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**EFFECTS OF LINEAR AND UNDULATING
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EXECUTIVE FUNCTIONS, PHYSICAL
ADAPTATIONS, AND PERIPHERAL MUSCLE-
BRAIN AXIS BIOMARKERS IN YOUNG
UNIVERSITY STUDENTS: A RANDOMIZED
PILOT TRIAL**
SAFETY, LEARNING CURVE, IN ROBOTIC COLORECTAL
SURGERY: INITIAL EXPERIENCE FROM A TERTIARY
CENTER

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Effects of Linear and Undulating Resistance Training Periodization on Executive Functions, Physical Adaptations, and Peripheral Muscle-Brain Axis Biomarkers in Young University Students: A Randomized Pilot Trial

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ABSTRACT

The potential contribution of resistance training to cognitive and systemic health has received increasing attention; however, less is known about whether different periodization models can be feasibly implemented in university settings while producing preliminary signals in executive functions, physical adaptations, and peripheral biomarkers related to the muscle-brain axis. This pilot randomized controlled trial examined the feasibility, safety, acceptability, and preliminary effects of 12 weeks of linear and undulating resistance training periodization compared with an active control condition in young university students. Sixty participants were randomized in a 1:1:1 ratio to linear periodization, undulating periodization, or active control. The primary outcome was feasibility, assessed through retention, adherence, data completeness, fidelity, acceptability, and adverse events. Secondary outcomes included inhibitory control, working memory, cognitive flexibility, estimated maximal strength, handgrip strength, countermovement jump, muscle mass, and body fat. Exploratory outcomes included peripheral BDNF, cathepsin B, IGF-1, IL-6, and C-reactive protein. Analyses included descriptive statistics, linear mixed models, ANCOVA sensitivity models, complete-case and per-protocol comparisons, Hedges' g , and exploratory association analyses. Posttest retention was 95.0%, data completeness was 95.0%, per-protocol inclusion was 90.0%, and no serious adverse events were observed. Adherence was high across groups, and acceptability was favorable, although lower in the active control group. Significant group-by-time signals were observed for executive function outcomes, physical performance, body composition, and peripheral biomarkers, with larger preliminary changes in the resistance training groups than in the active control condition. The findings support the feasibility and preliminary analytical stability of a university-based periodized resistance training protocol. Nevertheless, biomarker findings should be interpreted as peripheral exploration signals rather than direct evidence of central neuroplasticity. A fully powered preregistered trial is warranted to confirm efficacy and clarify mechanisms.

Keywords: Resistance training; periodization; executive functions; muscle-brain axis; BDNF; cathepsin B; pilot randomized trial; university students.

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Efectos de la periodización lineal y ondulatoria del entrenamiento de resistencia sobre las funciones ejecutivas, las adaptaciones físicas y los biomarcadores del eje músculo-cerebral periférico en jóvenes universitarios: un ensayo piloto aleatorizado

RESUMEN

La posible contribución del entrenamiento de fuerza a la salud cognitiva y sistémica ha recibido una atención creciente; sin embargo, se conoce menos sobre si diferentes modelos de periodización pueden implementarse de manera factible en entornos universitarios y, al mismo tiempo, producir señales preliminares en las funciones ejecutivas, las adaptaciones físicas y los biomarcadores periféricos relacionados con el eje músculo-cerebro. Este ensayo piloto aleatorizado y controlado examinó la factibilidad, seguridad, aceptabilidad y efectos preliminares de 12 semanas de periodización lineal y ondulatoria del entrenamiento de fuerza, en comparación con una condición de control activo, en estudiantes universitarios jóvenes. Sesenta participantes fueron aleatorizados en una proporción 1:1:1 a periodización lineal, periodización ondulatoria o control activo. El desenlace primario fue la factibilidad, evaluada mediante retención, adherencia, completitud de datos, fidelidad, aceptabilidad y eventos adversos. Los desenlaces secundarios incluyeron control inhibitorio, memoria de trabajo, flexibilidad cognitiva, fuerza máxima estimada, fuerza prensil, salto con contramovimiento, masa muscular y grasa corporal. Los desenlaces exploratorios incluyeron BDNF periférico, catepsina B, IGF-1, IL-6 y proteína C reactiva. Los análisis incluyeron estadística descriptiva, modelos lineales mixtos, modelos de sensibilidad mediante ANCOVA, comparaciones de casos completos y por protocolo, *g* de Hedges y análisis exploratorios de asociación. La retención posttest fue de 95.0 %, la completitud de datos fue de 95.0 %, la inclusión por protocolo fue de 90.0 % y no se observaron eventos adversos graves. La adherencia fue alta en todos los grupos y la aceptabilidad fue favorable, aunque menor en el grupo de control activo. Se observaron señales significativas de interacción grupo por tiempo en los desenlaces de función ejecutiva, rendimiento físico, composición corporal y biomarcadores periféricos, con cambios preliminares mayores en los grupos de entrenamiento de fuerza que en la condición de control activo. Los hallazgos respaldan la factibilidad y la estabilidad analítica preliminar de un protocolo universitario de entrenamiento de fuerza periodizado. No obstante, los hallazgos relacionados con biomarcadores deben interpretarse como señales exploratorias periféricas y no como evidencia directa de neuroplasticidad central. Se justifica realizar un ensayo preregistrado con potencia estadística suficiente para confirmar la eficacia y clarificar los mecanismos.

Palabras clave: entrenamiento de fuerza; periodización; funciones ejecutivas; eje músculo-cerebro; BDNF; catepsina B; ensayo piloto aleatorizado; estudiantes universitarios.

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INTRODUCTION

Resistance training has traditionally been framed as a method for improving muscular strength, hypertrophy, neuromuscular performance, body composition, and functional capacity. In contemporary exercise science, however, this view has expanded toward a systemic interpretation of skeletal muscle as an adaptive tissue with mechanical, metabolic, endocrine, and immunoregulatory roles. This broader perspective is relevant for university populations because young adulthood is a period in which physical inactivity, academic stress, sleep disruption, and high cognitive demand may converge. In this context, resistance training is not only a physical conditioning strategy, but also a plausible intervention for studying interactions between muscular adaptation, executive functioning, and peripheral biological signals associated with exercise-induced systemic regulation.

Recent evidence supports the general premise that exercise can benefit cognition, memory, and executive function across populations, although the magnitude of effect varies according to age, health status, exercise modality, intervention duration, intensity, and cognitive domain. In an umbrella review and meta-meta-analysis of randomized controlled trial evidence, Singh et al. (2025) reported favorable effects of exercise on general cognition, memory, and executive function, reinforcing the relevance of physical exercise as a broad strategy for cognitive health. Nevertheless, this evidence does not resolve which specific training structures are most feasible or potentially effective in young university students, nor does it clarify whether organizing resistance training through different periodization models produces distinct cognitive, physical, or peripheral biomarker responses. Therefore, a more specific experimental approach is warranted.

Resistance training may be particularly relevant for executive functions because it combines force production, motor planning, effort regulation, attentional control, interoceptive monitoring, and progressive adaptation to increasing task demands. Executive functions are commonly conceptualized around core domains such as inhibitory control, working memory, and cognitive flexibility, which support goal-directed behavior, academic performance, self-regulation, and adaptive decision-making (Diamond, 2013; Miyake et al., 2000). In university settings, these domains are not merely laboratory constructs; they are functionally related to study behavior, sustained attention, emotional regulation, and the ability to adapt to changing academic demands. From this perspective, examining whether structured



resistance training is associated with changes in Stroop performance, N-back accuracy, and Trail Making Test B performance is theoretically justified and educationally relevant.

The available literature on resistance exercise and executive function suggests promise, but also heterogeneity. Huang et al. (2022) found that acute resistance exercise can benefit executive function, with effects moderated by intensity and by the executive domain assessed. Their review indicated that inhibitory control, working memory, and cognitive flexibility may respond differently to resistance exercise, and that moderate-intensity protocols appear especially relevant for some domains. However, acute effects cannot be assumed to represent chronic adaptations, and findings from single exercise bouts cannot be directly generalized to 12-week periodized programs. This distinction is important because chronic resistance training introduces progressive overload, neuromuscular learning, recovery patterns, adherence demands, and repeated exposure to structured effort, all of which may shape cognitive and physiological outcomes differently from acute exercise.

