

# The efficacy of periodised resistance training on neuromuscular adaptation in older adults

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## Abstract

**Purpose** This study compared the effect of periodised versus non-periodised (NP) resistance training on neuromuscular adaptations in older adults.

**Methods** Forty-one apparently healthy untrained older adults (female = 21, male = 20;  $70.9 \pm 5.1$  years;  $166.3 \pm 8.2$  cm;  $72.9 \pm 13.4$  kg) were recruited and randomly stratified to an NP, block periodised (BP), or daily undulating periodised (DUP) training group. Outcome measures were assessed at baseline and following a 22-week resistance training intervention (3 day week<sup>-1</sup>), including: muscle cross-sectional area (CSA), vertical jump performance, isometric and isokinetic peak torque, isometric rate of force development (RFD), and muscle activation. Thirty-three participants satisfied all study requirements and were included in analyses (female = 17, male = 16;  $71.3 \pm 5.4$  years;  $166.3 \pm 8.5$  cm;  $72.5 \pm 13.7$  kg).

**Results** Block periodisation, DUP, and NP resistance training induced statistically significant improvements in

muscle CSA, vertical jump peak velocity, peak power and jump height, and peak isometric and isokinetic torque of the knee extensors at 60 and 180° s<sup>-1</sup>, with no between-group differences. Muscle activity and absolute RFD measures were statistically unchanged following resistance training across the entire cohort.

**Conclusions** Periodised resistance training, specifically BP and DUP, and NP resistance training are equally effective for promoting increases in muscular hypertrophy, strength, and power among untrained older adults. Consequently, periodisation strategies are not essential for optimising neuromuscular adaptations during the initial stages of resistance training in the aging population.

**Keywords** Elderly · Sarcopenia · Health · Adaptation · Training model

## Abbreviations

1RM	One repetition maximum
ADL	Activities of daily living
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
BMI	Body mass index
BP	Block periodisation
CI	Confidence intervals
CMJ	Countermovement jump
CSA	Cross-sectional area
DUP	Daily undulating periodisation
EMG	Electromyography
ES	Effect size
ICC	Intraclass correlation coefficient
MVIC	Maximal voluntary isometric contraction
mRF	Rectus femoris
mVL	Vastus lateralis
NP	Non-periodised

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RFD	Rate of force development
RM	Repetition maximum
RMS	Root mean square
SD	Standard deviation
WUP	Weekly undulating periodisation

## Introduction

The association between aging and the progressive loss of muscle mass is referred to as ‘sarcopenia’ (Roubenoff 2000), thought to be predominantly mediated by a reduction in the size of muscle fibers, commonly measured by the anatomical cross-sectional area (CSA), and/or number of individual muscle fibers (Essen-Gustavsson and Borges 1986; Lexell et al. 1988). Due to the fundamental relationship between maximal force production and muscle CSA, the ability of the neuromuscular system to express muscle strength and power diminishes with aging (Skelton et al. 1994) with power development suggested to decline more rapidly and be more strongly related to functional capacity (Bean et al. 2002; Izquierdo et al. 1999; Skelton et al. 1994). However, many activities of daily living (ADL) require a rapid development of force in a limited amount of time (<200 ms; e.g., preventing a fall) (Aagaard et al. 2002). Consequently, the ability to develop a rapid rise in muscle force and resultant large impulse under such time restrictions, i.e., rate of force development (RFD) ( $\Delta\text{force}/\Delta\text{time}$ ), is proposed to be most critical in older adults (Suetta et al. 2004). In addition, neural mechanisms also contribute to this cascade of age-related neuromuscular decline, including a reduction in the maximal voluntary activation of the agonist muscles (Häkkinen et al. 1998a). Overall, such unfavorable alterations in neuromuscular capacity are responsible for the compromised functional capacity observed in older adults, thereby increasing the risk of falls, reducing independence and quality of life (QOL), and ultimately increasing the economic burden of health care in this population.

Fortunately, a continually growing body of research highlights the adaptability of the aging neuromuscular system, with resistance training shown to induce marked increases in muscle CSA (Häkkinen et al. 1998b, 2000), maximal force (Caserotti et al. 2008; Häkkinen et al. 1998a, b, 2000, Häkkinen et al. 2001a), power (Caserotti et al. 2008; Häkkinen et al. 1998b), RFD (Caserotti et al. 2008; Häkkinen et al. 1998b), and muscle activation (Häkkinen et al. 2000; Häkkinen et al. 1998a, b Häkkinen et al. 2001a, b). Yet, a large variability in training intervention characteristics is evident. For instance, some studies combined progressive high resistance and maximal power resistance training, while others implemented daily variation in the training stimulus. Furthermore, training duration and

frequency varied from 10 to 24 weeks and 2–3 day week<sup>-1</sup>, respectively, and while machine-based exercises were most common, free weights and bodyweight trunk exercises were also reported. In addition, whether prescribed using the percentage of one-repetition maximum (1RM) or repetition maximum (RM) target, lifting loads ranged from 40 to 80% 1RM and 3-10RM within and between studies. Finally, the prescription and modification of set and repetition schemes within and between interventions differed extensively, and details of rest intervals, lifting velocity, and time between training sessions were often unreported.

The process of organising resistance training variables (load, volume, and frequency) within a training programme is typically referred to as periodisation, and can be complex in nature, particularly in a high-performance setting where specific training outcomes are warranted at pre-determined timepoints. Two of the most common periodisation strategies include block periodisation (BP) and daily undulating periodisation (DUP). Briefly, BP classically uses a four week block of highly concentrated training targeting specific training outcomes, e.g., muscular hypertrophy or maximal strength (Painter et al. 2012), whereas DUP varies training volume and intensity on a daily basis; hence, there is a more frequent manipulation of the training stimulus.

In older adults, the impact of periodised resistance training on 1RM strength (DeBeliso et al. 2005; Hunter et al. 2001; Jimenez and Paz 2011; Prestes et al. 2015), maximal force (Hunter et al. 2001), and power (Jimenez and Paz 2011) has been examined across 12 (Jimenez and Paz 2011), 16 (Prestes et al. 2015), 18 (DeBeliso et al. 2005), and 25 weeks (Hunter et al. 2001). Overall, similar improvements in outcome measures were evident following resistance training across the various training groups, despite the distinct differences in programme structures. However, a comprehensive assessment of long-term effects of periodised resistance training on neuromuscular adaptations in older adults has not been conducted, specifically muscle CSA, maximal force, power, RFD, and muscle activation.

Therefore, the aim of this study was to evaluate the impact of long-term (22 weeks) BP, DUP, and non-periodised (NP) resistance training on neuromuscular adaptations in older adults. We hypothesised that BP and DUP would produce greater improvements in training outcomes when compared to an NP structure.

## Methods

### Participants

Forty-one healthy older adults participated in the present study (female = 21, male = 20;  $70.9 \pm 5.1$  years; 65–81

years;  $166.3 \pm 8.2$  cm;  $72.9 \pm 13.4$  kg). Sample size estimation was based upon muscle CSA and activity measures during previous resistance training interventions of similar duration in older adults (Häkkinen et al. 1998b; Hunter et al. 2001), which displayed the most conservative ES among measures used in our study. An ES of 0.27 with a power of 80% at an alpha level of 0.05 produced a total sample size of 39, based on repeated measures, within-between ANOVA model (G\*Power 3.1 software).

All participants provided medical clearance from their personal physician and completed a health history questionnaire. Exclusion criteria included lactose intolerance (due to protein supplementation, to be described), a body mass index (BMI)  $\geq 30$  kg m<sup>2</sup>, any prescribed medication that could confound data, e.g., testosterone or corticosteroids, any pre-existing musculoskeletal, cardiovascular or neurological condition, or any other condition considered to cause risk to participants through resistance training or testing procedures, or reduce their ability to adapt. In addition, participants were untrained; specifically, they had not participated in structured exercise training designed to improve physical fitness over the previous 12 months. Finally, participants were instructed to continue with their normal daily activities and discouraged from engaging in any unaccustomed physical activity outside of their designated resistance training programme. The Edith Cowan University Human Research Ethics Committee approved the study and participants were fully informed of the nature and possible risks of all procedures before providing informed consent.

