster performances in the 50-m and 100-m events respectively ($p < 0.01$). For middle-distance swimmers a higher TTL in short-, medium-, and long-term training yielded faster competition performances (e.g., a 10% increase in TTL was associated with improvements of 0.1-1.0 s in 200-m events and 0.3-1.6 s in 400-m freestyle, $p < 0.01$). For sprinters, a 60-70% maximal ST load 6-8 weeks before competition induced the largest positive effects on performance ($p < 0.01$). **Conclusion:** An increase in TTL during the medium- and long-term preparation (6-11 weeks to competition) was associated with improved performances. Periodization plans should be adapted to specialty of swimmers.

Keywords: Swimming, periodization, mixed-models, cubic-splines, competition.

Résumé

En natation, la périodisation des phases d'entraînement précédant les compétitions majeures a été peu décrite. **Objectif:** Nous avons modélisé les relations entre les 11 dernières semaines d'entraînement et les performances en compétition chez 138 nageurs élités. **Méthode:** La charge d'entraînement totale (TTL), l'entraînement de force (ST), les variables d'entraînement de basse à moyenne et haute intensité ont été quantifiées. Les charges d'entraînement ont été normalisées en pourcentage du volume maximal individuel pour chaque niveau d'intensité. Quatre périodes d'entraînement (mésocycles) ont été définies, l'affûtage (semaines 1 à 2 avant la compétition), à court-terme (semaines 3 à 5), moyen-terme (semaines 6 à 8) et long-terme (semaines 9 à 11). Les modèles à effets mixtes ont été utilisés pour analyser les associations entre les charges d'entraînement dans chaque mésocycle et la performance de fin de saison. **Résultats:** Pour les sprinters, chaque augmentation de TTL de 10% entre ~20-70% dans les mésocycles à long et moyen-terme a été associée avec des performances plus rapides de 0.07-s et 0.20-s dans les épreuves de 50-m et 100-m ($p < 0.01$). Pour les nageurs de demi-fond une TTL plus élevée à court, moyen et long terme a induit des performances en compétition plus rapides (chaque augmentation de TTL de 10% entre ~20-70% a été associée à des performances plus rapides de 0.3-1.6-s au 400-m, $p < 0.01$). Pour les sprinters, une ST entre 60-70% 6-8 semaines avant la compétition a induit les effets positifs les plus élevés ($p < 0.01$). **Conclusion:** TTL 6-11 semaines avant la compétition a amélioré les performances en compétition.

Mots clefs: Natation, périodisation, modèles mixtes, splines cubiques, compétition.

Introduction

Performance times of top-ranked swimmers are typically very closely matched in international swimming competitions. For example, in the men's 100-m freestyle at the 2015 World Championships, the difference between the World Champion and the bronze medalist was 0.38 s, and 0.74 s between the latter and the 8th ranked swimmer. A widely held view in the international swimming community is that training periodization, particularly in the last 10-15 weeks before a major competition, is important to maximize performance.

Periodization has been defined as the purposeful sequencing of different training units (Issurin, 2016) designed to enhance performance gains, while limiting the odds of performance loss (injury, overtraining, detraining) (Turner 2011). Most short-term experimental studies have shown the greater effectiveness of polarized and block training paradigms than conventional training (Guellich et al. 2009; Neal et al. 2013; Rønnestad et al. 2014*a*, 2014*b*). In addition, approximately 75-80% of training for endurance athletes should be at speed (or power) <2 mmol \cdot l $^{-1}$ and 15-20% at or well above their speed (or power) corresponding to their individual lactate threshold, i.e. ~ 4 mmol \cdot l $^{-1}$ (Guellich et al. 2009; Tønnessen et al. 2014; Sylta et al. 2016). Moreover, these intensities should be distributed according to a sequence of specialized training cycles, with blocks of highly concentrated differentiated workloads (García-Pallarés et al. 2010; Rønnestad et al. 2014*a*, 2014*b*; Issurin 2016).

Observational studies in swimming (Mujika et al. 1995, 1996; Avalos et al. 2003; Hellard et al. 2006) have described periodized training similar to the so-called traditional theoretical and methodological models based on two or three cycle models of year round periodization

(Platonov 2006; Lyakh et al. 2014, 2015). Typically these models are characterized by cycles of 8-16 weeks, the assumption being that targeted training has to last long enough to induce the desired adaptations by a process of long-term cumulative summation of training effects. Within these cycles, low-, medium- and high-intensity training, strength and technical training are developed in combination, with the main training targets occurring in meso-cycles typically of 2-4 weeks duration (Platonov 2006; Lyakh et al. 2014, 2015). Recently, Issurin (2016) presented a multi-targeted block periodization model comprising three types of 2 to 4 week meso-cycles: accumulation (basic motor, technical abilities and aerobic endurance), transmutation (specific motor and technical abilities, anaerobic endurance), and realization (tapering and event preparation). In this model the sequencing of block meso-cycles involves targeted combination of compatible training modalities to elicit favorable training effects. Numerous technical reports indicate that successful coaches typically employ multi-targeted block periodization consisting of 10-15 week long cycles comprising 3 to 4 block meso-cycles (Touretsky 1998; Verhaeren 2006; Barnier 2012; Suguiyama 2012; Lange 2014). Another main characteristic of these successful international swimming programs is the specific periodization for sprint, middle-distance and long-distance swimmers. However, no scientific study in swimming has confirmed the effectiveness of periodized training across different events, nor evaluated intra-individual variations in responses to training loads (Afonso et al. 2017).

The aim of this study was to quantify the relationships between the effects of periodization variables on and competitive performance by sex, age, specialty (sprint, middle-distance, distance) in 138 elite swimmers during the 11-week training period before major competition.

Method

Cohort

The detailed training programs of 138 nationally- and internationally-ranked swimmers and their performance times ($n=2958$) were recorded over 20 competitive seasons from 1991-1992 to 2011-2012. The study cohort comprised 71 male and 67 female swimmers aged between 15 and 31 years, including 66 female and 33 male sprint swimmers (50-m and 100-m events), 38 female and 62 male middle-distance swimmers (200-m and 400-m events), and 33 female and 66 male long-distance swimmers (800-m to 10-km events). Some swimmers participated in two types of competition: sprint and middle-distance or middle- and long-distance. The swimmers were followed for an average of 3 years and competed in 22 ± 20 (sprint: mean \pm SD), 20 ± 23 (middle-distance) and 17 ± 14 (long-distance) competitions per year. All swimmers trained in one of three national training centers. Only those swimmers who met the inclusion criteria were selected. These included participation in the National Championships. The typical minimum number of training sessions per week was nine (including dryland conditioning). Swimmers were excluded if they had a chronic pathology (illness and/or injury) requiring medical treatment or missed training for 4 weeks or more. Swimmers were not eligible if they were taking medication known to affect immune function or inflammation. Written informed consent was obtained from each swimmer before entering the study.

Quantifying performance

All performance times were recorded at official competitions in Olympic size 50-m pools. Logarithmic transformation of the times was employed to correct any underlying heterogeneity in individual performances (Hopkins et al. 2009). To account for year-to-year changes in competition conditions, e.g. wearing of full-body swimsuits in 2007-2009, the performance times are expressed relative to the mean of the ten best world performance times ($m 10 WP$), in a given year for a given sex, stroke and distance:

$$Pr = \frac{\log(P) - \log(m \ 10 \ WP)}{\log(m \ 10 \ WP)} \times 100$$

where P is the absolute performance in seconds and Pr indicates the relative performance in percentage (the lower the Pr value, the higher the performance level of the swimmer relative to the current world level).

Quantifying training

Intensities for quantifying the swim workouts were determined according to Mujika et al. 1996. The application of the methodology was under the supervision of the French Swimming Federation, to which the three national training centers were affiliated over the course of the study.

An incremental test to exhaustion was performed at the beginning of each season (repeated and adjusted four 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, culminating in a maximal effort on the sixth and final swim. Lactate concentration was measured in capillary blood collected from the fingertip during the 1-min recovery period separating the 200-m swims (Mujika et al. 1996).

All swimming sessions were categorized into five intensity levels: (I1) below $\sim 2 \text{ mmol}\cdot\text{L}^{-1}$; (I2) between 2 and 4 $\text{mmol}\cdot\text{L}^{-1}$, the onset of blood lactate accumulation; (I3) between 4 and 6 $\text{mmol}\cdot\text{L}^{-1}$, (I4) above 6 $\text{mmol}\cdot\text{L}^{-1}$; and (I5) at maximal swimming speed. The speeds corresponding to each intensity level were then corrected to account for the swimming distance and rest intervals using Olbrecht's method (1985). For the European championships 400-m freestyle female winner (best personal performance 4 min-03-s -29), a typical level I2 training set was 10*400-m

with 40-s rest, performed in ~ 4 min-50-s with a $2.8 \text{ mmol}\cdot\text{L}^{-1}$ blood lactate concentration. A typical I3 training set for the same swimmer was 15*100-m, with 25-s rest, swam in ~1min-5-s with a $4.8 \text{ mmol}\cdot\text{L}^{-1}$ blood lactate concentration. Training at I4 incorporated training sets such as 8*100-m with 1 min-30-s rest and performed in ~ 1 min-01-s with a $7.2 \text{ mmol}\cdot\text{L}^{-1}$ blood lactate concentration. In-water workouts were quantified in meters per week at each intensity level. Strength training included dryland workouts at maximal strength (1-6 repetitions, 80%–100% of 1 repetition maximum (1RM)), muscular endurance, (6-15 repetitions, 60%–80% of 1RM), and general conditioning (e.g. stationary cycling, running, cross-country skiing, team sports, etc.).

Strength training was quantified in min of active exercise per week (Avalos et al. 2003).