Periodization is a central principle in resistance training prescription because it organizes training variables across time to manage adaptation, fatigue, recovery, and progression. Linear periodization usually progresses from higher volume and lower intensity toward lower volume and higher intensity across successive phases. Undulating periodization varies volume and intensity more frequently, often within the week, exposing participants to alternating stimuli such as hypertrophy-oriented, strength-oriented, and power-oriented sessions. Existing comparative evidence does not support a simplistic assumption that one model is universally superior. Earlier meta-analytic work suggested that differences between linear and undulating periodization for strength or hypertrophy are often small or inconsistent when training variables are reasonably controlled (Grgic et al., 2017; Harries et al., 2015). More recent synthesis comparing linear and undulating periodization across athletic capacities and health-related indicators also suggests that responses may depend on outcome, population, program duration, training history, and dose equivalence (Zhang et al., 2026). Consequently, the present study does not frame undulating or linear periodization as inherently superior. Instead, it treats periodization model as a structured experimental contrast in how training load is organized over time.

This distinction is methodologically important. If the objective is to compare periodization models, both resistance training arms must be similar in frequency, duration, exercise selection, supervision, and



general exposure, while differing primarily in the temporal distribution of intensity and volume. Otherwise, any observed difference could reflect unequal dose rather than periodization structure. In a pilot trial, this issue is especially relevant because feasibility outcomes, such as adherence, fidelity, perceived exertion, acceptability, and safety, may determine whether the intervention can be implemented with sufficient quality before attempting definitive efficacy claims. Therefore, a design that monitors internal load, attendance, progression, and adverse events is necessary to interpret cognitive, physical, and biomarker outcomes responsibly.

The biological rationale for examining peripheral biomarkers derives from the concept of skeletal muscle as an endocrine organ. Contracting muscle can release myokines and other exercise-responsive factors that participate in muscle-organ crosstalk, including communication with adipose tissue, liver, bone, vasculature, immune pathways, and the brain (Severinsen & Pedersen, 2020). Within this framework, the muscle-brain axis provides a plausible conceptual model for investigating how exercise-related muscular adaptations may coincide with changes in peripheral neurotrophic, metabolic, or inflammatory markers. However, this framework requires caution. Peripheral biomarkers are not direct windows into the brain, and changes in blood-based markers should not be interpreted as proof of central neuroplasticity, neurogenesis, or cognitive causation unless supported by stronger mechanistic methods. Among candidate biomarkers, brain-derived neurotrophic factors have received substantial attention because of their relevance to neuronal survival, synaptic plasticity, learning, and memory. Nevertheless, BDNF measured in blood is methodologically complex. Serum and plasma values may be influenced by matrix selection, platelet contribution, sample handling, storage, assay sensitivity, and preanalytical variability. Want et al. (2023) emphasized that serum BDNF measurements can be strongly influenced by platelet-derived BDNF, making functional interpretation of circulating levels difficult. Thus, in this trial, BDNF is best described as a peripheral neurotrophic marker rather than as a direct indicator of central neuroplasticity. This distinction is not merely semantic; it protects the study from overinterpreting biomarker changes that may reflect systemic, hematological, or procedural factors.

Cathepsin B is another relevant exploratory marker because it has been proposed as an exercise-responsive factor linking skeletal muscle, systemic circulation, and memory-related processes. Moon et al. (2016) reported that exercise increased circulating cathepsin B in animal models, primates, and



humans, and that circulating cathepsin B was associated with fitness and memory-related outcomes in humans. These findings support the plausibility of including cathepsin B in an exploratory muscle-brain axis panel. Nevertheless, the translation of this evidence to young university students undergoing resistance training remains uncertain, particularly because much of the mechanistic literature is based on endurance exercise, animal models, or older populations. Therefore, Cathepsin B should be interpreted as hypothesis-generating rather than confirmatory.

IGF-1, IL-6, and C-reactive protein provide complementary systemic information. IGF-1 is relevant to anabolic signaling, muscle adaptation, and neurotrophic pathways, but is also sensitive to nutrition, sleep, developmental status, and metabolic context. IL-6 is particularly complex because it may reflect inflammatory processes, muscle-derived signaling, or acute exercise responses depending on timing and physiological context. C-reactive protein offers a broader index of low-grade systemic inflammation, although it is nonspecific and can be affected by infection, stress, adiposity, sleep, and recent physical exertion. For these reasons, the biomarker panel in this study should be positioned as exploratory and peripheral. Its purpose is to examine whether favorable physical and executive function changes co-occur with systemic signals compatible with a muscle-brain axis framework, not to demonstrate a causal molecular pathway.

METHODOLOGY

Study Design

This study was structured as a three-arm, parallel-group, randomized pilot-controlled trial with blinded outcome assessment. Participants were allocated in a 1:1:1 ratio to one of three conditions: linear resistance training periodization, undulating resistance training periodization, or active control. The intervention lasted 12 weeks and included three supervised sessions per week. Assessments were organized at baseline, midpoint monitoring, and posttest, with feasibility defined as the primary outcome.

The methodological rationale followed the Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) statement, which establishes that a clinical trial protocol should function as the foundation for study planning, conduct, reporting, and appraisal (Chan et al., 2013). Because this was a pilot trial, reporting and interpretation were additionally aligned with the CONSORT extension



for randomized pilot and feasibility trials. This extension emphasizes that randomized pilot trials conducted before a definitive trial should primarily reduce uncertainty regarding feasibility, recruitment, retention, adherence, safety, acceptability, measurement procedures, and progression criteria, rather than make definitive claims of efficacy (Eldridge et al., 2016). Consequently, the present study prioritized feasibility and analytical stability over confirmatory inference.

Context and Participants

The study was conducted in a university-based exercise science context, using institutional spaces suitable for physical assessment, supervised resistance training, active control sessions, and cognitive testing. The target population consisted of young university students aged 18 to 25 years. This population was selected because young adulthood is characterized by high academic demands, executive function requirements, variable sleep patterns, and modifiable physical activity behaviors. In addition, university students represent a feasible population for structured exercise interventions under supervised academic conditions.

A total of 60 participants were randomized, with 20 assigned to each study arm. The sample size was consistent with the logic of a pilot randomized trial, whose main purpose is to estimate feasibility indicators, variability, adherence, retention, and preliminary effect sizes for a future definitive trial. The sample was not intended to provide a definitive test of efficacy or mechanism.

Eligibility Criteria

Participants were eligible if they met the following inclusion criteria: being between 18 and 25 years of age, being an active university student, providing written informed consent, being apparently healthy or cleared for participation in moderate to vigorous exercise, having no systematic resistance training experience during the previous six months, and being available to attend three supervised sessions per week for 12 weeks.

Exclusion criteria included any medical condition contraindicating exercise participation, recent musculoskeletal injury limiting resistance training or physical testing, neurological or cardiovascular conditions requiring clinical restriction, current participation in another structured resistance training program, use of non-prescribed anabolic agents or hormonal ergogenic substances, pregnancy, or inability to complete baseline assessments. Participants were also excluded if they presented any safety



condition identified during screening that made resistance training participation inappropriate without medical evaluation.

Randomization and Blinding

After baseline assessment, participants were randomized in a 1:1:1 ratio to linear periodization, undulating periodization, or active control. The randomization sequence was generated using a computer-based procedure. Allocation was concealed until baseline measurements were completed. Assignment was communicated only after eligibility confirmation, informed consent, and baseline testing.

Because of the nature of the exercise intervention, participants and trainers could not be blinded to group allocation. Nevertheless, outcome assessors were blinded whenever feasible. Cognitive and physical evaluators were instructed not to ask about group allocation, and participants were asked not to disclose their assigned condition during assessments. If laboratory analyses were conducted, biological samples were coded so that the laboratory personnel were unaware of group allocation. When feasible, the statistical dataset was coded using group labels that masked the intervention condition during initial analysis.

