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REVIEW ARTICLE

Short-term Periodization Models: Effects on Strength and Speed-strength Performance

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Abstract Dividing training objectives into consecutive phases to gain morphological adaptations (hypertrophy phase) and neural adaptations (strength and power phases) is called strength-power periodization (SPP). These phases differ in program variables (volume, intensity, and exercise choice or type) and use stepwise intensity progression and concomitant decreasing volume, converging to peak intensity (peaking phase). Undulating periodization strategies rotate these program variables in a bi-weekly, weekly, or daily fashion. The following review addresses the effects of different short-term periodization models on strength and speed-strength both with subjects of different performance levels and with competitive athletes from different sports who use a particular periodization model during off-season, pre-season, and in-season conditioning. In most periodization studies, it is obvious that the strength endurance sessions are characterized by repetition zones (12–15 repetitions) that induce muscle hypertrophy in persons with a low performance level. Strictly speaking, when examining subjects with a low training level, many periodization studies include mainly hypertrophy sessions interspersed with heavy strength/power sessions. Studies have demonstrated equal or statistically significant higher gains in maximal strength for daily undulating periodization compared with SPP in subjects with a low to moderate performance level. The relatively short intervention period and the lack of concomitant sports conditioning call into question the practical value of these findings for competitive athletes. Possibly owing to differences in mesocycle length, conditioning programs, and program variables, competitive athletes either maintained or improved strength and/or speed-strength performance by integrating daily undulating periodization and SPP during off-season, pre-season and in-season conditioning. In high-performance sports, high-repetition strength training (>15) should be avoided because it does not provide an adequate training stimulus for gains in muscle cross-sectional area and strength performance. High-volume circuit strength training performed over 2 years negatively affected the development of the power output and maximal strength of the upper extremities in professional rugby players. Indeed, meta-analyses and results with weightlifters, American Football players, and throwers confirm the necessity of the habitual use of $\geq$80 % 1 RM: (1) to improve maximal strength during the off-season and in-season in American Football, (2) to reach peak performance in maximal strength and vertical jump power during tapering in track-and-field, and (3) to produce hypertrophy and strength improvements in advanced athletes. The integration and extent of hypertrophy strength training in in-season conditioning depend on the duration of the contest period, the frequency of the contests, and the proportion of the conditioning program. Based on the literature, 72 h between hypertrophy strength training and strength-power training should be provided to allow for adequate regeneration times and therefore maximal stimulus intensities in training. This conclusion is only valid if the muscle is not trained otherwise during this regeneration phase. Thus, rotating hypertrophy and strength-power sessions in a

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microcycle during the season is a viable option. Comparative studies in competitive athletes who integrated strength training during pre-season conditioning confirm a tendency for gains in explosive strength and statistically significant improvements in medicine ball throw through SPP but not through daily undulating periodization. These findings indicate that to maximize the speed-strength in the short term (peaking), elite athletes should perform strength-power training twice per week. It is possible to perform a single strength-power session with the method of maximum explosive strength actions moving high-weight loads (90 % 1 repetition maximum [RM]) at least 1–2 days before competition because of the shorter regeneration times and potentiation effects. Compared with ballistic strength training (30 % 1 RM), this method has been shown to provide statistically superior gains in maximal strength, peak power, impulse size, and explosive strength during tapering in track-and-field throwers. The speed-strength performance in drop jumps of strength-trained subjects showed potentiation effects 48–148 h after a single strength-power training session. Regarding neuromuscular performance, plyometric exercises can even be performed after strength-power training on the same day if a minimum rest period of 3 h is provided.

Key Points

Studies have demonstrated equal or statistically significant higher gains in maximal strength for daily undulating periodization (DUP) compared to strength-power periodization (SPP) in subjects with a low to moderate performance level.

Possibly owing to differences in mesocycle length, conditioning programs, and program variables (training methods, content, frequency, volume, and intensity), competitive athletes either maintained or improved strength and/or speed-strength performance by integrating DUP and SPP during off-season, pre-season, and in-season conditioning.

Two comparative studies in competitive athletes who integrated strength training during pre-season conditioning confirmed a tendency for gains in explosive strength and statistically significant improvements in medicine ball throw through SPP but not through DUP. These findings indicate that to maximize speed-strength in the short term (peaking), elite athletes should perform strength-power training twice per week.