For each swimmer, the weekly training volumes at each intensity level were scaled for comparative purposes as a percentage of the maximal volume measured at the same intensity level during the entire season (Avalos et al. 2003). In-water workouts are usually highly auto correlated (i.e. training at intensity levels I1, I2 and I3 were highly correlated >0.9 , they evolved together; the same was true for levels I4 and I5). Therefore, the intensity levels were summarized as follows: the weekly low- to medium-intensity training load was the mean training volume (in percentage) at intensity levels 1 to 3, and the weekly high-intensity training load was the mean training volume (in percentage) at intensity levels 4 and 5. By differentiating in-water workouts into these two intensity classes, we avoided collinearity problems. The intensity levels were thus summarized via the weekly total training load (TTL) of the mean training volume (in percentage) for both in-water and dryland workouts (Avalos et al. 2003).

Calculating training loads for the meso-cycles

The 11 weeks of training before a competitive performance (w_1 to w_{11}) were analyzed to study the effects of training on performance. We employed the terminology of Platonov (Platonov 2006; Lyakh et al. 2014, 2015) given it is the closest to that usually used by elite swimming coaches (Pyne and Touretski 1993; Verhaeren 2006; Lange 2014; Vergnoux 2014). Four distinct training meso-cycles were defined (see Figure 1): the taper meso-cycle (weeks 1 to 2 before competition), short-term (weeks 3 to 5), medium-term (weeks 6 to 8) and long-term (weeks 9 to 11). The mean weekly TTL and the means of the high-intensity, low-medium intensity and strength training loads were calculated in each meso-cycle.

Place figure 1 about here.

Adjustment variables

To account for potential confounding factors in the relationship between training and performance, several adjustment variables (covariates) were included in the models. Age at the time of competition was taken into account using two terms, age and quadratic age, to model a possible age-dependent biphasic change in performance (Berthelot et al. 2012). Sex, distance, and specialty (swimming strokes) were also included. The quarter (phase of the season) was included to account for the relative importance of the competitions (i.e., national competitions in the first and second quarters and international competitions in the third). The training center was also included to account for any training differences from one center to another.

Statistical analysis

The adaptation to training and type of training may have differed with the distance of the competitive swimming event. Therefore, three stratified analyses were conducted according to competition distance. Mixed-effects models were employed to estimate the training effects on performance (as a continuous variable) (Wood 2006). These models are usually used to analyze

longitudinal data since they account for both inter-subject variability and intra-subject correlation. The effects common to the entire cohort are estimated with the fixed effects part of the model. We accounted for individual differences in baseline performance level by including random intercepts. All the models were adjusted for adjustment variables. For each distance class, we considered two mixed-effects models: the first one consisted in the taper, short-term, medium-term and long-term meso-cycles for the TTL quantification of training; the second one consisted in the same meso-cycle terms for the high-intensity, low-medium intensity and strength training. The non-linear effects of training on performance were estimated using cubic splines, which do not assume the functional form of the relation. To avoid overestimation, non-significant training measures were eliminated from the model. Among no significant training effects, the least significant was removed if the AIC (Akaike Information Criterion) of the model without this variable was improved. To report the practical significance, the standardized effect of a 10% increase in training load on competition performance was computed in seconds per 50-m, 100-m, 200-m, 400-m, 800-m, 1500-m event. For all three groups sprinters, middle-distance and distance swimmers, the determination coefficient was calculated as follows: $r^2 = 1 - (RSS / TSS)$, where RSS is the residual sum of squares and TSS the total sum of squares. The data were analyzed using the mgcv R package (R Core Team, 2016; Wood 2006). Significance was set at $p < 0.05$.

Results

Effects of age and sex

Table 1 shows associations between performance, age, sex, swimming strokes and swimming centers for each of the three distance specialties: sprint, middle-distance and long-distance. A biphasic evolution in performance with age was seen for the sprinters and middle-distance

swimmers. Performance progressed up to ~21 y for the former, ~24 y for the latter, and then regressed. For the long-distance swimmers, performance progressed linearly with age.

Training load effects on sprint performance over the four meso-cycles

Total training load and sprint performance

The coefficients of determination r^2 for the TTL model were 0.26 ± 0.20 , 0.45 ± 0.10 and 0.26 ± 0.05 for the sprinters, middle-distance and distance swimmers respectively. Fig. 2 shows the relationship between total training load (TTL) and performance over three of the four meso-cycles for sprint swimmers (only significant effects are shown). The higher the TTL in the 2 weeks before competition (i.e. the taper phase), the slower the competition performance times ($p < 0.01$). Between 20% and 80% of the TTL, the confidence intervals were narrow and the estimates were accurate. Every 10% increase in the TTL within this range was associated with a slower performance by ~0.07-s in 50-m events and 0.20-s in 100-m events. In contrast, during the medium-term meso-cycle (i.e. 6-8 weeks before competition), the training load had a positive effect on performance ($p < 0.01$). Between 20% and 70% of the TTL, the confidence intervals were narrow and the estimates were accurate. Within this range, every 10% increase in the total load was associated with faster performance ~0.07-s in 50-m events and 0.20-s in 100-m events. In the long-term meso-cycle 9-11 weeks before competition, the training load had a positive effect on performance ($p < 0.01$). Above 20% of the TTL, every 10% increase in the total load was associated with faster performance by ~0.03-s in 50-m events and ~0.02-s in 100-m events.

Place figure 2 about here.

Low-to medium intensity training and sprint performance

The coefficients of determination r^2 for the LMIT, HIT and ST model were 0.27 ± 0.18 , 0.45 ± 0.10 and 0.20 ± 0.05 for the sprinters, middle-distance and distance swimmers respectively. Figure 3 upper panels show the function relating low-to medium intensity training (LMIT) load to performance over the meso-cycles. Above 20% of the maximum individual training load, the higher the LMIT load in the 2 week taper before competition, the slower the performances ($p < 0.01$). Between 20 and 80% of LMIT, the confidence intervals were narrow and the estimates accurate. Every 10% increase in the total load was associated with a reduction in performance of 0.07-s in 50-m events and 0.20-s in 100-m events. In contrast, for the medium-term training meso-cycle, LMIT had a positive effect ($p < 0.01$) on sprint performance. Between 10% and 80% of the LMIT load each 10% increase in training load was associated with faster performance of 0.02-s in 50-m events and 0.08-s in 100-m events.

High-intensity training and sprint performance

Figure 3 (lower panels) also shows the function relating the high-intensity training (HIT) load and sprint performance. During the taper phase, between 30 and 60% of the maximal training load, high intensity training improved performance ($p < 0.0001$). On the other hand, between 60 and 80% of the high-intensity load, every 10% increase in the total load was associated with 0.10-s slower performance in 50-m events and 0.20-s in 100-m events. In contrast, with medium-term training, a logarithmic relationship was evident. Increasing the HIT load in this meso-cycle from 20 to 50% of the maximum HIT was associated with faster performance by ~ 0.03 -s in 50-m and 0.07-s in 100-m events ($p < 0.05$). A statistical trend was observed ($p = < 0.07$) between HIT load and sprint performance during the short-term phase (3-5 weeks before competition). In this phase, between 40 and 80% of the maximal individual load, every 10% increase in total load was associated with faster performance by ~ 0.02 -s in 50-m and 0.04-s in 100-m events. High intensity

training load differences during the long-term phase of training were not statistically associated with variation in performance.

Place figure 3 about here.

Strength training and sprint performance

Figure 4 shows the function relating load of strength training and sprint swimming performance. Increases in the training load during the taper were typically associated with a slower performance ($p < 0.01$). Above 10% of the strength load, the confidence intervals were narrow and the estimates accurate. Every 10% increase in the total strength load was associated with 0.1-s and 0.2-s slower performance for 50-m and 100-m events. For the medium-term training meso-cycle, a load increase between 60 and 80% was linked to faster performances ($p < 0.01$). Between 60 and 80% of the training load, the confidence intervals were narrow and the estimates accurate. Every 10% increase in the total load was associated with 0.1-s and a 0.2-s faster performance for 50-m and 100-m events, respectively. A load increase in the long-term meso-cycle (i.e. 9, 10 and 11 weeks before competition) was also associated with improved performance ($p < 0.01$). Between 10 and 70% of the strength load, the confidence intervals were narrow and the estimates accurate. Every 10% increase in the maximum strength load was associated with 0.02-s and 0.06-s faster performance in 50-m and 100-m events, respectively.

Place figure 4 about here.

Training load effects on middle-distance performance over the four meso-cycles

Total training load and middle-distance performance

During the taper, training between 20 and 40% of the individual maximal load improved middle-distance performance ($p < 0.01$) (Figure 5). Conversely, between 40 and 80% of the maximal individual load, every 10% increase in total load was associated with ~0.5-s and 1-s slower performance in 200-m and 400-m events, respectively. For the short-term training meso-cycle, increasing the total load between 20% and 70% of the maximal individual load was associated with faster performance ($p < 0.05$) in such a way that each 10% increase in the load yielded faster performance by 0.5-s and 1-s for 200-m and 400-m events, respectively.

For the medium-term meso-cycle (6, 7 and 8 weeks before competition), increasing the load between 20% and 70% of the maximal load was associated with a 1-s and a 1.6-s faster performances ($p < 0.01$) in 200-m and 400-m events, respectively (Fig. 5 lower left panel). For long-term training (9, 10 and 11 weeks before competition, Fig 5 lower right panel), increasing the load between 10% and 80% of the maximal load was associated with a 0.1-s and 0.3-s faster performance ($p < 0.01$) in 200-m and 400-m events, respectively.

Place figure 5 about here.

