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ORIGINAL ARTICLE

Periodization effects during short-term resistance training with equated exercise variables in females

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Abstract

Purpose During resistance training, volume and load can be altered either gradually (traditional periodization: TP) or with frequent changes between subsequent sessions (daily undulating periodization: DUP). We hypothesized that the periodization model employed would not impact upon training-induced adaptations when exercise variables are equated.

Methods Nineteen females (22.0 years, moderate resistance training experience of 27.9 months) performed 6 weeks of knee extensor training with 3 weekly sessions exercising one leg using TP and the contralateral leg using DUP. Training load varied between 40, 60, and 80% of one repetition maximum (1RM). Volume, range of motion, and time under tension were equated for each leg with a biofeedback software. Dynamometry, surface EMG and ultrasonography were used to determine temporal changes of knee extensor maximum voluntary strength (MVC), neural drive of the M. quadriceps femoris (QF) and vastus lateralis (VL) and rectus femoris (RF) muscle architecture.

Results Significant ($P<0.05$) gains for isometric (TP 15%, DUP 13%) and isokinetic-concentric (TP 8%, DUP 10%) MVC and knee extensor 1RM (TP 18%, DUP 24%) occurred post training. VL and RF-muscle thickness showed significant ($P<0.05$) increases ranging from 12 to 20% for TP and from 13 to 19% for DUP. Furthermore, significant ($P<0.05$) increases in VL-pennation angle and VL-fascicle length occurred in both legs while QF EMG remained unchanged. No significant temporal differences were found between both models, displaying similar small to large effect sizes.

Conclusion Periodization is no adaptation trigger during short-term resistance training with equated exercise variables.

Keywords Muscle architecture · Resistance exercise · Stimuli periodization · Short-term adaptations · Single-leg training · Ultrasonography

Abbreviations

1RM	One repetition maximum
DUP	Daily undulating periodization
EMG	Electromyography
MVC	Maximal voluntary contraction
RF	Rectus femoris
TP	Traditional periodization
VL	Vastus lateralis
VM	Vastus medialis

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Introduction

Periodization of resistance exercise programs refers to systematically manipulating training variables such as volume and load and has regularly been applied in various populations and training periods (Prestes et al. 2009; Simão et al. 2012; Bartolomei et al. 2014; Ullrich et al. 2015). Currently, traditional (TP) and daily undulating (DUP) periodization models are frequently discussed in the literature (Lima et al. 2012; Simão et al. 2012; Bartolomei et al. 2014; Ullrich et al. 2016). Characteristically for TP, training load increases gradually with concomitant reductions in training volume while undulating periodization models apply daily or weekly modifications of both volume and load (Poliquin 1988; Rhea et al. 2003; Kok et al. 2009). Major assumptions of undulating periodization are that more frequent changes of volume and load might induce larger neural and structural adaptations and furthermore may counteract fatigue during prolonged training periods (Poliquin 1988; Hoffman et al. 2009).

However, the current empirical basis to prove these mechanisms is poor (Mattocks et al. 2016) and the most effective resistance training periodization model for different populations is yet to be determined (Harries et al. 2015; Ullrich et al. 2015, 2016). Furthermore, a recent literature review has questioned that periodized short-term resistance training augments muscle growth over that achieved with progressive-load non-periodized regimens (Mattocks et al. 2016). In line with previous research (Kok et al. 2009; Ullrich et al. 2015), we noted several methodological limitations for studies examining periodization effects. These are related to the equation of training volume and load, control of the exercise variables, and use of untrained subjects (Monteiro et al. 2009; Apel et al. 2011; Simão et al. 2012; Harries et al. 2015; Ullrich et al. 2016). In addition, much work reported performance outcomes, but did not study neural or structural adaptations (Harries et al. 2015). Toigo and Boutellier (2006) recommended controlling for key exercise variables that trigger neuromuscular adaptations during resistance training such as time under tension, range of motion, duration of the positive and negative phases, and contraction velocity. Unfortunately, these variables have been rarely controlled when comparing periodization models (Ullrich et al. 2015). In contrast, most resistance training periodization studies have aimed to match athletic training conditions (Rhea et al. 2002; Fleck 2011; Harries et al. 2015; Ullrich et al. 2016). However, multiple machine exercises and free-weights regimen that are frequently used to optimize athletes's muscular power (Haff and Nimphius 2012) make it difficult to equate for key exercise variables (Toigo and Boutellier 2006). To overcome this methodological limitation, Ullrich et al. (2015) compared TP and DUP using a single-leg knee extensor training model with isometric exercise stimuli. This study found no periodization effects on neuromuscular outcomes when isometric exercise stimuli were applied on recreational active women (Ullrich et al. 2015). Obviously, transferring these findings to both athletic training and rehabilitation procedures needs further evaluation regarding dynamic training exercises and the training status of the subjects (Ullrich et al. 2015).

Evidence exists that alterations in neural drive (Narici et al. 1989; Seynnes et al. 2007) and muscle architecture can occur after short-term resistance training periods of 3–6 weeks (Blazevich et al. 2003; Tesch et al. 2004; Seynnes et al. 2007; Ullrich et al. 2016). A better understanding of periodization effects during short-term resistance training is important for many sports requiring short duration off-season and preseason programs (Mann et al. 2010; Fukuda et al. 2013) and rehabilitation procedures (Harries et al. 2015; Hoover et al. 2016; Ullrich et al. 2015). Therefore, this study aimed to extend recent findings (Ullrich et al. 2015) by investigating the effects of TP and DUP short-term dynamic resistance training that was equated for key exercise variables.

Periodization effects were examined on the temporal alterations of (1) knee extensor maximal voluntary force production, (2) vastus lateralis and rectus femoris muscle architecture, and (3) EMG estimated neural drive of the M. quadriceps femoris. We examined females with moderate resistance training experience as few studies have analyzed periodization effects in females (Kok et al. 2009; Ullrich et al. 2015) and findings from athletic populations are likely affected by confounding exercise stimuli (Ullrich et al. 2015). Based on previous results (Ullrich et al. 2015), we hypothesized that there would be no difference between TP and DUP in enhancing the present outcomes.

Methods

Experimental design

In order to evaluate the effects of two periodization models on the temporal changes of multiple neuromuscular outcomes during short-term resistance exercise in females, an experimental design similar to a recent isometric training study was adopted (Ullrich et al. 2015). The duration of the experimental period was 7 weeks (Fig. 1). Identical testing protocols were applied prior and after the training period. This work started with a 1-week familiarization phase (2 sessions) in which all subjects exercised both legs with the same loading regimen (3 sets × 15 repetitions at 40% of individual 1RM), following which all subjects completed a 6-week unilateral training period (3 sessions per week) for the knee extensors by randomly assigning an either TP or DUP model to each leg. For both periodization models, training loads corresponding with 40, 60, and 80% of individual 1RM were chosen, and the number of repetitions within each loading zone and total training volume were equated for each leg after 6 weeks of training (Fig. 1). For TP, training loads were increased within 2-week intervals

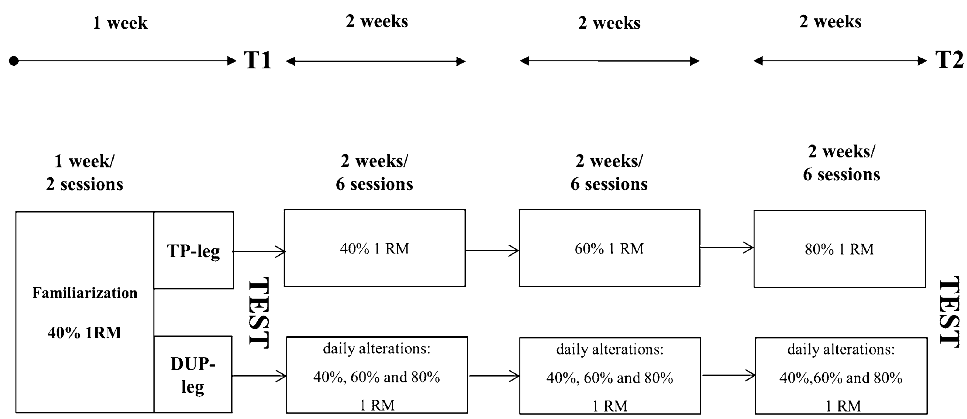

Fig. 1 Study design for a 7-week dynamic knee extensor resistance training period exercising one leg with traditional periodization (TP-leg) and the contralateral leg with daily undulating periodization (DUP-leg). Familiarization: all subjects exercised both legs with 3 sets × 15 contractions at 40% of individual 1RM for each leg; 40% training session: 3 sets × 15 contractions at 40% of 1RM for each leg; 60% training session: 3 sets × 10 contractions at 60% of 1RM for each leg; 80% training session: 3 sets × 6 contractions at 80% of 1RM for each leg; *Note* subjects exercised either the right or left lower extremity using TP or DUP assigned by randomization

