Review

Effect of training cessation on muscular performance: A meta-analysis

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The purpose of this study was to assess the effect of resistance training cessation on strength performance through a meta-analysis. Seven databases were searched from which 103 of 284 potential studies met inclusion criteria. Training status, sex, age, and the duration of training cessation were used as moderators. Standardized mean difference (SMD) in muscular performance was calculated and weighted by the inverse of variance to calculate an overall effect and its 95% confidence interval (CI). Results indicated a detrimental effect of resistance training cessation on all components of muscular performance: [submaximal strength; SMD (95% CI) = −0.62 (−0.80 to −0.45), $P < 0.01$], [maximal force; SMD (95% CI) = −0.46 (−0.54 to −0.37), $P < 0.01$], [maximal power; SMD (95% CI) = −0.20 (−0.28 to −0.13), $P < 0.01$]. A dose–response relationship between the amplitude of SMD and the duration of training cessation was identified. The effect of resistance training cessation was found to be larger in older people (> 65 years old). The effect was also larger in inactive people for maximal force and maximal power when compared with recreational athletes. Resistance training cessation decreases all components of muscular strength. The magnitude of the effect differs according to training status, age or the duration of training cessation.

Muscular strength is a major determinant of sport performance, both in explosive (Delecluse, 1997) and long-duration events (Saunders et al., 2004), as well as an important contributor to functional performance and health in older adults (Moreland et al., 2004; Hurley et al., 2011). The capacity of the skeletal muscle to generate a high level of force is a complex interplay between several factors, including muscle fiber type (Gollnick & Matoba, 1984), muscle cross-sectional area (Jones et al., 2008), muscle architecture (Aagaard et al., 2001), and neural drive to the muscle (Gandevia, 2001). Resistance training is a safe and effective intervention to improve these determinants and increase muscular strength, whatever age and sex (Falk & Tenenbaum, 1996; Latham et al., 2004; Ratamess et al., 2009). However, training-induced adaptations are transitory and may disappear when the training stimulus is withdrawn, thus leading to detraining. Detraining has been defined as the partial or complete loss of training-induced anatomical, physiological, and functional adaptations, as a consequence of training cessation (Mujika & Padilla, 2000a). The reasons for such a scenario are numerous in an individual's life, e.g., illness, injury, travel, loss of motivation, or post-season break in competitive athletes. Also, it appears that, even if recommendations are clear regarding the beneficial effects of strength training, adherence to those programs are still a challenge (Andersen, 2011). Identifying the kinetics of strength loss once resistance training ceases is important to design successful tapers and return to optimal fitness for competitive athletes, and more generally for the individualization of exercise training prescriptions whatever the characteristics of the population. The literature examining this issue is very heterogeneous in terms of training/training cessation characteristics, muscular strength tests and measures and population characteristics. Although there is consensus among narrative reviews that training cessation leads more or less rapidly to detraining (Mujika & Padilla, 2000a,b, 2001c,d), methodological heterogeneity does not allow to make direct comparisons between studies or to specify the overall detraining effect according to sex, age, training status, or other relevant variables such as the duration of training cessation.

The aim of this study was therefore to assess the effects of complete resistance training cessation on the different expressions of muscular strength, including maximal force, maximal power, and submaximal strength, through a meta-analysis of the available
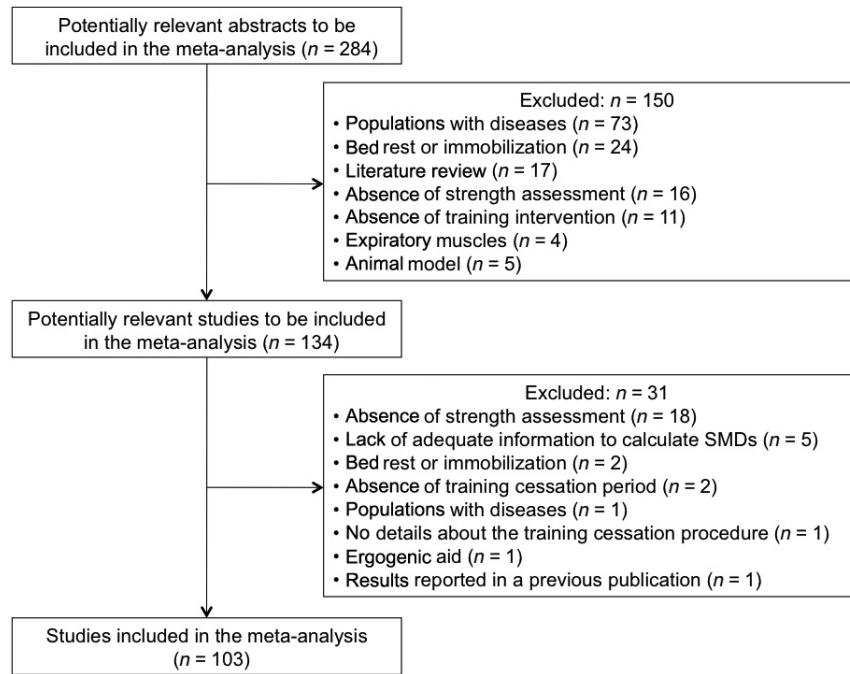
Potentially relevant abstracts to be
included in the meta-analysis ($n = 284$)