Interventions

The intervention description was aligned with the Template for Intervention Description and Replication (TIDieR) checklist and the Consensus on Exercise Reporting Template (CERT). TIDieR was developed to improve the completeness and replicability of intervention descriptions by specifying what was delivered, by whom, how much, and with what modifications (Hoffmann et al., 2014). CERT was specifically developed to improve the reporting of exercise interventions, including dose, tailoring, progression, supervision, adherence, and fidelity (Slade et al., 2016). These frameworks were used because incomplete reporting of exercise protocols limits replication, implementation, and interpretation.

All intervention arms included three supervised sessions per week for 12 weeks. The two resistance training groups used the same general session structure, exercise patterns, supervision procedures, and safety monitoring. Each session included brief pre-session screening, general warm-up, specific warm-up, main training block, complementary exercises, cool-down, and session rating of perceived exertion



(RPE). The main movement patterns included knee-dominant, hip-dominant, horizontal push, horizontal pull, vertical push or pull, and core stabilization exercises. Loads were adjusted according to technical execution, estimated strength level, RPE, and repetitions in reserve. Participants were not systematically trained to muscular failure.

Linear Periodization Group

Participants assigned to linear periodization completed a progressive 12-week resistance training program in which volume and intensity were organized sequentially across the intervention. The initial weeks emphasized anatomical adaptation, movement technique, and tolerance to resistance exercise. Subsequent weeks progressively increased training demand through hypertrophy-oriented loading, submaximal strength work, controlled power-oriented exercises, and a relative deload or consolidation phase before posttest assessment.

The defining feature of the linear model was gradual progression across phases. Training intensity increased in a structured manner, while total volume was adjusted to manage fatigue and support adaptation. This approach provided a conventional progression from technical preparation to higher neuromuscular demand.

Undulating Periodization Group

Participants assigned to undulating periodization completed a 12-week resistance training program using the same general exercises and session frequency as the linear group, but with more frequent variation in training stimulus. Weekly micro cycles alternate sessions emphasizing hypertrophy-oriented work, submaximal strength work, and controlled power or force-velocity work. The purpose was to vary intensity, repetitions, and neuromuscular demand within the week while maintaining comparable supervision and general exposure.

The defining feature of the undulating model was the temporal distribution of training load, not a higher overall training dose. Therefore, the comparison between the linear and undulating groups was interpreted as a comparison of load organization rather than as a comparison between training and non-training or between low and high total dose.

Active Control Group



The active control group attended supervised sessions with the same general frequency and similar contact time but without progressive resistance training. Sessions included mobility, stretching, body awareness, low-intensity movement, breathing exercises, and health-related body education. The active control condition was selected to reduce nonspecific effects related to attention, supervision, routine, group interaction, and expectation. It was not designed to produce substantial resistance training adaptations.

Active control participants did not complete progressive overload, strength-oriented sets near failure, or structured resistance training designed to improve maximal strength, hypertrophy, or power. Attendance, perceived exertion, safety events, and acceptability were monitored in the same manner as in the resistance training groups.

Outcomes and Measures

Primary Outcome: Feasibility

The primary outcome was feasibility of the 12-week university-based protocol. Feasibility was operationalized through retention, adherence, data completeness, intervention fidelity, acceptability, and adverse events. Retention was calculated as the proportion of randomized participants who completed posttest assessment. Adherence was calculated as the proportion of scheduled sessions attended. Data completeness was calculated as the proportion of expected measurements successfully obtained. Fidelity referred to the proportion of intervention components delivered according to protocol. Acceptability was assessed using a brief postintervention questionnaire. Safety was assessed through systematic registration of adverse events classified as mild, moderate, or serious.

The feasibility framework was prioritized because randomized pilot trials are designed to determine whether the methods, intervention, and measurement procedures are suitable for a larger definitive study (Eldridge et al., 2016). Therefore, feasibility indicators were interpreted before secondary and exploratory outcomes.

Secondary Cognitive Outcomes

Executive function outcomes included inhibitory control, working memory, and cognitive flexibility. Inhibitory control was assessed through Stroop performance, with lower response times or interference scores interpreted as better performance when applicable. Working memory was assessed through N-



back accuracy, with higher accuracy interpreted as better performance. Cognitive flexibility was assessed through Trail Making Test B performance, with lower completion time interpreted as better performance.

These three executive domains were selected because inhibitory control, working memory, and cognitive flexibility represent core components of executive function and are relevant to academic behavior, self-regulation, and adaptive performance in university students.

Secondary Physical and Morphological Outcomes

Physical outcomes included estimated one-repetition maximum (1RM), handgrip strength, and countermovement jump performance. Estimated 1RM was used instead of direct maximal testing to reduce risk and increase feasibility in a pilot sample that had not engaged in systematic resistance training during the previous six months. Handgrip strength was assessed using dynamometry, and countermovement jump performance was used as an indicator of lower-body neuromuscular performance.

Morphological outcomes included muscle mass and body fat percentage. These were assessed using standardized body composition procedures available in the institutional setting. Measurements were conducted under controlled conditions, including similar timing and preassessment instructions whenever possible.

Exploratory Peripheral Biomarkers

Exploratory biomarkers included brain-derived neurotrophic factors (BDNF), cathepsin B, insulin-like growth factor 1 (IGF-1), interleukin 6 (IL-6), and C-reactive protein (CRP), when laboratory conditions allowed. These markers were interpreted as peripheral exploratory indicators related to neurotrophic, metabolic, and inflammatory pathways. They were not interpreted as direct evidence of central neuroplasticity.

BDNF was treated as a peripheral neurotrophic marker because blood concentrations may be influenced by matrix selection, platelet release, sample handling, and preanalytical variability. Cathepsin B was included as an exploratory marker related to exercise-responsive systemic signaling. IGF-1, IL-6, and CRP were included to provide complementary information on anabolic, immunometabolic, and inflammatory status. Biomarker interpretation emphasized caution because peripheral circulating



markers cannot establish direct brain-level mechanisms in the absence of neuroimaging, cerebrospinal fluid measures, or more direct neurophysiological methods.

Covariates

Potential covariates included sleep quality, external physical activity, academic stress, caffeine intake, screen exposure, alcohol use, dietary conditions before testing, menstrual cycle phase when applicable, time of assessment, and baseline value of the outcome. These covariates were selected because they may influence executive performance, recovery, perceived exertion, inflammatory status, and body composition. Covariates were used descriptively and, when methodologically justified, in adjusted sensitivity models.

Procedure

The study procedure consisted of familiarization, baseline assessment, randomization, 12-week intervention, midpoint monitoring, posttest assessment, and optional follow-up if retained in the protocol.

During familiarization, participants received general instructions, practiced cognitive and physical testing procedures, and were oriented regarding safety, attendance, RPE reporting, and intervention expectations. Familiarization was included to reduce learning effects, test anxiety, and procedural variability.

Baseline assessment was conducted before randomization. It included eligibility confirmation, preassessment condition verification, executive function testing, physical performance testing, body composition assessment, questionnaires, and biomarker sampling when applicable. Cognitive testing was conducted before intense physical testing to avoid acute fatigue effects on executive performance. If blood sampling was included, it was performed before physical testing and under standardized preanalytical conditions.

After baseline testing, participants were randomized and began the 12-week intervention. Attendance, session RPE, adverse events, and protocol fidelity were recorded throughout the intervention. Midpoint monitoring occurred around week 6 and included adherence review, safety evaluation, internal load monitoring, and strength reassessment when appropriate for load adjustment.



Posttest assessment was conducted after completion of the 12-week intervention. Whenever possible, posttest measurements were scheduled 48 to 72 hours after the final training session to reduce the influence of acute fatigue, delayed-onset muscle soreness, and transient inflammatory responses. The same testing order and standardized procedures used at baseline were repeated at posttest.

Data Analysis Strategy

Analyses were planned according to the pilot nature of the study. First, feasibility indicators were described using frequencies, percentages, means, standard deviations, and 95% confidence intervals when appropriate. Retention, adherence, data completeness, fidelity, acceptability, and adverse events were interpreted as the primary analytical layer.