Table 1 Anthropometric data of the subjects during the study

Anthropometrics of the subjects ($n = 19$)	Pre training	Post training
Age (years)	22.0 ± 1.8	–
Height (cm)	166.9 ± 7.8	–
Body mass (kg)	58.5 ± 7.1	60.2 ± 8.4
BMI (kg/m^2)	20.9 ± 2.0	20.7 ± 1.7
Thigh length_TP (cm)	42.0 ± 2.4	–
Thigh length_DUP (cm)	42.1 ± 2.5	–
Thigh circumference_TP (cm)	48.7 ± 3.5	49.8 ± 3.7*
Thigh circumference_DUP (cm)	48.6 ± 3.0	49.5 ± 3.7*

Data are presented as mean ± SD

TP training leg with traditional periodization, *DUP* training leg with daily undulating periodization

*Significant differences ($P < 0.05$) to pre-training

starting at 40% of 1 RM and followed by 2 weeks at 60% and 2 weeks at 80% of 1RM. In contrast, DUP loads were altered in a daily rythm within one training week. In detail, DUP loads started at 40% of 1RM and were gradually increased up to 80% towards the last session of each week (Fig. 1). Overall and disregarding the familiarization period, the experimental design resulted in 18 training sessions for TP and DUP (Fig. 1).

Subjects

The study was conducted on 19 female university students (22.0 ± 1.8 years, 58.5 ± 7.1 kg, 166.9 ± 7.8 cm) that had experience with total body resistance exercises of 27.9 ± 4.4 months. The corresponding anthropometric data are given in Table 1. Typically, subjects were used to moderate-load machine and free-weight exercises for 2–3 weekly training sessions to optimize their general fitness level. Notably, no participants of competitive sports were recruited to avoid confounding exercise stimuli to the greatest extent possible. In addition, all subjects gave their written consent to avoid any resistance training for the lower extremity during the study period except the supervised experimental training sessions. Participants were asked to perform their habitual upper body and trunk muscle exercises and to maintain their normal diet during the study period. None of the subjects conducted systematic endurance training such as running and cycling or reported known medical conditions and dietary supplements that could confound the current outcomes. Each subject was informed of the experimental risks and signed an informed written consent for participation prior to the first familiarization training session. The work was approved by the Institutional Research Ethics Committee and was in accordance with the Declaration of Helsinki for the use of human subjects in research.

Ultrasonographic measurements

To analyze M. vastus lateralis (VL) and M. rectus femoris (RF) muscle thickness, fascicle angle and fascicle length, a brightness-mode ultrasound device (Vivid e, GE Medical System, Jiangsu, China; Scanning frequency: 7.5 MHz) was used. All scanning procedures were conducted with the subjects lying in a relaxed supine position with fully extended hip and knee joints and prior to any warm-up (Alegre et al. 2006; Ullrich et al. 2015). To account for possible selective architectural changes along the length of a muscle (Blazevich et al. 2003; Noorkõiv et al. 2014) all VL images were collected at 33% (proximal), 50% (mid), and 66% (distal) of the thigh length defined as the distance from the greater trochanter to the articular cleft of the knee joint

(Noorkõiv et al. 2014). RF scanning was performed at 56% (e.g., midregion) between the anterior superior iliac spine and the proximal superior border of the patella (Noorkõiv et al. 2014). After visualizing the width of the muscle by rotating the transducer head, the scanning procedures were conducted at one-half of the mediolateral width at the aforementioned measurements sites (Ullrich et al. 2015). Once the image was optimized, five consecutive images were collected. For further analysis, all images were stored on a data storage device. All measurements were conducted by the same operator and the individual anatomical measurement sides were marked during the pre-training testing occasion with a water-resistant pencil to ensure identical positioning between the testing occasions as far as possible. All subjects received these pencils and re-marked the measurement sides throughout the course of the study. The interday reliability was estimated in a pilot study that was conducted with recreational active young females ($n = 10$). According to measurement position, this pilot work yielded the following coefficient of variation (CV) values: VL-muscle thickness (0.9–4.3%), VL-fascicle angle (3.7–4.4%) and VL-fascicle length (4.4–6.1%). The respective interday average percentage changes were 1.3–6.2% for VL-muscle thickness, 5.2–6.3% for VL-fascicle angle, and 6.2–9.4% for VL-fascicle length. Corresponding significant ($P < 0.05$) intraclass correlation coefficient (ICC) values of 0.83–0.99, 0.89–0.94, and 0.72–0.87 were detected. For RF, CV values of 2.9% for muscle thickness, 4.9% for fascicle angle, and 6.4% for fascicle length and significant ($P < 0.05$) ICC values of 0.94, 0.74, and 0.77 were calculated. The interday average percentage changes were 4.2% for RF muscle thickness, 6.9% for RF fascicle angle, and 9.0% for RF fascicle length, respectively.

Maximal voluntary contraction (MVC) measurements

Maximal voluntary unilateral knee extensor moments were measured before and after training using standardized procedures (Ullrich et al. 2015). All subjects underwent a standardized warm-up consisting of 10 min of submaximal treadmill running and 3 min of submaximal isometric and dynamic unilateral knee extensor contractions on the dynamometer (Biodex Medical Systems. Inc., Shirley, NY, USA). Subsequently, two maximal voluntary isometric and two sets of three consecutive isokinetic-concentric unilateral knee extensor contractions (MVC) were performed with both legs, randomly starting with either the left or right lower extremity. The subjects were fixed to the dynamometer in a seated upright position and the axis of the knee joint was aligned to the axis of the dynamometers lever arm. The subjects were instructed to keep their upper extremities in the crossed position. All isometric MVCs were performed at a knee joint and hip joint positions of 70° as the maximum isometric knee extensor strength occurred in these positions (Herzog et al. 1991). The subjects were instructed to build up their MVC within 3 s and to provide a peak force plateau of at least 2 s. All subjects received verbal encouragement and a visual feedback was provided by the Biodex software. A 3-min rest period was given between each trial. Isokinetic-concentric MVC´s were performed at an angular velocity of 60°/s between 100° and 20° knee joint angle range of motion (ROM). Therefore, each of the three consecutive contractions should be performed with maximal effort throughout the given ROM. After each contraction, the leg was passively returned into the starting position. A 3-min rest period was given between each set. All measurements were automatically gravity corrected by the Biodex software. Trials were repeated if not judged to be maximal by the subjects. Previously conducted interday reliability tests for these MVC procedures showed CV values of 4.0% for isometric knee extensor MVC and 4.9% for isokinetic-concentric MVC. In addition, significant ($P < 0.05$) ICC values of 0.98 and 0.94 have been reported previously (Ullrich et al. 2015). The interday average percentage changes for isometric and isokinetic-concentric knee extensor MVC were 5.6 and 6.9%, respectively.