Excluded: $n = 150$
• Populations with diseases ($n = 73$)
• Bed rest or immobilization ($n = 24$)
• Literature review ($n = 17$)
• Absence of strength assessment ($n = 16$)
• Absence of training intervention ($n = 11$)
• Expiratory muscles ($n = 4$)
• Animal model ($n = 5$)

Potentially relevant studies to be included
in the meta-analysis ($n = 134$)

Excluded: $n = 31$
• Absence of strength assessment ($n = 18$)
• Lack of adequate information to calculate SMDs ($n = 5$)
• Bed rest or immobilization ($n = 2$)
• Absence of training cessation period ($n = 2$)
• Populations with diseases ($n = 1$)
• No details about the training cessation procedure ($n = 1$)
• Ergogenic aid ($n = 1$)
• Results reported in a previous publication ($n = 1$)

Studies included in the meta-analysis
($n = 103$)

Fig. 1. Flow chart of the study selection process.

literature. We also carried out exploratory subgroup analyses to determine whether population characteristics or training/training cessation characteristics were outcomes that may influence the magnitude of the effect.

Material and methods

Literature search strategy

The databases EBM reviews/CCRCT (1991 to 4th quarter 2011), Embase (1980 to 2011 weeks 50) Kinpubs (1947 to 2011), Physical Education Index (1970 to 2011), PubMed (1950 to 2011), SportDiscus (1830 to 2011), and Web of Science (1970 to 2011) were searched using the terms (detraining OR deconditioning OR training cessation) AND [(one repetition maximum OR 1 RM OR max$ strength OR max$ force) OR (power OR jump$ OR force-velocity) OR (muscular endurance OR RM)] for English-language and French-language randomized controlled trials, crossover trials, repeated-measure studies, theses, and dissertations. The reference lists of the articles obtained were searched manually to obtain further studies not identified electronically. This led to the identification of 284 potential studies for inclusion in the analysis (Fig. 1).

Selection criteria

Studies were eligible for inclusion if (a) they implemented a training intervention followed by a training cessation period and gave relevant details about the procedures, including the type and duration of training as well as the duration of training cessation; (b) the outcome included valid tests and measures of the upper or lower limb muscular performance in healthy humans; and (c) the paper reported the number of participants and all the necessary data to calculate effect sizes. Studies were excluded if they presented results reported in a previous publication.

Coding for the studies

Two independent reviewers who were blind to authors, affiliations, and the publishing journal (N. B. and O. D.) read and coded each included study using the following moderators: training status (competitive athletes, recreational athletes, or inactive people), sex (male, female, both), age (<65 years old, ≥65 years old), limb (upper, lower), duration of training and training cessation, and type of muscular performance (maximal force, maximal power, submaximal strength). Measures of maximal force included 1 to 5 RM during isoinertial contractions [constant weight lifted at a voluntary speed (Verdijk et al., 2009)], peak torque during isometric dynamometry, and peak torque during isokinetic dynamometry at 30 to 60°/s. Measures of maximal power included vertical jump height, sprint performance, peak power during a force–velocity test, and peak torque during isokinetic dynamometry at 120 to 240°/s. Measures of submaximal strength included 6 to 12 RM during isoinertial contractions, time to exhaustion during isometric dynamometry, and total work during an isokinetic fatigue test. An interval scale was used for the coding of performance and duration of training and training cessation, while a nominal scale was used for the coding of the other moderators. The duration of training cessation was *a posteriori* divided in seven categories: <7 days, 8 to 14 days, 15 to 28 days, 29 to 56 days, 57 to 112 days, 113 to 224 days, and >224 days. Any disagreement between both reviewers was discussed in a consensus meeting, and unresolved items were taken to a third reviewer (S. M.) for resolution.

Statistical analysis

Standardized mean differences (SMDs) for each study were calculated using Hedges' g (Hedges 1981). In the studies that used multiple measures of muscular performance, a single composite SMD was calculated (Borenstein et al., 2009). Considering that the effect of training cessation on muscular performance may differ according to the training status, age or other moderators, we *a priori* decided to use a random-effects model. Standardized mean differences were weighted by the inverse of variance to calculate an overall effect and its 95% confidence interval (CI). Cohen's criteria were used to interpret the magnitude of SMD: <0.5, small; 0.5 to 0.8, moderate; and >0.8, large (Cohen, 1988).