Low-to medium intensity training and performance

Low-to medium intensity training maintenance between 20% and 40% of the maximum load during the taper period improved performance (Fig. 6). Conversely, higher LMIT training load volume (between 40% and 80% of the maximal volume) was detrimental to performance ($p < 0.0001$). Indeed, every 10% load increase between 40% and 80% slowed the relative performance by 0.5 and 1-s for 200-m and 400-m events, respectively (Fig. 6 upper left panel). LMIT in the short- and medium-training meso-cycles improved performance ($p < 0.01$) (Fig. 6 upper right, bottom left panels). During both these periods, each 10% load increase between 20%

and 70% of the maximal individual workload improved relative performance by 0.2-s and 0.6-s for 200-m and 400-m events. In the long-term meso-cycle (Fig. 6 bottom right), the positive influence of LMIT on performance was less clear. Every 10% increase in the load between 10% and 80% of the maximal individual load induced faster performance by 0.10 and 0.20-s for 200-m and 400-m events, respectively.

Place figure 6 about here.

High-intensity training and performance

Over the 11-week training period, high-intensity loads were only linked to faster performance ($p < 0.01$) during the short-term meso-cycle (Fig. 7 upper left panel). During this period 3-5 weeks before competition, increasing HIT for load volumes between 50% and 70% was associated with faster performances, with each 10% load increase leading to faster performances by ~0.4-s for the 200-m and 0.8-s for the 400-m events. During this meso-cycle high intensity training between 20 and 50% of the maximum individual load maintained performance.

Strength training and performance

Strength training during the taper had a significant negative effect on performance ($p < 0.01$) (Fig. 7 upper right panel). Every 10% load increase between 10% and 50% was associated with a 0.2 and 0.5-s decrease in performance for 200-m and 400-m races, respectively. During the short-term training meso-cycles (Fig. 7 lower left panel), the strength loads significantly improved performance ($p < 0.05$). Every 10% load increase between 10% and 50% improved relative performance by 0.10-s and 0.15-s for 200-m and 400-m events, respectively. Finally, strength training in the long-term training meso-cycle had a significant positive influence on

performance. Each 10% load increase between 10% and 80% was linked to faster relative 200-m and 400-m performance by 0.15 and 0.25-s, respectively.

Place figure 7 about here.

Training load effects on long-distance performance over the four meso-cycles

Total training load and long-distance performance

The total training load in the medium-term ($p > 0.0001$) and the long-term meso-cycles ($p = 0.0001$) improved performance (Fig. 8 upper and lower panels). In both meso-cycles, each 10% increase between 10% to 60% of the individual maximal load improved the relative performance by ~1-s and 2-s for 800-m and 1500-m races, respectively.

Place figure 8 about here.

Low-to medium intensity training and long-distance performance

No significant effect was observed for the taper and short-term meso-cycles. The performances were faster with higher loads in the long-term and medium- meso-cycles ($p < 0.01$) (Fig. 9 upper and medium panel). LMIT from 11-6 weeks before competition showed positive effects. Each 10% increase between 10% to 60% in the individual maximum loads for LMIT improved the relative performance by ~1-s and 2-s for 800-m and 1500-m events, respectively.

High-intensity training and long-distance performance

HIT showed positive effects only during the short-term meso-cycle 3-5 weeks before competition (Fig. 9 lower panel). An increase in the load between 10% and 70% improved relative performance by ~1-s and 2-s for 800-m and 1500-m events, respectively.

Place figure 9 about here.

DISCUSSION

This is the first study that systematically examines the relationships between periodized training loads and performance in a large cohort of elite swimmers over the final 11-weeks of training prior to a major competition. The training meso-cycles for basic conditioning, general and specific preparation in the 3 to 11 weeks before major competition typically improved performance, with the most striking positive effects observed for the medium-term mesocycle 6-8 weeks before competition. In contrast, both higher swim training and dryland strength loads during the taper were detrimental to performance. On the other hand, relatively higher loads in the medium- (6-8 weeks) and long-term (9-11 weeks before competition) meso-cycles were typically associated with faster competition performance. These data reinforce that different types of training loads need to be periodized in wave-like cycles with concentrated training units in certain meso-cycles. Our results also show that periodization plans should be adapted to the distance specialty of swimmers.

We determined that training in the several weeks before major competition affects performance, with the medium-term preparation meso-cycle (i.e. weeks 6 to 8 prior to competition) having the greatest positive impact. This outcome supports the training plans for elite athletes in endurance sports like swimming (Mujika et al. 1996; Hellard et al. 2006, 2013), long-distance running (Tønnessen et al. 2014), cross-country skiing (Tønnessen et al. 2014) and cycling (Rønnestad et al. 2014a, 2014b; Syllta et al. 2016), composed of long cycles of about 11 weeks or more. Long cycles induce the cumulative effects described as changes in physiological capabilities and level of physical/technical abilities resulting from a long-lasting athletic preparation (Lyaac et al. 2014, 2015; Issurin 2010, 2016). Since the pioneering work of Saltin and colleagues in 1977, several

studies on the time course of physiological adaptations have provided strong evidence in support of training cycles that last at least 10 weeks (Abe et al. 2000; Holliday and Jeukendrup 2012; Baroni et al. 2013). Most of the metabolic, neuromuscular and cardiovascular adaptations to constant or incremental training begin after 2 weeks of training, peak between 4 and 6 weeks, and continue up to the twelfth week or more. For instance, studies have reported that concentrations of both citrate synthase and succinate dehydrogenase increase ~100% after 10-12 weeks of aerobic training, whereas short-term training studies of less than 2 weeks have at times failed to increase tricarboxylic acid cycle enzymes (Green et al. 1991*a*, 1991*b*; Holliday and Jeukendrup 2012). The production of glycolytic enzymes (glycogen phosphorylase, pyruvate kinase, phosphofructokinase) following a short, intense anaerobic workout indicated similar dynamics with 16-50% increases for training periods ranging from 2-7 weeks (Ross and Leveritt, 2001). To build physical strength, resistance training needs to be long enough (2-6 weeks) to induce neuromuscular and hypertrophic adaptations, as the later were only observed after the fourth week of strength training (Abe et al., 2000). Taken together, these studies are in keeping with our results and confirm the necessity of cycles and preparation periods long enough to develop athletic abilities (Matveiv 1977; Platonov 2006; Lyakh et al. 2014, 2015). Swimmers need a solid physiological base developed using low-, medium- and high-intensity training loads during the medium- and long-term meso-cycles (6 to 11 weeks before the competition). Strength capacities need to be developed progressively in the medium- and long-term training meso-cycles, maintained in the short-term meso-cycle, and loads finally reduced to avoid detrimental effects in the taper period. Most of these outcomes are consistent with the practices of leading international swimmers. This study confirms these field models showing either linear or logarithmic relationships with threshold values and ranges.

Our results indicate that in the medium-term period for sprinters and the short-term periods for middle-distance swimmers, LMIT, HIT and ST together improved all performance. It appears that some meso-cycles should focus on training units that combine several types of training (low-medium, high intensity, and strength training). Issurin (2016) argued that the rationale for this multi-targeted periodization is to combine compatible training loads causing positive interactions and the superposition of training effects. Some experimental results support this notion of later positive interactions, showing the potential for combined strength and endurance training to amplify endurance performance (Rønnestad and Mujika, 2014). The second interest for a combined training is to maintain certain skills or adaptations throughout the training cycles. After a few days to 3 weeks of training cessation, rapid physiological, muscular power and metabolic losses in adaptation occur, leading to 4-25% decreases in endurance performance (Coyle et al. 1984; Costill et al. 1985; Mujika and Padilla, 2000a, 2000b). These reports underline the importance of a periodization model based on a steady and optimized training stimulus, irrespective of whether aerobic or anaerobic training is targeted (Issurin 2013).

The periodization models with 9- to 11-week cycles examined in this study were similar to other block periodization models (Rønnestad et al. 2014a, 2014b; Issurin 2010, 2016). The influence curves connecting training loads to performance showed that optimal periodization was characterized by cyclical changes in the loads, with concentration on specific training units in meso-cycles of 2-3 weeks duration. For example, the maximum concentration on strength training for the middle-distance swimmers occurred optimally in the long-term cycle, low-to-medium-intensity training was most effective in the medium- and long-term cycles, and the high-intensity load exerted the greatest positive effects 3-5 weeks before the final competition of the season. Block periodization consists of concentrating specific high-intensity training in short

periods of 1-4 weeks, while maintaining the training level for other physiological qualities and abilities (Breil et al. 2010; Issurin 2010, 2016). The main objective of block periodization is to concentrate on delivering specific training stimuli to induce specific adaptations at different times, which is not possible with a mixed training program that addresses all physical abilities equally (Issurin, 2010). Moreover, block training seems particularly well suited to elite athletes who have been training for many years (Platonov 2006; Hellard et al. 2013). For these athletes, the training modes that facilitate further progress are increasingly limited despite an increase in their underlying abilities. Over the course of swimmers' careers, better performances were obtained by increasing the training load during the overload period and then sharply decreasing the load in the taper (Hellard et al. 2013). Intensive training in elite athletes could cause an epigenetic effect bound to a decline of the multiyear exercise-induced molecular response to each acute training session (Lindholm et al. 2014). This possible loss of reactivity in the genetic and molecular response indicates the importance of a new and gradual overload that causes sufficient stimulus to induce new adaptations (Coffey and Hawley 2007). Furthermore, the results of four relevant studies (Breil et al. 2010; Rønnestad et al. 2014a, 2014b; Rønnestad et al. 2016) all show the superior effects of block training on performance and several of its physiological determinants, compared with traditional periodization. In line with our results, training loads need to be concentrated in 2 to 4 weeks blocks to induce sufficient impact for physiological adaptations.