1RM testing

Approximately 15 min after the MVC testing, standardized unilateral one repetition maximum (1RM) testing for maximal voluntary dynamic knee extensor strength was performed (Kok et al. 2009). Subjects were seated upright on a traditional knee extension training machine (Sygnum Line, Gym 80 international MbH, Gelsenkirchen, Germany) equipped with a training software as described in previous work (Ullrich et al. 2015). A ROM from 100° to 20° of the knee joint angle was defined for all 1RM trials and subjects received online feedback of knee joint ROM during contractions by the software. The upper body was fixed with straps to the chair of the training machine and the upper extremities were maintained in the crossed position. Subjects started the procedure with either the right or left leg according to random assignment. First, subjects performed a warm-up set of ten repetitions with a load approximating 30% of their estimated 1RM. This was followed by sets of ten repetitions of 50% of their estimated 1RM and five repetitions of 75% of their estimated 1RM. A load approximating 3RM was then applied, and subjects were asked to lift it no more than three times. Taking into consideration the number of lifts during this performance, the 1RM load was estimated. Thereafter, trials for 1RM assessment were conducted. Successful trials were followed by a 4-min rest period, with heavier loads being attempted until the 1RM was determined. This process generally took no more than five trials and verbal encouragement was provided for all attempts. To estimate the interday reliability for the 1RM tests, CV values and corresponding ICCs were calculated separately for both legs using the data from the familiarization period and the respective outcomes during the pre-training testing occasion. This procedure yielded CV values of 4.7% (TP-leg) and 4.9% (DUP-leg) with corresponding significant ($P<0.05$) ICCs of 0.96 and 0.93, respectively. In addition, the average interday percentage changes for knee extensor 1RM were 6.7% for TP and 7.0% for DUP.

Electromyographic (EMG) measurements

Maximal voluntary M. vastus lateralis (VL), M. vastus medialis (VM), and M. rectus femoris (RF) surface EMG activity was recorded at 1000 Hz with a telemetric EMG-system with pre-amplification during all isometric knee extensor MVCs (Telemyo G2, Noraxon Inc., Scottsdale, Arizona, USA; CMRR > 100dB, band-pass 10–500Hz, 16-bit-resolution). The dynamometer and the EMG system were synchronized by a synchronization device (TeleMyo, 2400 T receiver, Noraxon Inc., Scottsdale, Arizona, USA). EMG signals were recorded by adhesive surface electrodes (blue sensor-Medicotest, Ballerup, Denmark). Recording electrodes were placed at the midpoint of the respective muscle belly with an inter-electrode distance of 20 mm. Before electrode placement, skin impedance was reduced by shaving, abrasion, and cleaning with alcohol. To account for adequate signal quality, submaximal contractions were performed and visually controlled prior to all measurements. As was described for muscle architectural analysis, the individual anatomical electrode positions that were used during the pre-training testing occasion were marked with a water-resistant pencil. Thereafter, all subjects received these pencils to re-mark the respective positions.

Experimental protocol

The current protocol was adopted from previous work (Ullrich et al. 2015). At the beginning of both testing occasions, anthropometric data such as body mass (kg) and height (cm) were measured. Thigh circumference (cm) was determined for both legs at 50% of the thigh length (Kok et al. 2009). Thereafter, all ultrasonographic analysis was conducted in both legs. Ultrasonographic analysis was started either in the right or left lower extremity according to random assignment. In a further step, MVC testing was conducted and the subjects performed all MVCs randomly starting with their left or right leg. Approximately 15 min after the MVC measurements, unilateral knee extensor 1RM testing was performed. Pre-to-post training testing occasions were performed for all subjects at similar time of day either in the morning (between 9 and 12 A.M.) or in the afternoon (between 3 and 6 P.M.).

Experimental resistance training

The total duration of the study was 7 weeks, including a 1-week familiarization period (Fig. 1). During the familiarization, all subjects exercised both legs with the same loading scheme (3 sets × 15 contractions at 40% of individual 1RM) in two weekly sessions. Thereafter, the subject's right and left lower extremity was randomly assigned to either a TP or DUP periodization scheme. Notably, average 1RM data at the start of the familiarization displayed no significant side-to-side differences and individual leg dominance did not exceed 5% in all subjects. Therefore, the same number of right and left legs ($n=19$) was either assigned to TP or DUP. Besides the familiarization, the subjects performed 6 weeks of unilateral dynamic resistance training with 3 weekly sessions, resulting in 18 training sessions for each leg. Sessions were randomly started with either the TP-leg or the DUP-leg to avoid systematic fatigue. All sets were completed with one leg before changing to the contralateral side. Between each set, a recovery time of 2.5 min was provided. As none of the subjects missed any session, this work reached 100% compliance. To equate for key exercise variables (Toigo and Boutellier 2006), dynamic knee extensor training was performed on a traditional knee extension training machine (Sygnum Line, Gym 80 International MbH, Gelsenkirchen, Germany) equipped with a training software (Digimax-Biofeedback, Version 3.2, Mechatronic MbH, Hamm, Germany). Briefly, the software uses data from a displacement sensor (cm) to control for knee joint ROM, time under tension, and the duration of the positive and negative phases. Subjects were seated upright, and the upper extremities were maintained in crossed positions. A knee joint ROM from 100° (starting position) to 10° (final position) was used during all sessions. Manual goniometry was conducted at the start of each session to adjust the displacement sensor to these knee joint positions for all subjects. Within one contraction cycle, subjects had to accelerate the load within 0.1 s throughout the ROM (explosive positive phase), to lower the load within 0.5 s (negative phase) and to relax for 1 s before starting the next cycle. Notably, the displacement data were used to define a 5%-ROM error range around the optimal individual time–distance curves. Training ROM accuracy was defined as 100% when subjects remained within this error range during all contraction cycles. This scheme was performed in the TP-leg and the DUP-leg using online feedback from the software. As all sessions were performed on this equipped knee extensor training device, a supervision ratio of 1:1 was provided for all subjects. Throughout the course of training, loads corresponding to 40, 60, and

80% of individual 1RM were used in both legs. With the subjects having finished the familiarization, the TP-leg was exercised for 2 weeks with 3 sets of 15 contractions at 40% of the individual 1RM. Thereafter, 2 weeks of training with thee sets of ten contractions at 60% of 1RM were conducted in the TP-leg. During the final 2 weeks of training, the TP-leg was exercised at 80% of 1RM with three sets of six contractions. In contrast, the DUP-leg was exercised in a daily undulating periodization scheme starting at 40% of 1RM and gradually increasing up to 80% towards the last session of each week (Fig. 1). Throughout the course of training, the regimens with either 40, 60, or 80% of 1RM were conducted six times in either the TP-leg or the DUP-leg resulting in equal overall training volume and loading zones (Fig. 1). At the beginning of the first training session in every week, standardized 1RM testing (Blazevich et al. 2003) was performed in both legs to account for progressive strength increases. Having finished the 1RM testing, subjects were given a recovery time of 15 min before starting their first weekly training. Notably, 1RM results were always used to determine the training loads for all sessions of the particular week.

Data analysis

Moment and EMG-signals from all isometric and isokinetic trials were organized in a measurement software (MyoResearch XP Master Edition, Noraxon Inc., Scottsdale, Arizona, USA). Isometric MVC was calculated as the average of 500 ms at peak moment plateau while the isokinetic MVC was determined as the averaged 3 maximums of one contraction sequence. The corresponding EMG-signals of the RF, VM, and VL were initially smoothed and rectified before being integrated for a time window of 500 ms at isometric peak MVC. Finally, the integrated QF-EMG activity (IEMG) was calculated as follows (RF + VM + VL)/3 (Ullrich et al. 2015): all muscle architectural analysis was conducted with the software of the ultrasound device (Vivid e, GE Medical System, Jiangsu, China). The vertical distance from the superficial to the deeper aponeurosis was taken to calculate muscle thickness. Within one image, thickness values were determined at the most proximal end, approximately one-half the longitudinal distance (mid), and the most distal end to calculate an average muscle thickness (Ullrich et al. 2015). The pennation angle was defined as the angle between the fascicle and the deep aponeurosis. Muscle thickness and pennation angle were determined five times within one image. After deleting the maximal and minimal values, the residual 3 values were averaged. Fascicle lengths were estimated by the formula presented by Alegre et al. (2006), assuming a straight course of the fascicle: fascicle length = average muscle thickness/sin (pennation angle). Muscle thickness values were additionally normalized to thigh length.