## Experimental design

A 3 (groups)  $\times$  3 (time-points) between/within participant design was used, with a total duration of 31 weeks, comprising two familiarisation sessions, a 4-week control period, a 22-week resistance training period, and completion of all testing procedures. Participants completed testing sessions in weeks 2, 7, and 31, using identical

protocols. Weeks 3–6 were used as a control period to ensure reliability and stability of baseline measures, during which no resistance training was performed, and participants simply maintained their normal recreational physical activities. Thereafter, participants commenced a 22-week resistance training intervention at a frequency of 3 day week<sup>-1</sup>, excluding weeks 22, 25, and 28 where participants trained 1 day week<sup>-1</sup>. These weeks were classed as transition weeks and modified ad hoc, with aim to promote recovery and reduce the potential for injury or illness due to observing signs of persistent fatigue and a reduced motivation to train among some participants. Furthermore, no training was performed during week 19 for the completion of testing procedures at the mid-training timepoint (data not included in the present study) and continued as normal in week 20. Therefore, a total number of 60 training sessions were prescribed across the intervention. Finally, participants were randomly stratified into the three experimental resistance training groups (NP, BP, and DUP) based on gender, age, BMI, and strength (peak isometric torque of the right knee extensors). Participant descriptives across training groups are displayed in Table 1, and a visual depiction of the experimental design is provided in Fig. 1.

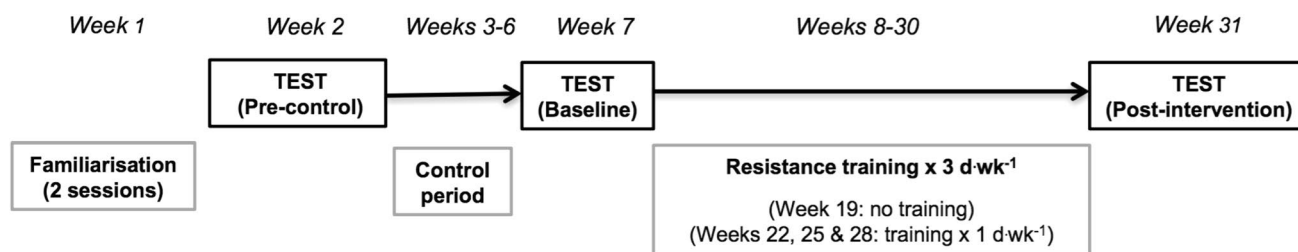
## Testing procedures

Participants were fully familiarised and instructed in the proper execution of all testing protocols across two familiarisation sessions to reduce the influence of any acute learning effects. Testing procedures were conducted using the same equipment at one location, at a similar time of day across the study to reduce the effect of any diurnal variations, and by the same researcher who was blinded to participants training group assignments. At each testing timepoint, participants were required to visit the testing location on three occasions, separated by approximately 48 h to complete all procedures.

**Table 1** Training groups' physical descriptive data at baseline and post-training

	NP		BP		DUP	
	Baseline	Post-training	Baseline	Post-training	Baseline	Post-training
Gender	F = 6; M = 4	–	F = 6; M = 7	–	F = 5; M = 5	–
Age (years)	$70.4 \pm 6.1$	–	$71.8 \pm 5.4$	–	$71.2 \pm 4.2$	–
Height (cm)	$166.4 \pm 10.6$	$166.3 \pm 10.5$	$164.9 \pm 5.8$	$164.9 \pm 5.7$	$167.2 \pm 9.9$	$167.4 \pm 10.2$
BM (kg)	$72.2 \pm 17.9$					
	$72.0 \pm 17.7$	$71.7 \pm 10.4$	$72.5 \pm 10.7$	$74.6 \pm 14.2$	$75.8 \pm 14.4$	
BMI (kg m <sup>2</sup> )	$25.8 \pm 4.2$	$25.8 \pm 4.3$	$26.3 \pm 3.1$	$26.6 \pm 3.2$	$26.7 \pm 4.3$	$27.0 \pm 4.0$

NP non-periodised; BP block periodisation; DUP daily undulating periodisation; BM body mass; BMI body mass index



**Fig. 1** Visual depiction of the experimental design including familiarisation, all testing procedures and the 22-week resistance training intervention (reproduced from Conlon et al. 2016, with permission from Wolters Kluwer Health, Inc.)

### Anthropometric measures

Body mass was measured by a calibrated electronic scale (HW200, A&D Mercury Pty, Ltd, Thebarton, SA, Australia) to the nearest 100 g and height was determined with a wall-mounted stadiometer (Model 220, SECA, Hamburg, Germany) to the nearest millimeter.

### Muscle hypertrophy

Muscle CSA of the quadriceps femoris muscle group, specifically the vastus lateralis (mVL) and rectus femoris (mRF), was measured using B-mode axial-plane ultrasound (Aloka SSD- $\alpha$ 10, software version 6.1.09, Aloka Co., Ltd., Tokyo, Japan). Images were captured using a 10 MHz linear-array probe (60 mm width) implementing the extended field of view technique (Noorkoiv et al. 2010). Specifically, a line from the lateral epicondyle of the femur to the greater trochanter was highlighted and two perpendicular lines at 50 and 66% from the greater trochanter were marked. A continuous single view was taken by moving the probe transversely across the thigh on the marked site, applying minimal pressure to avoid compression of the underlying tissue. Three images of each site were analyzed for CSA values using the ImageJ digitising software (1.46r, National Institutes of Health, USA) by one researcher, with mean data included in statistical analyses. The average intraclass correlation coefficient (ICC) (with 95% confidence intervals: CI) for muscle CSA measures was 0.993 (0.985–0.996).

### Neuromuscular Performance

Measures of neuromuscular performance included isometric and isokinetic peak torque, vertical jump VJ, isometric RFD, and muscle activation via surface electromyography (EMG). Prior to these tests, participants completed a warm-up consisting of 5 min of light stationary cycling. Vertical jump performance was assessed following anthropometric and muscle CSA measures at the start of the test week, with peak torque and related surface EMG measures carried out

approximately 96 h following. Strong verbal encouragement was provided throughout all protocols.

**Isometric and isokinetic peak torque** An isokinetic dynamometer (Biodex System 3 Pro, Ronkonkoma, NY) was used to measure isometric peak torque (Nm) and isokinetic peak torque ( $\text{Ns}^{-1}$ ) of the right knee extensors. To prevent an order effect, protocols were randomised using a freely available online computer programme (<http://www.psychicscience.org/random.aspx>). The torque signal was collected at a sampling frequency of 1000 Hz and recorded on a computer for later analysis using the LabChart 8 software (PowerLab System, ADInstruments, NSW, Australia). Participants were seated with the thigh and trunk secured to the device for all test protocols. Both isometric and isokinetic measures were normalised ( $n$ ) using body mass ( $m$ ) to assess strength ( $S$ ) independent of any changes in body size during the intervention using the following equation:

$$S_n = S/m^b$$

where  $b$  is the allometric parameter, specifically 0.67 for isometric and 1 for isokinetic peak torque (Jaric 2002).

Isometric peak torque was measured with the hip and knee angles at 110° and 120°, respectively (180° refers to full extension). Participants completed one submaximal 3 s contraction at 50% of perceived maximal intensity. Following 1 min of rest, participants performed a maximal voluntary isometric contraction (MVIC) for 3 s, with 1-min rest between three separate repetitions. If any countermovement was evident or if peak torque differed by >5% between attempts, a further repetition was performed. The average peak torque measured across the three MVIC trials was included in statistical analyses. The ICC (with 95% CI) for isometric peak torque was 0.949 (0.897–0.975).

Isokinetic peak torque was measured at 60° s<sup>-1</sup>, 180° s<sup>-1</sup>, and 300° s<sup>-1</sup>, with the hip and knee at 110° and 90°, respectively. Participants completed one submaximal set of three repetitions at 50% of self-perceived maximal intensity, before two sets of three maximal repetitions were performed at each angular velocity, with 1 min recovery between sets. The average peak torque at each

angular velocity was used for statistical analyses. The average ICC (with 95% CI) for isokinetic peak torque measures was 0.924 (0.847–0.963).