Optimal periodization models were specific to the distance specialty, from a block-type periodization for the sprinters to a more linear and continuous model for the long-distance swimmers. For sprinters, training for maximal strength and power was the priority in the long-term meso-cycle (weeks 9, 10 and 11). This work was followed by a period of low-to medium-

intensity training in the medium-term meso-cycle (weeks 6, 7 and 8). The peak high-intensity load was periodized in the medium-term and in the short-term meso-cycles (3-8 weeks before the main competition). This organization of training is similar to that reported for four Olympic and World champion sprint swimmers (Touretsky 1998; Verhaeren 2006; Barnier 2012; Lange 2014). Elite sprinters need to develop muscle strength and power, metabolic power and swimming efficiency (Vorontsov 2011), which explains the logic of this type of periodization.

Improving and maintaining the strength and power of the sprinters is a priority. In this study most sprinters athletes undertook a heavy dryland strength-training program (i.e., 2-6 sets of 2-10 repetitions of 70-90% 1RM) alternating with a program of light loads (i.e., 2-6 sets of 8-20 repetitions of 30-60% of 1RM) at a fast contraction velocity (Vorontsov 2011). Strength training in the long-term meso-cycle lasted 3 weeks and typically comprised five sessions: two maximum strength, one power, and two sessions per week focused on athletic skills and strengthening and stabilizing the lumbar and abdominal regions (i.e. “core” strength). This work preceded the development of aerobic and anaerobic endurance to limit negative effects of concurrent training on strength building (Izquierdo et al. 2004). In the medium-term cycle, strength training was characterized by a substantial reduction in the intensity and duration of the sessions, to 40 minutes, with two power sessions and two sessions for athletic skills, core strengthening and stabilization. The influence curves in this meso-cycle indicated the total training load was at its highest, composed of maximal volume of low-to medium-intensity training associated with a high volume of high-intensity training. Hypothetically, this three-week block of general preparation (weeks 6, 7 and 8) combining moderate intensity muscle power workouts with intensive training of the oxidative and glycolytic metabolic pathways can increase short-term endurance (conversion of fast-twitch type IIx muscle fibers into fatigue-resistant type IIa)

(Aagaard and Raastad 2012) while developing the oxidative and glycolytic metabolism in proportions similar to those seen in sprint training (Rodriguez and Mader 2011). Our results for sprint swimmers in comparison to long-distance and middle-distance swimmers confirm the notion that training loads need to be reduced substantially during the taper (Mujika et al. 1995; Avalos et al. 2003; Hellard et al. 2013).

For middle-distance swimmers, the optimal periodization showed fewer distinct cyclical variations than for sprinters. Total training load was associated with improved performance over 9 weeks. The greatest positive effects were in the medium-term preparation (weeks 6-8). Aerobic training completed during the six weeks of the long- and medium-term meso-cycles improved performance six weeks later, as did high-intensity training in the medium-term meso-cycle. The model of optimal periodization for dryland strength training showed a progressive decrease in the positive influence from the long-term to the medium-term cycle. This organization of training is similar to that reported for Olympic and World medallists (Suguiyama 2012; Vergnoux 2014). The estimated aerobic contribution for the 200-m (58%) and 400-m (73%) freestyle (Rodriguez and Mader 2011) underlines the critical involvement of both aerobic and anaerobic metabolism in middle-distance events. There is considerable plasticity of central and local factors, for both development of the training response and loss of adaptations after training cessation or reduction (Mujika and Padilla 2000*a*, 2000*b*). For this reason, low-to medium intensity endurance training continued through the taper period until a 40% threshold of total load was reached. In the medium-term meso-cycle, the positive influences of strength training and low-to medium intensity training were particularly pronounced, possibly because strength training combined with high- and low-to medium intensity endurance training can promote the physiological adaptations for endurance (Coffey and Hawley 2007; Rønnestad and Mujika 2014). To sum up,

the most effective training load pattern for middle-distance swimmers was characterized by a continuous high training load during the first six weeks, a low-, medium- and high-intensity training peak during the medium-term meso-cycle, and maintenance of low-to medium-intensity training during the short-term period.

The preparation of long-distance swimmers (competing in 800-m and 1500-m events) was characterized by the positive effect of low-to medium-intensity aerobic training in weeks 6-11 before competition. Beneficial effects of aerobic training were indicated by each 10% increase in load between 10% and 70% improving relative performance by 1-s and 2-s for 800-m and 1500-m events. This result indicates the greater effectiveness of longer training periods in distance swimmers compared with sprinters and middle-distance swimmers. The influence of high-intensity anaerobic training was also positive in the short-term meso-cycle. In this final 11-week cycle of a year-long preparation for the main competition, strength training did not improve performance. This periodization model showed strong similarities with that of World and Olympic medalists in long-distance swimming, and is consistent with the results of studies in cross-country skiing, cycling and track and field. Tønnessen et al. (2014), for example, described modest training variations in the annual cycle of biathletes and cross-country skiers, all World and/or Olympic medalists.

In contrast to sprinters and middle-distance swimmers, short-term training did not negatively influence performances of distance swimmers in the last 3 weeks before competition. This outcome is consistent with methodological (Platonov 2006) and experimental (Mujika et al 1995, 1996; Avalos et al. 2003) studies, asserting that the training load should be higher during the taper for endurance athletes. From classification of individual responses to short-, medium- and long-term training in a group of 13 swimmers, performances improved as a direct response to a

high training load (Avalos et al. 2003). From a similar perspective, Mujika and colleagues (1996) modeled the training-performance relationship and observed faster absorption of positive and negative training influences in middle- distance swimmers, indicating the need for a shorter taper period with a limited decreasing load. In Tønnessen's study, 11 Olympic and World medalists in long-distance skiing did not follow the tapering recommendations suggested by short-term experimental studies. The training volume was reduced by only 5% and 11% in the last 2 weeks and only three of these 11 skiers took a rest day prior to their gold medal performance. It can be argued that the combination of individual predisposition and the type of training typical of long-distance swimmers is characterized by both rapid recovery and a loss of aerobic adaptations in the case of excessively decreased training. The swim speeds of long-distance swimmers in low-to medium-intensity zones are usually close to their competitive swimming speeds, and maintaining high-volume low-to medium-intensity training is in itself sports-specific preparation. The most striking issues of this study are as follows. First, the training loads in the general preparation (long-term) and specific preparation (middle-and short-term) meso-cycles, from week 11 to week 3, showed positive impacts on performance with the most striking positive effects observed for the general preparation meso-cycles (weeks 6, 7, 8 before competition). These positive influences conformed to a cyclical wave pattern, with the specific training focus depending on the meso-cycle and type of training load. The optimal periodization designs were specific to distance specialties ranging from a highly periodized model for the sprinters to a more constant pattern of training for the middle-distance and long-distance swimmers.

Above 70-80% of the maximal individual training load, the wider confidence interval of the values is a limitation of this research, making the estimations less precise. This wider confidence interval indicates fewer observations in these high-load zones and probably reflects different

adaptation responses among individuals above 70-80%. As this was an observational study, our analysis may have been biased by unmeasured confounders such as the basal fitness level of the swimmers, current life constraints, nutrition, recovery measures, psychological responses and the technical quality of swimming during training. Furthermore, the training prior to the 11 weeks training period (i.e. very long term training effects (months, years)) likely impacted performances. Averaging the training loads in the 3-week meso-cycles may have also limited the precision of our results, as several empirical and methodological studies have shown the effects of variation within training meso-cycles. On the other hand, the main strengths of this work are: 1/ it is a longitudinal study on a large cohort of French elite swimmers that includes a long study period, 2/ which allows us for exploring the impact of short term up to long term training on performance, and 3/ appropriate statistical methods are applied, specifically, we adjusted for potential confounders, we accounted for individual differences, and we estimated the effects of training on performance using cubic splines, without assuming any hypothesis on the structure of this effect. As the external training load *per se* only explains 20-45% of the variation in performance, a future study will aim to model the relationships between performances and a combination of independent variables including external training load, internal training load and technical quality (Bourdon, 2017).

Conclusion

For this cohort of elite swimmers, increased training loads up to 70-80% of the maximal individual training load in pool and strength training in the gym during the medium- and long-term preparation meso-cycles (6-11 weeks to competition) improved competition performances. The influence curves indicated the optimal periodization models were cyclical wave patterns. These training models were specific to the swimmer's event, from highly periodized training for

sprint swimmers to more continuous and progressively changing training for distance and long-distance swimmers. Changes in training load as little as 10% can make important differences to competition performance.

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The authors report non conflicts of interest associated with the manuscript.

Draft

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Table 1. Adjusted regression coefficients of random intercept models with of competitive performance according to distance specialty.

Covariates	Sprint		Middle-distance		Long-distance	
	(n=1249 performances)		(n=1455 performances)		(n=254 performances)	
	Coefficients	P	Coefficients	P	Coefficients	P
Age		<0.001		<0.001		
Age	-0.390	<0.001	-0.438	<0.001	-0.016	0.141
Age squared	0.009	<0.001	0.008	<0.001	-	-
Sex (Male; ref: Female)	0.436	0.443	-0.425	0.001	0.254	0.045
Macrocycles (ref: Sept-Dec)		0.597		0.738		0.359
Jan-April	-0.041	0.287	0.080	0.769	0.053	0.018
May-July	-0.058	0.166	0.022	0.439	0.064	0.169
Strokes (ref: Freestyle)		0.141		<0.001		
Butterfly	0.527	0.036	0.912	<0.001	-	-
Backstroke	0.022	0.941	0.387	0.053	-	-
Breaststroke	-0.004	0.988	0.645	0.004	-	-
Medley	-	-	0.185	0.231	-	-
Swimming center (ref: 1)		0.022		<0.001		0.231
2	0.186	0.544	0.628	0.001	-0.063	0.691
3	-0.594	0.130	0.139	0.528	0.274	0.439

The coefficients associated to a category represent the mean decline (if positive sign) or mean improvement (if negative sign) in relative performance compared to the reference (ref) category, the other covariates are held fixed. The effect of age on the mean change in relative performance is estimated as: $\text{intercept} - 0.390 \times \text{Age} + 0.009 \times \text{Age}^2$ (Sprint), $\text{intercept} - 0.438 \times \text{Age} + 0.008 \times \text{Age}^2$ (Middle-distance), $\text{intercept} - 0.016 \times \text{Age}$ (Long-distance) the other covariates are held fixed. P-values associated to a single coefficient correspond to the Student T-test, P-values associated to a covariate correspond to the ANOVA-F test.