Second, baseline characteristics were summarized by group. Continuous variables were reported as means and standard deviations when approximately normally distributed, or as medians and interquartile ranges when distributional assumptions were not appropriate. Categorical variables were reported as frequencies and percentages. Baseline comparisons were treated descriptively and were not interpreted as formal equivalence tests.

Third, preliminary intervention effects were estimated using linear mixed models with fixed effects for group, time, and the group-by-time interaction, and with participant-level random intercepts when model assumptions allowed. The group-by-time interaction was the main term of interest for preliminary signals in executive function, physical outcomes, body composition, and biomarkers. When appropriate, ANCOVA sensitivity models were conducted using posttest values adjusted for baseline values, age, and sex.

Fourth, analyses were conducted using both intention-to-treat and per-protocol perspectives. The intention-to-treat approach included all randomized participants according to original allocation, using all available data. The per-protocol analysis included participants who met the predefined adherence criteria and completed relevant posttest assessments. Complete-case analyses were used for outcomes requiring both baseline and posttest measures.

Fifth, effect sizes were emphasized because pilot trials should estimate direction, magnitude, variability, and precision rather than rely exclusively on statistical significance. For pretest-posttest-control group comparisons, standardized effect sizes were interpreted with reference to the approach described by



Morris (2008), which supports estimating the difference in pre-post changes between intervention and control groups using the pooled pretest standard deviation. Hedges-corrected standardized mean differences and 95% confidence intervals were reported for main outcomes when appropriate.

Sixth, exploratory association analyses were conducted to examine whether changes in physical performance, body composition, internal load, or peripheral biomarkers were associated with changes in executive function. Pearson or Spearman correlations were selected according to distributional properties, and partial correlations adjusted for group, age, and sex were used as sensitivity analyses. Regression, mediation, and moderation models were interpreted as exploratory and hypothesis-generating only. Multiple comparisons were handled through domain-level interpretation, cautious reporting, and false discovery rate procedures when appropriate.

Ethical Considerations

The study required review and approval by an institutional research ethics committee before recruitment. Participation was voluntary and required written informed consent. Participants were informed about the purpose of the study, randomization, intervention procedures, possible risks, potential benefits, confidentiality, data protection, and their right to withdraw without academic or institutional consequences.

Ethical procedures were aligned with the Declaration of Helsinki, which establishes principles for research involving human participants, including respect for autonomy, protection of dignity, informed consent, risk-benefit assessment, privacy, and scientific transparency (World Medical Association, 2025). In the Mexican context, the study also followed the ethical and methodological criteria established by NOM-012-SSA3-2012 for health research projects involving human beings (Secretaría de Salud, 2013).

RESULTS AND DISCUSSION

Participant Flow and Baseline Characteristics

A total of 75 candidates were assessed for eligibility. Fifteen were excluded before randomization, and 60 participants were randomized in a 1:1:1 ratio to linear periodization, undulating periodization, or active control. Each group included 20 participants at allocation. One participant per group was unavailable for posttest assessment, resulting in 57 complete-case posttest records. The intention-to-



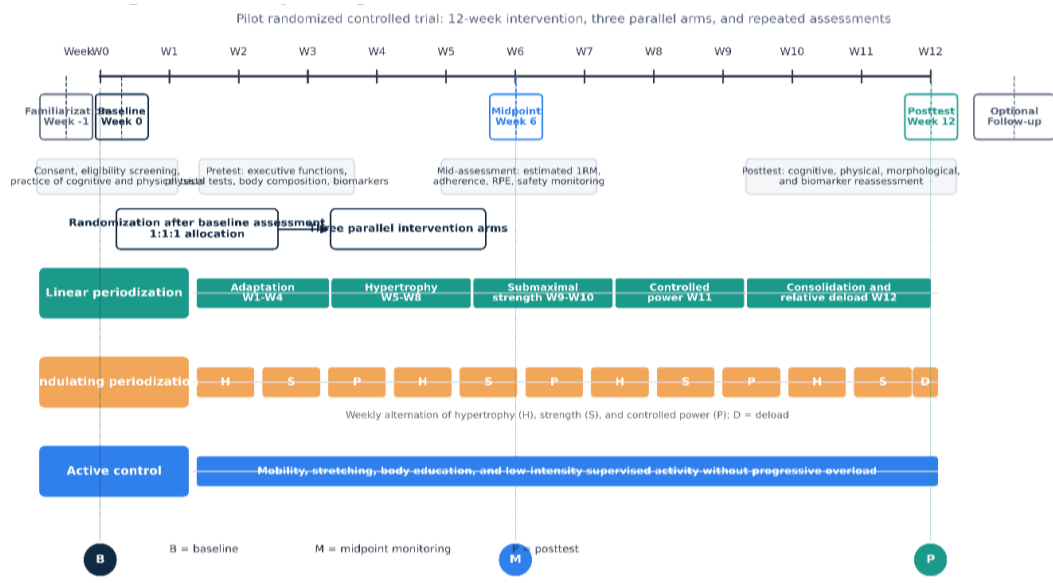
treat population included all randomized participants ($n = 60$), whereas the per-protocol population included 54 participants who met the predefined adherence criteria.

One participant per group was unavailable for posttest assessment, resulting in 57 complete-case posttest records. The intention-to-treat analysis included all randomized participants ($n = 60$), whereas the per-protocol analysis included participants who met the adherence criterion: linear periodization, $n = 19$; undulating periodization, $n = 17$; and active control, $n = 18$. Complete case analysis included participants with valid pretest and posttest data; per-protocol analysis included participants meeting the predefined adherence criterion.

The overall study sequence, measurement schedule, and intervention timeline are presented in Figure 1. This figure describes the methodological structure of the trial, including familiarization, baseline testing, randomization, the 12-week intervention, midpoint monitoring, and posttest assessment.



Figure 1
Study Design, Measurement Schedule, and Intervention Timeline



Note. The figure summarizes the methodological structure of the pilot randomized controlled trial. After familiarization and baseline assessment, participants were randomized in a 1:1:1 ratio to linear periodization, undulating periodization, or active control.

The intervention lasted 12 weeks, with midpoint monitoring in week 6 and post test assessment in week 12. Executive function, physical performance, body composition, and peripheral biomarkers were assessed at baseline and posttest; estimated strength and feasibility indicators were monitored at midpoint. Biomarkers should be collected 48 to 72 h after the final session to reduce the influence of acute exercise responses.

Figure 1 should be interpreted as a design and procedural figure rather than as an outcome figure. Its role is to clarify when each assessment occurred and how the three parallel arms were organized across the intervention period. This is important for the interpretation of the results because the cognitive, physical, morphological, and biomarker outcomes were not measured in isolation; they were embedded in a controlled timeline that included pretest standardization, supervised exposure, midpoint monitoring, and posttest assessment after the intervention. The figure also reinforces the methodological distinction between the two resistance training groups and the active control condition before the reader examines weekly load, executive function, physical adaptation, and biomarker results.

Baseline characteristics are presented in Table 1. The groups were balanced in sample size and showed no relevant differences in sex distribution, N-back accuracy, Trail Making Test B, estimated 1RM, handgrip strength, countermovement jump, muscle mass, body fat, peripheral biomarkers, sleep quality, or stress scores. Two baseline differences were observed: age differed across groups ($p = .042$), and baseline Stroop performance also differed across groups ($p = .044$).