Statistical heterogeneity, which refers to the percentage of the variability between studies that is due to clinical and methodologi-

cal heterogeneity rather than the sampling error, was assessed by the I^2 statistic (Borenstein et al., 2009). According to Higgins et al. (2003), I^2 values of 25%, 50%, and 75% represent low, medium, and high heterogeneity, respectively. The presence of medium or high heterogeneity may provoke further investigation through subgroup analysis of moderator variables, even if the overall effect is considered nonsignificant (Higgins & Green, 2006). Weighted SMDs and standard errors were then calculated for each category within moderator variables, as well as 95% CIs to determine whether each SMD was different from 0. A Q-test based on the analysis of variance was performed to test the null hypothesis that the effect of training cessation was similar between the categories of a moderator variable (Borenstein et al., 2009). When the null hypothesis was rejected, pairwise comparisons were performed with a Z-test, the alpha value for significance being adjusted according to the procedure of Bonferroni (Vincent & Weir, 2012). The criterion level for significance was set at $P < 0.016$ (i.e., 0.05/3) for training status, which corresponds to a z-score higher than 2.41, and at $P < 0.0024$ (i.e., 0.05/21) for the duration of training cessation, which corresponds to a z-score higher than 3.04. Finally, a metaregression was performed to assess the relationship between the duration of training cessation and muscular performance. All calculations were made with Comprehensive Meta-analysis (http://www.meta-analysis.com).

Results
Overall results

The literature search allowed to identify 284 potentially relevant publications spanning from 1956 to 2011, of which 103 met all inclusion criteria. The most common reasons for exclusion were (a) the presence of pathological populations, (b) the absence of training/training cessation interventions, (c) the absence of upper or lower limb muscular performance assessment, and (d) the lack of adequate information to calculate SMDs. The overall SMD indicated a detrimental effect of training cessation on all components of muscular performance, since we found a moderate decrease in submaximal strength [SMD (95% CI) = −0.62 (−0.80 to −0.45), $P < 0.01$, $I^2 = 33.0\%$] and a small decrease in maximal force [SMD (95% CI) = −0.46 (−0.54 to −0.37), $P < 0.01$, $I^2 = 75.6\%$], and maximal power [SMD (95% CI) = −0.20 (−0.28 to −0.13), $P < 0.01$, $I^2 = 69.9\%$]. The presence of medium to large statistical heterogeneity for maximal power and maximal force justified the subgroup analysis of moderator variables. Similar analyses were performed for submaximal strength in an exploratory manner, given that I^2 was less than 50%.

Moderating variables: population characteristics and limb

The potential effect of population characteristics and limb on the magnitude of the decrease in maximal force, maximal power, and submaximal strength is presented in Tables 1, 2, and 3, respectively.

The effect of training cessation was found to be larger in older people (≥65 years old) for maximal force ($z = 5.38$, $P < 0.01$), maximal power ($z = 2.03$, $P < 0.05$), and submaximal strength ($z = 2.00$, $P < 0.05$). The effect

Table 1. Effect of training cessation on maximal force according to population characteristics and limb

Moderator	SMD*	95% CI	z	P
Age				
<65 years old	−0.31	−0.40 to −0.21	−6.40	<0.01
≥65 years old	−0.76[†]	−0.90 to −0.62	−10.89	<0.01
Sex				
Males	−0.49	−0.61 to −0.38	−8.45	<0.01
Females	−0.45	−0.70 to −0.19	−3.45	<0.01
Training status				
Inactive people	−0.55[‡]	−0.65 to −0.44	−10.26	<0.01
Recreational athletes	−0.31	−0.45 to −0.16	−4.18	<0.01
Competitive athletes	−0.29	−0.69 to 0.11	−1.41	0.16
Limb				
Upper	−0.81	−1.06 to −0.56	−6.29	<0.01
Lower	−0.88	−1.14 to −0.63	−6.77	<0.01

*SMD: < 0.5, small; 0.5 to 0.8, moderate; and > 0.8, large.
[†]Different from < 65 years old ($P < 0.01$).
[‡]Different from recreational athletes ($P < 0.01$).
SMD, standardized mean difference; CI, confidence interval.