1 Introduction

In high-performance sports, an appropriate periodization of training is needed to achieve high maximal strength and speed-strength levels. The primary underlying concept of periodization is to transfer a variety of performance variables (strength, speed-strength, strength endurance) to their highest rate of development with the aim of peaking at a precise time and avoiding stagnation, injury, or overtraining [1, 2]. These objectives are accomplished through variation in program variables (training methods, contents, frequency, volume, and intensity) in consecutive phases (mesocycles) during the preparation and competition periods. Whereas each training phase typically lasts 2–10 weeks, the complete training cycle ranges from approximately 8–35 weeks [1, 3]. There are differences in the duration of the competition periods and the number of competitions among different team sports and among individual sports that necessitate different periodization schedules. The competition period (playing season) for soccer, rugby, basketball, ice hockey, and American Football lasts 12–35 weeks in Europe and North America [3, 4]. In Australian Rules football, the players must maintain strength, speed-strength, and lean mass for up to 26 weeks (regular season and playoffs) [4]. The following review addresses the effects of different short-term periodization models over 5–36 weeks on strength and speed-strength characteristics both with subjects of different performance levels [2, 5–27] and with athletes from different individual and team sports [28–53]. These athletes used a particular periodization model during pre-season [29–32, 40, 41, 45–47, 50], in-season [28, 31, 39, 51], or off-season training [33–38, 42, 48, 49, 52, 53]. The possible underlying physiological adaptations can only be discussed within the short training periods of these studies. The long-term effects over 2–6 years are only known for a minority of periodization strategies [54–58].

2 Literature Search Methodology

A literature search of PubMed was conducted including articles published up to February 2015. The main search terms were 'training periodization,' 'undulating periodization,' 'block periodization,' 'periodization training,' 'periodization strength,' 'daily undulating periodization,' 'linear periodization,' 'strength training periodization,' 'block periodization training,' 'periodization strength training,' 'periodization athletes,' 'nonlinear periodization,' 'non-linear periodization,' 'strength training and periodization,' and 'strength-power periodization.'

The inclusion criteria for the research were data regarding periodized strength training with subjects of different performance levels and athletes from tennis, track and field, throwing events, volleyball, American Football, Australian Rules football, and rugby who used a particular periodization model during off-season, pre-season, and in-season conditioning.

The exclusion criterion for periodization studies in athletes was missing data about the timing of the integrated strength training and the periodization model. For four studies, personal communication with the authors revealed the missing information as follows:

track-and-field athletes performed block training with traditional and weightlifting exercises [41] (Michael H. Stone, personal communication).

All of the football players in the studies by Hoffman et al. [34–36] were participating in the off-season conditioning program, which included spring football, with sprints, agility, and plyometric training (Jay R. Hoffman, personal communication).

According to the authors of one study [59], the subjects performed deep squats (Jacob M. Wilson, personal communication).

3 Periodization Models of Mesocycle Length

Dividing training objectives into consecutive phases to gain morphological adaptations (hypertrophy phase) and neural adaptations (strength and power phases) is called strength-power periodization (SPP) [1] or block periodization [3]. Stepwise intensity progression and concomitant volume decreases are used to converge into an intensity peak (peaking phase). A number of studies show the superiority of SPP over non-periodized single-set [24, 42] and non-periodized multiple-set programs [2, 17, 23–27] with respect to improvements in maximal strength [2, 17, 23–27, 42] and vertical jump performance [2, 24, 42]. However, there are also studies that find no statistically significant differences between SPP and non-periodized multiple-set programs [7, 11, 16, 22] regarding improvements in strength [7, 11, 16, 22] and vertical jump performance [7].

Another popular periodization model is based on an undulating load dynamic in which hypertrophy and strength-power phases are alternated every week (weekly undulating periodization = WUP) [6, 8] or 2 weeks [60] (undulating periodization = UP). Daily undulating periodization (DUP), also called non-linear periodization [42], is characterized by daily alterations in volume, intensity, and exercise choice or type. There are three exercise types: (1) general (e.g., bench press, squats), (2) special (e.g., loaded jump squats, bench press throw, plyometric push-ups), and (3) specific (e.g., jumps, sprints, throws) [61].

Baker et al. [7] found equal gains in maximal strength between SPP and UP. Apel et al. [6] identified statistically significant higher gains in maximal strength in three of five exercises after 12 weeks of SPP compared with WUP. Buford et al. [8] were not able to detect statistically significant differences in the development of maximal strength among SPP, DUP, and WUP. Souza et al. [22] found statistically significant gains in strength only for DUP and non-periodized training in parallel squats, but no statistically significant improvements for SPP. However, there were no statistically significant group differences in the untrained men. Despite this fact, SPP had a higher effect size than did DUP (0.60 vs. 0.51). The superiority of UP in gains of strength is only documented in comparison with non-periodized strength training with Russian athletic throwers [12].

DUP protocols that developed a combination of strength, speed-strength, hypertrophy, and strength endurance alternated strength-power, hypertrophy, and strength endurance sessions in a rotational manner [10, 14, 16, 21, 42–44]. In DUP studies, common repetition zones for strength-power sessions ranged between 2–4 and 4–6 repetitions, for hypertrophy sessions between 8 and 12 [10, 13, 14, 16, 21, 22, 42–44], and for strength endurance sessions between 12 and 15 [13, 14, 16, 21, 42–44] and 20–25 [10]. Other studies alternated hypertrophy sessions with strength-power and speed-strength days [13] (30 % of one-repetition maximum = 1 RM) or with one or two strength-power sessions [15, 20, 47], whereas Harris et al. [9] alternated only between strength-power and speed-strength days (30–60 % 1 RM) and different exercises.

