International Journal of
EXERCISE SCIENCE

Original Research

Three Weeks of Detraining Does Not Decrease Muscle Thickness, Strength or Sport Performance in Adolescent Athletes

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ABSTRACT

***International Journal of Exercise Science* 13(6): 633-644, 2020.** The purpose of this study was to examine the effects of detraining following a block (BLOCK) or daily undulating periodized (DUP) resistance training (RT) on hypertrophy, strength, and athletic performance in adolescent athletes. Twenty-one males (age = 16 ± 0.7 years; range 15-18 years) were randomly assigned to one of two 12-week intervention groups (three full-body RT sessions per week): BLOCK ($n = 9$); DUP ($n = 12$). Subsequently a three-week detraining period was applied. Body mass, fat mass (FM), fat-free mass (FFM), muscle mass, muscle thickness (rectus femoris, vastus lateralis and triceps brachii), one-repetition maximum squat and bench press, countermovement jump (CMJ), peak power calculated from CMJ (Ppeak), medicine ball put distance, and 36.58m sprint were recorded before and after RT as well as after detraining. BLOCK and DUP were equally effective for improvements of athletic performance in young athletes. Both groups displayed significantly ($\rho \leq 0.05$) higher values of all measures after RT except FM, which was unchanged. Only FM increased ($p = 0.010$; ES = 0.14) and FFM decreased ($p = 0.018$; ES = -0.18) after detraining. All other measurements were unaffected by the complete cessation of training. Values were still elevated compared to pre-training. Linear regression showed a strong correlation between the percentage change by resistance training and the decrease during detraining for CMJ ($R^2 = 0.472$) and MBP ($R^2 = 0.629$). BLOCK and DUP RT seem to be equally effective in adolescent athletes for increasing strength, muscle mass, and sport performance. In addition, three weeks of detraining did not affect muscle thickness, strength, or sport performance in adolescent athletes independent of previous resistance training periodization model used.

KEY WORDS: Youth, weight training, resistance training, hypertrophy, American Football, periodization

INTRODUCTION

Resistance training (RT) is widely accepted as a safe and effective method to increase muscle mass (MM), strength, and power, as well as athletic performance in adults (30), children, and adolescents (19). Thus, it is recommended for young athletes to participate in RT programs to improve performance (8). In RT programs, it is recommended to divide the training regimen into sequential phases, to improve strength qualities by employing different loading schemes (intensity, volume, and rest) (12). This aspect is one important aim of periodization (9). Concerning strength and hypertrophy in adults, periodized RT has been shown to be superior to non-periodized RT if training duration is longer than six weeks (32). The same applies to young athletes since a study, comparing non-periodized to daily undulating periodization (DUP) showed periodized RT to be slightly superior concerning strength and sprinting performance (24). The two most frequently documented RT periodization models in the literature are undulating and block periodization (BLOCK). Undulating periodization models are characterized by frequent and substantial variations of training variables within a meso- (several weeks) or microcycle (typically one week) (12). In BLOCK, sequencing cycles lasting several weeks are employed, each focusing on a limited number of goals; thus, concentrated workloads of limited variation are used (12). Consequently, in BLOCK, different strength qualities are trained sequentially instead of simultaneously, as with DUP. The rationale for this is to make transfer of residual training effects to the subsequent block possible (14). However, the disadvantage of this could be that the strength qualities neglected during a block decrease, whereas in DUP all qualities are developed simultaneously.

In the long-term training process of young athletes, however, there are phases in which RT will be interrupted (e.g. post-season or school breaks). This cessation of RT is called detraining (DTR) (17). The literature on DTR in adults on body composition, MM, strength, and power is very heterogeneous. Previous research has shown that short-term DTR (≤ 8 weeks) lead to an increase in fat mass (FM) (11) and decreases in muscle cross-sectional area (CSA) (11), whereas others found neither FM (16) nor CSA changes (27). Furthermore, studies have found a reduction in one-repetition maximum (1-RM) (back squat [BS] (11, 16) and bench press [BP] (16)), while other studies did not (27). Jumping ability was also negatively affected in some DTR studies (16), while others showed no decline (11). Findings on DTR effects in young athletes are also inconsistent. For example, studies with young males (7-13 years) showed that four weeks of DTR led to a decline in strength (2, 5), while another study found no difference (mid- and post-peak-height-velocity) after eight weeks of DTR (22). The same applies to upper and lower body power. A number of studies with children and adolescents have found upper- (28) and lower-body power (2, 4, 22, 28) is maintained for up to 16 weeks of DTR. Conversely, two studies with 11- to 14-year-old boys show a decline in muscular power following three (13) and four months (6) of DTR. Concerning anthropometric data after DTR, studies found losses in fat-free mass (FFM) and increased FM after 12 (13) and 16 weeks of DTR (6), while only one found FM unchanged following a 12-week DTR period (28).