Figures legends.

Fig. 1. Training loads in high intensity (dotted lines with circles), low-to-medium intensity (hatched lines with squares) and strength training (solid lines with triangles) for a World champion during the last 11 weeks and the four meso-cycles (long-term, middle-term, short-term, taper) before competition. This figure shows typical 2-3 week building periods followed by “recovery weeks” built into the overall 11-week period. In the long-term, short-term and taper periods, LMIT, HIT and ST tended to increase or decrease in parallel. In the middle phase (weeks 6, 7, 8), block loading can be discerned. Weeks 9, 6 and 3 highlight a joint concentration of LMIT, HIT and ST.

Fig. 2. Relative decrement or improvement in performance (y-axis) as a function of training load (x-axis) for sprint swimmers over the taper (top panel), medium-term (middle panel), and long-term (bottom panel) training meso-cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 3. Relative decrement or improvement in performance (y-axis) as a function of low-to medium intensity training (x-axis) for sprint swimmers over the taper (upper panel left) and medium-term (upper panel right) meso-cycles. Relative decrement or improvement in performance (y-axis) as a function of high intensity training (x-axis) for sprint swimmers over the taper (lower panel left) and the medium-term (lower panel right) meso-cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 4. Relative decrement or improvement in performance (y-axis) as a function of strength training (x-axis) for sprint swimmers during the taper (upper panel), the medium-term (middle panel), and the long term (lower panel) meso- cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 5. Relative decrement or improvement in performance (y-axis) as a function of training load (x-axis) for middle-distance swimmers over taper (upper left), short-term (upper right), medium-term (lower left), and long-term (lower right) meso-cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 6. Relative decrement or improvement in performance (y-axis) as a function of low-to medium intensity training (x-axis) for middle-distance swimmers over taper (upper left panel), short-term (upper right), medium-term (lower left), and long-term (lower right) training meso-cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 7. Relative decrement or improvement in performance (y-axis) as a function of high-intensity training (x-axis) for middle-distance swimmers over the short-term meso-cycle (upper left panel). Relative decrement or improvement in performance (y-axis) as a function of strength training (x-axis) for middle-distance swimmers over taper (upper right panel), short-term (lower

left- panel), and long-term (lower right-panel) meso-cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 8. Relative decrement or improvement in performance (y-axis) as a function of training load (x-axis) for long-distance swimmers over medium-term (upper panel), and long-term (lower panel) meso-cycles. The solid line represents the training effect and the dotted lines, the 95% confidence interval.

Fig. 9. Relative decrement or improvement in performance (y-axis) as a function of low-to medium intensity training (x-axis) for long-distance swimmers over medium-term (upper panel), and long-term (middle panel) meso-cycles. Relative decrement or improvement in performance (y-axis) as a function of high intensity training (x-axis) for long-distance swimmers over long-term meso-cycles (lower panel). The solid line represents the training effect and the dotted lines, the 95% confidence interval.

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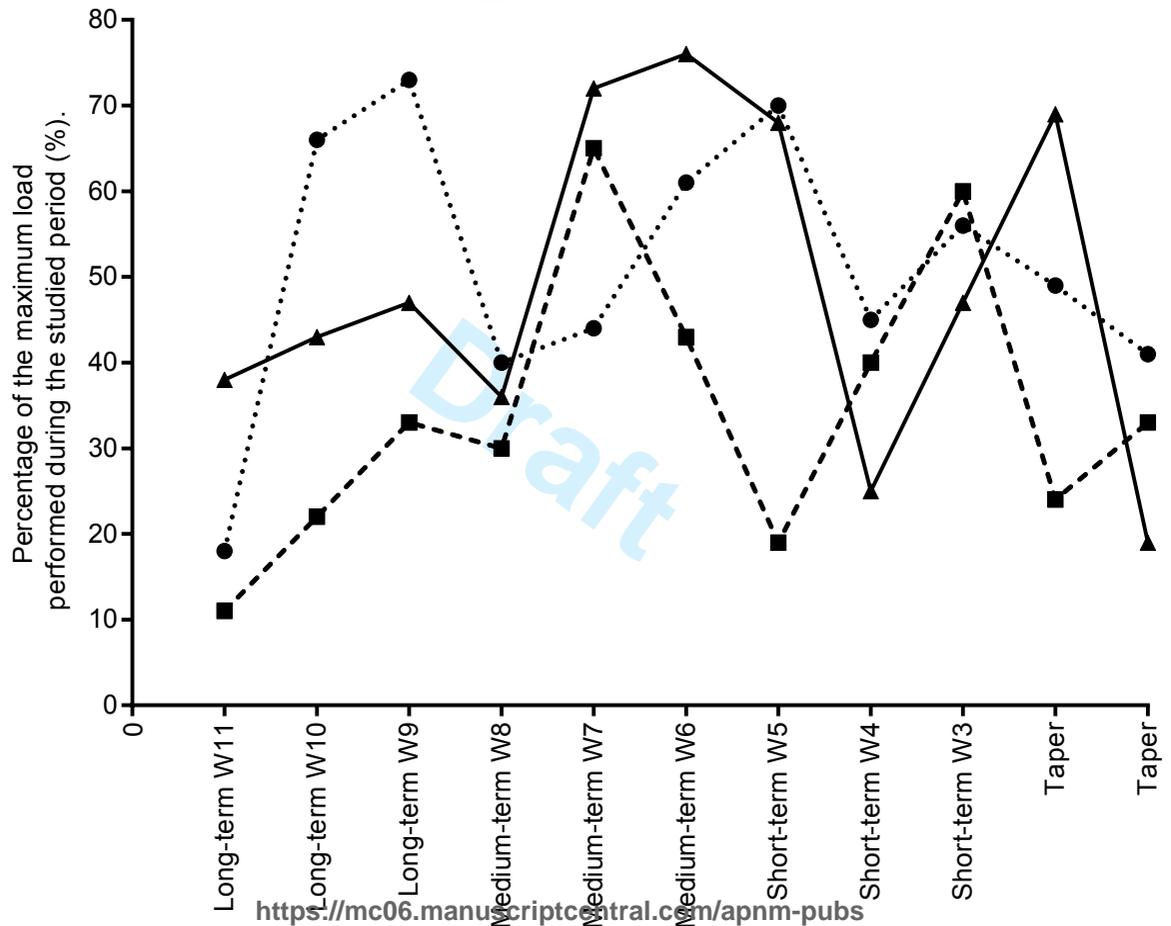
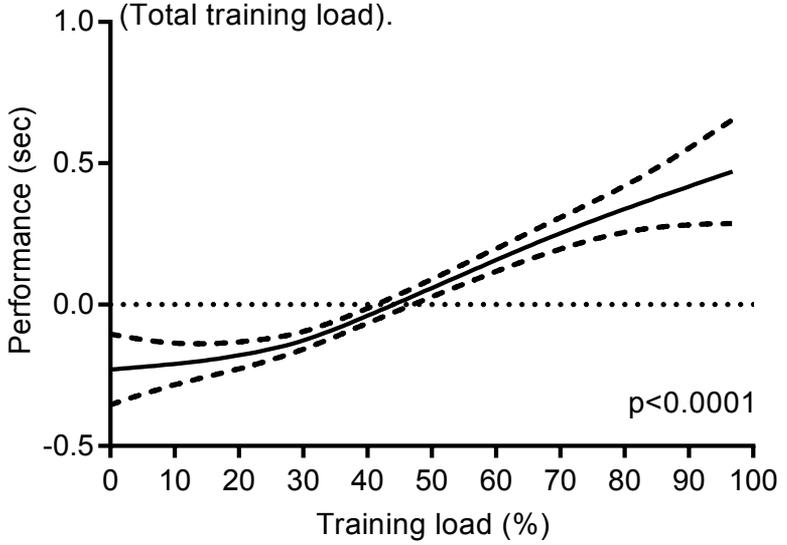
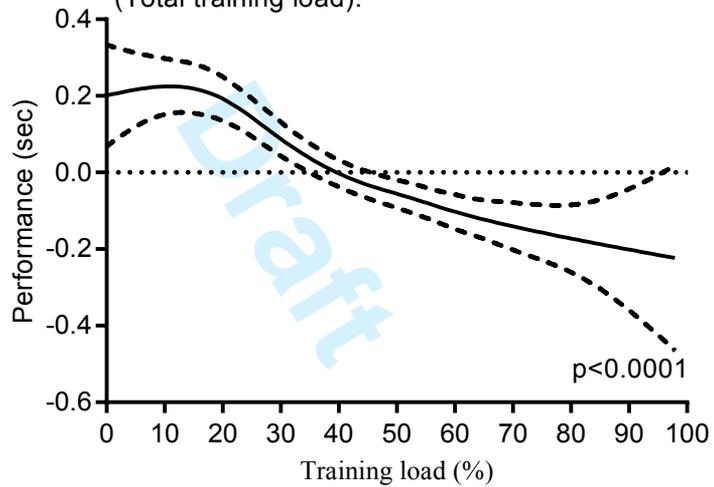


Figure 1.