**Vertical jump** Peak velocity, peak force, peak power, and jump height were measured during a countermovement jump (CMJ) using a force plate (400 s Performance Plate, Fitness Technology, Adelaide, Australia). Participants were instructed to lower to a self-selected depth and maximally jump upward as quickly as possible with their hands held on their hips. Vertical ground reaction forces were recorded via the force plate, collected at a sampling frequency of 600 Hz using the Ballistic Measurement System software (Fitness Technologies, Adelaide, Australia). Three total trials were performed with mean data used for statistical analyses. The average ICC (with 95% CI) for vertical jump measures was 0.961 (0.919–0.982).

**Rate of force development** The isometric RFD ( $Ns^{-1}$ ) was defined as the slope of the isometric torque–time curve in the time intervals 0–30 ms (RFD<sub>30</sub>), 0–50 ms (RFD<sub>50</sub>), 0–100 ms (RFD<sub>100</sub>), and 0–200 ms (RFD<sub>200</sub>) (Aagaard, Simonsen 2002). The onset of muscle contraction was defined as the timepoint at which the torque curve exceeded the baseline by >7.5 Nm to account for electromechanical delay (Aagaard et al. 2002), and if torque dropped >5 N·m below the baseline at the beginning of a contraction, RFD analysis was not undertaken based on excessive countermovement. Offline analysis was performed using the LabChart software with mean data included in statistical analyses. The average ICC (with 95% CI) for RFD measures was 0.891 (0.776–0.947).

**Surface EMG** Muscle activity of the mVL and mRF of the right leg was measured during isometric neuromuscular assessments via surface EMG using a Bagnoli-8 desktop EMG system (Delsys, MA, USA). Prior to electrode placement, the skin was carefully prepared via shaving, gentle abrading, and cleaning with alcohol. A surface bipolar electrode (DE-2.1 single differential surface EMG sensor) with a 1 cm inter-electrode distance was positioned on the skin over the belly of each muscle, parallel to the direction of muscle fibers, according to SENIAM recommendations (Freriks and Hermens 1999). A sampling frequency of 2000 Hz with a gain of 2000 and a bandwidth frequency filter of 10–450 Hz were used. The signal was full wave rectified with the average root mean square (RMS) amplitude (mV) calculated for both muscles using a 250 ms window around the point of peak torque during the MVIC. The LabChart software was used to record and analyse data with mean data included in statistical analyses. The average ICC (with 95% CI) for EMG measures was 0.868 (0.657–0.949).

### *Physical activity and dietary intake standardization*

Participants were encouraged to maintain their habitual physical activity and dietary intake throughout the study. Physical activity was assessed via the Community Health Activities Model Program for Seniors (CHAMPS) Physical Activity Questionnaire for Older Adults (University of California, USA) (Giles and Marshall 2009). Dietary intake was assessed using a 3-day weighed food diary, recorded by participants during the week prior to testing weeks, and assessed for any significant changes in energy intake and macronutrient profile using the FoodWorks 7 software (Xyris, QLD) and the AUSNUT 2007 database of Australian foods. Specifically, participants were provided with validated scales and measuring devices, with dietary intake recorded on the same days throughout the study. However, this was across three non-training days during weeks 1 and 6, and two “normal” days and one training day during week 30.

### *Resistance training*

All exercises were executed on resistance training machines (Cybex, MA, USA) due to the smaller learning curve and reduced potential for injury in comparison with free weight alternatives. Resistance and repetitions performed were recorded in a training log and served as a written record for participants at the start of training sessions. Participants were fully familiarised with all machines prior to commencing the intervention. Furthermore, training sessions were performed at a regular time of day, with a minimum of 48 h between sessions, and were supervised by trained instructors to ensure proper exercise technique and reduce the risk of injury.

Training sessions commenced with a 5 min standardised warm-up consisting of light stationary cycling, rowing or brisk walking on an ergometer or treadmill (Technogym, London, UK). Resistance exercises remained consistent targeting concentric and eccentric muscle actions of major muscle groups, using alternating lower- and upper-body exercises. Yet, upper-body outcome measures are not included in the present study and are reported elsewhere (Conlon et al. 2016). Specifically, exercises included: seated leg press, lat pull-down, seated leg-curl, chest press, leg extension, and seated row. A warm-up set of each exercise was completed at approximately 50% of the resistance of the first work set. Regarding recovery, a rest interval of 1 min was required between the warm-up set and the first work set, and a 1.5–2 min recovery period was employed between consecutive work sets. Participants were instructed to perform the concentric portion of exercises with maximal velocity to promote optimal neuromuscular adaptation and functional performance (Bottaro et al. 2007), and

control the eccentric portion using a 2 s cadence as monitored by the instructors.

Exercise resistance was prescribed using RM sets to ensure that the resistance stimulus was progressive to accommodate strength adaptations, requiring adjustment of the exercise resistance to ensure momentary neuromuscular concentric failure (i.e., inability to complete a repetition in a full range of motion due to fatigue) at the prescribed RM target. At no point did participants continue performing repetitions above the required RM target, yet the resistance was increased as necessary in 1.25-, 2.5-, or 5-kg increments, depending on the absolute resistance. However, if a participant failed to complete the required number of repetitions, the number performed was recorded and the resistance was reduced accordingly for any remaining sets. Instructors initially led this careful adjustment of exercise resistance based on visual cues of exertion and by asking participants how difficult they perceived work sets. Once participants were competent in ensuring muscular failure at the required RM target, instructors simply prescribed the resistance of the first work set for each exercise based on the training log records and then observed to ensure that this was modified as necessary.

The RM targets prescribed for each group across the intervention is outlined in Table 2. The training focus for each RM target was: 15RM = strength endurance, 10RM = hypertrophy, and 5RM = maximal strength. The training intervention is displayed in blocks of training (mesocycles) to clearly outline the BP programme. Overall, BP and DUP groups completed the same number of training sessions at each RM target. In addition, as differences in the overall training volume between resistance training programs have been proposed to influence performance (Fleck 1999), total repetitions were equalised between training groups to reduce potential confounding factors, thereby allowing the sole examination of the effect of programme structure on outcome measures. Therefore, the only difference between DUP and BP groups was the timing and sequence of the load application. Furthermore, to check for any differences in workload between training groups across training blocks and the total training period, volume load [number of sets  $\times$  number of repetitions  $\times$  weight lifted (kg)] was calculated (Haff 2010).

## Protein supplementation

On completion of each training session, each participant ingested a 30 g serving of a standard liquid whey protein supplement mixed with 200 ml of water according to current recommendations (Bauer et al. 2013). Each serving contained 498 kJ energy, 24.1 g protein, 1.7 g total fat, 1.1 g saturated fat, 1.4 g sugars, and 42.6 mg sodium. This was completed before leaving the facility to ensure full compliance.

## Statistical analyses

Data were analyzed using the SPSS statistical software (SPSS Inc., Version 22, NY, USA). Normality of distribution was assessed using the Shapiro–Wilk statistic and where data were not normally distributed ( $p < 0.05$ ) and log transformation procedures were applied with data rechecked for normality before applying parametric tests.

To validate the random stratification of participants, a one-way analysis of variance (ANOVA) was used to check for between-group differences in baseline demographics and peak isometric torque. This analysis was also conducted on volume load and repetitions performed across each training block and the total training period.

To check for any changes in outcome measures across the control period (pre-control to baseline), a group  $\times$  time ( $3 \times 2$ ) repeated measures ANOVA was used to assess main effects for time and group  $\times$  time interactions. A separate  $3 \times 2$  repeated measures ANOVA was performed on outcome measures across the training period (baseline to post-intervention). Furthermore, an analysis of covariance (ANCOVA) was used to analyse between-group differences in the absolute change of outcome measures (i.e., post-intervention—baseline) including baseline data as the covariate. To examine any gender effects, a separate ANCOVA was performed on absolute change data including gender as the independent variable and baseline data as the covariate. When required, Tukey's test was used for post hoc analyses.