Table 1
Baseline Characteristics and Group Comparability of the Analytical Sample

Variable	Linear periodization (n = 20)	Undulating periodization (n = 20)	Active control (n = 20)	P
Age, years	20.75 ± 2.47	21.40 ± 2.41	22.65 ± 2.18	0.042
Sex, male/female	08-dic	12-ago	10-oct	0.449
Stroop, ms	638.67 ± 45.29	616.56 ± 64.67	593.65 ± 54.25	0.044
N-back accuracy	0.76 ± 0.05	0.73 ± 0.08	0.75 ± 0.07	0.456
Trail Making Test B, s	64.29 ± 13.36	64.84 ± 11.01	62.08 ± 9.44	0.719
Estimated 1RM, kg	89.43 ± 13.23	86.05 ± 10.53	83.62 ± 16.32	0.403
Handgrip strength, kg	37.14 ± 7.00	36.71 ± 8.05	34.40 ± 6.58	0.427
Countermovem ent jump, cm	33.14 ± 4.42	32.60 ± 4.36	31.62 ± 4.38	0.55
Muscle mass, kg	31.91 ± 4.11	32.07 ± 4.01	31.10 ± 3.94	0.719
Body fat, %	23.36 ± 4.04	22.12 ± 4.21	22.44 ± 4.15	0.626
BDNF, ng/mL	15.59 ± 2.84	15.70 ± 2.75	15.19 ± 2.57	0.823
Cathepsin B, ng/mL	42.60 ± 4.76	42.33 ± 4.45	41.82 ± 4.46	0.86
IGF-1, ng/mL	182.96 ± 21.37	183.84 ± 22.51	181.32 ± 19.63	0.931
IL-6, pg/mL	1.63 ± 0.29	1.68 ± 0.32	1.62 ± 0.33	0.785
C-reactive protein, mg/L	0.41 ± 0.16	0.42 ± 0.17	0.42 ± 0.16	0.977
PSQI score	6.96 ± 1.44	6.92 ± 1.66	7.06 ± 1.55	0.961
DASS-21 stress score	18.67 ± 4.10	19.33 ± 4.42	19.22 ± 4.38	0.87

Note. Data are presented as mean ± standard deviation or absolute frequencies. Baseline comparisons were conducted using one-way ANOVA, Kruskal-Wallis tests, or chi-square tests as appropriate. Baseline comparisons are descriptive and should not be interpreted as formal equivalence tests. BDNF = brain-derived neurotrophic factor; IGF-1 = insulin-like growth factor 1; IL-6 = interleukin 6; PSQI = Pittsburgh Sleep Quality Index.

The baseline profile indicates that the randomization process generated broadly comparable groups, although age and baseline Stroop performance should be considered when interpreting subsequent cognitive models. These differences do not invalidate the pilot design, but they justify the use of adjusted



sensitivity models, particularly ANCOVA models adjusted for baseline values, age, and sex. In pilot trials, baseline comparisons are best interpreted descriptively rather than as formal equivalence tests. Therefore, the relevant conclusion is not that groups were statistically identical, but that the baseline structure was sufficiently coherent to proceed with feasibility and preliminary signal analyses.

Feasibility, Safety, Adherence, Fidelity, and Acceptability

Posttest retention was 95.0% overall, with identical retention in the three groups. Complete posttest data was available for 57 of 60 randomized participants. The per-protocol population included 90.0% of randomized participants. Mean adherence across the total sample was $90.28\% \pm 8.20$, and intervention fidelity was $92.93\% \pm 2.52$. Data completeness was 95.0%.

These findings indicate that the 12-week university-based protocol was feasible under supervised conditions. The retention, adherence, fidelity, and data completeness values exceeded conventional progression thresholds for a pilot trial. Importantly, feasibility was not restricted to one intervention arm; retention was identical across groups, and adherence remained high across all conditions. This supports the practical viability of implementing structured resistance training and active control sessions in a university setting.

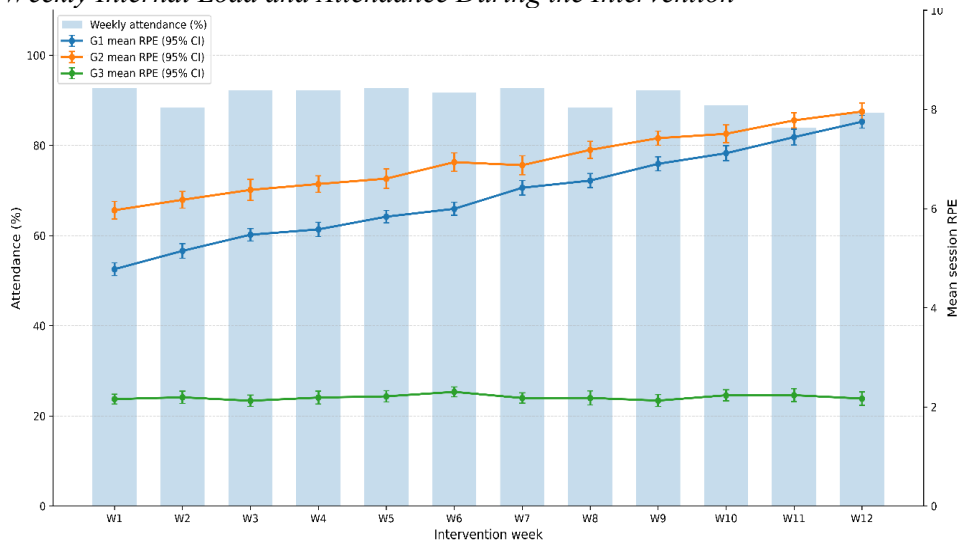
Safety outcomes were also favorable. No serious adverse events were observed. Seven mild and two moderate adverse events were recorded, with events concentrated in the resistance training groups and none observed in the active control condition. This distribution is plausible because the resistance training arms involved progressive loading and greater neuromuscular demand. However, the absence of serious adverse events suggests that the intervention was tolerable when supervised and progressed conservatively.

Acceptability was favorable overall, although it differed between groups ($p = .012$), with lower acceptability in the active control condition. This difference is an important implementation finding. Active control conditions may reduce nonspecific expectancy bias, but participants may perceive them as less beneficial or less engaging than resistance training. Therefore, future trials should retain the active control design while improving its perceived relevance, for example by strengthening the educational component or ensuring that participants understand its scientific purpose.



Weekly attendance and internal load are presented in Figure 2. Attendance remained stable throughout the 12-week intervention, whereas session RPE clearly differentiated the active control group from both resistance training groups.

Figure 2
Weekly Internal Load and Attendance During the Intervention



Note. Bars represent weekly attendance percentage across all scheduled sessions. Lines represent group-specific weekly mean session RPE with 95% confidence intervals.

Attendance remained stable throughout the 12-week intervention, whereas internal load was clearly lower in the active control group than in both resistance training groups, with the highest perceived effort observed in the undulating periodization group across most weeks.

Figure 2 reinforces the feasibility interpretation by showing that weekly attendance was maintained while internal load followed the expected pattern. The active control group remained at low perceived exertion, whereas the linear and undulating periodization groups demonstrated substantially higher perceived effort. This contrast is important because it indicates that the intervention arms were meaningfully different in training demand while remaining sufficiently tolerable to sustain adherence. The highest perceived effort was observed in the undulating periodization group across most weeks, which should be considered when interpreting differences in outcomes between the two resistance training models.

Intervention Exposure and Load Progression

Intervention exposure and accumulated training dose are reported in Table 3. The number of sessions attended did not differ significantly between groups ($p = .357$), indicating comparable attendance exposure. However, accumulated training volume, accumulated internal load, mean session RPE, and RPE area under the curve differed clearly between conditions (all $p < .001$ for load-related indicators). The linear periodization group accumulated $241,526.12 \pm 40,811.47$ kg of external volume, whereas the undulating periodization group accumulated $226,767.07 \pm 36,967.08$ kg. The active control group had no comparable progressive external resistance volume. Conversely, accumulated internal load was higher in the undulating group ($12,400.07 \pm 1,270.77$) than in the linear group ($11,358.16 \pm 1,046.35$), and both were higher than active control ($3,833.19 \pm 410.91$).