Statistics

The statistical analysis was conducted with SPSS (version 23.0; SPSS Inc., Chicago, IL, USA). The level of statistical significance was set to $\alpha = 0.05$. Kolmogorov–Smirnov testing indicated normal distribution for all outcomes. A *t* test for dependent samples was applied to compare all major outcomes after the pre-training testing occasion between TP and DUP assuming both legs as dependent groups. Regarding the unilateral training, the subject's right and left lower extremities were defined as dependent groups for this pre-training statistical analysis. A 2-factor ANOVA (2 within group factors: time × training legs) was undertaken to detect temporal changes for all major outcomes for TP and DUP and between the compared periodization models. The weekly changes of knee extensor 1RM were analyzed using one-way repeated measures with Bonferroni adjustments. Finally, we calculated effect sizes for all major outcomes in both legs using the following formula: [(mean $_{\text{post-test}}$ − mean $_{\text{pre test}}$)/SD $_{\text{pre test}}$] according to Rhea et al. (2003). Effect sizes were then adjusted to sample size bias in smaller ($n < 20$) sample sizes (Hedges and Olkin 1985). Results are presented as mean ± standard deviation (SD) in the tables, and as mean ± standard error (SE) in the figures, respectively. A post hoc power analysis ($\alpha = 0.05$, 2-tailed) showed that statistical power for the temporal changes that occurred in the TP-leg was about 93% for the isometric MVC, about 72% for the isokinetic MVC, about 99% for 1RM, and about 13% for the percentage change in QF-EMG. According to muscle and measurement position, statistical power for the temporal changes in the TP-leg ranged from 99 to 100% for muscle thickness and from 38 to 87% for fascicle length. Statistical power for the changes occurring in the DUP-leg was about 94% for the isometric MVC, about 91% for the isokinetic MVC, about 100% for 1RM, and about 42% for the percentage change in QF-EMG. According to measurement position, statistical power for the temporal alterations in the DUP-leg ranged from 93 to 99% for muscle thickness and from 21 to 69% for fascicle length. A priori sample size calculations assuming moderate (0.3) periodization effects on the major outcomes yielded sample sizes of $n = 38$ to prove these effects with a statistical power of 60%. In contrast, large (0.5) effect size estimations for periodization effects yielded respective sample size values of $n = 13$. In consequence, we used a smaller sample size ($n = 19$) than would have been needed to detect small to moderate periodization effects.

Results

Before the start of the training period, no significant differences were detected for all anthropometric values, isometric and isokinetic knee extension MVC, 1RM, QF-IEMG, and RF and VL-muscle architectural parameters between both periodization models (Tables 1, 2; Figs. 2, 3, 4). Body mass remained unchanged pre- to post training (Table 1). Following training, small but statistically significant ($P<0.05$) increases were detected for thigh circumference in both legs (Table 1). No significant time × leg effect occurred for changes in thigh circumference (Table 1). Total training volume load showed no significant differences between the periodization models yielding about 12,401 ± 2680 kg for TP and about 12,803 ± 2476 kg using DUP, respectively. In addition, training ROM accuracy revealed no significant differences between TP (94.7 ± 2.4%) and DUP (95.3 ± 2.3%).

Strength changes of the knee extensors

Absolute (Nm) and body mass-normalized (Nm/kg) isometric and isokinetic-concentric net knee extension moments and 1RM values (kg) were significantly ($P<0.05$) higher post-training in both legs (Figs. 2, 3). In the TP-leg, average percentage increases in isometric and isokinetic-concentric net knee extension moments were about 15 and 8%, respectively. These average percentage MVC increases were about 13 and 10% using DUP (Fig. 5). In addition, the average percentage increase in knee extensor 1RM was about 18% in the TP-leg and about 24% in the DUP-leg, respectively (Fig. 5). According to the respective parameter of maximal voluntary knee extensor strength, similarly large effect sizes (Hedges g) ranging from 0.52 to 1.06 were detected for both periodization models (Table 3). No significant time × leg effect occurred for any changes in knee extensor strength (Figs. 2, 3).

Changes of VL and RF-muscle architecture

For both legs, absolute (cm) and normalized VL and RF-muscle thickness values were significantly ($P<0.05$) increased at all measurement positions post-training (Table 2). VL-pennation angle showed significant ($P<0.05$) increases after 6 weeks of training at all thigh regions in both legs (Table 2). In contrast, RF-pennation angle remained unchanged during the study. Absolute (cm) and normalized fascicle length values were significantly ($P<0.05$) higher post training in both legs at the mid VL measurement site (Table 2). In the TP-leg, average

Table 2 Muscle architecture of the M. vastus lateralis (VL) and M. rectus femoris (RF) for the TP-leg and DUP-leg during the study

VL and RF: muscle architecture ($n=19$)	TP-leg: pre training	TP-leg: post training	DUP-leg: pre training	DUP-leg: post training
Proximal VL muscle thickness (cm)	1.75 ± 0.24	2.08 ± 0.32*	1.85 ± 0.27	2.11 ± 0.38*
Proximal VL pennation angle (°)	14.5 ± 2.33	16.6 ± 3.05*	15.9 ± 1.92	17.8 ± 3.22*
Proximal VL fascicle length (cm)	7.07 ± 1.01	7.33 ± 0.67	6.78 ± 0.69	6.96 ± 0.93
Proximal VL fascicle length/thigh length	0.170 ± 0.022	0.177 ± 0.019	0.163 ± 0.016	0.167 ± 0.023
Proximal VL muscle thickness/thigh length	0.041 ± 0.006	0.050 ± 0.008*	0.044 ± 0.006	0.050 ± 0.008*
Mid VL muscle thickness (cm)	1.88 ± 0.26	2.22 ± 0.27*	1.90 ± 0.27	2.22 ± 0.32*
Mid VL pennation angle (°)	16.2 ± 2.01	17.8 ± 3.15*	16.3 ± 1.84	18.0 ± 2.71*
Mid VL fascicle length (cm)	6.80 ± 0.81	7.34 ± 0.71*	6.76 ± 0.73	7.21 ± 0.72*
Mid VL fascicle length/thigh length	0.163 ± 0.020	0.176 ± 0.016*	0.162 ± 0.020	0.173 ± 0.016*
Mid VL muscle thickness/thigh length	0.044 ± 0.007	0.053 ± 0.007*	0.045 ± 0.007	0.053 ± 0.008*
Distal VL muscle thickness (cm)	1.54 ± 0.19	1.87 ± 0.27*	1.60 ± 0.20	1.90 ± 0.28*
Distal VL pennation angle (°)	14.7 ± 2.19	17.3 ± 2.58*	15.6 ± 1.52	17.4 ± 2.18 *
Distal VL fascicle length (cm)	6.13 ± 0.60	6.34 ± 0.61	5.98 ± 0.66	6.39 ± 0.83
Distal VL fascicle length/thigh length	0.148 ± 0.020	0.153 ± 0.016	0.144 ± 0.020	0.154 ± 0.022
Distal VL muscle thickness/thigh length	0.037 ± 0.005	0.046 ± 0.007*	0.039 ± 0.005	0.046 ± 0.007*
RF muscle thickness (cm)	1.29 ± 0.19	1.49 ± 0.21*	1.35 ± 0.23	1.50 ± 0.16*
RF pennation angle (°)	11.2 ± 1.80	12.1 ± 1.64	11.6 ± 2.07	12.0 ± 1.07
RF fascicle length (cm)	6.76 ± 1.33	7.18 ± 0.95	6.86 ± 1.35	7.25 ± 0.75
RF fascicle length/thigh length	0.162 ± 0.030	0.173 ± 0.024	0.165 ± 0.030	0.175 ± 0.022
RF muscle thickness/thigh length	0.031 ± 0.005	0.035 ± 0.006*	0.031 ± 0.007	0.035 ± 0.005*

Data are presented as mean ± SD

TP training leg with traditional periodization, *DUP* training leg with daily undulating periodization