Taper meso-cycle weeks 1,2 before competition
(Total training load).



Medium-term meso-cycle weeks 6,7,8 before competition
(Total training load).



Long-term meso-cycle weeks 9,10,11 before competition
(Total training load).

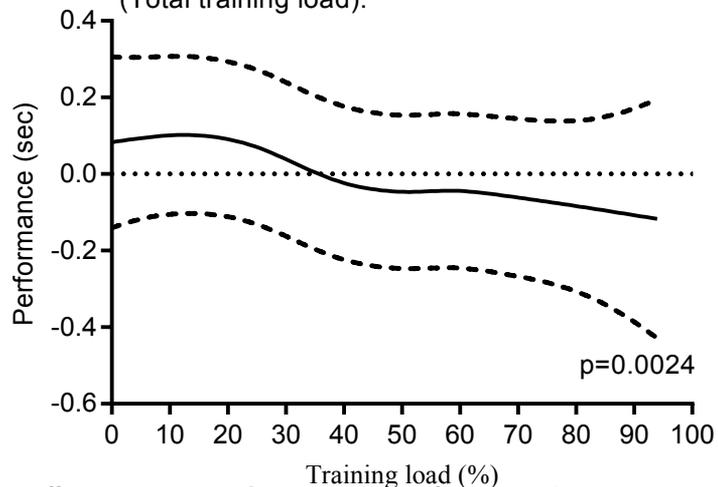


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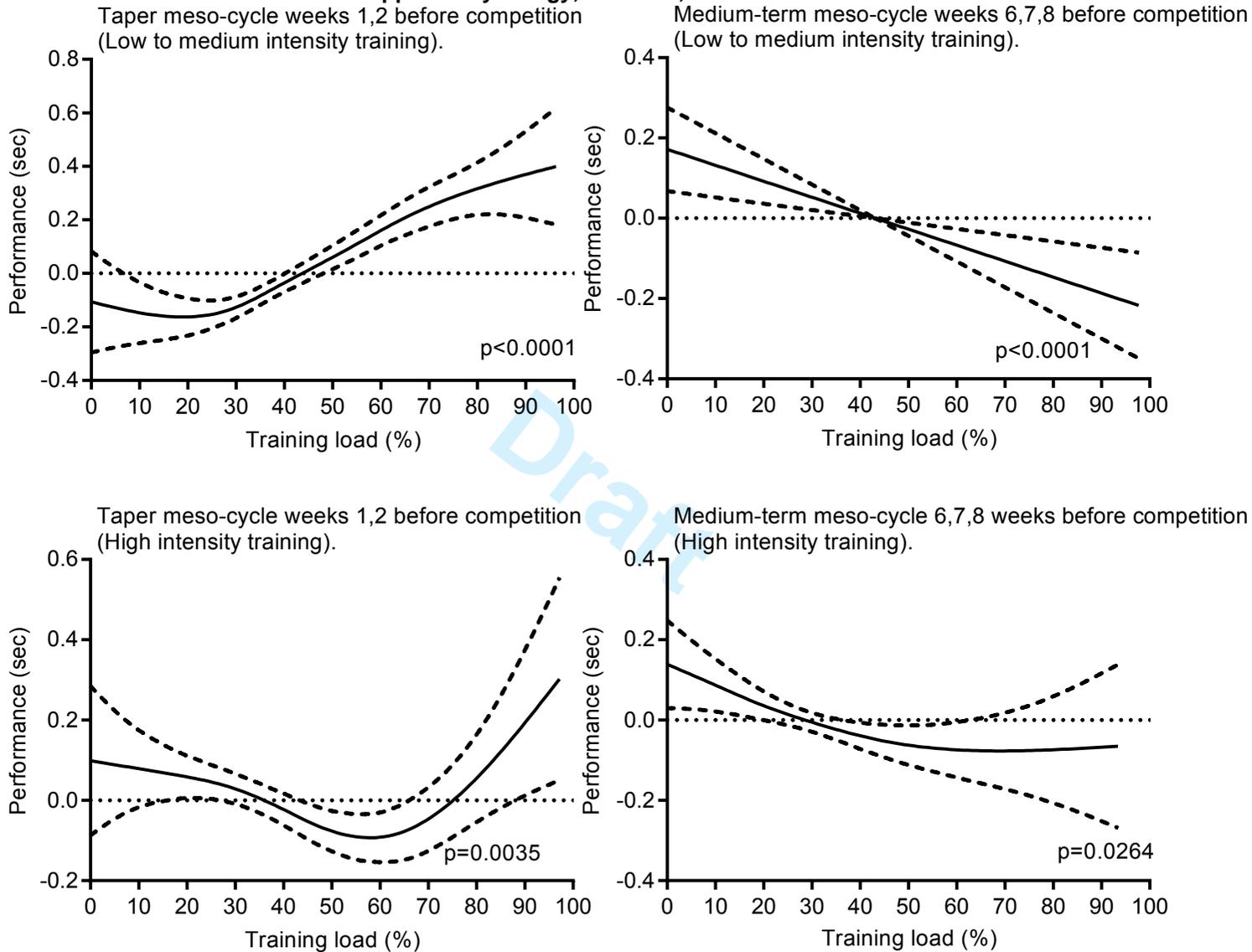


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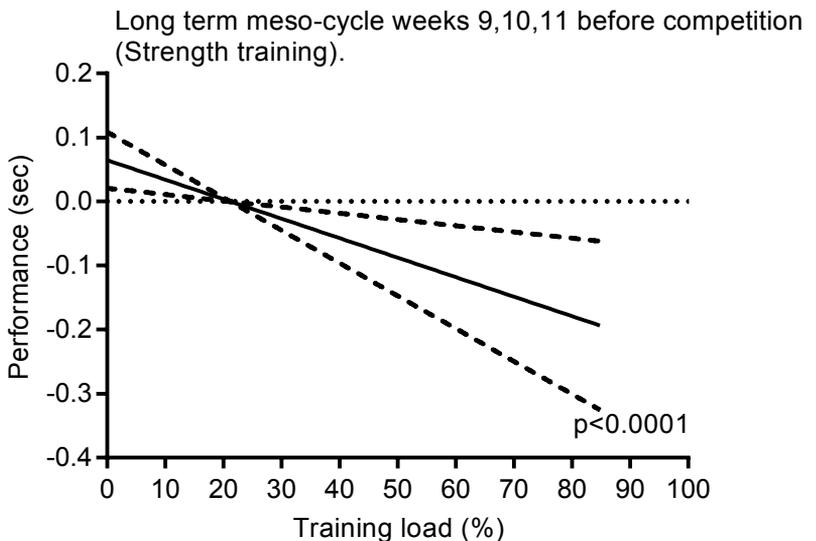
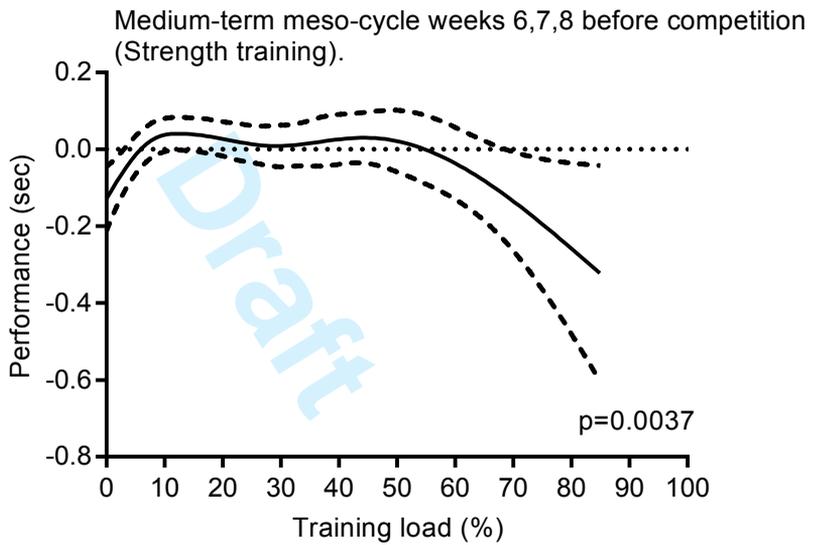
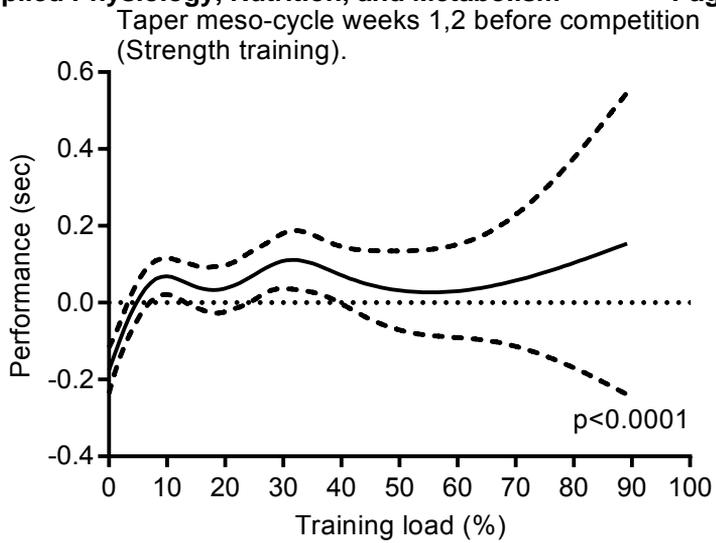
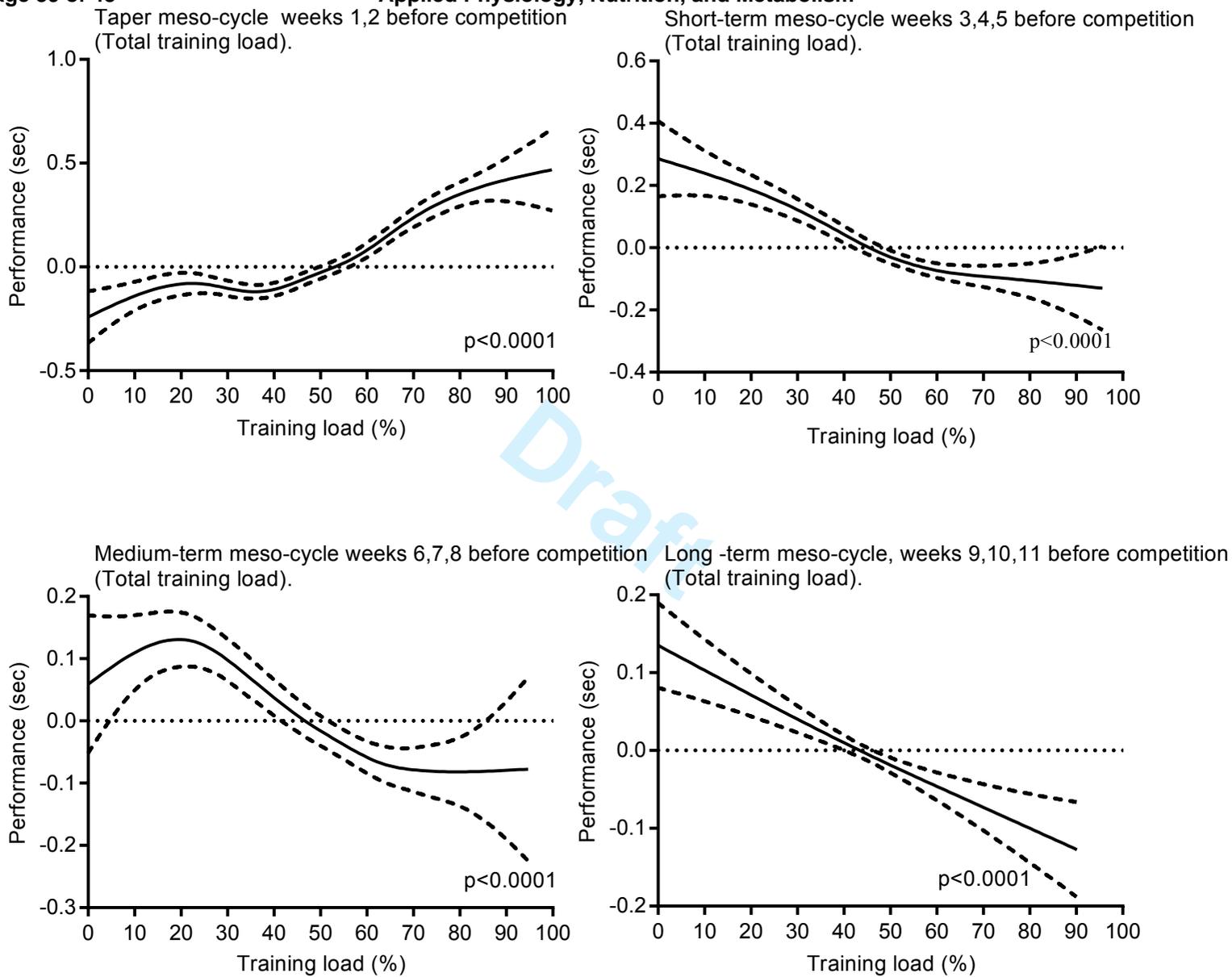