With growing strength-training experience, a greater variation in volume and intensity is necessary to induce further statistically significant gains in muscle mass [62–64]. According to the American College of Sports Medicine [62], for advanced subjects, a repetition range of 6–12 must be emphasized to generate muscle hypertrophy. This repetition zone equates to training intensities of 70–85 % 1 RM [62–64]. Based on a meta-analysis of 2004, Fry [65] stressed the importance of the routine use of ≥80 % 1 RM to produce maximal hypertrophy. However, depending on the muscle group and the exercise, even for trained subjects, the load that is quantified at this lower percentage range of 80 % can be too low to ensure a 12 RM load, for example in the leg press [1]. Therefore, repetition zones have been reported to be feasible in the training literature. In five of seven DUP studies [13, 14, 16, 21, 42–44] with integrated strength endurance sessions, the recruited subjects were untrained women [13, 14], collegiate tennis players with no strength training experience [43, 44], or subjects who refrained from strength training 6 months before beginning the intervention [21]. The integrated strength endurance sessions (12–15 RM) can be considered as hypertrophy sessions because 15 RM induces statistically significant muscle hypertrophy in persons with a low performance level [66]. Campos et al. [67] did not observe statistically significant gains in muscle cross-sectional area (CSA) in untrained persons after an 8-week high-repetition training (20–28 RM), but Léger et al. [68] detected statistically significant gains in muscle mass after such repetition zones in subjects who were untrained. In a strict sense, when examining untrained subjects or participants with minimal strength-training experience, these DUP studies [13, 14, 21, 43, 44] include mainly hypertrophy sessions interspersed with heavy strength-power sessions. Compared with SPP, DUP also uses RM loads and the same basic rotation of targets. Therefore, the DUP model is a linear model at the microcycle level and has less overall variation than more traditional block models.

DUP demonstrated a statistically significant superiority in enhancing strength [9, 14, 16, 20, 21, 42–44] and vertical jump performance [14, 42, 44] vs. single-set programs [14, 42, 44], non-periodized multiple-set programs [9, 16, 43], and SPP models [16, 20, 21]. Other studies found equal gains between DUP and SPP in strength [8, 10, 13, 15, 18] and speed-strength performance [10, 13] with subjects with a low to moderate performance level. Souza et al. [22] found no statistically significant differences between SPP and DUP in strength improvements after 6 weeks; however, only DUP achieved statistically significant gains in 1 RM.

There are, to some extent, no conformities with respect to program variables, regeneration times, training duration, mesocycle length, and definitions of periodization models among different periodization studies. For example, Prestes et al. [19] found equal gains in maximal strength between DUP and "linear periodization" that increased in intensity every week and was repeated after 4 weeks with the same schedule (starting with low intensity again). However, this wave-shaped load dynamic is structurally equivalent to the "traditional periodization" (TP) that was published by Matveyev in 1964 (compare Issurin [3]). In the scientific literature, the term 'linear periodization' is synonymous with SPP [7, 8, 13, 15, 16, 20, 21, 69] and with TP [3, 19, 69]. To further complicate this issue, Apel et al. [6] and Souza et al. [22] used the term "traditional periodization," although the examined periodization model was an SPP. Linear periodization (as is used for SPP and TP) [7, 8, 13, 15, 16, 19–21] and non-linear periodization (as is used for UP and DUP) [16, 21, 43, 44, 69] are terminologically incorrect [70]. In TP, the load dynamic is "non-linear" or undulatory rather than linear [3, 69]. The same issue is true of SPP: in high-performance sports, SPP is integrated in other forms of training that must be organized with regard to changes in the training volume, intensity, and training emphasis (increased power, speed, and explosive strength) that do not represent a strictly linear periodization [71]. To avoid confusion, we therefore suggest the use of the terms that are established in the literature (SPP, TP, UP, WUP, and DUP).

Fröhlich et al. [72] suggested in a meta-analysis that in general, the positive effects of DUP could be based on the fact that every week the schedule starts with intensities in the range of 3 RM (strength-power session). Two days of rest after the last training session (last session on Friday, next session on Monday) could therefore guarantee a recovered training condition to train with maximal loads in the next strength-power session. However, this session order has been confirmed only by Hartmann et al. [10] and Monteiro et al. [16]. The majority of DUP protocols used the highest intensities of the strength-power session in the last workout of the week [8, 15, 20, 21, 47] or on the second training day in the week, 48 h after the hypertrophy session [13] [upper body 18]. Therefore, the explanation of Fröhlich et al. [72] seems to be questionable. Furthermore, there can be differences in the repetition zones within a study that complicate a comparison with other studies: Souza et al. [22] matched the SPP and DUP for volume load, but the SPP constituted approximately half of the training at a lower intensity (12 RM) than did the DUP (approximately 8 RM) for the majority of the 6-week intervention. This result might explain the statistically significant gains in strength for DUP of 12.9 % and the non-significant improvement for SPP of 7.7 %. However, there were no statistically significant group differences. Equal [8, 15, 21] or higher gains [16, 20, 21] in strength for DUP compared with SPP may be based on the fact that subjects with a low to moderate performance level were recruited who were not involved in additional sports-specific training [8, 15, 16, 20–22], except for the study of Painter et al. [47], who used experienced, resistance-trained, competitive track-and-field athletes. Painter et al. [47] integrated DUP into fall preparation training and demonstrated a diminished explosive strength capacity compared with that of SPP that showed a tendency to gains in the rate of force development (RFD) after the last three weekly training blocks (see Sect. 4). The former training studies [8, 15, 16, 20–22] were unable to simulate the stress situations and resultant exhaustion factors of competitive sports because of their comparatively short duration and lack of basic conditions (skill, plyometric, and conditioning training). The next section incorporates training studies that fulfill this last criterion.