Table 2. Effect of training cessation on maximal power according to population characteristics and limb

Moderator	SMD*	95% CI	z	P
Age				
<65 years old	−0.18	−0.26 to −0.10	−4.46	<0.01
≥65 years old	−0.46[†]	−0.72 to −0.21	−3.55	<0.01
Sex				
Males	−0.13	−0.23 to −0.03	−2.49	<0.01
Females	−0.28	−0.46 to −0.09	−2.95	<0.01
Training status				
Inactive people	−0.34[‡]	−0.47 to −0.22	−5.32	<0.01
Recreational athletes	−0.09	−0.21 to 0.02	−1.64	0.10
Competitive athletes	−0.20	−0.38 to −0.02	−2.15	<0.05
Limb				
Upper	−0.37	−0.61 to −0.14	−3.15	<0.01
Lower	−0.26	−0.48 to −0.05	−2.44	<0.01

*SMD: < 0.5, small; 0.5 to 0.8, moderate; and > 0.8, large.
[†]Different from < 65 years old ($P < 0.01$).
[‡]Different from recreational athletes ($P < 0.01$).
SMD, standardized mean difference; CI, confidence interval.

of training cessation was also larger in inactive people for maximal force ($z = 2.67$, adjusted $P < 0.05$) and maximal power ($z = 2.99$, adjusted $P < 0.05$) when compared with recreational athletes, but not for submaximal strength ($z \leq 1.19$, adjusted $P > 0.05$). Finally, we did not find any difference between males and females, or between upper and lower limb, whatever the type of muscular performance ($z \leq 1.40$, $P > 0.05$).

Moderating variables: training/training cessation characteristics

Regarding the type of training performed before the training cessation, it has to be mentioned that out of the 103 studies included in this meta-analysis, only 19 proposed a strength training protocol that was not based on submaximal/hypertrophy prescription guidelines. In

Table 3. Effect of training cessation on submaximal strength according to population characteristics.

Moderator	SMD*	95% CI	z	P
Age				
<65 years old	−0.48	−0.70 to −0.26	−4.27	<0.01
≥65 years old	−0.85[†]	−1.13 to −0.57	−5.88	<0.01
Sex				
Males	−0.61	−0.89 to −0.32	−4.11	<0.01
Females	−0.68	−1.07 to −0.29	−3.42	<0.01
Training status				
Inactive people	−0.61	−0.81 to −0.41	−6.08	<0.01
Recreational athletes	−0.79	−1.24 to −0.34	−3.45	<0.01
Competitive athletes	−0.16	−1.10 to 0.79	−0.32	0.75
Limb				
Upper	−0.77	−1.08 to −0.46	−4.86	<0.01
Lower	−0.83	−1.14 to −0.52	−5.26	<0.01

*SMD: < 0.5, small; 0.5 to 0.8, moderate; and > 0.8, large.
[†]Different from < 65 years old ($P < 0.05$).
SMD, standardized mean difference; CI, confidence interval.

other words, most of the training interventions were similar with regards to the training programs/objectives. For these 19 other studies, different training methods were used (plyometrics, maximal strength, electrostimulation, vibration). It also has to be mentioned that 24 studies out of the 103 implemented a training program using a combination of methods (hypertrophy, maximal force, and power development). Even though there is a rationale to analyse training cessation effects separately based on each specific training intervention, training programs were not included as a moderator. This decision was based upon the fact that a great majority of studies presented similar training intervention (submaximal/hypertrophy). Also, a minority of studies used significantly different training prescriptions making it statistically irrelevant to consider all these variables as separate moderators. In contrast, the duration of training programs could differ widely between studies. We performed a meta-regression analysis that did not reveal any relationship between the exact duration of training and the magnitude of the effect of training cessation on muscular performance, as the slope was not different from 0. In contrast, the slope of the relationship between the magnitude of the effect of training cessation and the exact duration of training cessation was significantly different from 0 ($z \geq 2.27$, $P < 0.05$), whatever the type of muscular performance, thus suggesting a close association between both variables. Exact duration of training cessation was a posteriori divided in seven categories. The Q-test based on the analysis of variance allowed us to reject the null hypothesis that the effect of training cessation was similar between these categories, whatever the type of muscular performance ($P < 0.05$). Weighted SMDs and significant pairwise comparisons are presented in Figs 2–4. The effect of training cessation became statistically significant between the third and fourth week for maximal force, maximal power, and submaximal strength. Although a dose–response rela-

tionship is visually evident, the difference between categories was significant only for durations longer than 8 (submaximal strength) or 16 weeks (maximal force and maximal power).

Discussion

The aim of this study was to assess the effect of training cessation on maximal force, maximal power, and submaximal strength through a systematic review of the literature and meta-analysis. We found a moderate decrease in submaximal strength and a small decrease in maximal force and maximal power. This detrimental effect was found to differ according to the duration of training cessation, age, and training status, but was not influenced by sex or the characteristics of previous training.