Since most studies on DTR with children and adolescents have focused on muscular strength and power, whereas there is a gap of data on the effects on changes in MM following DTR, it is hoped that this research, for the first time, will give deeper insight of the effects of three weeks of DTR in adolescent athletes on measures of body composition and muscle thickness. Furthermore, the effects of a three-week DTR on strength, power, and performance be investigated to contribute to the current state of knowledge. Besides, to the best of our knowledge, there is no study about the effects of DTR following different periodization models in RT. Due to the sequencing of training goals in BLOCK, other time courses may be observed during periods of DTR compared to DUP. It is hypothesized that BLOCK might show greater changes in MM than DUP since hypertrophy oriented training is neglected for a longer period of time compared to DUP. For the same reason on the other hand, it is hypothesized that the maximum strength changes may be more profound in DUP comparted to BLOCK. Therefore, the present research compares, for the first time, the effects of a three-week DTR period following BLOCK or DUP RT on MM, strength, power, and sport performance.

METHODS

Participants

This study was conducted during the off-season of the German Football League Juniors and fully in accordance to the ethical standards of the International Journal of Exercise Science (26). The research design was approved by the Ethics Committee of the IST-University of Applied Sciences. Participants were 47 players recruited from a German first division U16 and U19 team. Three participants did not meet medical inclusion criteria and were prevented from participating. The remaining athletes did not report cardiorespiratory, metabolic, or musculoskeletal impairments. Participants, as well as their parents, were informed about the procedures and methods used prior to the study. Athletes at the age of 18 gave written informed consent. For each underage participant, informed consent was obtained by both participants and their legal guardian. All players completed a questionnaire about their RT experience and agreed to abstain from any additional RT during this study.

Protocol

Two weeks prior to the intervention, participants underwent a familiarization period (once a week for two weeks), to learn the exercise and test techniques used in this study. In the following week, pre-testing was performed (T1) in two separate sessions. Session One included anthropometric and strength testing. Body mass (BM) was measured using electronic scale (Seca 803, Hamburg, Germany). Height was recorded using a wall-mounted stadiometer. Body composition (FM, FFM, and MM) was analyzed using bioelectrical impedance analysis (Akern BIA 101, Akern, Firenze, Italy). Muscle thickness was measured by the same researcher at three anatomical sites of the subjects' right side as described previously using B-mode US (Mindray DP-50, Shenzhen, China) with 8.5-Mhz linear probe (Mindray 75L53EA, Shenzhen, China) (20). Vastus lateralis muscle (VL) at 50% distance between the most prominent point of the greater trochanter of the femur and the lateral condyle of the tibia (20), and Rectus femoris muscle (RF) at half distance between the anterior inferior suprailiac crest and the proximal boarder of the patella (20), both with 43 dB gain and image depth of 3.7 cm. Triceps brachii (TB) was measured at 60% distal between the acromial process of the scapula and the lateral epicondyle of the humerus (gain = 43 dB; image depth = 5.5 cm) (20). A water-soluble gel was applied on the probe, before three images of each site were taken without depression of the dermal surface. The average value for muscle thickness of the three images of each muscle was used for further analysis to increase intra-rater reliability. Following a standardized warm-up a 1-RM parallel BS and BP was performed as described by Haff & Triplett (9). Strong verbal encouragement was given by the researcher.

Session Two included athletic performance assessments. Jumping ability was tested using Optojump photocell system (Microgate, Bolzano, Italy). After a standardized warm-up comprised of five minutes of low intensity cardio on a treadmill followed by eight dynamic mobility exercises for the shoulders, hip flexors, hip extensors, quadriceps and calves, subjects were allowed two jumps to get familiar with the procedure. Subsequently, participants performed three maximal countermovement jumps (CMJ) with hands on hips and one minute of rest between attempts. Best jump height was recorded for further analysis. Ppeak was estimated from CMJ and player BM using the Sayers equation (29). Upper-body power was tested using the seated medicine ball put (MBP), as described previously (9). Players completed three trials with one minute of rest and the best attempt was recorded. Speed was tested over 36.58m on an indoor athletic track with participants starting when ready from a self-chosen three-point stance. Time was recorded by two coaches using stopwatches, starting the measurement on first movement by the athlete. Participants performed two trials with three minutes of rest between. The mean value of the two measured times was calculated, and the best average time of a trial was documented for analysis. The two-way random effects, absolute agreement, single measurement Intraclass Correlation Coefficients (ICC) range in the present population of male adolescent subjects for muscle thickness was 0.690 – 0.974 (RF ICCT1-T2 = 0.760, ICCT2-T3 = 0.951; VL ICCT1-T2 = 0.803, ICCT2-T3 = 0.965; TB ICCT1-T2 = 0.690, ICCT2-T3 = 0.974). ICC for measures of performance were CMJ ICCT1-T2 = 0.868, ICCT2-T3 = 0.971; Ppeak ICCT1-T2 = 0.857, ICCT2-T3 = 0.983; MBP ICCT1-T2 = 0.606, ICCT2-T3 = 0.857; 40yd ICCT1-T2 = 0.936, ICCT2-T3 = 0.922).