4 Effects of Different Periodization Models on Strength and Speed-strength During Seasonal Sports Practice

Advanced strength-power athletes profit from concurrent strength and power exercises in a periodized fashion to improve and maintain power over years of resistance training [55, 56], whereby maximal strength builds a strong to nearly perfect correlation ($r \geq 0.50$–0.96) for a high-power output moving different loads in a bench press throw [28, 55, 57, 73–75], mid-thigh pull [50], leg press [76], jump squats, unloaded countermovement jump (CMJ), squat jump (SJ) [56, 77–88], and for (loaded) vertical jump height [CMJ, SJ, Jump-and-Reach-Test (J-R-T)] [79, 81, 84–86, 88–98]. However, there are a few studies with athletes that show only weak to moderate correlations between maximal strength in parallel [83, 99, 100] or box squats [101] and jump squat average power ($r = 0.42$) [99] /peak power ($r = -0.15$ to 0.32) [100, 101], jumping heights in CMJ ($r = 0.14$ [99], $r = 0.29$ [100], $r = 0.22$ [83]), and in SJ ($r = 0.16$ [99]).

The higher the load that has to be accelerated in jump squats (SJ and CMJ) [92, 102], bench throw [103–105], power cleans [106], and mid-thigh pulls [50, 81], the larger the influence of maximal strength of snatch [92], bench press [103–105], and the isometric mid-thigh pull [50, 81, 102, 106] in developing high peak forces [50, 81, 103, 104, 106], movement velocity [105], and jumping heights [92, 102]. This major influence of maximal strength diminishes as the external load decreases to a point at which a high rate of force development becomes more important [105]. With a decreasing external load and decreasing time to peak force (277–120 ms), some researchers found general trends for increasing dynamic RFD and decreasing dynamic peak force (dynamic mid-thigh clean pull [81, 106]). For example, in the SJ, the shorter time to peak force and the peak force were more strongly correlated with the dynamic RFD ($r = -0.67$ and 0.76) than the longer time to peak force and RFD in the J-R-T (197 vs. 239 ms) ($r = -0.46$; peak force and RFD $r = 0.64$) [107]. In contrast, other studies found with increases in external load in bench throw [104] and in SJ and CMJ [102] higher correlations between the isometric RFD (IRFD) and dynamic peak force [104] and jumping heights [102]. IRFD showed strong correlations with isometric peak force ($r = 0.67$–0.88 [88, 102, 104, 106, 108]), dynamic peak force ($r = 0.65$–0.75 [106]), and maximal strength in snatch and clean and jerk ($r = 0.69$–0.79 [80]). Although not all studies agree [10, 50, 81, 88, 94, 95] and weaker relations between IRFD and dynamic maximal strength ($r = < 0.27$ [50], $r = 0.30$ [10]), isometric peak force ($r = < 0.27$ [50], $r = 0.33$ [10], $r = 0.46$ [88]), and dynamic peak force ($r = 0.17$–0.60 [81]) have been reported, Kawamori et al. [81] reported higher correlations between dynamic RFD and isometric peak force ($r = 0.54$–0.74). Therefore, many findings [80, 81, 88, 102, 104, 106, 108] agree with the observation that stronger athletes tend to develop forces faster.