Effect of training cessation on maximal force

Maximal force represents the peak force or peak torque reached during a maximal voluntary contraction. It is often considered fundamental for both athletic performance and a healthy lifestyle (Abernethy et al., 1995; Kraemer et al., 2002). Overall SMD revealed a small decrease in maximal force once training ceases. It is worth noting that this decrement grew with the duration of training cessation. As shown in Fig. 2, the decrease in maximal force became significant from the third week of inactivity, and its magnitude increased thereafter as a function of time. Many physiological factors may be involved in this process. They are typically classified as central (or neural) and peripheral (or morphological) factors. Central factors refer to motor unit recruitment and synchronization, firing frequency, and intermuscular coordination (Cormie et al., 2011a). Central adaptations occur rapidly with training and are thought to explain the greatest part of short-term strength gains in previously untrained individuals (Moritani & deVries, 1979; Hakkinen, 1989; Folland & Williams, 2007). Peripheral factors refer to muscle fiber type and architecture, as well as tendon properties (Cormie et al., 2011a). Although the cellular adaptations that subtend muscle hypertrophy may occur early in a training program (DeFreitas et al., 2011), it is generally considered that the relative contribution of morphological adaptations increases gradually as training proceeds (Narici et al., 1996; Folland & Williams, 2007), with an increasing role of the endocrine system (Crewther et al., 2006, 2011). Although it was beyond the scope of this meta-analysis to study specifically these underlying factors, one may hypothesize that this sequence of events also exists in the disadaptation process, the factors underpinning the continuous decrease in maximal force being mainly central during the first weeks of training cessation, and mainly peripheral afterwards. This hypothesis is in accordance with the data published by the group of
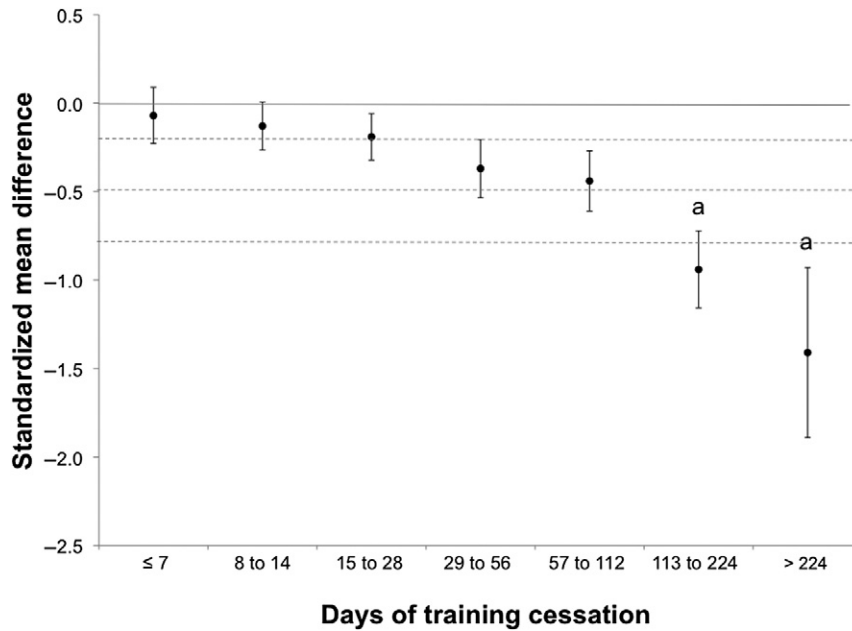
Fig. 2. Dose–response curve for the effect of the duration of training cessation on maximal force. (a) Different from standardized mean differences computed for ≤ 112 days of training cessation.
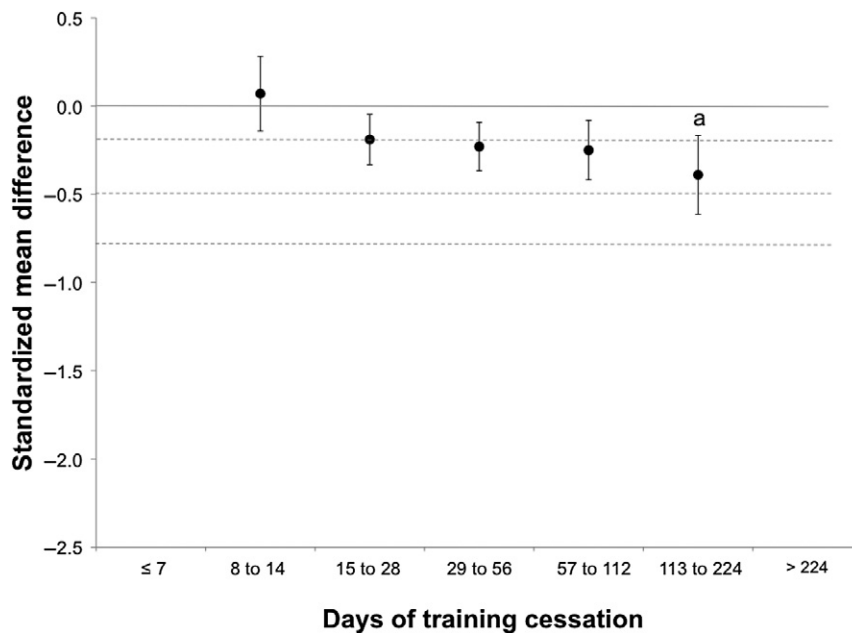

Fig. 3. Dose–response curve for the effect of the duration of training cessation on maximal power. (a) Different from the standardized mean difference computed for ≤ 14 days of training cessation.