Participants were randomly assigned to either the BLOCK or DUP RT group. RT took place in addition to the players' team practice (twice per week, no systematic sprint or plyometric exercises). Three supervised full-body RT sessions per week were performed on non-consecutive days. Warm-up (as described earlier), selection, and sequence of exercises were identical in both groups. All exercises were performed with maximum range of motion. Rest and training volume were altered according to the assigned group (Table 1) and equated over the course of the study.

Players performed all sets to concentric muscle fatigue or failure of exercise technique. Athletes increased resistance when the number of completed repetitions exceeded the prescribed number of the set by three or more. When the number of performed repetitions was three less than stipulated, participants reduced resistance. Cadence was set at two-second eccentric phase and, one-second concentric phase with no hold at the bottom or top of the repetition.

Table 1. Sets, repetition and rest periods according to training group for core and assistance exercises.

	Weeks 1 - 3	Week 4	Weeks 5 - 7	Week 8	Weeks 9 - 11	Week 12
BLOCK	Core exercises *Session 1 – 3:* 2 x 20 (1 min) Assistance exercises *Session 1 – 3:* 3 x 10 (2 min)	Core exercises *Session 1 – 3:* 1 x 20 (1 min) Assistance exercises *Session 1 – 3:* 2 x 10 (2 min)	Core exercises *Session 1 – 3:* 3 x 10 (2 min) Assistance exercises *Session 1 – 3:* 3 x 10 (2 min)	Core exercises *Session 1 – 3:* 2 x 10 (2 min) Assistance exercises *Session 1 – 3:* 2 x 10 (2 min)	Core exercises *Session 1 – 3:* 4 x 5 (3 min) Assistance exercises *Session 1 – 3:* 3 x 10 (2 min)	Core exercises *Session 1 – 3:* 2 x 5 (3 min) Assistance exercises *Session 1 – 3:* 2 x 10 (2 min)
DUP	Core exercises *Session 1:* 2 x 20 (1 min) *Session 2:* 4 x 5 (3 min) *Session 3:* 3 x 10 (2 min) Assistance exercises *Session 1 – 3:* 3 x 10 (2 min)	Core exercises *Session 1:* 1 x 20 (1 min) *Session 2:* 2 x 5 (3 min) *Session 3:* 2 x 10 (2 min) Assistance exercises *Session 1 – 3:* 2 x 10 (2 min)	Core exercises *Session 1:* 2 x 20 (1 min) *Session 2:* 4 x 5 (3 min) *Session 3:* 3 x 10 (2 min) Assistance exercises *Session 1 – 3:* 3 x 10 (2 min)	Core exercises *Session 1:* 1 x 20 (1 min) *Session 2:* 2 x 5 (3 min) *Session 3:* 2 x 10 (2 min) Assistance exercises *Session 1 – 3:* 2 x 10 (2 min)	Core exercises *Session 1:* 2 x 20 (1 min) *Session 2:* 4 x 5 (3 min) *Session 3:* 3 x 10 (2 min) Assistance exercises *Session 1 – 3:* 3 x 10 (2 min)	Core exercises *Session 1:* 1 x 20 (1 min) *Session 2:* 2 x 5 (3 min) *Session 3:* 2 x 10 (2 min) Assistance exercises *Session 1 – 3:* 2 x 10 (2 min)
Core exercises	Session 1 to 3: Back squat Bench press					
Assistance exercises	Session 1: Romanian deadlift (barbell), Bent-over barbell row, Incline dumbbell press, Calf raises (leg press machine), Hammer curls, Triceps cable pushdown, Side plank		Session 2: Good-mornings, 1-arm dumbbell row, 2-arms triceps extension, Seated calf raises, Barbell biceps curls, Triceps kickbacks, Russian twist		Session 3: Romanian deadlift (dumbbell), Reverse grip bent-over row, Barbell shrugs, Calf raises (leg press machine), Barbell biceps reverse curls, Cable overhead triceps extension, Plank	

Note. BLOCK = block periodization; DUP = daily undulating periodization.

In order to minimize possible dietary bias, subjects were instructed to maintain their normal diet without taking additional supplements, besides the post-workout supplement provided during the intervention to maximize muscle protein synthesis after every RT session. One serving of the post-workout whey protein supplement contained 23g protein (3g L-leucin), 1.9g carbohydrate and 0.9g fat (inkospor X-TREME Whey, Roth, Germany).