*Significant differences ($P<0.05$) to pre-training

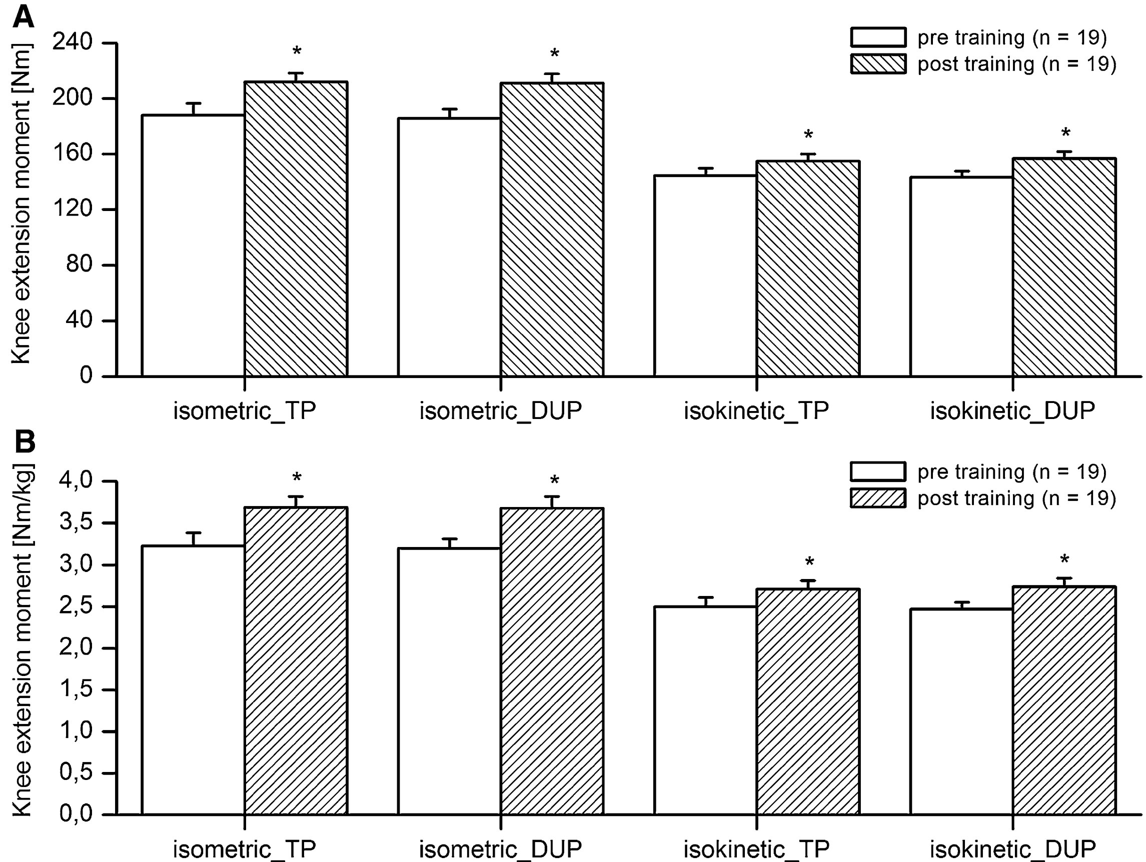

Fig. 2 Absolute (Nm) and body mass normalized (Nm/kg) knee extensor MVC for the TP-leg and DUP-leg during the study. *Significant differences ($P<0.05$) to pre-training; *TP* training leg with traditional periodization, *DUP* training leg with daily undulating periodization. Data are presented as mean ± SE

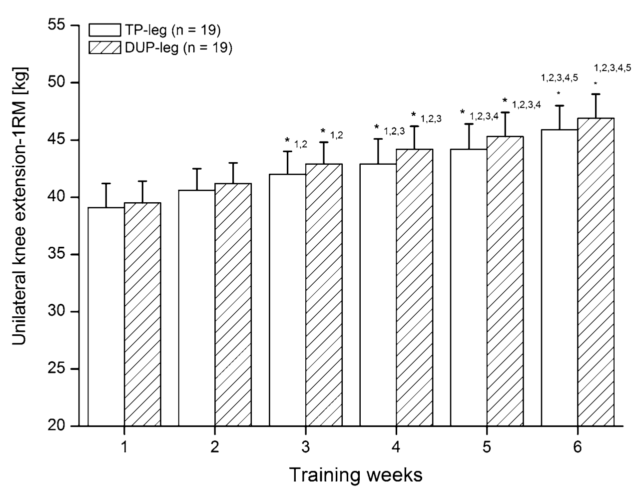

Fig. 3 One repetition maximum (1RM) for the TP-leg and DUP-leg during the study. *1,2,3,4,5 Significant differences ($P<0.05$) to training weeks 1, 2, 3, 4, and 5, respectively. *TP* training leg with traditional periodization, *DUP* training leg with daily undulating periodization. Data are presented as mean ± SE

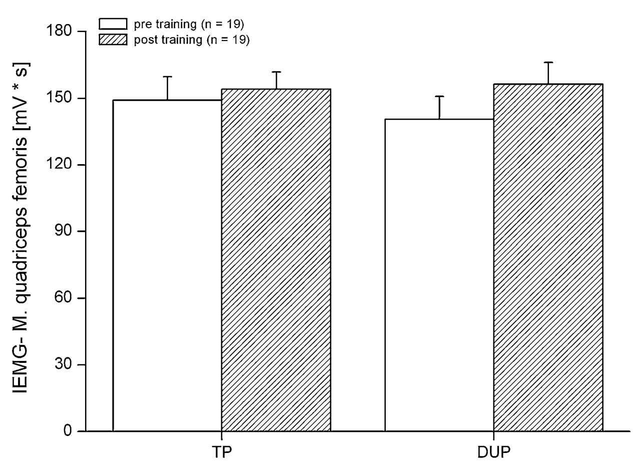

Fig. 4 M. quadriceps femoris integrated EMG changes during the study. *TP* training leg with traditional periodization, *DUP* training leg with daily undulating periodization. Data are presented as mean ± SE

percentage increases in VL-muscle thickness values ranged from about 15 to 20% (Fig. 6) with concomitant average fascicle length changes ranging from about 4 to 9%. These

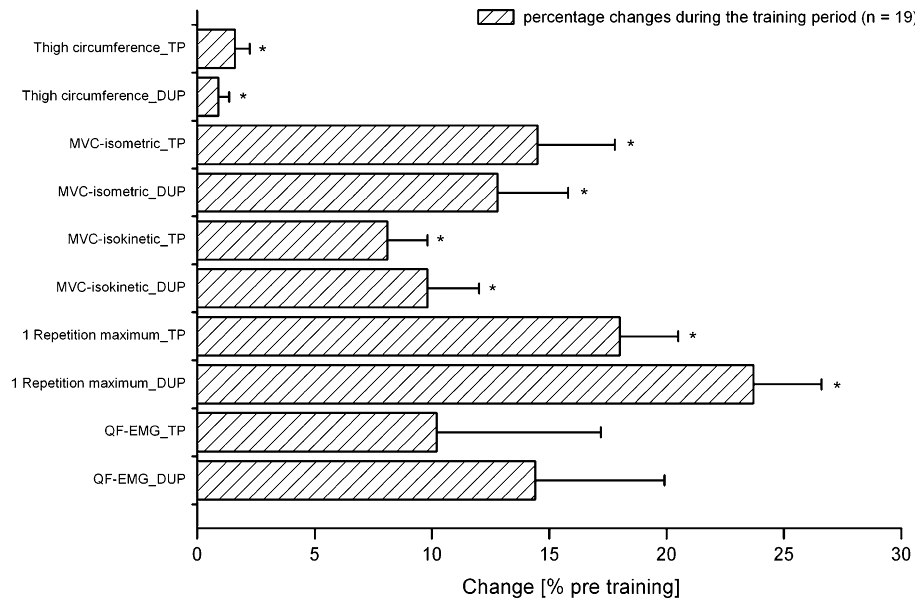

Fig. 5 Percentage differences (% pre training) of thigh circumference, isometric and isokinetic-concentric knee extensor MVC, 1RM, and maximum voluntary EMG activity of the M. quadriceps femoris (QF) for the TP-leg and DUP-leg during the study. *Significant differences ($P < 0.05$) to pre-training; *TP* training leg with traditional periodization, *DUP* training leg with daily undulating periodization. Data are presented as mean ± SE

Table 3 Effect sizes for the major study outcomes for both training legs

Study outcome	ES: TP-leg	ES: DUP-leg
Absolute isometric knee extension MVC	0.76	0.75
Absolute isokinetic knee extension MVC	0.52	0.71
1RM knee extension	0.94	1.06
QF-EMG	0.12	0.34
Thigh circumference	0.23	0.12
Proximal VL-muscle thickness	1.27	0.85
Mid VL-muscle thickness	1.11	1.01
Distal VL-muscle thickness	1.26	1.10
Proximal VL-fascicle length	0.36	0.20
Mid VL-fascicle length	0.65	0.50
Distal VL-fascicle length	0.41	0.34
Proximal VL-pennation angle	0.74	0.68
Mid VL-pennation angle	0.58	0.70
Distal VL-pennation angle	1.06	0.90
RF-muscle thickness	0.98	0.73
RF-fascicle length	0.32	0.25
RF-pennation angle	0.50	0.22

Effect sizes (Hedges g) were calculated for the major study outcomes for the TP-leg and DUP-leg, respectively

percentage changes ranged from 14 to 19% for VL-muscle thickness (Fig. 6) and from 3 to 7% for VL-fascicle length in the DUP-leg, respectively. The average percentage increase in RF-muscle thickness was about 12% for TP and about 13% using DUP (Fig. 6) with concomitant percentage changes in RF-fascicle length of about 5% and about 7%, respectively. According to position, TP yielded average percentage increases in VL-pennation angle ranging from 8 to 14% whereas these changes varied between 11 and 16% using DUP. For most architectural parameters, comparable moderate to large effect sizes (Hedges g) were detected for both lower extremities (Table 3). No significant time × leg effect occurred for any muscle architectural changes (Table 2; Fig. 6).