Häkkinen (Hakkinen & Komi, 1983; Hakkinen et al., 2000), who reported a rapid decrease (of small amplitude) in the neural activation once training ceases, followed by a muscular atrophy when this period of inactivity exceeds several weeks.

Effect of training cessation on maximal power

Although they are often used as synonymous, maximal force and maximal power are different facets of muscular strength. Maximal power represents the ability to produce high amounts of force over a short period of time, and plays a crucial role in many athletic events (Mero et al., 1992; Duthie et al., 2003; Stolen et al., 2005). Considering that training cessation results in a significant reduction of maximal force, it would be expected to reduce maximal power as well. However, maximal power is also determined by factors related to velocity that are independent from maximal force (Kraemer et al., 2002; Cormie et al., 2011b). Therefore,
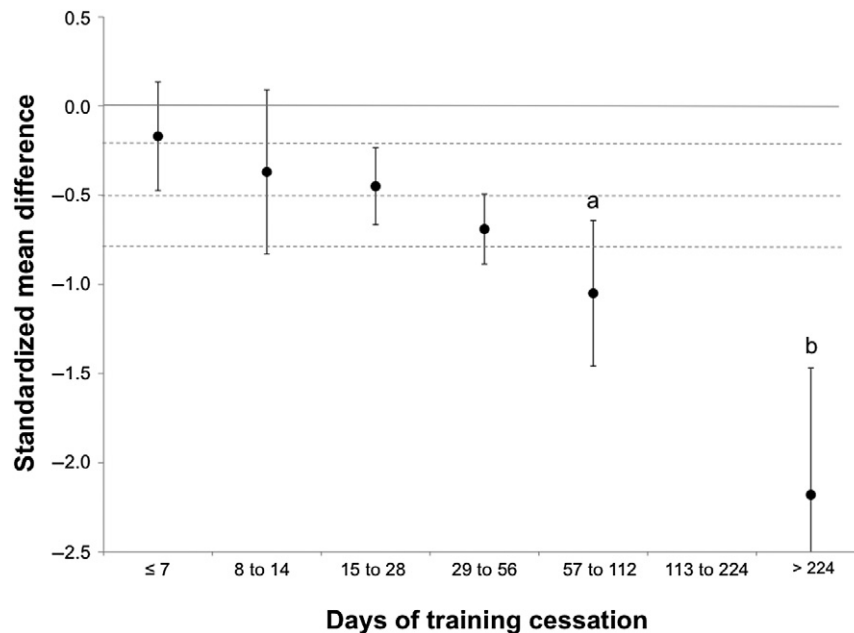
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Fig. 4. Dose–response curve for the effect of the duration of training cessation on submaximal strength. (a) Different from the standardized mean difference computed for ≤ 7 days of training cessation. (b) Different from standardized mean differences computed for ≤ 112 days of training cessation.

depending on the effect of training cessation on these factors, the rates of decline of maximal power and maximal force are not necessarily the same. Indeed, our meta-analysis showed that the magnitude of the effect of training cessation on maximal power was smaller than that observed for maximal force. This difference between both muscular properties concerned overall SMD, but also the kinetics of the disadaptation process. As shown in Figs 2 and 3, the effect of training cessation on maximal force and maximal power was quite similar during the first weeks, but although an improvement may be expected in maximal power after short-term training cessation (i.e., 2 weeks or less) in relation with recovery from training-induced neuromuscular fatigue, this was less probable in maximal force. However, there appears to be dissociation after 16 weeks of inactivity since we found a large decrease in maximal force while maximal power was not different from the previous weeks. Andersen and Aagaard (2000) observed a decrease in the proportion of IIb muscle fibers in the vastus lateralis of healthy young males after a 3-month training period. Of all muscle fibers, type IIb represented 10.2 ± 2.5% at pretraining measurement time. After 38 resistance training sessions within a 90-day period, this proportion decreased to 4.1 ± 1.2%. Surprisingly, this proportion increased to 18.8 ± 3.5% after 3 months of training cessation. Andersen et al. (2005) later showed that this detraining-induced overshoot in IIX muscle fiber proportion was accompanied by an increase in the electrically evoked twitch rate of force development, and in the maximal unloaded knee extension velocity and power, while cross-sectional area and peak torque decreased to baseline level. Although other factors may

contribute to explain the difference in the effect of training cessation on maximal force and maximal power, this overshoot of IIX muscle fibers is probably central since the resulting increase in maximal velocity may compensate for the loss in maximal force to maintain maximal power.