During the RT period participants had to attend at least 32 of the 36 training sessions. With that, 17 participants were disqualified from further analysis (illness *n* = 5; football-related injury *n* = 3; non-football injury *n* = 3; personal reasons *n* = 6). None of the participants were injured during RT. A minimum of three days after the RT period, post-testing was conducted (T2).

In the following three weeks, the DTR period was implemented (no RT nor football training). The procedures of T2 and post-DTR (T3) were the same as T1. Six participants missed T3 testing sessions and were eliminated for final analysis. Of the remaining 21 athletes, 13 were defined as untrained (< 1 year RT) and eight as trained (≥ 1 year RT). The final number of participants by group were BLOCK $n = 9$ (age 16.89 ± 4.77 years; height 181.8 ± 4.6 cm; weight 81.79 ± 19.01 kg; RT history 0.72 ± 1.18 years) and DUP $n = 12$ (age 16.67 ± 0.50 years; height 186.8 ± 5.3 cm; weight 84.77 ± 10.40 kg; RT history 0.56 ± 0.69 years).

Statistical Analysis

Statistical analyses were performed using SPSS (Version 25, Chicago, IL, USA). All results are expressed as mean ± standard deviation (SD). Significance was set at $p \leq 0.05$. Normality homogenity of variance were tested using Kolmogorov-Smirnov test and Levene´s test, respectively. One-way analysis of variance (ANOVA) was performed to examine differences between groups at baseline. Two-way ANOVA (time*group) with repeated measures was performed. A one-way ANOVA was used to examine the time effect of both groups combined. Post-hoc analyses were performed using Bonferroni's adjustment. Cohen’s d effect sizes (ES) were calculated between trials (ES of ≤ 0.2, ≤ 0.5, ≤ 0.8 and > 0.8 were considered trivial, small, moderate and large, respectively) (3). Linear regression was used to quantify the amount of shared variance between RT (relative changes from T1 to T2) and DTR changes (relative changes from T2 to T3).

RESULTS

There were no significant group differences for any measurement at baseline. BLOCK completed 95 ± 5% and DUP 93 ± 3% of training sessions. There were significant time effects for all measurements. No group effects or time-group interactions were found. Detailed results are shown in Table 2.

When both groups were analyzed combined, there was a significant improvement through RT (T1-T2) in every measurement, except for FM ($p = 0.322$). Following DTR (T2-T3) there was a significant increase in FM ($p = 0.010$; ES = 0.14), and decrease in FFM ($p = 0.018$; ES = -0.18). All other values were unaffected by DTR and still elevated compared to baseline after DTR (T1-T3). Detailed results are illustrated in Table 3.

Table 2. Time and group effects as well as time by group interactions.

	Time		Group		Time * Group	
	η_p^2	*p*	η_p^2	*p*	η_p^2	*p*
BM	0.391	0.012*	0.000	0.985	0.037	0.714
FM	0.358	0.018*	0.006	0.728	0.223	0.103
FFM	0.667	< 0.001***	0.010	0.672	0.212	0.118
MM	0.633	< 0.001***	0.019	0.548	0.216	0.111
RF	0.481	0.003**	0.018	0.847	0.006	0.733
VL	0.400	0.010*	0.000	0.949	0.039	0.699
TB	0.653	< 0.001***	0.000	0.996	0.217	0.110
BS	0.782	< 0.001***	0.019	0.550	0.172	0.184
BP	0.848	< 0.001***	0.003	0.835	0.080	0.511
CMJ	0.626	< 0.001***	0.015	0.595	0.101	0.383
Ppeak	0.692	< 0.001***	0.010	0.664	0.121	0.314
MBP	0.674	< 0.001***	0.001	0.992	0.082	0.464
Sprint	0.427	0.007**	0.087	0.194	0.202	0.131

Note. BM = body mass; FM = fat mass; FFM = fat-free mass; MM = muscle mass; RF = M. rectus femoris thickness; VL = M. vastus lateralis thickness; TB = M. triceps brachii thickness; BS = back squat; BP = bench press; CMJ = countermovement jump; Ppeak = peak power; MBP = medicine ball put; Sprint = forty yard sprint. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 3. Changes from pre-training (T1) to post-training (12 weeks = T2), and after three weeks of detraining (T3).