Data are presented as mean  $\pm$  SD, with 95% CI and Cohen's  $d$  within-group effect size (ES) calculated for the main outcome measures using the pooled SD, with an ES

**Table 2** Prescribed repetition maximum (RM) targets for training groups across the training intervention (training session numbers presented in brackets)

	Block 1 (1–11)	Block 2 (12–22)	Block 3 (23–33)	Block 4 (34–42)	Block 5 (43–51)	Block 6 (52–60)
NP	3 $\times$ 10RM					
BP	3 $\times$ 15RM	3 $\times$ 10RM	3 $\times$ 5RM	3 $\times$ 15RM	3 $\times$ 10RM	3 $\times$ 5RM
DUP	Session 1: 3 $\times$ 15RM Session 2: 3 $\times$ 10RM Session 3: 3 $\times$ 5RM					

of 0.2, 0.5, and 0.8 representing small, moderate, and large differences, respectively. Statistical significance was set at  $p < 0.05$  for all analyses.

## Results

Unfortunately, one participant experienced an unforeseen accident not related to the study and did not commence resistance training, and one participant dropped out in week 1 feeling unable to complete the training requirements. In addition, there were six further dropouts over the course of the intervention due to injury or illness (NP = 2; BP = 1; DUP = 3), with three injury cases relating directly to the study (NP = 1; BP = 1; DUP = 1). Specifically, two participants experienced a minor muscle tear during 1RM procedures and one participant suffered an overuse injury. Therefore, a total of thirty-three participants completed the study (female = 17, male = 16;  $71.3 \pm 5.4$  years;  $166.3 \pm 8.5$  cm;  $72.5 \pm 13.7$  kg), with only these data included in the analyses based on a per-protocol approach.

Participants' demographics at baseline and post-training are presented in Table 1, with no between- or within-group differences noted. The only measure to demonstrate a gender effect was EMG amplitude (RMS) of the mVL ( $p = 0.043$ ); therefore, data are presented for the entire training group for all other outcome measures to maximise statistical power.

### Resistance training

An adherence rate of  $\geq 85\%$  to resistance training was achieved by all participants with no between-group differences (NP = 95.6%; BP = 96.9%; DUP = 96.8%). The group mean total volume load was not statistically different between groups (NP =  $514,104 \pm 149,938$  kg; BP =  $495,559 \pm 128,169$  kg; DUP =  $554,068 \pm 151,897$  kg) (NP versus BP ES = 0.13; NP versus DUP ES = 0.26; BP versus DUP = 0.42), which was also true for group mean total repetitions performed (NP =  $13,287 \pm 579$ ; BP =  $13,675 \pm 354$ ; DUP =  $13,609 \pm 619$ ) (NP versus BP ES = 0.81; NP versus DUP ES = 0.54; BP versus DUP = 0.13), respectively.

### Outcome measures

#### Control period

There was a significant main effect of time on isokinetic peak torque at  $180^\circ \text{ s}^{-1}$  ( $p = 0.02$ ) and vertical jump peak power ( $p = 0.001$ ) across the control period, with no significant interactions or between-group differences noted ( $p > 0.05$ ). Specifically, isokinetic peak torque (normalised

to body mass) at  $180^\circ \text{ s}^{-1}$  decreased by 6.3% (ES = 0.30) in NP, 12.6% (ES = 0.33) in BP, and 2.9% (ES = 0.08) in DUP. Furthermore, peak power increased by 2.0% (ES = 0.02), 6.0% (ES = 0.16), and 1.4% (ES = 0.01), in NP, BP, and DUP groups, respectively. No other main effects, interactions, or between-group differences were apparent for any other variable across the control period.

#### Muscle hypertrophy

Group mean  $\pm$  SD, 95% CI and ES data for muscle CSA of the mVL and mRF is presented in Table 3. A significant main time effect ( $p < 0.001$ ) was evident across the training intervention for mVL 50 and 66%, and mRF 50 and 66% sites; however, no significant interactions or between-group differences were noted.

#### Neuromuscular performance

**Isometric and isokinetic peak torque** Group mean  $\pm$  SD, 95% CI and ES data for isometric and isokinetic peak torque normalised to body mass is presented in Table 3. There was a significant main time effect ( $p < 0.001$ ) for peak isometric torque and isokinetic torque at  $60^\circ \text{ s}^{-1}$  and  $180^\circ \text{ s}^{-1}$ , but not  $300^\circ \text{ s}^{-1}$  across the resistance training period. However, no significant interactions or between-group differences were detected.

**Vertical jump** Group mean  $\pm$  SD, 95% CI and ES data for peak velocity, peak force, peak power, and jump height derived from vertical jump assessment is presented in Table 4. There was a significant main time effect ( $p < 0.001$ ) for peak velocity, peak power, and jump height from baseline to post-resistance training, yet no significant interactions or between-group differences were noted. Peak force remained statistically unaltered following resistance training.

**Rate of force development (RFD)** Group mean  $\pm$  SD, 95% CI and ES data for RFD measures is presented in Table 5. No significant main time effects, interactions, or between-group differences were noted for RFD across any time interval assessed, from baseline to post-training.

**Surface EMG** Group mean  $\pm$  SD, 95% CI and ES data for average RMS amplitude EMG during peak isometric torque is presented in Table 4. No main time effect or significant interactions were noted for mRF RMS. There was no significant main time effect for mVL RMS ( $p > 0.05$ ), yet a significant interaction ( $p = 0.03$ ) was noted. However, there were no between-group differences based on ANCOVA. As described, a significant gender effect was found for mVL RMS ( $p = 0.043$ ) with a statistically greater change evi-

**Table 3** Changes in muscle size and peak torque across the training period

	NP			BP			DUP			All Groups		
	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES
<b>mVL 50% (cm<sup>2</sup>)</b>												
Baseline	15.0 ± 4.70	11.6–18.4	–	16.0 ± 4.81	13.1–18.9	–	18.1 ± 5.84	13.9–22.2	–	16.3 ± 5.10	14.5–18.1	–
Post-training	18.9 ± 5.60	14.9–22.9	0.75	20.0 ± 6.04	16.4–23.7	0.73	21.5 ± 5.29	17.7–25.3	0.61	20.1 ± 5.61	18.1–22.1	0.71
<b>mVL 66% (cm<sup>2</sup>)</b>												
Baseline	12.4 ± 4.58	9.12–15.7	–	12.9 ± 4.00	10.5–15.4	–	13.4 ± 4.62	10.1–16.7	–	12.9 ± 4.25	11.1–14.1	–
Post-training	13.5 ± 4.39	10.4–16.7	0.25	14.7 ± 4.42	12.0–17.3	0.43	15.7 ± 4.08	12.8–18.6	0.53	14.6 ± 4.26	13.1–16.2	0.40
<b>mRF 50% (cm<sup>2</sup>)</b>												
Baseline	5.58 ± 2.75	3.61–7.54	–	5.35 ± 2.22	4.01–6.69	–	6.13 ± 2.76	4.15–8.10	–	5.66 ± 2.49	4.77–6.54	–
Post-training	6.27 ± 2.45	4.51–8.02	0.29	6.38 ± 2.69	4.75–8.00	0.42	7.41 ± 2.10	5.91–8.91	0.52	6.66 ± 2.43	5.80–7.52	0.41
<b>mRF 66% (cm<sup>2</sup>)</b>												
Baseline	2.46 ± 1.32	1.51–3.40	–	2.30 ± 1.26	1.54–3.05	–	2.74 ± 1.30	1.81–3.67	–	2.48 ± 1.26	2.03–2.93	–
Post-training	2.80 ± 1.61	1.65–3.96	0.23	2.84 ± 1.33	2.04–3.64	0.42	3.28 ± 1.08	2.51–4.06	0.45	2.96 ± 1.33	2.49–3.44	0.37
<b>*Isometric PT (Nm)</b>												
Baseline	8.41 ± 2.14	6.97–10.1	–	8.14 ± 2.13	6.95–9.56	–	8.66 ± 2.58	6.91–10.7	–	8.38 ± 2.21	7.59–9.16	–
Post-training	9.20 ± 2.58	7.46–11.2	0.37	9.52 ± 2.06	8.39–10.9	0.70	9.32 ± 1.90	8.08–10.8	0.39	9.36 ± 2.12	8.61–10.1	0.45
<b>*Isokinetic PT at 60° s<sup>-1</sup></b>												
Baseline	1.51 ± 0.30	1.30–1.73	–	1.43 ± 0.51	1.12–1.73	–	1.67 ± 0.52	1.30–2.04	–	1.53 ± 0.46	1.37–1.69	–
Post-training	1.74 ± 0.34	1.49–1.98	0.72	1.63 ± 0.56	1.29–1.97	0.37	1.94 ± 0.64	1.48–2.40	0.46	1.76 ± 0.53	1.57–1.94	0.46
<b>*Isokinetic PT at 180° s<sup>-1</sup></b>												
Baseline	1.04 ± 0.21	0.89–1.19	–	0.90 ± 0.41	0.66–1.15	–	1.18 ± 0.38	0.90–1.45	–	1.03 ± 0.36	0.90–1.16	–
Post-training	1.16 ± 0.25	0.98–1.34	0.52	1.10 ± 0.35	0.89–1.31	0.52	1.26 ± 0.38	0.99–1.53	0.21	1.17 ± 0.33	1.05–1.29	0.41
<b>*Isokinetic PT at 300° s<sup>-1</sup></b>												
Baseline	0.76 ± 0.14	0.66–0.86	–	0.73 ± 0.31	0.55–0.92	–	0.91 ± 0.32	0.68–1.14	–	0.80 ± 0.28	0.70–0.89	–
Post-training	0.84 ± 0.17	0.72–0.97	0.51	0.86 ± 0.43	0.60–1.12	0.35	0.94 ± 0.35	0.69–1.18	0.09	0.88 ± 0.34	0.76–1.00	0.26