Effect of training cessation on submaximal strength

Submaximal strength represents the ability of the neuromuscular system to sustain a high fraction of maximal force for a long period of time or a high number of repetitions. This specific ability is particularly important in the maintenance of autonomy in older adults (Hunter et al., 2004), but also in many long-duration sporting events such as cycling or triathlon (Marcora et al., 2008). We found a moderate decrease in submaximal strength once training ceases. The negative impact of exercise cessation duration on submaximal strength was bigger than on maximal force and maximal power. Physiological factors related to oxygen transport and energy production should be added to the neural and morphological factors previously discussed to explain the detrimental effect of training cessation on muscular force and power. The rapid decrease in blood volume that is observed very shortly once training ceases (Houmard et al., 1992) is the starting point of a cascade of events leading to a decrease in cardiac output (Coyle et al., 1984, 1985). Training cessation is also associated with a greater reliance on glucose for energy provision that is concomitant with a rapid decrease in muscle glycogen stores (Costill et al., 1985; Mikines et al., 1989) and a rapid decrease in the activity of oxidative enzymes such as citrate synthase,

succinate dehydrogenase and malate dehydrogenase (Coyle et al., 1984, 1985). All together, these disadaptations clearly compromise oxygen transport, aerobic energy production, and submaximal strength. Through an additive effect to neural and morphological disadaptations, they probably contribute to the larger decrease we found in submaximal strength in comparison with maximal force and maximal power.

Moderating variables

Senescence induces both neural and morphological changes that have a detrimental effect on muscular strength (Manini & Clark, 2012). In fact, maximal force and maximal power have been shown to decrease from the fourth decade by approximately 2% and 4%, respectively (Bosco & Komi, 1980; Bassey et al., 1992; Skelton et al., 1994; Phillips, 2007). This age-related muscle weakness, also called dynapenia (Manini & Clark, 2012), has been associated with an increased risk of falls (Moreland et al., 2004) and with adverse physiological changes that may predispose elderly people to osteoporosis, atherosclerosis, diabetes, and other chronic diseases and functional limitations (Hyatt et al., 1990). Strength training has been shown to be an effective intervention to counteract these adverse effects (Hurley et al., 2011). However, considering the dynapenia phenomenon (Manini & Clark, 2012), it could be argued that older adults are more vulnerable to the detrimental effects associated with strength training cessation. In this study, we arbitrarily set the limit between adults and seniors at 65 years old. As shown in Tables 1–3, we actually found a larger magnitude of decrease in older people, whatever the expression of muscular strength (i.e., maximal force, maximal power or submaximal strength). The mechanisms underlying this larger decrease are probably a combination of neural and morphological factors. The difficulty to maintain muscle mass is probably involved (Goodpaster et al., 2006), but the relative weight of central factors is certainly more important than usually thought (Manini & Clark, 2012). The larger rate of decline of maximal power after the fourth decade when compared with maximal force (Bosco & Komi, 1980; Bassey et al., 1992; Skelton et al., 1994; Phillips, 2007) goes in this sense. Part of the larger training cessation effect in the older population could also be related to a more sedentary lifestyle. Altogether, these results underscore the importance of following a regular and uninterrupted strength training program in elderly people. The larger decrease in muscular strength when training ceases, associated to a decreased adaptation capacity when compared with healthy adults (Staron et al., 1990; Charette et al., 1991) may accelerate dynapenia and functional limitation.

Females generally have lower muscular strength than males (Miller et al., 1993; Martel et al., 2006). The greatest part of this sex difference is attributable to a larger muscle mass in males since the force to cross-sectional area ratio, the number of muscle fibers, and the characteristics of motor units are not different between males and females (Miller et al., 1993). Interestingly, some data suggest that training-induced improvement in maximal force mainly depends on muscular hypertrophy in males, and nonmuscular (possibly neural) adaptations in females (Hakkinen et al., 2001; Delmonico et al., 2005). Considering this sex specificity in the adaptation to resistance training, the question of a sex specificity in the response to training cessation deserves attention. As shown in Tables 1–3, we did not find any difference in the magnitude of decrease in maximal force, maximal power, and submaximal strength between males and females. Although the relative weight of central and peripheral factors probably differs between males and females, the effect of training cessation on muscular strength is similar.