Changes of maximal voluntary EMG-activity of the QF

In both lower extremities, maximal voluntary EMG activity of the M. quadriceps femoris (QF) did not change significantly after 6 weeks of training (Fig. 4). Average maximal QF IEMG values were about 10% higher in the TP-leg and about 14% higher in the DUP-leg post-training (Fig. 5). Effect size calculations for the temporal IEMG changes yielded small and moderate values of 0.12 and 0.34 using TP or DUP, respectively (Table 3). No significant time × leg effect was detected for maximal voluntary QF IEMG (Fig. 5).

Discussion

This study investigated the effects of traditional (TP) and daily undulating (DUP) periodized dynamic knee extensor resistance training equated for key exercise variables on neuromuscular outcomes in moderately trained females. An important feature of this study is that total training volume load, number of repetitions within each loading zone, and range of motion and time under tension were equated between the periodization models. The main finding was that 6 weeks of knee extensor training (18 sessions) yielded profound strength and muscle architectural gains, without significant differences between TP and DUP. These results

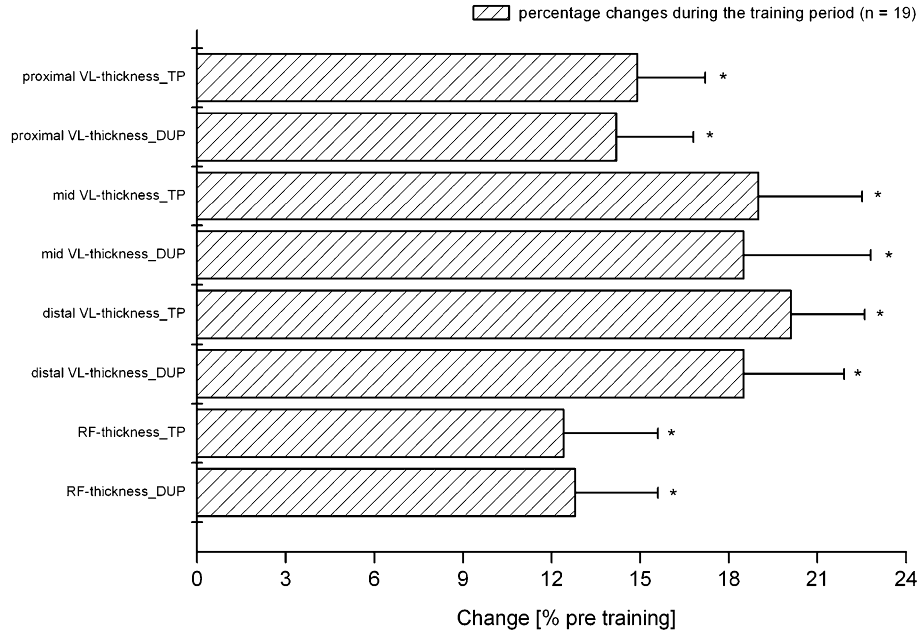

Fig. 6 Percentage changes (% pre training) of proximal, mid and distal VL and RF-muscle thickness for the TP-leg and DUP-leg during the study. *Significant differences ($P<0.05$) to pre-training; *TP* training leg with traditional periodization, *DUP* training leg with daily undulating periodization. Data are presented as mean ± SE

support previous suggestions that periodization may not be a major trigger of neuromuscular adaptations during short-term training periods with male and female subjects of different fitness levels (Kok et al. 2009; Harries et al. 2015; Ullrich et al. 2015, 2016).

The average gains in isometric and isokinetic knee extensor MVC varied from about 8 to 15% with concomitant average 1RM icreases between 18 and 24%. These changes are in line with previous literature following short-term resistance training with moderately trained subjects (Ullrich et al. 2009; Mann et al. 2010; Fukuda et al. 2013). For example, Fukuda et al. (2013) presented average increases ranging from 7.7 to 26.7% for power, force, and velocity during countermovement jumps following a 4-week preparatory period with youth judoka. After 8 weeks of resistance training with males that had about 2 years of training experience, Mangine et al. (2015) reported average 1RM gains of about 15%. Similar MVC increases were found after 5 weeks of muscular power training (13 overall sessions) in team sports athletes (Ullrich et al. 2009). Kok et al. (2009) compared TP and DUP on strength and muscle cross-sectional adaptations in untrained women following a 9-week resistance training regimen with 3 weekly sessions. The higher 1RM improvements of about 22–35% that were detected by these authors are most likely attributed to the longer training period and recreational training status of their subjects (Kok et al. 2009). Similar to our findings, no periodization effects on the temporal strength changes occurred in this study (Kok et al. 2009). A previous work with recreationally active women also failed to detect significant periodization effects, yielding knee extensor MVC gains of 9% using TP and 14% using DUP following 6 weeks (12 sessions) of isometric knee extensor training (Ullrich et al. 2015). Differences in the training status of the subjects, the loading zones, the training sessions per week, and the training volume make it difficult to compare strength changes among studies (Toigo and Boutellier 2006; Harries et al. 2015). However, in agreement with our findings, evidence suggests that TP and DUP provoke similar development of upper and lower body strength (Simão et al. 2012; Harries et al. 2015; Ullrich et al. 2016). Notably, much of the work was performed with subjects that had no resistance training experience (Kok et al. 2009; Ullrich et al. 2015) and who might show similar adaptations to any overload stimulus during the first several weeks of training (Kraemer et al. 1999). Furthermore, most periodization studies aimed to match athletic training, but did not control major exercise variables (Kraemer et al. 1999; Rhea et al. 2002; Toigo and Boutellier 2006; Hoffman et al. 2009; Ullrich et al. 2016). Therefore, our findings that were derived with a single-leg laboratory training model providing controlled dynamic exercise stimuli strengthens previous suggestions (Franchini et al. 2015; Harries et al. 2015; Ullrich et al. 2015) that periodization might not be a major adaptation trigger during short-term training programs.

Much work comparing periodization models has gone into assessing muscular strength and power, but only a few studies have examined structural or neural dimensions (Kok et al. 2009; Simão et al. 2012; Souza et al. 2014; Ullrich et al. 2015, 2016).