NP non-periodised; BP block periodisation; DUP daily undulating periodisation; mVL vastus lateralis; mRF rectus femoris; PT peak torque

\* Normalised to body mass



**Table 4** Changes in vertical jump performance, surface EMG, and RFD outcome measures across the training period

	NP			BP			DUP			All Groups		
	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES
<b>VJ PF (N)</b>												
Baseline	3406.6 ± 1234.1	2458.0–4355.3	–	3235.7 ± 1085.5	2546.0–3925.3	–	3271.7 ± 731.6	2709.4–3834.1	–	3297.8 ± 1010.1	2920.6–3674.9	–
Post-training	3583.8 ± 1334.7	2557.9–4609.8	0.14	3395.9 ± 795.6	2890.3–3901.4	0.17	3552.2 ± 874.9	2879.7–4224.7	0.35	3499.2 ± 974.8	3135.2–3863.2	0.20
<b>VJ PV (ms<sup>-1</sup>)</b>												
Baseline	1.63 ± 0.20	1.48–1.79	–	1.66 ± 0.35	1.44–1.89	–	1.79 ± 0.32	1.54–2.04	–	1.69 ± 0.30	1.58–1.81	–
Post-training	1.75 ± 0.19	1.61–1.89	0.63	1.71 ± 0.32	1.50–1.91	0.15	1.84 ± 0.27	1.63–2.05	0.17	1.76 ± 0.27	1.66–1.86	0.25
<b>VJ PP (W)</b>												
Baseline	1794.0 ± 651.4	1293.3–2294.7	–	1798.2 ± 604.9	1413.9–2182.5	–	2163.6 ± 752.3	1585.3–2741.9	–	1906.6 ± 664.3	1658.5–2154.6	–
Post-training	1947.5 ± 710.7	1401.2–2493.8	0.23	1872.8 ± 561.3	1516.1–2229.4	0.13	2263.4 ± 772.4	16.669.7–2857.2	0.13	2012.4 ± 672.6	1761.2–2263.5	0.16
<b>VJ JH (cm)</b>												
Baseline	11.9 ± 3.24	9.40–14.4	–	13.3 ± 6.32	9.29–17.3	–	14.9 ± 6.12	10.2–19.6	–	13.4 ± 5.45	11.3–15.4	–
Post-training	14.1 ± 3.15	11.7–16.5	0.69	14.3 ± 6.08	10.5–18.2	0.16	15.3 ± 5.33	11.2–19.4	0.07	14.5 ± 4.98	12.7–16.4	0.21
<b>mVL RMS (mV)</b>												
Baseline	84.2 ± 57.6	39.9–128.5	–	114.4 ± 58.8	64.9–163.2	–	84.2 ± 42.3	55.2–116.8	–	94.0 ± 52.3	71.7–115.7	–
Post-training	78.5 ± 44.6	44.2–112.8	0.11	104.3 ± 56.8	56.8–151.8	0.17	114.2 ± 49.1	72.7–155.7	0.65	99.9 ± 50.4	77.3–119.1	0.12
<b>mRF RMS (mV)</b>												
Baseline	54.6 ± 31.2	30.6–78.6	–	56.9 ± 25.3	35.8–78.1	–	50.5 ± 18.5	34.9–66.0	–	54.0 ± 24.9	43.8–64.3	–
Post-training	58.1 ± 34.3	31.8–84.4	0.11	56.9 ± 27.3	34.1–79.7	0.00	64.9 ± 31.7	38.4–91.4	0.55	59.9 ± 30.2	47.4–72.4	0.21

NP non-periodised; BP block periodised; DUP daily undulating periodisation; VJ vertical jump; PF peak force; PV peak velocity; PP peak power; JH jump height; mVL vastus lateralis; mRF rectus femoris; RMS root mean square

Table 5 Changes in RFD across the training period

	NP			BP			DUP			All Groups		
	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES	Mean ± SD	95% CI	ES
<b>RFD<sub>30</sub> (Ns<sup>-1</sup>)</b>												
Baseline	934.7 ± 388.3	656.6–1212.9	–	952.3 ± 404.0	708.1–1196.4	–	1152.9 ± 566.6	747.5–1558.2	–	1007.7 ± 451.1	847.8–1167.7	–
Post-training	1097.0 ± 550.2	703.4–1490.6	0.34	1086.0 ± 457.2	809.7–1362.2	0.31	1103.0 ± 409.1	810.4–1395.6	0.10	1094.5 ± 458.9	931.7–1257.2	0.19
<b>RFD<sub>50</sub> (Ns<sup>-1</sup>)</b>												
Baseline	831.9 ± 331.1	595.1–1068.7	–	838.0 ± 370.2	614.3–1061.7	–	940.1 ± 396.6	656.4–1223.8	–	867.1 ± 359.0	739.8–994.4	–
Post-training	1006.0 ± 594.8	580.5–1431.4	0.57	976.3 ± 438.4	711.4–1241.2	0.34	953.7 ± 373.1	686.8–1220.6	0.04	978.5 ± 459.5	815.5–1141.4	0.27
<b>RFD<sub>100</sub> (Ns<sup>-1</sup>)</b>												
Baseline	718.6 ± 302.4	502.3–935.0	–	701.0 ± 307.9	514.9–887.0	–	849.6 ± 436.9	537.1–1162.1	–	751.4 ± 345.4	628.9–873.8	–
Post-training	797.3 ± 366.8	534.9–1059.7	0.23	736.8 ± 300.2	555.3–918.2	0.12	793.1 ± 391.7	512.9–1073.3	0.14	772.2 ± 340.0	651.6–892.7	0.06
<b>RFD<sub>200</sub> (Ns<sup>-1</sup>)</b>												
Baseline	441.6 ± 186.8	308.0–575.3	–	467.3 ± 195.5	349.2–585.5	–	561.2 ± 281.6	359.8–762.7	–	488.0 ± 221.3	409.5–566.5	–
Post-training	500.8 ± 177.2	374.1–627.6	0.33	470.2 ± 164.1	371.1–569.3	0.02	537.1 ± 214.1	383.9–690.2	0.10	499.8 ± 180.6	435.7–563.8	0.06

NP non-periodised; BP block periodised; DUP daily undulating periodisation; RFD<sub>30</sub> 0–30 ms; RFD<sub>50</sub> RFD 0–50 ms; RFD<sub>100</sub> RFD 0–100 ms; RFD<sub>200</sub> RFD 0–200 ms

dent in males (10.9%, ES = 0.08) versus females (7.4%, ES = 0.09), baseline to post-training.