				dTime	Cohen's d		dTime	Cohen's d		dTime	Cohen's d	
	T1 ± SD	T2 ± SD	T3 ± SD	T1-T2	T1-T2	*p*	T1-T3	T1-T3	*p*	T2-T3	T2-T3	*p*
BM [kg]	82.2 ± 14.2	84.2 ± 13.8	84.1 ± 13.8	2.1	0.15	0.007**	1.9	0.14	0.017*	-0.1	-0.01	1.000
FM [kg]	16.0 ± 7.9	15.2 ± 8.1	16.3 ± 8.3	-0.9	-0.11	0.322	0.3	0.03	1.000	1.1	0.14	0.010*
FFM [kg]	66.1 ± 7.4	69.1 ± 7.5	67.8 ± 7.0	2.9	0.40	< 0.001***	1.7	0.23	0.008**	-1.3	-0.18	0.018*
MM [kg]	46.1 ± 4.8	48.8 ± 5.2	47.8 ± 5.0	2.7	0.54	< 0.001***	1.7	0.35	0.010*	-1.0	-0.20	0.117
RF [cm]	2.56 ± 0.33	2.71 ± 0.27	2.68 ± 0.26	0.15	0.50	0.001**	0.12	0.41	0.009**	-0.03	-0.11	0.214
VL [cm]	1.60 ± 0.26	1.71 ± 0.27	1.69 ± 0.26	0.11	0.42	0.004**	0.09	0.35	0.011*	-0.02	-0.08	0.608
TB [cm]	3.85 ± 0.59	4.25 ± 0.58	4.25 ± 0.57	0.40	0.68	< 0.001***	0.40	0.69	< 0.001***	0.00	0.00	1.000
BS [kg]	101.5 ± 18.9	120.8 ± 23.5	118.1 ± 20.1	19.3	0.91	< 0.001***	16.6	0.85	< 0.001***	-2.7	-0.13	0.250
BP [kg]	72.9 ± 15.3	83.3 ± 16.1	83.6 ± 16.3	10.5	0.67	< 0.001***	10.7	0.68	< 0.001***	0.2	0.01	1.000
CMJ [cm]	39.2 ± 7.6	41.9 ± 7.9	42.0 ± 8.6	2.7	0.35	0.003**	2.8	0.34	< 0.001***	0.1	0.01	1.000
Ppeak [W]	4047 ± 620	4303 ± 602	4301 ± 640	256	0.42	< 0.001***	254	0.40	< 0.001***	-2	0.00	1.000
MBP [m]	3.23 ± 0.35	3.54 ± 0.49	3.48 ± 0.47	0.31	0.74	< 0.001***	0.3	0.61	< 0.001***	-0.1	-0.13	0.932
Sprint [s]	5.31 ± 0.45	5.21 ± 0.42	5.23 ± 0.42	-0.1	-0.23	0.005**	-0.08	-0.18	0.027*	0.02	0.05	0.385

Note. BM = body mass; FM = fat mass; FFM = fat-free mass; MM = muscle mass; RF = M. rectus femoris thickness; VL = M. vastus lateralis thickness; TB = M. triceps brachii thickness; BS = back squat; BP = bench press; CMJ = countermovement jump; Ppeak = peak power; MBP = medicine ball put; Sprint = forty yard sprint. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Linear regression showed shared variances between RT and DTR changes in MBP ($R^2 = 0.629$), CMJ ($R^2 = 0.472$), Ppeak ($R^2 = 0.401$), FM ($R^2 = 0.362$), BS ($R^2 = 0.337$), FFM ($R^2 = 0.161$), MM ($R^2 = 0.147$), BP ($R^2 = 0.141$), BW ($R^2 = 0.074$), and 40yd ($R^2 = 0.028$; Figure 1).