Figure 4.



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Figure 5.

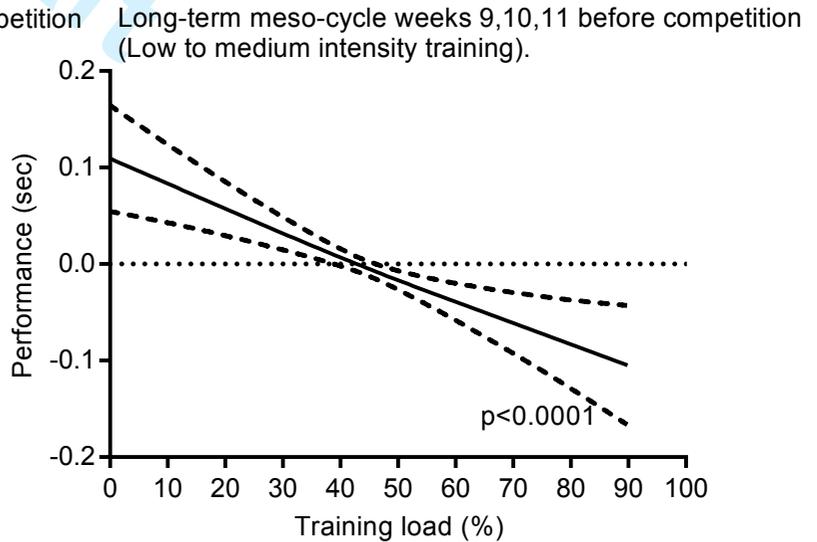
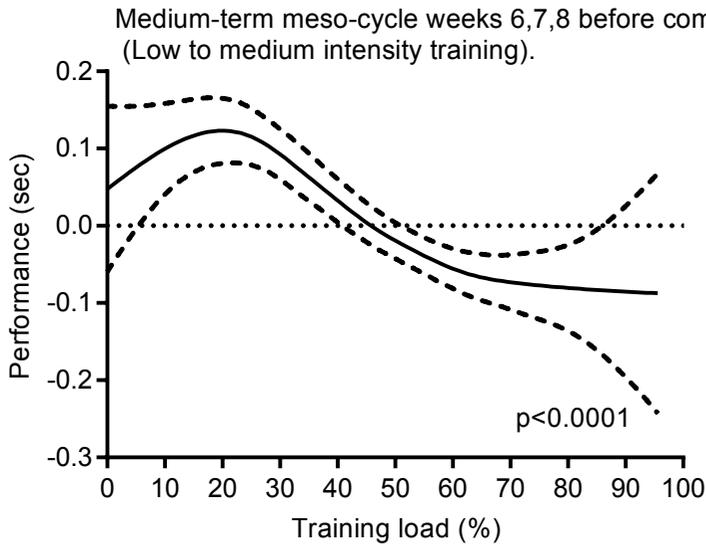
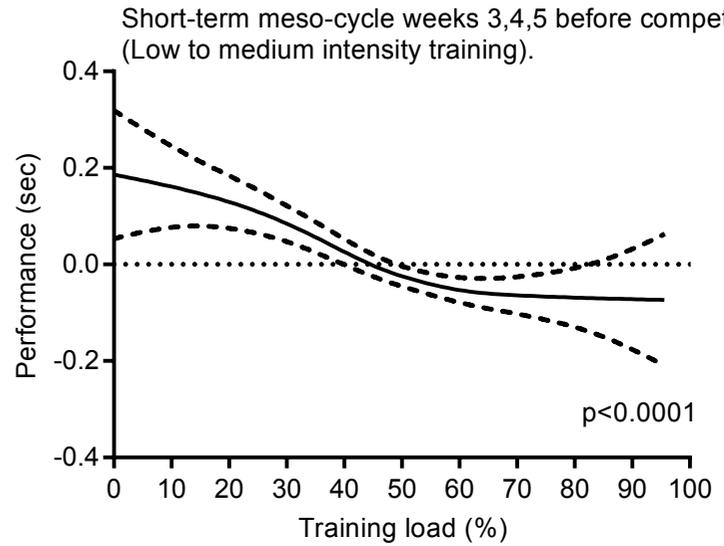
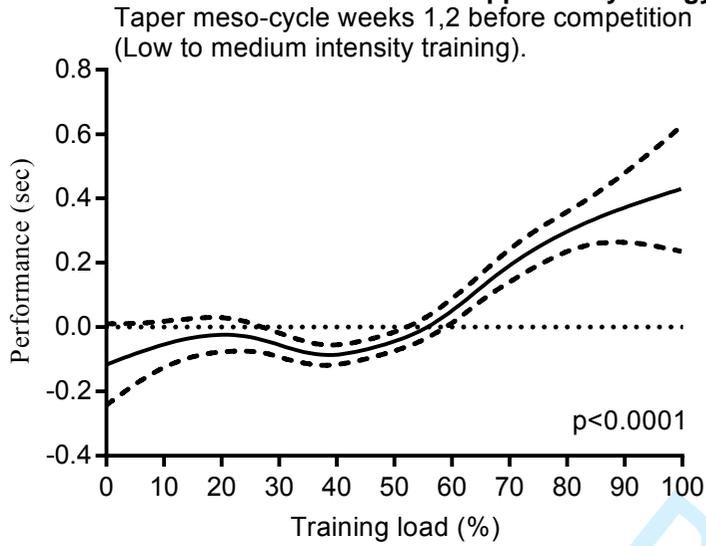
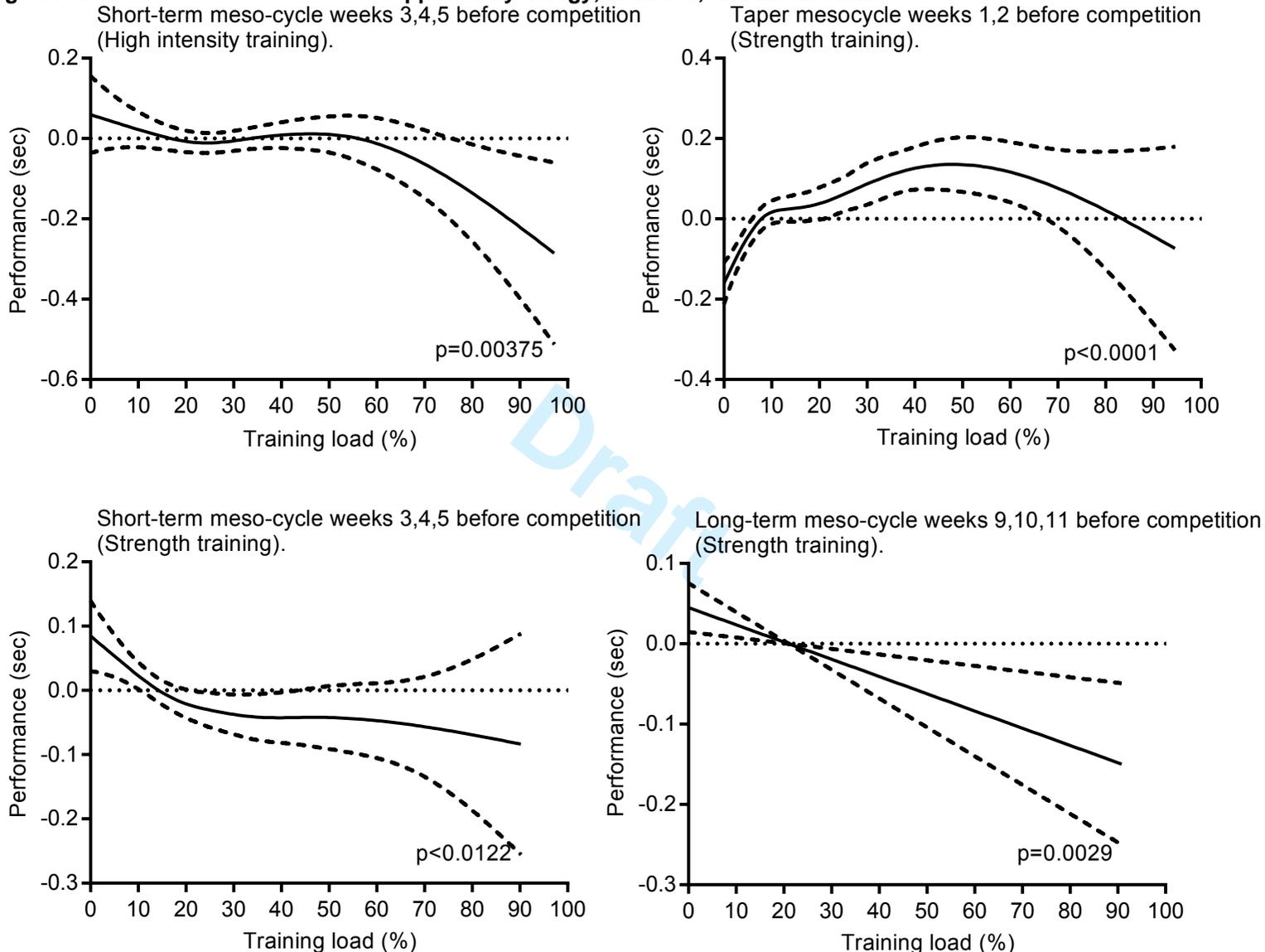