#### Physical activity and dietary intake standardization

There was no significant interaction or main time effect for the frequency of total and moderate-intensity physical activity performed. In addition, habitual dietary intake (excluding protein supplementation) did not change significantly in the pooled data of the whole cohort for energy intake across the overall study period (7981.1 ± 1552.1 to 7847.8 ± 1992.8 kJ, ES = 0.07). Furthermore, the percentage of energy derived from carbohydrate was statistically unchanged (38.9 ± 7.2 to 40.3 ± 8.7%, ES = 0.17). However, the percentage of energy derived from protein significantly increased ( $p = 0.007$ ) (19.5 ± 4.3 to 21.2 ± 4.9%, ES = 0.37) and the percentage of energy derived from fat significantly decreased ( $p = 0.029$ ) (33.8 ± 6.4 to 31.1 ± 6.3%, ES = 0.43) for the entire cohort over the course of the study.

#### Discussion

This study evaluated the impact of periodised (BP and DUP) and NP resistance training on neuromuscular outcomes across a 22-week training intervention in previously untrained older adults. The main finding was that all three resistance training models induced similarly significant improvements in muscular size, strength, and power, specifically mVL and mRF CSA, vertical jump peak velocity, peak power and jump height, and peak isometric torque and isokinetic torque of the knee extensors at 60° s<sup>-1</sup> and 180° s<sup>-1</sup>. Therefore, in contrast to our original hypothesis, BP and DUP resistance training did not induce superior neuromuscular adaptations compared to an NP model during the initial stages of training among the elderly. In addition, noteworthy was the unchanged muscle activity and RFD measures following resistance training.

The present data confirm that aging muscle retains the capacity to undergo positive hypertrophic adaptations to resistance training, central in counteracting sarcopenia. Previously, the magnitude of CSA in response to resistance training was described as minor in comparison with neural and strength changes in this population (Häkkinen et al. 2000; Häkkinen et al. 1998b). However, studies demonstrating muscular hypertrophy over short-term resistance training challenge this notion, with reports of a 7.1% increase in mVL CSA following only 9 weeks (18 sessions) (Lixandrão et al. 2016). Although we did not assess the timecourse of muscle hypertrophy, participants experienced an average 24% increase in quadriceps femoris CSA (mVL and mRF) over the 22-week training period (Table 5). With

total muscle mass and size estimated to decline ~1–2% per year over the age of 50 years (Roubenoff 2000), our data supports the substantial benefit of engaging older adults in resistance training ~3 h per week, with an average weekly muscle hypertrophy of ~1.1% in the initial stages of RT (i.e., 22 weeks).

The current resistance training interventions produced positive improvements in several physical performance measures, including vertical jump peak velocity (average change across entire cohort, 4.5%), peak power (6.3%), and jump height (12.2%). Despite no statistical between-group differences, NP displayed a considerably greater effect on peak velocity and jump height compared to BP and DUP (Table 4), signifying a potential advantage in this population. Furthermore, significant increases in peak isometric torque (13.8%) and isokinetic torque at  $60^\circ \text{ s}^{-1}$  (17.7%) and  $180^\circ \text{ s}^{-1}$  (19.8%) were observed across all groups, with no statistical between-group differences. Yet, BP demonstrated a markedly greater effect on peak isometric torque (ES = 0.70), in contrast to NP (ES = 0.37) and DUP (ES = 0.39) (Table 3). However, considering the concentrated 5RM block in BP immediately prior to the post-training assessments, participants ultimately practiced the specific motor schema associated with lifting heavier loads and greater force production. Conversely, DUP lifted 5RM loads 1 day week<sup>-1</sup> and NP were only exposed to 10RM loads. Therefore, greater maximal strength adaptation in BP is unsurprising and may explain previous findings (Painter et al. 2012).

Considering isokinetic torque, NP displayed the greatest increase at  $60^\circ \text{ s}^{-1}$ , while NP and BP exhibited a slightly greater increase at  $180^\circ \text{ s}^{-1}$  compared to DUP (Table 3). Interestingly, despite showing the greatest increase in isometric torque, BP only displayed only a small effect for isokinetic torque  $60^\circ \text{ s}^{-1}$  (ES = 0.37) along with DUP (ES = 0.46), in contrast to NP (ES = 0.72). This variability between performance assessments highlights the importance of comprehensively evaluating strength expression following resistance training. In addition, although not statistically significant, NP displayed the greatest effect on isokinetic torque at  $300^\circ \text{ s}^{-1}$  (NP = 0.51; BP = 0.35; DUP = 0.09). Considering this and the greater effect on vertical jump peak velocity and jump height, NP may be a potentially superior resistance training model for maximal impulse (force  $\times$  time) and power development in older adults. While rejecting our original hypothesis, perhaps, excessive variation in the training stimulus in DUP compromised physical performance adaptations, while the final 5RM block in BP favored improvements in peak isometric torque, yet inhibited maximal impulse and power development.

This outlines the challenges of evaluating resistance training models with timing constraints, as more frequent

assessments in BP between-and-within-training blocks would have been preferable. Yet, whether a traditional BP model comprised of intensive training blocks ~4 weeks in duration targeting minimal training outcomes is the most appropriate training structure in older adults is questionable. Ultimately, resistance training should promote concurrent improvements in the most meaningful morphological and physical performance qualities, i.e., muscular hypertrophy, strength, and power. Although DUP may theoretically achieve this, when considering the present findings, a weekly undulating periodisation (WUP) with weekly shifts between training outcomes may hold promise, thereby avoiding longer intensified training blocks in BP, and excessive variation in DUP. Therefore, further exploration of WUP resistance training in this context is warranted.

The RFD is an additional important performance measures, particularly in ADL performance and fall prevention among older adults (Suetta et al. 2004). Based on previous findings, a concurrent increase in isometric torque and RFD in the initial and early phase of the isometric torque–time curve was anticipated (Aagaard et al. 2002; Suetta et al. 2004). Conversely, RFD remained statistically unchanged on the completion of training across the entire cohort. Nevertheless, NP induced a greater increase in all RFD measures, particularly RFD<sub>50</sub> and RFD<sub>200</sub> (Table 5), consistent with the greater effect on other high impulse characteristics (vertical jump peak velocity and jump height, and isokinetic torque at  $300^\circ \text{ s}^{-1}$ ). We propose several possible theories for why RFD measures remained statistically unchanged in the present study. First, RFD in the early phase of rising muscle force (0–10, 0–20, ... 0–200 ms) was previously unchanged following high-intensity resistance training among untrained young males (Andersen et al. 2010). Specifically, muscle biopsies revealed a decreased proportion of fast type IIX muscle fibers following RT, with a transition toward the slow type II phenotype, i.e., type IIX to IIA, which was believed to be at least partially responsible for the unchanged RFD measures. Thus, the balance between increased muscle strength and decreased proportion of type IIX muscle fibers appears important for potential changes in early RFD and such shifts in fiber type may have been evident in the present cohort. Although this remains speculative, this is particularly significant due to the selective atrophy of type II muscle fibers in the elderly, with the greatest atrophy observed in IIX fibers (Aniansson et al. 1986; Coggan et al. 1992). However, improvements in the initial and early phase RFD (0–30, 0–50, 0–100, 0–200 ms) have been reported in aging individuals following 12 weeks of RT (Suetta et al. 2004). Therefore, possible fiber-type shifting phenomenon in the elderly warrants further investigation.