Table 2
Intervention Exposure, Internal Load, and Accumulated Training Dose

Indicator	Linear periodization	Undulating periodization	Active control	p
Attended sessions	33.20 ± 2.55	32.45 ± 3.05	31.85 ± 3.22	0.357
Adherence, %	92.22 ± 7.07	90.14 ± 8.48	88.47 ± 8.93	0.357
Accumulated volume, kg	$241,526.12 \pm 40,811.47$	$226,767.07 \pm 36,967.08$	0.00 ± 0.00	< .001
Accumulated internal load	$11,358.16 \pm 1,046.35$	$12,400.07 \pm 1,270.77$	$3,833.19 \pm 410.91$	< .001
Mean session RPE	6.24 ± 0.12	6.93 ± 0.12	2.19 ± 0.04	< .001
RPE area under the curve	67.76 ± 4.88	75.50 ± 3.76	23.70 ± 2.02	< .001

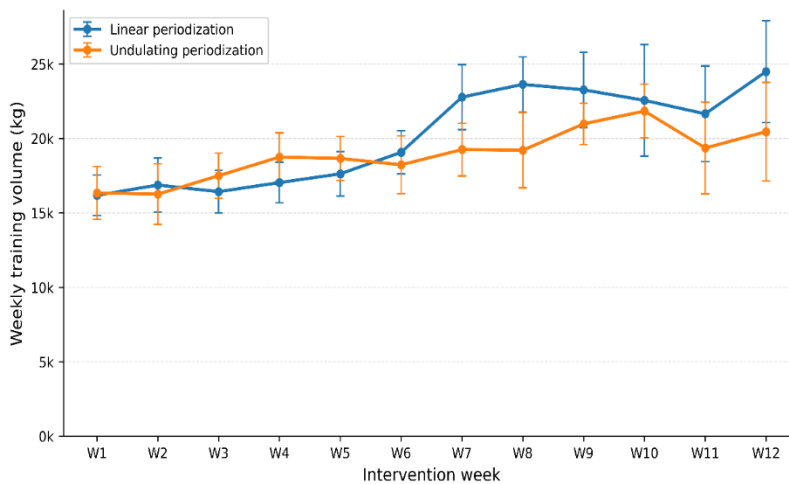
Note. RPE = rating of perceived exertion. Accumulated volume was calculated only for resistance training exercises; therefore, the active control group was not exposed to progressive external load. The active control condition is retained in the table to show differential exposure and internal load.

The exposure profile confirms that the study successfully generated two distinct resistance training conditions and a low-load active control condition. The comparison between linear and undulating periodization should therefore not be interpreted as a simple comparison of training versus no training. Both resistance training groups received supervised, progressive, multiweek exposure. Their difference lies in the temporal organization of load and internal effort. The linear model accumulated slightly greater external volume, whereas the undulating model produced greater perceived internal load. This

distinction is central because some outcome differences may reflect the subjective and neuromuscular demands of load variation rather than total external volume alone.

Weekly training volume for the two resistance training groups is shown in Figure 3. The active control group is not shown because it did not complete progressive resistance training with comparable external load.

Figure 3
Weekly Training Volume in Linear and Undulating Periodization



Note. Lines represent weekly mean training volume (kg) per participant for the two resistance training groups; error bars indicate 95% confidence intervals.

The active control group is not shown because it did not perform progressive resistance training with comparable external load. This figure is intended to describe the temporal organization of training load and should not be interpreted as evidence that one periodization model was superior solely based on volume.

Figure 3 illustrates the intended temporal contrast between the two periodization structures. The linear periodization condition displayed a more sequential progression of training volume, whereas the undulating condition showed a more variable weekly pattern. The figure should not be interpreted as evidence that one model was superior because of volume alone. Rather, it documents that the two resistance training programs were organized differently over time, which is necessary for interpreting subsequent executive, physical, morphological, and biomarker outcomes.

Executive Function Outcomes

Preliminary changes in executive function outcomes are summarized in Table 3 and visualized in Figure 3. For Stroop and Trail Making Test B, negative change values indicate improvement because they represent shorter response or completion time. For N-back accuracy, positive change values indicate improvement.

Table 3
Preliminary Changes in Executive Function Outcomes by Group

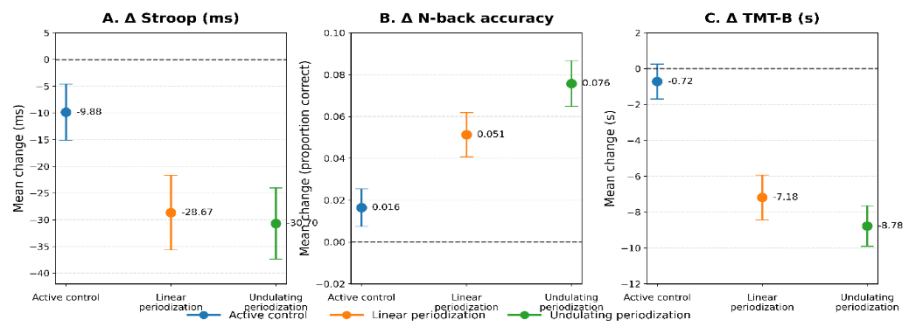
Outcome	Active control $\Delta M \pm SD$	Linear	Undulating	F	p	η^2
		periodization ΔM $\pm SD$	periodization $\Delta M \pm SD$	chang e		
Stroop, ms	-9.88 \pm 10.91	-28.67 \pm 14.48	-30.70 \pm 13.79	14.49	< .001	0.349
N-back accuracy	0.02 \pm 0.02	0.05 \pm 0.02	0.08 \pm 0.02	37.68	< .001	0.583
Trail Making Test B, s	-0.72 \pm 2.02	-7.18 \pm 2.60	-8.78 \pm 2.35	63.57	< .001	0.702

Note. Δ = posttest minus pretest. For Stroop and Trail Making Test B, negative values indicate improvement because they represent reduced completion or response time. For N-back accuracy, positive values indicate improvement. η^2 = partial eta squared.

The active control group showed a mean Stroop change of -9.88 ± 10.91 ms, whereas the linear and undulating periodization groups showed larger reductions of -28.67 ± 14.48 ms and -30.70 ± 13.79 ms, respectively. The group difference in change was significant, $F = 14.49$, $p < .001$, $\eta^2 = .349$. N-back accuracy increased by 0.02 ± 0.02 in the active control group, 0.05 ± 0.02 in the linear group, and 0.08 ± 0.02 in the undulating group, with a significant group difference, $F = 37.68$, $p < .001$, $\eta^2 = .583$. Trail Making Test B performance improved minimally in the active control group (-0.72 ± 2.02 s) but showed larger reductions in the linear (-7.18 ± 2.60 s) and undulating (-8.78 ± 2.35 s) groups, $F = 63.57$, $p < .001$, $\eta^2 = .702$.

Figure 4
Executive Function Changes by Group





Note. The figure shows mean change scores with 95% confidence intervals for executive function outcomes across groups. Panel A presents Δ Stroop (ms), Panel B presents Δ N-back accuracy, and Panel C presents Δ TMT-B (s).

Negative changes indicate improvement for Stroop and TMT-B because they represent reduced response or completion time, whereas positive changes indicate improvement for N-back accuracy. Values were calculated from complete posttest cases and are fully consistent with the analytical matrix and the results reported in Table 3.

Figure 3 provides a visual synthesis of the cognitive pattern. Both resistance training groups demonstrated more favorable changes than active control across inhibitory control, working memory, and cognitive flexibility. The largest separation was observed for Trail Making Test B and N-back accuracy, while Stroop also showed a consistent favorable direction. The undulating group showed numerically greater gains than the linear group in N-back accuracy and Trail Making Test B, although the pilot design does not justify a definitive claim of superiority. These findings should be interpreted as preliminary functional signals that support progression to a larger trial, not as conclusive evidence of cognitive efficacy.

From an interpretive standpoint, the convergence across the three executive outcomes is more important than any single p value. The findings suggest that a 12-week periodized resistance training protocol may be associated with improvements in cognitive domains relevant to attention, working memory updating, and cognitive flexibility in university students. However, because practice effects, expectancy, sleep, stress, and baseline cognitive differences can influence executive task performance, the results require replication in a fully powered trial with stronger control of covariates and preregistered cognitive endpoints.

Physical and Morphological Adaptations



Physical and morphological outcomes are presented in Table 4 and Figure 5. The resistance training groups showed larger preliminary improvements than active control in estimated maximal strength, handgrip strength, countermovement jump, muscle mass, and body fat percentage.