Because an increase in strength in the long term can only be realized with very high to maximal loads [109, 110], it becomes clear why this method of strength training is essential for speed-strength development and why training with ballistic actions and medium loads can only have a complementary function, particularly because the loads that can be used are directly dependent on the extent of maximal strength [50, 87, 104, 111]. Gorostiaga et al. [112], who used low intensities of 51–77 % 1 RM in the half squat (power training) with elite handball players, were not capable of inducing any performance gains in CMJ height, loaded jump squat power output, and sprint running velocity for 5 and 15 m during 45 weeks pre- and in-season training. During a 29-week in-season study of professional rugby players, Baker [28] used a traditional periodization [4] with strength-training and weightlifting exercises that maintained bench press 1 RM and bench throw power and jump squat power at the pre-season level. A change from this high-intensity wavelike progression to a high-volume circuit strength training, performed over 2 years, elicited deleterious effects on the development of the power output and maximal strength of the upper extremities [113]. Other authors have stressed the importance of training intensity with loads ≥80 % 1 RM to improve maximal strength [37, 52, 109, 114, 115], peak power, impulse size, and explosive strength [115] in elite athletes [37, 52, 109, 114, 115]. Based on their meta-analysis, Rhea et al. [110] confirmed this recommendation for improving maximal strength for trained athletes. In junior soccer players without any strength training experience, Keiner et al. [116] performed SPP with high loads (>80 % 1 RM) over 2 years during the seasons and statistically significant improved parallel squat 1 RM and sprint and vertical jump performances. Baker and Newton [56] found correlations between changes in the deep squat 1 RM and changes in the power output in jump squats (40–100 kg) of $r = 0.83$–0.96 over a 4-year period. Given that the highest power values are found in athletes with a high maximal strength level, it is obvious that the development of maximal strength must be considered a decisive factor in the long-term training process [28, 50, 55, 56, 73, 74, 77, 79, 80, 82, 87, 101, 117–119].

The higher the strength level of an athlete is, the less a further increase in the maximal strength will contribute to an improvement in power output and speed-strength performances [55, 57, 74, 94, 101, 109, 120–123]. The intervention periods that are cited in Sects. 3 and 4 are too short to analyze this transfer problem for high-performance sports. Examining periodized strength training in competitive athletes has the major challenge that there is usually no control group of athletes that refrain from strength training and that these athletes only take part in specific conditioning for their particular sport.

There are two studies that considered this issue: Kraemer et al. [43, 44] compared the effects of DUP and non-periodized single-set [44] and non-periodized multiple-set training [43] with competitive women tennis players during off-season and in-season conditioning. The control groups only performed tennis-specific training and conditioning drills. DUP induced statistically significant gains in strength of the lower and upper extremities [43, 44], CMJ height [43], and peak ball velocities in tennis serve [43, 44], forehand stroke, and backhand stroke [43]. DUP outperformed controls after 4, 6, and 9 months in all of the strength and speed-strength parameters [43, 44]. Unfortunately, the subjects of all of the groups had no strength-training experience, which may have confounded the findings of this study.

Five studies over 6–16 weeks incorporated SPP [40, 41, 45, 47, 50] or DUP [46] into the pre-season training of competitive athletes from track and field [40, 41, 45–47, 50]. The particular periodization model produced statistically significant gains in maximal strength of the lower extremities [40, 45, 47, 50], vertical jump height [40, 41, 46], and power [45], long jump distance, overhead shot distance [40], shot put distance [45, 50], and dynamic rate of force development (explosive strength) [50]. It is worth noting that in studies with athletes from throwing events [40, 50] and Division I-A American Football [53], no performance stagnation occurred after 4–5 weeks of training with SPP [40, 50, 53] as proposed by Poliquin [60].

Several studies (duration 5–24 weeks) examined professional rugby players [30, 32], Australian Rules football players [39], volleyball players [31], and American Football players of different divisions [29, 33–38, 42, 48, 49, 51–53] to determine the effects of DUP [29, 30, 37, 42, 52] or SPP [31–39, 42, 48, 49, 51, 53] on developing maximal strength or speed-strength during off-season [33–36, 42, 48, 49, 52, 53], pre-season [29–32], and in-season conditioning [31, 39, 51]. These studies included traditional strength-training exercises [33] or traditional strength-training and weightlifting exercises [29–38, 42, 48, 49, 51–53]. Many of these interventions statistically significant improved maximal strength of the upper [34–36, 38, 42, 49, 51, 52] and lower extremities [30–36, 38, 42, 49, 51–53], vertical jump performance [31, 42], peak power of the upper and lower extremities [38], and 5- to 20-m sprint times [30].

However, the findings were inconsistent: Two studies found no statistically significant increases in strength [29, 48]. Others identified statistically significant gains in 1 RM squat, but no transfer effects into vertical jump performance were seen [32, 51, 52]. After 16 weeks of SPP during the pre-season, Hrysomallis and Buttifant [39] examined a periodization model with wave-like intensity progression every 4 weeks during the season [124] over 22 weeks in Australian Rules footballers who maintained upper body strength in teams with young and old players. The younger footballers demonstrated statistically significant declines in the bench throw power output, whereas the older footballers did not [39]. The interventions in these studies were characterized by differences in duration, program variables, and training frequency (1–6/week); the long-term effects of which are unknown.