Considering muscle growth, more frequent changes of training volume and load were originally suggested to be advantageous for the maintenance of muscle volume throughout the course of training (Stone et al. 1981;

Poliquin 1988). However, the literature basis to prove this hypothesis with magnetic resonance or ultrasound data is weak (Mattocks et al. 2016; Ullrich et al. 2016). Currently, there is no literature model comparing the mechano-chemical signal transduction between TP and DUP periodized exercise stimuli (Toigo and Boutellier 2006; Mattocks et al. 2016). As previously reported after short-term training (Tesch et al. 2004; Blazevich et al. 2007; Seynnes et al. 2007; Souza et al. 2014; Ullrich et al. 2016), the present strength gains were accompanied by early muscle hypertrophy at different anatomical thigh regions in both training legs. With no significant differences between TP and DUP, the current gains in muscle thickness ranged between 14 and 20% and, therefore, were similar to those reported for untrained subjects after 24 sessions of isometric knee extensor training (Ullrich et al. 2015). In addition, Kok et al. (2009) reported changes in rectus femoris CSA of approximately 11% after 6 weeks of multi-exercise resistance training with recreational active females. These profound muscle thickness adaptations illustrate that the examined females were experienced to moderate-load resistance training, but were not accustomed to the specific loading scheme of this work (Peterson et al. 2005). In general line with our results, Blazevich et al. (2003) and Ullrich et al. (2016) reported that muscle architectural adaptations occurred rapidly during resistance training with explosive exercise characteristics while others have detected structural adaptations only after 8 to 12 weeks of resistance training (Higbie et al. 1996; Kraemer and Ratamess 2004; Ullrich et al. 2015). Our data indicate the importance to account for region-specific muscle architectural adaptations (Blazevich et al. 2003; Noorkõiv et al. 2014), as gains in VL- and RF muscle thickness occurred at all measurement positions, while VL-fascicle length increases only occurred at the mid thigh region. In line with Blazevich et al. (2003), the architectural changes in both legs appeared to be greater in the VL compared with the biarticular RF. This might be explained with fewer changes in RF muscle length during monoarticular knee extensor training resulting in reduced stimuli transmission to the RF (Blazevich et al. 2003; Jacobs and van Ingen 1992). The finding of enhanced muscle thickness and fascicle length after 18 exercise sessions suggests an early stimulation of both adaptational mechanisms, an addition of sarcomeres in parallel and in series (Blazevich et al. 2003, 2007; Seynnes et al. 2007). Increases in fascicle length affect the force–length relationship and force–velocity relationship (Alegre et al. 2006; Blazevich et al. 2003, 2007) and can reduce the risk of injury when sarcomeres are forced to operate on the descending limb of their force–length relation (Brockett et al. 2001). Importantly, similar moderate to large effect sizes were detected for most of these architectural changes in both TP and DUP. Thus, we suggest that exercise variables such as training range of motion and the duration of the positive and negative loading phases act as major adaptation triggers for radial and longitudinal muscle growth during short-term training, rather than periodization (Toigo and Boutellier 2006; Ullrich et al. 2015).

Strength gains during the first weeks of training were mostly attributed to neural alterations (Moritani and deVries 1979; Aagaard 2003; Kraemer and Ratamess 2004; Ullrich et al. 2015). EMG increases during resistance training were explained by adaptations of the motoneuron recruitment, firing frequency, and synchronization of motor unit firing (Aagaard 2003; Gruber and Gollhofer 2004). As was expected for subjects with moderate resistance training experience, the EMG alterations of 10% in the TP-leg and 14% in the DUP-leg were lower than those reported for recreationally active persons after short-term training (Seynnes et al. 2007; Ullrich et al. 2015). Seynnes et al. (2007) showed average EMG gains of about 20% in the vastus lateralis following 10 days of high-load resistance training with recreationally active subjects. Ullrich et al. (2015) found average EMG increases of the quadriceps femoris between 26 and 29% after 12 sessions of isometric knee extensor training in recreationally active women. Rhea et al. (2002) suggested that undulating periodization may exert higher stress on the neuromuscular system compared with traditional periodization thereby causing earlier neural adaptations. Furthermore, prolonged linear progression of training loads may cause neural fatigue that could counteract strength improvements (Poliquin 1988; Baker et al. 1994; Hoffman et al. 2009). However, there is a lack of evidence to prove these assumptions during training studies that were equated for key exercise variables (Ullrich et al. 2015). In agreement with our results, TP and DUP provoked similar gains in neural drive during 14 weeks of isometric knee extensor training that equated for training volume and load (Ullrich et al. 2015). Therefore, we suggest that TP and DUP may exert similar neuronal alterations during short-term resistance training.

In summary, our data indicate that TP and DUP were equally adept in improving maximal voluntary strength, muscle architecture, and neural drive during short-term resistance training with moderately trained females. Identifying the most effective periodization model was discussed as an important feature for sports requiring short duration off-season and preseason programs (Fukuda et al. 2013) and furthermore to optimize rehabilitation procedures (Harries et al. 2015; Ullrich et al. 2015; Hoover et al. 2016). However, the current study strengthens previous suggestions that stimuli periodization is no adaptation trigger during short-term resistance training (Harries et al. 2015; Ullrich et al. 2015, 2016; Mattocks et al. 2016). Based on these findings, practitioners are recommended to adjust key exercise variables rather than complex periodization approaches in short-term training and rehabilitation settings.

Some limitations are worth noting. Possibly, longer training periods might have provoked periodization influences that were suppressed by the current study design. However, providing equated exercise variables, our results support previous work that did not detect periodization effects during training periods ranging between 4 and 10 weeks (Kok et al. 2009; Souza et al. 2014; Mattocks et al. 2016; Ullrich et al. 2016). A further assumption is that the adaptations were not strongly influenced by confounding exercise stimuli (Ullrich et al. 2015). Therefore, we examined women with about 2 years of moderate resistance training experience for general fitness reasons, but excluded athletes that conducted confounding training sessions. Obviously, one would expect much smaller strength and muscle architectural gains in subjects with long-term high-loading resistance training experience (Hartmann et al. 2015). To provide controlled dynamic exercise stimuli, we combined a muscular power training program from previous work (Ullrich et al. 2009) with an experimental single-leg knee extensor training model (Ullrich et al. 2015). In consequence, the mechanical specificity of this laboratory training did not fully match real athletic explosive movements (Kawamori and Haff 2004; Ullrich et al. 2010, 2016). However, the current single-leg model enabled us to control the key exercise variables (Toigo and Boutellier 2006; Ullrich et al. 2015). In addition, this research design reduces selection bias in rather small sample sizes (Hedges and Olkin 1985) assuming an identical cellular response matrix (Toigo and Boutellier 2006) between the individual training legs. This within-subject design may furthermore equalize influences of the menstrual cycle during training studies with females that, therefore, has not been controlled in our work (Toigo and Boutellier 2006). Besides these methodological advantages, a major limitation of the single-leg model is the possible influence of cross-training effects (Zhou 2000; Adamson et al. 2008; Lee et al. 2009; Beyer et al. 2016). Importantly, cross-training effects were restricted to neural parameters and strength gains and no evidence exists that structural alterations were influenced by cross training (Zhou 2000). Regarding maximal voluntary muscle strength, average cross effects of about 8% were reported for different muscle groups when one leg was trained and the contralateral leg served as control (Lee and Carroll 2007). However, the examined females only showed low to moderate effect sizes for EMG alterations. It is, therefore, reasonable to argue that cross effects will not have influenced our findings to any great extent. Finally, high to moderate statistical power values were calculated for the temporal changes of the major outcomes. However, a priori calculations for sample size adjustments showed that more subjects would have been needed to document small to moderate periodization effects. As the percentage temporal changes and effect sizes were quite similar between TP and DUP, this might be assessed as a minor limitation of this work.

Conclusion

This study examined possible differences in TP and DUP periodized dynamic resistance training equated for key exercise variables on neuromuscular outcomes in moderately-trained females. The present results indicate that both periodization programs were equally adept in improving knee extensor strength, VL- and RF muscle architecture, and maximum voluntary QF-EMG activity following a 6-week resistance training period. Notably, rapid muscle architectural adapatations occurred using contractions with explosive force–velocity characteristics. Thus, further evidence is presented that key exercise variables act as major triggers for neuromuscular adaptations during short-term resistance training, rather than stimuli periodization. These findings might facilitate the planning of athletic conditioning programs and rehabilitation regimens.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

Aagaard P (2003) Training-induced changes in neural function. Exerc Sport Sci Rev 31:61–67

Adamson M, Macquaide N, Helgerud J, Hoff J, Kemi OJ (2008) Unilateral arm strength training improves contralateral peak force and rate of force development. Eur J Appl Physiol 103:553–559

Alegre LM, Jiménez F, Gonzalo-Orden JM, Martín-Acero R, Aguado X (2006) Effects of dynamic resistance training on fascicle length and isometric strength. J Sports Sci 24:501–508

Apel JM, Lacey RM, Kell RT (2011) A comparison of traditional and weekly undulating periodized strength training programs with total volume and intensity equated. J Strength Cond Res 25:694–703

Baker D, Wilson G, Carlyon R (1994) Periodization: The effect on strength of manipulating volume and intensity. J Strength Cond Res 8:235–242