Table 4
Preliminary Changes in Strength, Neuromuscular Performance, and Body Composition

Outcome	Active control $\Delta M \pm SD$	Linear	Undulating	F change	p	η^2
		periodization $\Delta M \pm SD$	periodization Δ M \pm SD			
Estimated 1RM, kg	3.46 \pm 2.75	13.30 \pm 3.01	16.34 \pm 2.68	108.42	< .001	0.801
Handgrip strength, kg	-0.17 \pm 0.85	2.59 \pm 0.78	2.37 \pm 0.91	61.7	< .001	0.696
Countermovement jump, cm	0.41 \pm 0.77	2.26 \pm 0.91	3.33 \pm 0.79	60.91	< .001	0.693
Muscle mass, kg	-0.07 \pm 0.26	1.07 \pm 0.37	1.28 \pm 0.43	76.65	< .001	0.74
Body fat, %	-0.18 \pm 0.30	-0.95 \pm 0.34	-1.34 \pm 0.30	66.71	< .001	0.712

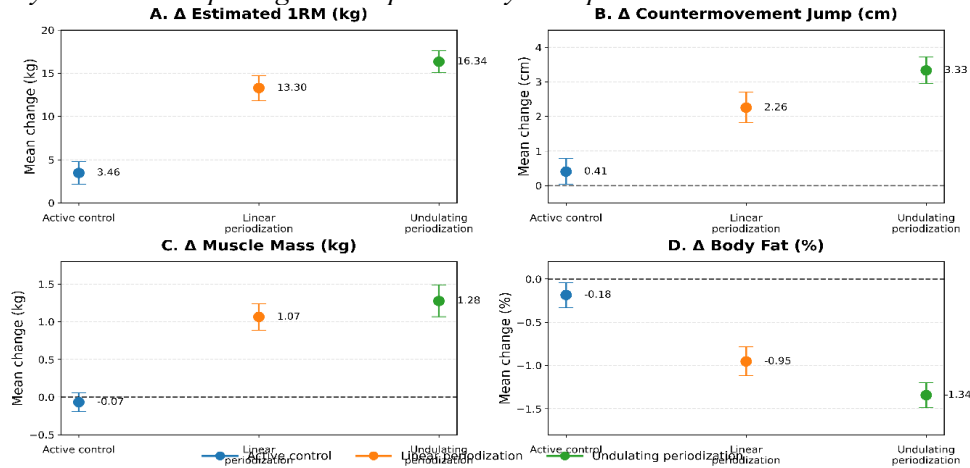
Note. Δ = posttest minus pretest. Positive values indicate improvement for estimated 1RM, handgrip strength, countermovement jump, and muscle mass. Negative values indicate favorable reduction for body fat percentage. 1RM = one-repetition maximum; η^2 = partial eta squared.

Estimated 1RM increased by 3.46 \pm 2.75 kg in the active control group, 13.30 \pm 3.01 kg in the linear periodization group, and 16.34 \pm 2.68 kg in the undulating periodization group, $F = 108.42$, $p < .001$, $\eta^2 = .801$. Handgrip strength changed by -0.17 \pm 0.85 kg in active control, 2.59 \pm 0.78 kg in linear periodization, and 2.37 \pm 0.91 kg in undulating periodization, $F = 61.70$, $p < .001$, $\eta^2 = .696$. Countermovement jump increased by 0.41 \pm 0.77 cm, 2.26 \pm 0.91 cm, and 3.33 \pm 0.79 cm in active control, linear, and undulating groups, respectively, $F = 60.91$, $p < .001$, $\eta^2 = .693$.

Muscle mass showed a small negative change in active control (-0.07 \pm 0.26 kg), while increasing in the linear (1.07 \pm 0.37 kg) and undulating (1.28 \pm 0.43 kg) periodization groups, $F = 76.65$, $p < .001$, $\eta^2 = .740$. Body fat percentage decreased across groups, but the reduction was larger in the resistance training

groups: $-0.18 \pm 0.30\%$ in active control, $-0.95 \pm 0.34\%$ in linear periodization, and $-1.34 \pm 0.30\%$ in undulating periodization, $F = 66.71$, $p < .001$, $\eta^2 = .712$.

Figure 5
Physical and Morphological Adaptations by Group



Note. The figure shows mean change scores with 95% confidence intervals for physical and morphological outcomes across groups.

Panel A presents Δ Estimated 1RM (kg), Panel B presents Δ Countermovement Jump (cm), Panel C presents Δ Muscle Mass (kg), and Panel D presents Δ Body Fat (%). Positive changes indicate improvement for estimated 1RM, countermovement jump, and muscle mass, whereas negative changes indicate favorable reduction for body fat percentage. Values were calculated from complete posttest cases and are fully consistent with the analytical matrix and the results reported in Table 5.

Figure 5 shows that the physical and morphological outcomes followed a coherent adaptation pattern. The resistance training groups improved strength, neuromuscular performance, and body composition more than active control. This is important because the cognitive and biomarker findings should be interpreted only after confirming that the resistance training intervention produced measurable physical adaptation. In other words, the intervention was not merely a supervised activity exposure; it generated objective physiological and performance-related changes consistent with resistance training adaptation. The physical findings also clarify the interpretation of periodization. The undulating group showed numerically larger changes in estimated 1RM, countermovement jump, muscle mass, and body fat reduction, whereas the linear group showed slightly higher handgrip improvement. This mixed pattern

does not support a simplistic claim that one model was universally superior. Rather, it suggests that different adaptation domains may respond differently to the temporal organization of load.

Peripheral Biomarker Outcomes

Changes in peripheral biomarkers are summarized in Table 5. The biomarker analyses were exploratory and were interpreted as peripheral systemic signals rather than direct evidence of central neuroplasticity.



Table 5
Peripheral Biomarker Changes and Log-Transformed Sensitivity Analysis

Biomarker	Active	Linear	Undulating	ANCOVA log p	η^2
	control Δ M \pm SD	periodization Δ M \pm SD	periodization Δ M \pm SD		
BDNF, ng/mL	0.01 \pm 0.92	2.88 \pm 1.30	3.83 \pm 1.21	< .001	0.69
Cathepsin B, ng/mL	0.96 \pm 2.54	4.36 \pm 1.72	4.95 \pm 2.39	< .001	0.379
IGF-1, ng/mL	1.74 \pm 8.44	14.88 \pm 9.35	16.45 \pm 8.49	< .001	0.385
IL-6, pg/mL	0.04 \pm 0.10	-0.19 \pm 0.10	-0.21 \pm 0.10	< .001	0.487
C-reactive protein, mg/L	0.05 \pm 0.09	-0.20 \pm 0.11	-0.29 \pm 0.11	< .001	0.447

Note. Δ = posttest minus pretest. ANCOVA log p refers to the log-transformed posttest model adjusted for log-transformed baseline value, age, and sex. BDNF = brain-derived neurotrophic factor; IGF-1 = insulin-like growth factor 1; IL-6 = interleukin 6. These biomarkers are interpreted as peripheral exploratory markers and not as direct evidence of central neuroplasticity.

BDNF changed minimally in active control (0.01 \pm 0.92 ng/mL), while increasing in the linear (2.88 \pm 1.30 ng/mL) and undulating (3.83 \pm 1.21 ng/mL) periodization groups. Cathepsin B increased by 0.96 \pm 2.54 ng/mL in active control, 4.36 \pm 1.72 ng/mL in linear periodization, and 4.95 \pm 2.39 ng/mL in undulating periodization. IGF-1 increased by 1.74 \pm 8.44 ng/mL in active control, 14.88 \pm 9.35 ng/mL in linear periodization, and 16.45 \pm 8.49 ng/mL in undulating periodization. IL-6 increased slightly in active control (0.04 \pm 0.10 pg/mL) but decreased in linear (-0.19 \pm 0.10 pg/mL) and undulating (-0.21 \pm 0.10 pg/mL) periodization. C-reactive protein increased slightly in active control (0.05 \pm 0.09 mg/L) but decreased in linear (-0.20 \pm 0.11 mg/L) and undulating (-0.29 \pm 0.11 mg/L) periodization. Log-transformed ANCOVA sensitivity models remained significant for all biomarker outcomes (all p < .001).