An important issue when we aim at assessing the effect of training cessation on muscular strength is the dose of physical activity that will be maintained by the participants in the duration of the training cessation period. In fact, depending on the duration, intensity, and frequency of this physical activity, the stimulus could be high enough to maintain training-induced neural and morphological adaptations. In this sense, if we consider that legs are used in a greater extent than arms in daily physical activity (walking, stair climbing, cycling, and so on), one could hypothesize that the magnitude of decrease in muscular strength when training ceases is larger for the upper limb when compared with the lower limb. Contrarily to this hypothesis, we did not found any effect of limb, whatever the component of muscular strength, thus suggesting that daily physical activity does not reach the level required to maintain training-induced adaptations when the duration of training cessation exceeds a given level.

As discussed before, there is a time sequence in the adaptation to strength training. Neural adaptations, which refer to motor unit recruitment, firing frequency, and intermuscular coordination (Cormie et al., 2011a) are thought to explain the greatest part of short-term strength gains (Moritani & deVries, 1979; Hakkinen, 1989; Narici et al., 1996; Folland & Williams, 2007), while morphological adaptations, which refer to muscle fiber type and architecture, as well as tendon properties (Cormie et al., 2011a) are thought to explain the greatest part of long-term strength gains (Moritani & deVries, 1979; Hakkinen, 1989; Narici et al., 1996; Folland & Williams, 2007). Training status, which is closely linked to training history, directly determines the type of adaptations that subtends strength gains, and probably the speed of reversibility. In fact, it is reasonable to think that adaptations induced by an 8- to 12-week training program in a previously untrained individual will disappear more rapidly than adaptations obtained after several months to several years of training in recreational or

competitive athletes. In line with this assertion, we found a larger decrease in maximal force and maximal power in previously inactive people when compared with recreational athletes. Surprisingly, we found no difference with competitive athletes. One of the main reasons is probably the complexity of the training stimulus and its corollary, the adaptation process. In fact, most competitive athletes are using a block periodization that plans an alternance between training methods. Contrarily to previously inactive people and to an important proportion of recreational athletes, the type of adaptation (i.e., central vs peripheral) is mainly a consequence of the training methods and their periodization rather than training experience. It should also be kept in mind that the relative weight of strength training in the overall training load is less important for athletes than inactive people since they have many other technical-tactical or conditioning sessions in their training plan. The maintenance of a high physical activity level despite the cessation of strength training probably accounts for the difference we found with inactive people. A meta-analysis such as that performed in this study does not provide the precision required to address these specific issues. However, it provides a conceptual framework that may be useful to design successful tapers since the knowledge of strength loss kinetics allows to plan more precisely the moment when the resistance training load should be decreased to peak for a given competition.

Limits

The meta-analysis methodology allows to quantify the size of effects across a number of independent empirical studies while simultaneously eliminating inherent biases in the research (Hagger, 2006). This does not mean however that it is free from bias. Publication and, to a lesser extent, language restriction bias are expected to inflate estimates of the effect (Moher et al., 1999). Care was therefore taken to control these sources of bias as far as possible. Three databases we used in our literature search (Kinpubs, Physical Education Index, and Sport-Discus) covered theses and dissertations, thus allowing the access to this "gray literature" (i.e., literature that is difficult to locate or retrieve; Moher et al., 1999). Our literature search was restricted to English- and French-languages studies. Nevertheless, with the exception of a paper published in Japanese but with an English abstract,(Tsuyama et al., 2005), we did not find additional relevant reports when extending our search to studies in all languages (with the Web of Science database). Some limitations that were specific to the topic of this meta-analysis have probably restricted the thorough-

ness of the analyses. Training-induced adaptations depend on a number of moderators and their interaction. Some of them have been coded in this study, such as age, training status, or training characteristics. However, it was not possible to address the interactions between these moderators, although it may well be the cornerstone of success, particularly in competitive athletes.

Also, in a training cessation protocol with humans, it is very difficult to control the intensity/volume/type of physical activity performed by the participants during the training cessation period. Even though clear instructions were given to the participants and reported by the authors to avoid any form of resistance training during the training cessation protocol, it is not impossible that some participants chose to ignore these recommendations for different reasons. As mentioned in the previous paragraph, this limitation is probably more important with an athlete population.

Perspective

The purpose of this investigation was to assess the effects of training cessation on the different expressions of muscular strength, including maximal force, maximal power, and submaximal strength, by means of a systematic review of the literature and a meta-analysis. We found a moderate decrease in submaximal strength and a small decrease in maximal force and maximal power. This detrimental effect was found to differ according to the duration of training cessation, age, and training status, but was not influenced by sex, limb, or the characteristics of previous training. This meta-analysis provides a framework that can be useful for the optimization of taper strategies and return to fitness in competitive athletes, and more generally for exercise prescription in the general population.

Key words: detraining, maximal force, maximal power, submaximal strength, aging.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

References included in the meta-analysis.

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