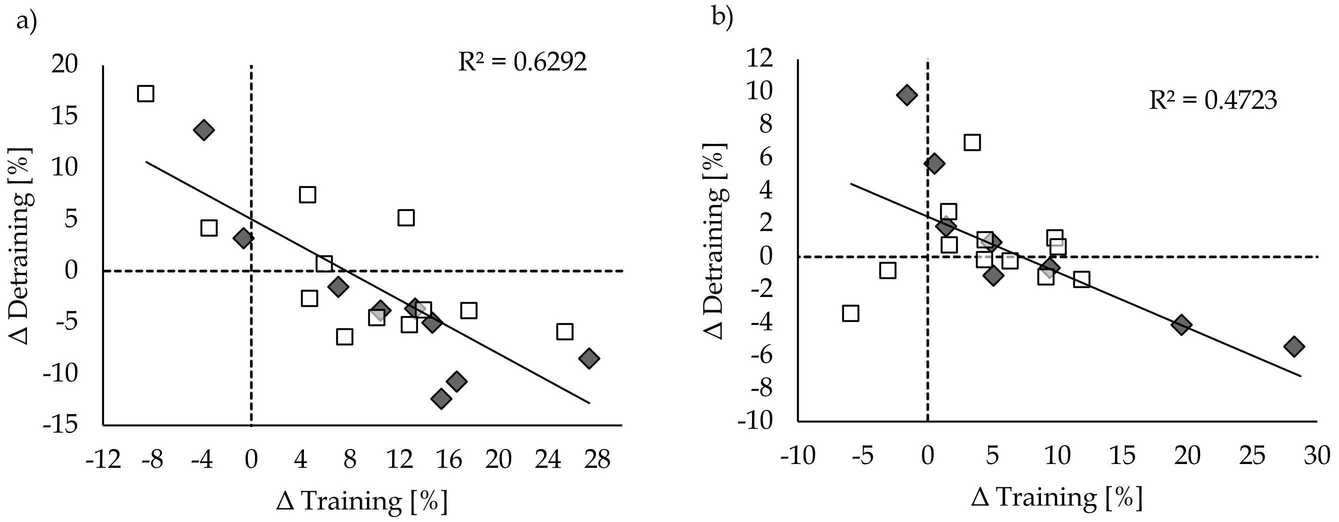

Figure 1. Correlation between relative changes in training and detraining period. a) Counter movement jump, b) medicine ball put, linear regression line represents all participants (both groups combined). BLOCK = block periodization; DUP = daily undulating periodization.

DISCUSSION

This study showed improvements in muscle thickness, strength, and performance following 12 weeks of hypertrophy-centered RT in adolescents, with BLOCK and DUP periodization being equally effective. These adaptations were still present after DTR. Only FM increased, while FFM decreased during DTR. However, the ES were only small or trivial. In line with previous studies with adults (12) and adolescents (7), BLOCK and DUP were equally effective in increasing MM, strength, and performance. Therefore, it is still unclear which model is the most effective for adolescents and adults alike. In addition, contrary to our hypotheses, no difference following DTR could be demonstrated after BLOCK or DUP RT, which necessitates further study.

Athletes showed a significantly higher BM following RT, which can be explained by an increase in MM, since FM was unchanged. This is confirmed by increases in MM, FFM, and measurements of muscle thickness. Our findings are contrary to previous studies, which failed to detect BM changes after RT in youths (13, 28). This could be explained by more power-oriented RT design, in contrast to our hypertrophy-centered program. Another possible explanation is that the participants in the aforementioned research were younger than the athletes participating in this study. It assumed that children benefit from RT primarily through neuronal adaptations, while adolescents possess a higher potential for structural adaptations such as hypertrophy (25). The observed gain in BM in our study was not affected by DTR, which is considered advantageous for American football players (23). FM was unaltered through RT. This is contrary to previous studies who showed a reduction of FM in children following different types of RT (6, 13, 28). Furthermore, FM increased during DTR. Other studies also observed gains in FM after periods of DTR (11). This underlines the importance of reduced energy intake in phases of DTR to avoid excessive gains in FM. It should be mentioned that nutrition was not monitored during this study. More studies including nutritional monitoring are desirable. Participants expressed small gains in FFM after RT, while MM was moderately increased. These results are consistent with other research on young participants (7, 13). Moreover, athletes were able to maintain MM, while showing only trivial reduction in FFM after DTR. However, the loss of FFM should be interpreted with caution. Firstly, our direct measures of muscle thickness via ultrasound were not affected by DTR. Secondly, bioelectrical impedance analysis, as used in this study, in general has limited measurement accuracy and is susceptible to measurement errors (e.g. hydration status of the participants). More accurate methods, such as Dual-energy X-ray absorptiometry, should be considered in future studies. The preservation of MM has also been reported in several other studies with adults (15, 27).

Muscle thickness increased at all sites with small to moderate ES. Similar findings were reported previously in young soccer players following RT (21). Our athletes´ gains could even be preserved during DTR. This is a novel finding, since maintenance of muscle thickness following DTR in adolescents has not yet been documented. In adults, there are only few studies that have shown MM being maintained during DTR (15, 27).

The current study found that strength in adolescent athletes was increased by hypertrophy-oriented RT with moderate to large ES. This is in line with previous work done with young populations (22). Structural adaptations, such as muscle thickness, were present and therefore partly explain the strength increases. It is also likely in adolescents that neuronal adaptations have occurred (8), which contribute to increased strength. Strength increments were also conserved during DTR, which, was likewise demonstrated in studies on adult (27) and young populations (22). In contrast, there are findings that DTR leads to a loss of strength in youth (2, 5, 13). However, course and magnitude of the effects following DTR are influenced by duration, type of the preceding RT, and the length of DTR (17). This could explain the reported decline of strength, contrary to our findings, since either lower training frequencies, shorter RT intervention (2, 5), or longer DTR periods were used (5, 10, 11, 13, 16). Future studies should therefore investigate the effects of DTR on strength following different types of RT in adolescents.