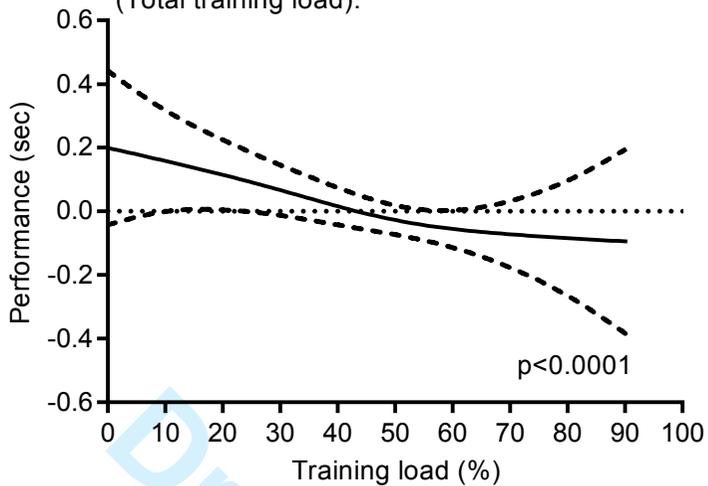
Figure 6.



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Figure 7.

Medium-term meso-cycle weeks 6,7,8 before competition
(Total training load).



Long-term meso-cycle weeks 9,10,11 before competition
(Total training load).

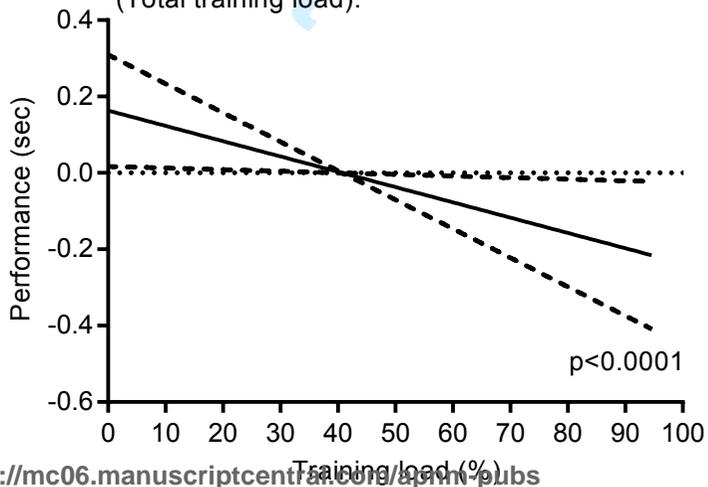
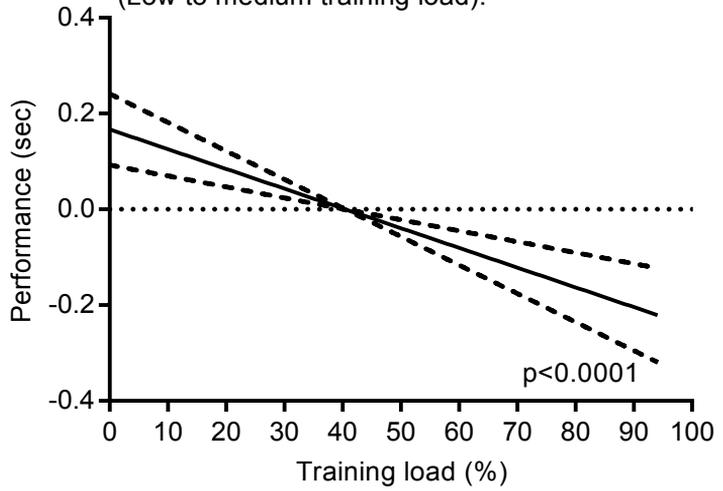
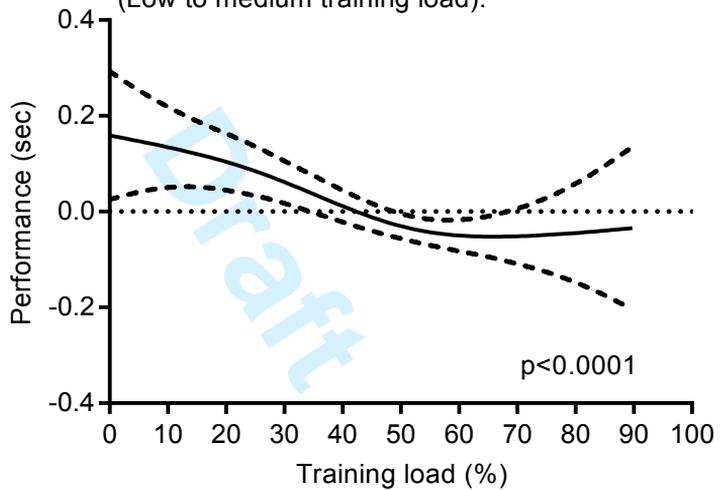


Figure 8.

Long term meso-cycle weeks 9,10,11 before competition
(Low to medium training load).



Medium term meso-cycle weeks 6,7,8 before competition
(Low to medium training load).



Short term meso-cycle, weeks 3,4,5 before competition
(High intensity training).

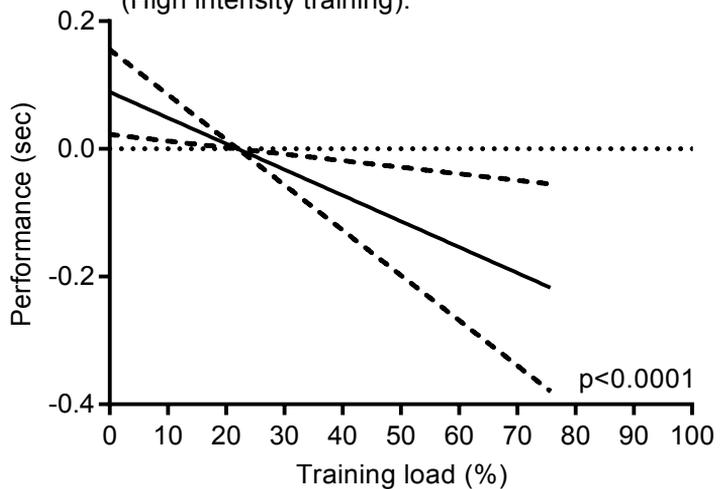


Figure 9.