Second, due to assessing RFD under isometric conditions, a lack of specificity between training (dynamic

contractions) and assessment protocols may have inhibited the transfer of training. In support, RFD remained unaltered following 10 weeks of DUP resistance training involving training to muscular failure using RM zones, i.e., 8-10RM (Häkkinen et al. 1998a), and 20 weeks of ‘hypertrophic’ resistance training (i.e., medium load, high volume) in healthy older men (Walker et al. 2015). Likewise, both studies assessed RFD exclusively during isometric muscle contraction, whereas training was comprised entirely of dynamic actions.

Finally, based on ample data showing significant muscular power improvements in older adults following resistance training incorporating ballistic training protocols (Bottaro et al. 2007; Caserotti et al. 2008; Häkkinen et al. 2000; Häkkinen et al. 2001a), the inclusion of such training in a comprehensive periodised resistance training program is advocated to ensure that muscular strength, hypertrophy and power are equally optimised. Therefore, due to the absence of ballistic training in the study, whether routinely targeting specific power development within a periodised resistance training model is superior to an NP training structure in older adults requires further investigation.

The absence of a statistical increase in muscle activity pre-to-post-resistance training, specifically mRF and mVL RMS amplitude EMG was also unexpected. Considering the body of evidence showing significant increases in muscle activity following resistance training among the aged (Aagaard et al. 2002; Häkkinen et al. 2000; Häkkinen et al. 1998a, b; Suetta et al. 2004), it seems unlikely that the present physical performance improvements were solely due to morphological adaptation (i.e., muscle CSA). Nevertheless, muscle activation is a major limiting factor influencing the expression of RFD (Blazevich et al. 2009; Folland et al. 2014), consistent with both RFD and muscle activity parameters remaining statistically unchanged in the present study. Similarly, there was no increase in muscle activity following 8 or 12 weeks of resistance training in healthy young males (Thorstensson et al. 1976) and the elderly (Harridge et al. 1999), respectively. Considering the principle of specificity of training once more, both studies assessed isometric knee extensor muscle activity, whereas all training was performed using dynamic actions. Therefore, the nature of the specific adaptation to resistance training appears, as within younger counterparts, to be highly specific to the mode of training, and suggests adaptation in the actual skill of performing the task (Harridge et al. 1999).

Nevertheless, DUP demonstrated a 37.3% and 20.7% increase in mVL ( $ES = 0.65$ ) and mRF ( $ES = 0.55$ ) RMS amplitude, respectively, with no change or only trivial effects in NP and BP groups (Table 4). This suggests that a frequent manipulation of training stimuli may stimulate greater increases in muscle activity among older adults.

Considering the smaller improvements in high impulse strength qualities (vertical jump peak velocity and power, and peak isokinetic torque at  $300^\circ \text{ s}^{-1}$ ) and maximal force production in DUP, the current findings are somewhat inconsistent, with no single training model demonstrating superiority across the entire spectrum of neuromuscular adaptations. In addition, as muscle activity was measured during MVIC assessment, it is important to consider the moderate increase in EMG measures in DUP (average  $ES = 0.60$ ) versus NP (average  $ES = 0.00$ ), but similar improvements in isometric peak torque (NP = 0.37; DUP = 0.39). Therefore, greater muscle activation for the same magnitude of improvements in force expression was noted in DUP, when compared to NP, thereby indicating a potential maladaptation in neural outcomes following DUP. Consequently, the relationship between various outcome measures to different models of resistance training among older adults requires further investigation. In addition, periodised and NP models may have provided a similarly novel training stimulus among the present resistance training naïve participants. Therefore, whether the differences in training outcomes would be amplified among previously trained individuals due to a potential increased sensitivity to training variety remains unknown.

The 4-week control period served to ensure reliability and stability of baseline measures. Accordingly, the significant main time effect for isokinetic peak torque at  $180^\circ \text{ s}^{-1}$  and vertical jump peak power over this period must be acknowledged. In detail, isokinetic peak torque at  $180^\circ \text{ s}^{-1}$ , when normalised to body mass, decreased by 3.6% ( $ES = 0.30$ ) in NP, 12.6% ( $ES = 0.33$ ) in BP and 2.9% ( $ES = 0.08$ ) in DUP. As all other performance measures were unchanged during this period, it is difficult to understand why this may have occurred at an angular velocity of  $180^\circ \text{ s}^{-1}$ . However, the magnitude of effect was small for NP and BP, and trivial for DUP, and this finding does not question the positive increase in this measure post-training being a direct result of the intervention. Second, peak power increased by 2.0, 6.0, and 1.4% for NP, BP, and DUP groups, respectively, with no between-group differences evident. Such increases in peak power are likely due to practice and increased familiarity with vertical jump assessment, particularly as the present cohort were largely unaccustomed to any jumping actions, despite familiarisation sessions to reduce the influence of acute learning effects. Therefore, multiple familiarisation sessions are recommended for practicing particularly unfamiliar protocols in older adults. Such increases in peak power across the control period were trivial based on  $ES$  (NP = 0.02; BP = 0.16; DUP = 0.01). Yet, despite a significant main time effect following resistance training, the magnitude of  $ES$  remained trivial to small (NP = 0.23; BP = 0.13;

DUP = 0.13). Consequently, increases in vertical jump peak power must be interpreted with caution.

Concurrent resistance training and protein supplementation is considered the gold standard for maximising the anabolic environment in senescent muscle (Breen and Phillips 2011), ultimately promoting skeletal muscle hypertrophy and consequent neuromuscular adaptation (Esmarck et al. 2001; Micah et al. 2008). Therefore, it must be acknowledged that the inclusion of protein supplementation in the present study may have influenced greater improvements in outcome measures, in comparison with isolated resistance training. Nevertheless, the current RDA for protein is likely insufficient among the elderly (Bauer et al. 2013), and a large proportion of this population fail to meet this inadequate guideline (Roubenoff and Hughes 2000). Therefore, consuming an adequate amount of high-quality protein at each meal, in combination with resistance training, represents a promising strategy to prevent or delay the onset of sarcopenia in older adults (Padon-Jones et al. 2015).

Thirty-three participants fulfilled all study requirements and were included in the final analyses; however, this did not satisfy the a priori sample size estimate of thirty-nine participants. Therefore, the present sample size is a potential limitation and it could be argued that between-group statistical differences were possibly undetected due to type II error. It is recommended that future long-term training studies recruit an adequate cohort to ensure sufficient statistical power, considering the present dropout rate of 19.5%.

In summary, NP, BP, and DUP resistance training produces similar improvements in various morphological and physical performance parameters among apparently healthy untrained older adults, specifically muscle CSA, vertical jump performance, and peak isometric and isokinetic torque. Therefore, periodisation strategies do not appear to be critical during the initial stages of resistance training in the aging population. Alternatively, practitioners should focus on engaging the elderly in regular resistance training to experience the substantial impact on overall health, physical function and QOL. Finally, the examination of periodisation strategies among previously trained older adults is warranted, with alternate training models such as WUP recommended for consideration.

## Perspective

This study supports the efficacy of both periodised and NP resistance training for important morphological and physical performance improvements among the aging population. Therefore, practitioners may implement basic periodisation strategies, or an NP programme, when aiming to induce muscular size, strength, and power

adaptations in resistance trained-naïve elderly. These findings support the considerable public health implications of resistance training, ultimately lowering the risk of chronic disease while preserving independence and increasing QOL. The impact of periodisation strategies in previously trained older adults, and on long-term enjoyment, tolerance, and adherence remains unknown. Ultimately, exercise and health practitioners should concentrate efforts on increasing resistance training participation in older persons via feasible and efficacious interventions targeting long-term adherence in minimally supervised settings.