All power and performance measures were improved via RT. These findings are consistent with a vast number of studies of RT on power and performance in children and adolescents (2, 4, 6, 22, 28). One explanation could be observed increases in strength. It can be speculated that these increases would have been greater if sprint or jump training had been performed simultaneously. It should be noted, however, that manually measured sprint times involve measurement inaccuracy and should therefore be interpreted with caution. It is desirable that future studies consider the use of more accurate measurement techniques, such as timing gates. None of the performance parameters were affected by DTR. These results are in accordance with studies indicating that the effects of RT on power, as well as sprinting, seem to persist longer in children (2, 4, 5) and adolescents (22, 28) than other qualities during DTR. Perhaps everyday activities are sufficient to maintain performance adaptations of children and adolescents. In addition, DTR effects are less substantial in young adults compared to older individuals (1). This may in part, explain the maintenance of all the aforementioned parameters in our participants.

Another effect observed in this study, especially with regard to power measurements, was that the higher the increase through RT, the faster it decreased with DTR. In the literature, this phenomenon was previously described as "soon ripe, soon rotten" (33). The underlying mechanisms of this phenomenon are difficult to explain, since the adaptations to RT are rather complex (CSA, pennation angle, motor unit recruitment etc.) (4). Furthermore, the course of these adaptations across time differ greatly with respect to RT and DTR, both from a timing point of view (18) and in relation to the individual (due to athlete age and training experience) (1). For example, Kubo et al. (18) found that skeletal muscle adaptations following RT are slower than strength and neural changes, and that, during DTR, strength could be maintained although MM decreased. Concerning neural adaptations, changes caused by DTR are also very diverse. Tallent et al. (31) observed no change in strength and V-wave after two weeks of DTR, whereas corticospinal excitability decreased. However, the underlying mechanisms of this effect are unclear and further research is needed. Zatsiorsky & Kraermer state that more mature athletes with extensive training backgrounds have longer lasting training effects (33). If this holds true, it could explain why the participants in this study, most of whom were untrained, showed a rapid decline in measures of power. This emphasizes the importance of long-term RT concept for young athletes, as recommended by Granacher et al. (8).

This study has several limitations, as there was no control group. This is particularly important when performing tests such as CMJ and MBP, as considerable motor learning effects are possible and improvements cannot solely be explained by RT. Furthermore, it is possible that the effects of RT shown in this study can be partly attributed to the effects of normal growth and maturation. Another possible source of error could be the lack of nutritional monitoring. Future studies on DTR should include some sort of dietary assessments. Furthermore, this study was conducted with male adolescent American football players. Studies with different young populations are needed.

This study demonstrates that three-weeks of DTR does not affect muscle thickness, strength, or athletic performance previously gained by high-volume RT in male adolescent athletes, independent of the periodization model being used. Future studies should include different DTR periods following various types of RT and periodization models with both female and male adolescents, as well as athletes from different sports.

ACKNOWLEDGEMENTS

We thank FitX Deutschland GmbH for their support by letting us use their facilities. Also, we are deeply grateful to inkospor for providing the whey protein used in this study. We are very grateful for each participant involved in this study and for the efforts and hard work they put into it.

REFERENCES

1. Bosquet L, Berryman N, Dupuy O, Mekary S, Arvisais D, Bherer L, Mujika I. Effect of training cessation on muscular performance: A meta-analysis. Scand J Med Sci Sports 23(3): 140-149, 2013.

2. Chaouachi A, Othman AB, Makhlouf I, Young JD, Granacher U, Behm DG. Global training effects of trained and untrained muscles with youth can be maintained during 4 weeks of detraining. J Strength Cond Res 33(10): 2788-2800, 2018.

3. Cohen J. Statistical power analysis for the behavioral sciences. London: Taylor & Francis; 1988.

4. Faigenbaum AD, Farrell AC, Fabiano M, et al. Effects of detraining on fitness performance in 7-year-old children. J Strength Cond Res 27(2): 323-330, 2013.

5. Faigenbaum AD, Westcott WL, Micheli LJ, Outerbridge AR, Long CJ, LaRosa-Loud R, Zaichkowsky LD. The effects of strength training and detraining on children. J Strength Cond Res 27(2): 323-330, 1996.

6. Fathi A, Hammami R, Moran J, Borji R, Sahli S, Rebai H. Effect of a 16 week combined strength and plyometric training program followed by a detraining period on athletic performance in pubertal volleyball players. J Strength Cond Res 33(8): 2117-2127, 2019.

7. Gavanda S, Geisler S, Quittmann OJ, Schiffer T. The effect of block versus daily undulating periodization on strength and performance in adolescent football players. Int J Sports Physiol Perform 14(6): 814-821, 2019.

8. Granacher U, Lesinski M, Büsch D, et al. Effects of resistance training in youth athletes on muscular fitness and athletic performance: A conceptual model for long-term athlete development. Front Physiol 7(164): 2016.