There are only two comparative studies over 10 [47] and 14 weeks [37] that used SPP and DUP during the regular sports practices of experienced resistance-trained competitive football players [37] and track-and-field athletes [47]. Hoffman et al. [37] reported that 7 weeks of SPP, DUP, and non-periodized strength training elicited equal statistically significant gains in vertical jump performance, bench press, and parallel squat 1 RM during the off-season of Division III football players. The additional 7 weeks of training coincided with the 5-week plyometric, speed, and agility program of the players and did not produce further performance enhancements of the lower extremities. Hoffman et al. [37] suggested that these cumulative training stresses may result in a potential overtraining syndrome that reduces the performance gains in the lower extremities. For football players, Moore and Fry [125] and Smith et al. [52] confirmed such a maladaptation in speed-strength development, which is known as nonfunctional over-reaching [126]. In the study by Hoffman et al. [37], only the SPP group that used strength-power training twice per week demonstrated statistically significant speed-strength improvements in the upper extremities (medicine ball throw) from pre- to post-tests. The non-periodized group and the DUP group (with rotating hypertrophy and strength-power training) did not show any statistically significant gains during the intervention period.

A limitation of the study by Hoffman et al. [37] was that the subjects did not perform extensive strength training before the beginning of the study during their 10-week recovery phase. A rapid return to previous strength levels because of neural adaptations in the first 7 weeks may have prevented detection of statistically significant differences in performance gains between the periodization models. For heavy-resistance-trained women, such retraining effects on the trained levels in a relatively short time period of 6 weeks were documented by Staron et al. [127].

In the short term, these findings indicate the importance of the use of strength-power sessions more than once per week to improve speed-strength performance while avoiding higher repetition schemes with possible accumulative fatigue effects. The resultant high anerobic stress (lactate levels greater than 16 mmol/L [128]) may impair the performance of maximal strength and speed-strength and the motor performance in sport-specific training over several days. According to the findings of Schmidtbleicher and Frick [129], after a bout of hypertrophy (80 % 1 RM, 5 × 8 RM, 3-min rest) as well as strength endurance training (60 % 1 RM, 5 × 25 RM, 1.5-min rest) in the leg press, the recovery of the speed-strength performance in the short stretch–shortening cycle (SSC, drop jumps) to the baseline level is not expected until 72 vs. 3 h after strength-power training with the method of maximum explosive strength actions moving high-weight loads (90 % 1 RM, 5 × 3 RM, 6-min rest). The subjects were sport students with a strength-training background ($n = 8$) [129]. The short SSC (e.g., ground contact phases in sprinting, drop jumps, high jump, or long jump) shows only small angular displacements in the hip, knee, and ankle joints and lasts 100–250 ms [105]. Resistance hypertrophy training between 6 and 12 weeks of duration caused negative effects on the IRFD [130] and speed of motor unit activation [131], although conflicting findings for strength-training novices exist [132]. Furthermore, Verkhoshansky (1979, 1981, cited in Stone et al. [50]) reported a diminished power capability among track-and-field athletes that could occur after several weeks of a concentrated load of strength or strength-endurance training. Similar assumptions were made by Painter et al. [47]. These researchers found equally statistically significant gains in maximal strength in parallel squats between SPP and DUP in track-and-field athletes who integrated the strength training into fall preparation training (outside practice and conditioning). Despite the fact that no statistically significant increases in the RFD were seen in either group from pre- to post-test, the last 3 weeks induced a tendency to gains in RFD (15 %) for SPP and losses in RFD (−22 %) for DUP. Furthermore, SPP was performed in less training time with a 35 % statistically significant lower volume load and 52 % statistically significant fewer repetitions than in the DUP. The ratio of gains in the 1 RM squat per volume load resulted in a statistically significant superiority of SPP over DUP. Therefore, block training was the more efficient training regime.

4.1 Progression Rates of Strength and Speed-strength Characteristics in Long-term Training with Competitive Athletes

Only a few studies assessed the development of the speed-strength characteristics and maximal strength of competitive athletes from rugby, Australian Rules football, American Football, and weightlifting that underwent periodization for between 1 and 5 years [54, 58, 109, 121, 133–136]. These studies commonly indicated that with increasing training, the rate of performance progression decreased, as long as it can be concluded that no performance-enhancing drugs are consumed during the career [58, 120].

Bartolomei et al. [137] compared TP, weekly intensification with wavelike rotation every 5 weeks, and SPP with strength-trained subjects from track-and-field throwing events, rugby, and football. For the 1 RM bench press, there was only a tendency of gains for SPP (7 %) and no statistically significant improvements for TP (2 %). Both of the periodization models failed to induce any statistically significant gains in power output in bench press and speed-strength in SJ and CMJ after 15 weeks of training. The athletes did not concomitantly perform any jumps or sports conditioning during the intervention. These findings indicate the general problem of short-term training studies to evaluate performance gains in athletes with strength-training experience who require longer training durations and concomitant sports conditioning. For example, in American Football, increases in vertical jump power, speed, and agility became statistically significant only after 3–4 years of training [58]. In Division I football players, Jacobson et al. [133] documented statistically significant gains of 3.3 % in 1 RM squat and bench press and statistically significant increases in vertical jump height and power of 1.1 and 1.4 % between the third and fourth year of training. These low progressions in elite athletes demonstrate the limited scope for gains in power output and maximal strength. Based on the statistically significant relationship between the magnitude of lower body strength improvements and the change in lean mass of $r = 0.69$–0.88, Appleby et al. [54] stressed the importance of hypertrophy training for highly trained professional rugby athletes requiring improvements in strength, whereas Baker and Newton [56, 57] did not confirm these correlations and suggestions for professional rugby players.