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## References

- Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P (2002) Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol* 93:1318–1326
- Andersen LL, Andersen JL, Zebis MK, Aagaard P (2010) Early and late rate of force development: differential adaptive responses to resistance training? *Scand J Med Sci Sports* 20:e162–e169
- Aniansson A, Hedberg M, Henning GB, Grimby G (1986) Muscle morphology, enzymatic activity, and muscle strength in elderly men: a follow-up study. *Muscle Nerve* 9:585–591
- Bauer J, Biolo G, Cederholm T, Cesari M, Cruz-Jentoft AJ, Morley JE, Phillips S, Sieber C, Stehle P, Teta D (2013) Evidence-based recommendations for optimal dietary protein intake in older people: a position paper from the PROT-AGE study group. *J Am Med Dir Assoc* 14:542–559
- Bean JF, Kiely DK, Herman S, Leveille SG, Mizer K, Frontera WR, Fielding RA (2002) The relationship between leg power and physical performance in mobility-limited older people. *J Am Geriatr Soc* 50:461–467
- Blazevich AJ, Cannavan D, Horne S, Coleman DR, Aagaard P (2009) Changes in muscle force–length properties affect the early rise of force in vivo. *Muscle Nerve* 39:512–520
- Bottaro M, Machado SN, Nogueira W, Scales R, Veloso J (2007) Effect of high versus low-velocity resistance training on muscular fitness and functional performance in older men. *Eur J Appl Physiol* 99:257–264
- Breen L, Phillips SM (2011) Skeletal muscle protein metabolism in the elderly: interventions to counteract the ‘anabolic resistance’ of ageing. *Nutr Metab* 8:68
- Caserotti P, Aagaard P, Buttrup Larsen J, Puggaard L (2008) Explosive heavy-resistance training in old and very old adults: changes in rapid muscle force, strength and power. *Scand J Med Sci Sports* 18:773–782
- Coggan AR, Spina RJ, King DS, Rogers MA, Brown M, Nemeth PM, Holloszy JO (1992) Histochemical and enzymatic comparison of the gastrocnemius muscle of young and elderly men and women. *J Gerontol* 47:B71–B76
- Conlon JA, Newton RU, Tufano JJ, Banyard HG, Hopper AJ, Ridge AJ, Haff GG (2016) Periodization Strategies in Older Adults: Impact on Physical Function and Health. *Med Sci Sports Exerc* 48:2426

- DeBeliso M, Harris C, Spitzer-Gibson T, Adams KJ (2005) A comparison of periodised and fixed repetition training protocol on strength in older adults. *J Sci Med Sport* 8:190–199
- Esmarck B, Andersen JL, Olsen S, Richter EA, Mizuno M, Kj  r M (2001) Timing of postexercise protein intake is important for muscle hypertrophy with resistance training in elderly humans. *J Physiol* 535:301–311
- Essen-Gustavsson B, Borges O (1986) Histochemical and metabolic characteristics of human skeletal muscle in relation to age. *Acta Physiol Scand* 126:107–114
- Fleck SJ (1999) Periodized strength training: a critical review. *J Strength Cond Res* 13:82–89
- Folland JP, Buckthorpe MW, Hannah R (2014) Human capacity for explosive force production: neural and contractile determinants. *Scand J Med Sci Sports* 24:894–906
- Freriks B, Hermens HJ (1999) SENIAM 9: European recommendations for surface electromyography. Roessingh Research and Development Enschede
- Giles K, Marshall AL (2009) The repeatability and accuracy of CHAMPS as a measure of physical activity in a community sample of older Australian adults. *J Phys Activity Health* 6:221–229
- Haff GG (2010) Quantifying workloads in resistance training: a brief review. *UK Strength Cond Assoc* 10:32
- H  kkinen K, H  kkinen A, Humphries BJ, Kraemer WJ, Newton RU, Gordon SE, McCormick M, Volek JS, Nindl BC, Gotshalk LA, Campbell WW, Evans WJ (1998a) Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. *J Gerontol Biol Sci* 53:B415–B423
- H  kkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Malkia E, Kraemer WJ, Newton RU, Alen M (1998b) Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J Appl Physiol* 84:1341
- H  kkinen K, Alen M, Kallinen M, Newton RU, Kraemer WJ (2000) Neuromuscular adaptation during prolonged strength training, detraining and re-strength-training in middle-aged and elderly people. *Eur J Appl Physiol* 83:51–62
- H  kkinen K, Kraemer WJ, Newton RU, Alen M (2001a) Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. *Acta Physiol Scand* 171:51
- H  kkinen K, Pakarinen A, Kraemer WJ, H  kkinen A, Valkeinen H, Alen M (2001b) Selective muscle hypertrophy, changes in EMG and force, and serum hormones during strength training in older women. *J Appl Physiol* 91:569–580
- Harridge SDR, Kryger A, Stensgaard A (1999) Knee extensor strength, activation, and size in very elderly people following strength training. *Muscle Nerve* 22:831–839
- Hunter GR, Wetzstein CJ, McLafferty JCL, Zuckerman PA, Landers KA, Bamman MM (2001) High-resistance versus variable-resistance training in older adults. *Med Sci Sports Exerc* 33:1759–1764
- Izquierdo M, Gorostiaga E, Garrues M, Anton A, Larrion JL, Haekkinen K (1999) Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men. *Acta Physiol Scand* 167:57–68
- Jaric S (2002) Muscle strength testing. *Sports Med* 32:615–631
- Jimenez A, Paz JDE (2011) Short-term effect of two resistance training periodization models (linear vs undulating) on strength and power of the lower-body in a group of elderly men. *J Strength Cond Res* 25:S20A
- Lexell J, Taylor CC, Sj  str  m M (1988) What is the cause of the ageing atrophy?: total number, size and proportion of different fiber types studied in whole vastus lateralis muscle from 15- to 83-year-old men. *J Neurol Sci* 84:275–294
- Lixandr  o ME, Damas F, Chacon-Mikahil MPT, Cavaglieri CR, Ugrinowitsch C, Bottaro M, Vechin FC, Concei  o MS, Berton R, Libardi CA (2016) Time course of resistance training-induced muscle hypertrophy in the elderly. *J Strength Cond Res* 30:159–163
- Micah JD, Hans CD, Bart P, Christopher SF, Shaheen D, Edgar LD, Melinda SM, Elena V, Blake BR (2008) Skeletal muscle protein anabolic response to resistance exercise and essential amino acids is delayed with aging. *J Appl Physiol* 104:1452–1461
- Noorkoiv M, Nosaka K, Blazevich AJ (2010) Assessment of quadriceps muscle cross-sectional area by ultrasound extended-field-of-view imaging. *Eur J Appl Physiol* 109:631–639
- Paddon-Jones D, Campbell WW, Jacques PF, Kritchevsky SB, Moore LL, Rodriguez NR, van Loon LJC (2015) Protein and healthy aging. *Am J Clin Nutr* 101:1339S–1345S
- Painter KB, Haff GG, Ramsey MW, McBride J, Triplett T, Sands WA, Lamont HS, Stone ME, Stone MH (2012) Strength gains: block versus daily undulating periodization weight training among track and field athletes. *Int J Sports Physiol Perform* 7:161
- Prestes J, da Cunha Nascimento D, Tibana RA, Teixeira TG, Vieira DCL, Tajra V, de Farias DL, Silva AO, Funghetto SS, de Souza VC (2015) Understanding the individual responsiveness to resistance training periodization. *Age* 37:1–13
- Roubenoff R (2000) Sarcopenia and its implications for the elderly. *Eur J Clin Nutr* 54:S40
- Roubenoff R, Hughes VA (2000) Sarcopenia current concepts. *J Gerontol Ser A Biol Sci Med Sci* 55:M716–M724
- Skelton DA, Greig CA, Davies JM, Young A (1994) Strength, power and related functional ability of healthy people aged 65–89 years. *Age Ageing* 23:371–377
- Suetta C, Aagaard P, Rosted A, Jakobsen AK, D  us B, Kjaer M, Magnusson SP (2004) Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. *J Appl Physiol* 97:1954–1961
- Thorstensson A, Karlsson J, Viitasalo JHT, Luhtanen P, Komi PV (1976) Effect of strength training on EMG of human skeletal muscle. *Acta Physiol Scand* 98:232–236
- Walker S, Peltonen H, H  kkinen K (2015) Medium-intensity, high-volume “hypertrophic” resistance training did not induce improvements in rapid force production in healthy older men. *Age* 37:1–10