Bartolomei S, Hoffman JR, Merni F, Stout JR (2014) A comparison of traditional and block periodized strength training programs in trained athletes. J Strength Cond Res 28:990–997
Beyer KS, Fukuda DH, Boone CH, Wells AJ, Townsend JR, Jajtner AR et al (2016) Short-term unilateral resistance training results in cross education of strength without changes in muscle size, activation, or endocrine response. J Strength Cond Res 30:1213–1223
Blazevich AJ, Gill ND, Bronks R, Newton RU (2003) Training-specific muscle architecture adaptation after 5-week training in athletes. Med Sci Sports Exerc 35:2013–2022
Blazevich AJ, Gill ND, Deans N, Zhou S (2007) Lack of human muscle architectural adaptation after short-term strength training. Muscle Nerve 35:78–86
Brockett CL, Morgan DL, Proske U (2001) Human hamstring muscles adapt to eccentric exercise by changing optimum length. Med Sci Sports Exerc 33:783–790
Fleck SJ (2011) Non-linear periodization for general fitness & athletes. J Hum Kinet 29:41–45
Franchini E, Branco BM, Agostinho MF, Calmet M, Candau R (2015) Influence of linear and undulating strength periodization on physical fitness, physiological, and performance responses to simulated judo matches. J Strength Cond Res 29:358–367
Fukuda DH, Stout JR, Kendall KL, Smith AE, Wray ME, Hetrick RP (2013) The effects of tournament preparation on anthropometric and sport-specific performance measures in youth judo athletes. J Strength Cond Res 27:331–339
Gruber M, Gollhofer A (2004) Impact of sensorimotor training on the rate of force development and neural activation. Eur J Appl Physiol 92:98–105
Haff G, Nimphius S. (2012) Training Principles for Power. Strength Cond J 34:2–12.
Harries SK, Lubans DR, Callister R (2015) Systematic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. J Strength Cond Res 29:1113–1259
Hartmann H, Wirth K, Keiner M, Mickel C, Sander A, Szilvas E (2015) Short-term periodization models: effects on strength and speed-strength performance. Sports Med 45:1373–1386
Hedges LV, Olkin I (1985) Statistical methods for meta-analysis. Orlando, Acad. Pr
Herzog W, Guimaraes AC, Anton MG, Carter-Erdman KA (1991) Moment-length relations of rectus femoris muscles of speed skaters/cyclists and runners. Med Sci Sports Exerc 23:1289–1296
Higbie EJ, Cureton KJ, Warren GL, Prior BM (1996) Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. J Appl Physiol 81:2173–2181
Hoffman JR, Ratamess NA, Klatt M, Faigenbaum AD, Ross RE, Tranchina NM et al (2009) Comparison between different off-season resistance training programs in Division III American college football players. J Strength Cond Res 23:11–19
Hoover DL, vanWye WR, Judge, LW (2016) Periodization and physical therapy: Bridging the gap between training and rehabilitation. Phys Ther Spor 18:1–20.
Jacobs R, van Ingen Schenau, G J (1992) Control of an external force in leg extensions in humans. J Physiol 457:611–626
Kawamori N, Haff GG (2004) The optimal training load for the development of muscular power. J Strength Cond Res 18:675–684
Kok L, Hamer PW, Bishop DJ (2009) Enhancing muscular qualities in untrained women: linear versus undulating periodization. Med Sci Sports Exerc 41:1797–1807
Kraemer WJ, Ratamess NA (2004) Fundamentals of resistance training: progression and exercise prescription. Med Sci Sports Exerc 36:674–688
Kraemer WJ, Fleck SJ, Maresh CM, Ratamess NA, Gordon SE, Goetz KL et al (1999) Acute hormonal responses to a single bout of heavy resistance exercise in trained power lifters and untrained men. Can J Appl Physiol 24:524–537
Lee M, Carroll TJ (2007) Cross education: possible mechanisms for the contralateral effects of unilateral resistance training. Sports Med 37:1–14
Lee M, Gandevia SC, Carroll TJ (2009) Unilateral strength training increases voluntary activation of the opposite untrained limb. Clin Neurophysiol 120:802–808
Lima C de, Boullosa DA, Frollini AB, Donatto FF, Leite RD, Gonelli PRG et al (2012) Linear and daily undulating resistance training periodizations have differential beneficial effects in young sedentary women. Int J Sports Med 33:723–727
Mangine GT, Hoffman JR, Gonzalez AM, Townsend JR, Wells AJ, Jajtner AR et al (2015) The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. Physiol Rep 3:e12472
Mann JB, Thyfault JP, Ivey PA, Sayers SP (2010) The effect of autoregulatory progressive resistance exercise vs. linear periodization on strength improvement in college athletes. J Strength Cond Res 24:1718–1723
Mattocks KT, Dankel SJ, Buckner SL, Jessee MB, Counts BR, Grant Mouser J et al (2016) Periodization: What is it good for? J Trainology 5:6–12.
Monteiro AG, Aoki MS, Evangelista AL, Alveno DA, Monteiro GA, Piçarro IDC et al (2009) Nonlinear periodization maximizes strength gains in split resistance training routines. J Strength Cond Res 23:1321–1326
Moritani T, deVries HA (1979) Neural factors versus hypertrophy in the time course of muscle strength gain. Am J Phys Med 58:115–130
Narici MV, Roi GS, Landoni L, Minetti AE, Cerretelli P (1989) Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. Eur J Appl Physiol Occup Physiol 59:310–319.
Noorkõiv M, Nosaka K, Blazevich AJ (2014) Neuromuscular adaptations associated with knee joint angle-specific force change. Med Sci Sports Exerc 46:1525–1537
Peterson MD, Rhea MR, Alvar BA (2005) Applications of the dose-response for muscular strength development: a review of meta-analytic efficacy and reliability for designing training prescription. J Strength Cond Res 19:950–958
Poliquin C (1988) Five steps to increasing the effectiveness of your strength training program. Natl Strength Cond Assoc J 10:34–39.
Prestes J, Frollini AB, Lima C de, Donatto FF, Foschini D, Cássia Marqueti R de et al (2009) Comparison between linear and daily undulating periodized resistance training to increase strength. J Strength Cond Res 23:2437–2442.
Rhea MR, Ball SD, Phillips WT, Burkett LN (2002) A comparison of linear and daily undulating periodized programs with equated volume and intensity for strength. J Strength Cond Res 16:250–255
Rhea MR, Phillips WT, Burkett LN, Stone WJ, Ball SD, Alvar BA et al (2003) A comparison of linear and daily undulating periodized programs with equated volume and intensity for local muscular endurance. J Strength Cond Res 17:82–87
Seynnes OR, Boer M de, Narici MV (2007) Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. J Appl Physiol 102:368–373
Simão R, Spineti J, Salles BF de, Matta T, Fernandes L, Fleck SJ et al (2012) Comparison between nonlinear and linear periodized resistance training: hypertrophic and strength effects. J Strength Cond Res 26:1389–1395
Souza EO, Ugrinowitsch C, Tricoli V, Roschel H, Lowery RP, Aihara AY et al (2014) Early adaptations to six weeks of non-periodized and periodized strength training regimens in recreational males. J Sports Sci Med 13:604–609

Stone MH, O'Briant H, Garhammer J (1981) A hypothetical model for strength training. J Sports Med 21:342–351

Tesch PA, Ekberg A, Lindquist DM, Trieschmann JT (2004) Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. Acta Physiol Scand 180:89–98

Toigo M, Boutellier U (2006) New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. Eur J Appl Physiol 97:43–663

Ullrich B, Kleinöder H, Brüggemann GP (2009) Moment-angle relations after specific exercise. Int J Sports Med 30:293–301

Ullrich B, Heinrich K, Goldmann JP, Brüggemann GP (2010) Altered squat jumping mechanics after specific exercise. Int J Sports Med 31:243–250

Ullrich B, Holzinger S, Soleimani M, Pelzer T, Stening J, Pfeiffer M (2015) Neuromuscular responses to 14 weeks of traditional and daily undulating resistance training. Int J Sports Med 36:554–562

Ullrich B, Pelzer T, Oliveira S, Pfeiffer M (2016) Neuromuscular responses to short-term resistance training with traditional and daily undulating periodization in adolescent elite judoka. J Strength Cond Res 30:2083–2099

Zhou S (2000) Chronic neural adaptations to unilateral exercise: mechanisms of cross education. Exerc Sport Sci Rev 28:177–184