9. Haff GG, Triplett NT. Essentials of strength training and conditioning. Champaign: Human Kinetics; 2016.

10. Häkkinen K, Komi PV. Changes in electrical and mechanical behavior of leg extensor muscles during heavy resistance strength training. Scand J Med Sci Sports 7(2): 55–64, 1985.

11. Häkkinen K, Komi PV, Tesch PA. Effect of combined concentric and eccentric strength training and detraining on force-time, muscle fiber and metabolic characteristics of leg extensor muscles. Scand J Med Sci Sports 3: 50-58, 1981.

12. Harries SK, Lubans DR, Callister R. Systematic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. J Strength Cond Res 29(4): 1113-1125, 2015.

13. Ingle L, Sleap M, Tolfrey K. The effect of a complex training and detraining programme on selected strength and power variables in early pubertal boys. J Sports Sci 24(9): 987-997, 2006.

14. Issurin VB. Benefits and limitations of block periodized training approaches to athletes' preparation: A review. Sports Med 46(3): 329-338, 2016.

15. Ivey FM, Tracy BL, Lemmer JT, NessAiver M, Metter EJ, Fozard JL, Hurley BF. Effects of strength training and detraining on muscle quality: Age and gender comparisons. J Gerontol A Biol Sci Med Sci 55(3): 152-159, 2000.

16. Izquierdo M, Ibañez J, González-Badillo JJ, et al. Detraining and tapering effects on hormonal responses and strength performance. J Strength Cond Res 21(3): 768-775, 2007.

17. Kraemer WJ, Häkkinen K. Strength training for sport: Olympic handbook of sports medicine. Hoboken: John Wiley & Sons; 2002.

18. Kubo K, Ikebukuro T, Yata H, Tsunoda N, Kanehisa H. Time course of changes in muscle and tendon properties during strength training and detraining. J Strength Cond Res 24(2): 322-331, 2010.

19. Lesinski M, Prieske O, Granacher U. Effects and dose-response relationships of resistance training on physical performance in youth athletes: A systematic review and meta-analysis. Br J Sports Med 50(13): 781-795, 2016.

20. Mangine GT, Hoffman JR, Gonzalez AM, et al. The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. Physiol Rep 3(8): 2015.

21. McKinlay BJ, Wallace P, Dotan R, Long D, Tokuno C, Gabriel DA, Falk B. Effects of plyometric and resistance training on muscle strength, explosiveness, and neuromuscular function in young adolescent soccer players. J Strength Cond Res 32(11): 3039-3050, 2018.

22. Meylan CMP, Cronin JB, Oliver JL, Hopkins WG, Contreras B. The effect of maturation on adaptations to strength training and detraining in 11-15-year-olds. Scand J Med Sci Sports 24(3): 156-164, 2014.

23. Miller TA, White ED, Kinley KA, Congleton JJ, Clark MJ. The effects of training history, player position, and body composition on exercise performance in collegiate football players. J Strength Cond Res 16(1): 44-49, 2002.

24. Moraes E, Fleck SJ, Ricardo Dias M, Simão R. Effects on strength, power, and flexibility in adolescents of nonperiodized vs. daily nonlinear periodized weight training. J Strength Cond Res 27(12): 3310-3321, 2013.

25. Myers AM, Beam NW, Fakhoury JD. Resistance training for children and adolescents. Transl Pediatr 6(3): 137-143, 2017.

26. Navalta JW, Stone WJ, Lyons S. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1-8, 2019.

27. Ogasawara R, Yasuda T, Sakamaki M, Ozaki H, Abe T. Effects of periodic and continued resistance training on muscle CSA and strength in previously untrained men. Clin Physiol Funct Imaging 31(5): 399-404, 2011.

28. Santos AP, Marinho DA, Costa AM, Izquierdo M, Marques MC. The effects of concurrent resistance and endurance training follow a detraining period in elementary school students. J Strength Cond Res 26(6): 1708-1716, 2012.

29. Sayers SP, Harackiewicz DV, Harman EA, Frykman PN, Rosenstein MT. Cross-validation of three jump power equations. Med Sci Sports Exerc 31(4): 572-577, 1999.

30. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: Training considerations. Sports Med 48(4): 765-785, 2018.

31. Tallent J, Goodall S, Gibbon KC, Hortobágyi T, Howatson G. Enhanced corticospinal excitability and volitional drive in response to shortening and lengthening strength training and changes following detraining. Front Physiol 8(57): 2017.

32. Williams TD, Tolusso DV, Fedewa MV, Esco MR. Comparison of periodized and non-periodized resistance training on maximal strength: A meta-analysis. Sports Med 47(10): 2083-2100, 2017.

33. Zatsiorsky VM, Kraemer WJ. Science and practice of strength training. Champaign: Human Kinetics; 2006.