Development of passive tissues was not discussed in these studies. However, from a preventive and performance condition perspective, this development constitutes a key factor in high stress tolerance in many sports. Because of the slow turnover rate of the particular tissue (tendons, ligaments, bones, and articular cartilage), the necessary periods for the required adaptations amount to many months or years. These studies are unable to provide any information about these relevant morphological adaptations. Therefore, the relevance of these studies to high-performance sports is questionable.

In cross-sectional studies with powerlifters, a very strong relationship of $r = 0.90$ was found between the magnitude of the bone mineral content (BMC) of lumbar vertebral bodies (L3) and the load lifted per year (300–5000 tons) [138], which indicates a positive influence of the volume of strength training on the development of BMC. Lang et al. [139] and Loehr et al. [140] found statistically significant increases in the bone mineral density (BMD) of lumbar vertebral bodies (L1–L2) of between 7 and 12.3 % after only 4 months of DUP with 6–10 RM [139] and 70–80 % 1 RM [140]. The subjects performed parallel squats and dead lifts. However, Almstedt et al. [141] were not able to confirm statistically significant increases after 6 months of DUP with the same training exercises (67–95 % 1 RM). According to Dalsky et al. [142], the remodeling processes of bones range from 4 to 6 months. Based on these facts, Chilibeck et al. [143] stressed the importance of strength-training periods that last two to three times longer than this adaptation period to induce statistically significant increases in BMD. Cross-sectional findings of female athletes (age 21.3–24.6 years) from different sports show that weightlifters ($n = 18$, age 24.6 years) with an average training experience of 3.6 years had a statistically significantly higher relative BMD of L2–L4, femur, patella, and radius compared with that of orienteers ($n = 30$), cyclists ($n = 29$), cross-country skiers ($n = 28$), and controls ($n = 25$). Only weightlifters demonstrated a statistically significantly higher BMD of L2–L4 of 12 % compared with that of controls [144]. Additional studies with male weightlifters with many years of training experience verify the statistically significant higher BMD and BMC of the lumbar spine compared with those of controls [145–148]. The maximal compression strength of lumbar vertebral bodies (L3, $n = 101$) showed a linear and positive correlation to BMD of $r = 0.91$ ($p \leq 0.00001$) and BMC of $r = 0.84$ ($p \leq 0.00001$) [149]. Furthermore, strength-training studies found statistically significant increases in the cross-sectional area of the patella tendon at its insertion sites after 9 and 12 weeks [150, 151]. The effects of longitudinal studies over several months or years are not known. When compared with age-matched untrained controls with no statistically significant group differences in body height and weight, weightlifters had statistically significant larger cross-sectional areas of the mid-substance of the patella tendon [152] and cruciate ligaments [153] and statistically significant greater cartilage thickness of the patella [154]. The minimal relative strength for the deep front/back squat in perennial (over several years) training programs of general strength training for elite athletes was suggested to be 1.5–2.0 times the body weight (bw) [155]. In junior athlete development, Keiner et al. [116] suggested the following relative strength values that should be achieved in the parallel back/front squat after 4–5 years of strength training: 11–12 years 0.7-fold bw; 13–15 years 1.5-fold bw; and 16–19 years two-fold bw.

Another publication from the same authors [156] was cited in the “Position statement on youth resistance training: the 2014 International Consensus” [157] and was regarded as a proof that periodized maximal strength training in parallel squats is unproblematic, even in children and young athletes, as long as a correct movement pattern and a gradual increase of loads in the long-term training structure are provided. Exercise during growth (especially before puberty) facilitates preferential bone formation on the periosteal surface [158–160]. According to Gunter et al. [161], substantial skeletal benefits are higher during pre- and early-puberty (“window of opportunity”) and are considerably smaller thereafter. Therefore, early commencement of strength training during prepuberty is strongly recommended.

5 Possible Physiological Adaptation Differences

According to Kraemer and Fleck [162], the advantage of undulating periodization is that lighter intensity training sessions (e.g., 12–15 RM) permit the resting of high-threshold type II motor units that are recruited in higher intensity workouts. Such resting provides for the recovery of these units. However, scientific facts argue against “the idea of exclusive fiber type recruitment” [69]. According to intramuscular electromyographic studies, the maximal recruitment domain differs among muscles of different sizes because of the different fiber type composition [163]. Motor unit recruitment appears to be essentially complete at approximately 50 % of the maximal voluntary contraction (MVC) in small muscles (e.g., adductor pollicis) with mainly type I fibers and continues until 80–90 % MVC in larger muscles (e.g., biceps brachii, brachialis, and deltoid muscles) composed of both type I and II fibers [163, 164]. “Small muscles may therefore be at increased risk for overtraining despite the implementation of light workouts because many FT (fast twitch) fibers are recruited even with light resistance” [69]. These data were recorded in a small number of MVCs. As demonstrated by glycogen use studies [128, 165–167], it can be assumed that high-threshold type II units of large muscle groups are recruited during submaximal intensities as well. Data from a longitudinal study with muscle biopsies of the vastus lateralis confirm conversions within the fast-fiber population from type IIx to type IIa after 8 weeks of strength endurance training with three leg exercises (2 × 20–28 RM, 1-min rest) [67]. These results suggest a progressive recruitment of type IIx fibers into the contraction process as fatigue develops.

Statistically significant increases in muscle CSA in male [22, 168, 169] and female subjects [170] without strength training experience have been observed after training durations of 8 [169] and 12 weeks [170] of the upper extremities [169, 170] and after training durations of 6 [22] and 12 weeks of the lower extremities [168, 170]. Souza et al. [22] found equal statistically significant gains in the muscle CSA of the quadriceps after three training protocols (non-periodized, SPP, and DUP) over 6 weeks (half squats and knee extension). However, in strength-trained subjects, Ahtianen et al. [171] and Wilson et al. [59] did not identify statistically significant gains in the muscle mass of the quadriceps after 12 weeks. Multi-joint exercises (parallel squats and leg press) are partly expected to statistically significant increase muscle CSA after 24 weeks in trained subjects [171]. For this reason, the greater part of the pre-season periodization in individual sports should be oriented towards hypertrophy strength training. These studies only confirm the fact that muscle hypertrophy occurred within these periods of investigation. These studies do not indicate the time periods necessary to develop the muscle mass that is optimal for the particular sports discipline (years!).

6 Conclusions

During the season, Fleck and Kraemer [1] suggest the use of DUP for team sports, which should be suited to a high performance level throughout the entire course of the season. Fleck and Kraemer [1] assert that the disadvantages of SPP are the low performance at the beginning of the season and the risk of over-fatigue at the end of the season. In our opinion, these effects depend on a general inaccurate application of strength training rather than on the type of periodization that is used. For the organization of strength training, it must not be forgotten that the particular sports discipline dictates the organization of the strength training sessions and not the opposite. Stone [172] summarizes the facts with the following concise and appropriate formulation: “Periodization is the overall concept of training and deals with subdividing the training process into specific periods and phases—programming is the creation of the programs inside of these periods—often it is difficult to separate these two aspects of the training process” [172]. In other words, much of what is called periodization is really the study of programming (i.e., sets and reps) rather than an actual concept [172]. Meta-analyses [65, 110] and results with weightlifters [109], American Football players [37, 52, 114], and throwers [115] confirm the necessity of the habitual use of $\geq$80 % 1 RM: (1) to improve maximal strength during the off-season [37, 52] and in-season [114] in American Football [37, 52, 114], (2) to reach peak performance in maximal strength and vertical jump power during tapering in track-and-field [115], and (3) to produce hypertrophy [65] and strength improvements [109, 110] in advanced athletes. The integration and extent of hypertrophy strength training in in-season conditioning depend on the duration of the contest period, the frequency of the contests, and the proportion of the conditioning program. As a possible guiding principle for adequate regeneration times, 72 h between hypertrophy strength training and strength-power training should be provided to allow for maximal stimulus intensities [10, 129]. According to the findings of Schmidtbleicher and Frick [129], after a bout of hypertrophy training, the recovery of the speed-strength performance in the short SSC to the baseline level is not expected until 72 vs. 3 h after strength-power training with the method of maximum explosive strength actions moving of high-weight loads (90 % 1 RM, 5 × 3 RM, 6-min rest). Speed-strength production in the short SSC showed potentiation effects 48–148 h after the single strength-power training session [129]. Thus, rotating hypertrophy and strength-power sessions in a microcycle throughout the season is a viable option [37, 52]. This conclusion is only valid if the muscle is not trained otherwise during this regeneration phase. Raastad and Hallén [173] reported recovered isokinetic knee extension strength and squat jump heights to baseline levels in 10 male athletes 33 h after a heavy strength-training protocol with back squats (3 × 3 RM, 6-min rest), front squats (3 × 3 RM, 6-min rest), and bilateral leg extensions (3 × 6 RM, 4-min rest). The duration of regenerartion is dependent on training session design and performance level of an athlete. Regarding neuromuscular performance, plyometric exercises can be performed after the strength-power training mentioned above at the same day if a minimum rest period of 3 h is provided [129]. Therefore, it is quite possible to perform a single strength-power session with the method of maximum explosive strength actions moving high-weight loads (90 % 1 RM) at least 1–2 days before competition because of shorter regeneration times and potentiation effects [129]. Compared with ballistic strength training (30 % 1 RM), this method has been shown to provide statistically superior gains in maximal strength, peak power, impulse size, and explosive strength during tapering in track-and-field throwers [115]. For maximizing speed-strength over the short-term (peaking), elite athletes should accomplish strength-power training twice per week [37].

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