These results are consistent with a favorable peripheral profile in the resistance training groups. However, they should be interpreted cautiously. Blood-based BDNF, cathepsin B, IGF-1, IL-6, and C-reactive protein are influenced by multiple biological, behavioral, and preanalytical factors. Therefore,

the biomarker pattern should be described as an exploratory systemic signal compatible with exercise adaptation, not as proof that resistance training directly produced central neuroplasticity. The biomarker findings are useful for hypothesis generation and trial planning, particularly if future research includes stricter laboratory controls, larger samples, and complementary neurophysiological measures.

Standardized Effect Sizes Across Main Outcomes

Standardized effect sizes are shown in Table 6 and Figure 6. Table 6 reports Hedges' *g* for the main outcomes using the original directional meaning of each variable, whereas Figure 6 provides a visual synthesis of effect magnitude across domains. For lower-is-better outcomes such as Stroop, Trail Making Test B, body fat, and C-reactive protein, negative values in Table 6 indicate favorable reductions. For higher-is-better outcomes such as N-back, estimated 1RM, countermovement jump, muscle mass, and BDNF, positive values indicate favorable increases.

Table 6
Standardized Effect Sizes for Main Outcomes

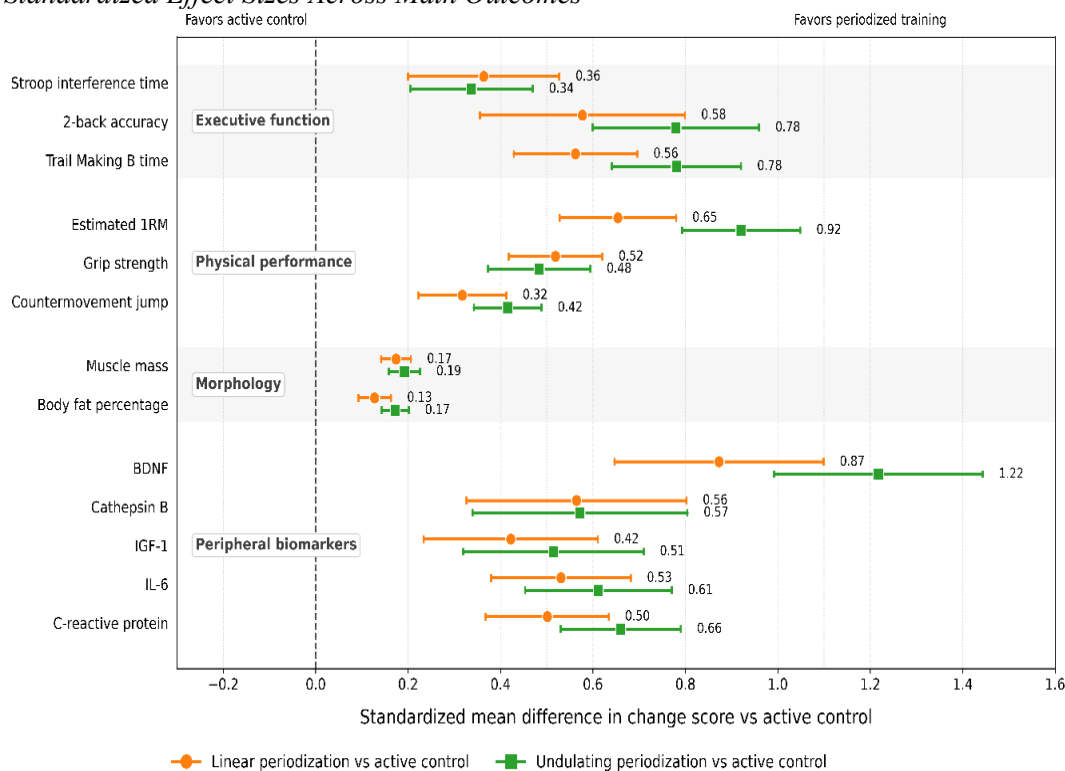
Outcome	Linear vs active control g [95% CI]	Undulating vs active control g [95% CI]	Undulating vs linear g [95% CI]
Δ Stroop	-1.44 [-2.15, -0.72]	-1.64 [-2.38, -0.90]	-0.14 [-0.78, 0.50]
Δ N-back	1.68 [0.93, 2.42]	2.79 [1.89, 3.70]	1.07 [0.39, 1.75]
Δ Trail Making Test B	-2.72 [-3.61, -1.83]	-3.61 [-4.66, -2.56]	-0.63 [-1.28, 0.02]
Δ Estimated 1RM	3.34 [2.34, 4.34]	4.64 [3.40, 5.89]	1.04 [0.36, 1.72]
Δ Countermovement jump	2.15 [1.34, 2.95]	3.66 [2.60, 4.72]	1.24 [0.54, 1.93]
Δ Muscle mass	3.50 [2.47, 4.53]	3.69 [2.63, 4.76]	0.52 [-0.13, 1.16]
Δ Body fat	-2.34 [-3.17, -1.50]	-3.80 [-4.88, -2.71]	-1.18 [-1.88, -0.49]
Δ BDNF	2.50 [1.64, 3.36]	3.49 [2.46, 4.51]	0.74 [0.08, 1.39]
Δ C-reactive protein	-2.43 [-3.27, -1.58]	-3.28 [-4.27, -2.29]	-0.78 [-1.44, -0.12]

Note. *g* = Hedges' *g*. Negative values indicate favorable reductions for Stroop, Trail Making Test B, body fat, and C-reactive protein. Positive values indicate favorable increases for N-back, estimated 1RM, countermovement jump, muscle mass, and BDNF.



The effect size pattern favored both resistance training groups over active control across executive function, physical performance, morphology, and peripheral biomarkers. For executive function, linear periodization versus active control showed large, standardized differences for Stroop ($g = -1.44$), N-back ($g = 1.68$), and Trail Making Test B ($g = -2.72$). Undulating periodization versus active control showed similarly large or larger differences for Stroop ($g = -1.64$), N-back ($g = 2.79$), and Trail Making Test B ($g = -3.61$). Physical and morphological outcomes also showed large effects, particularly estimated 1RM, countermovement jump, muscle mass, and body fat percentage.

Figure 6
Standardized Effect Sizes Across Main Outcomes



Note. Values are Hedges-corrected standardized mean differences for posttest minus pretest change scores versus active control, standardized by pooled baseline standard deviation.

Positive values favor periodized training. For lower-is-better outcomes, the sign was reversed for interpretive consistency. The figure integrates executive function, physical performance, morphology, and peripheral biomarkers.

Figure 6 functions as the main integrative visual summary of the trial. It shows that the strongest preliminary signals were not isolated to one domain but were distributed across executive function,

neuromuscular adaptation, morphology, and selected peripheral biomarkers. This multidomain pattern strengthens the internal coherence of the pilot findings. However, effect sizes in pilot trials are often unstable and can be inflated, especially with small samples and optimized adherence. Therefore, these values should be used primarily to inform the design and sample size estimation of a definitive trial, not to make confirmatory claims.

Exploratory Associations Between Physical, Biomarker, and Executive Function Changes

Exploratory associations are presented in Table 7. These analyses examined whether changes in physical adaptation, internal load, and peripheral biomarkers were associated with changes in executive function outcomes.

Table 7
Exploratory Associations Between Physical, Biomarker, and Executive Function Changes

Predictor	Outcome	Pearson r	p	Partial r adjusted for group, age, and sex	p adjusted	Interpretation
Δ Estimated 1RM	Δ N-back	0.705	< .001	0.159	0.256	Strong bivariate association attenuated after adjustment
Δ Estimated 1RM	Δ Trail Making Test B	-0.759	< .001	-0.054	0.702	Bivariate association largely explained by group
Δ Muscle mass	Δ Trail Making Test B	-0.774	< .001	-0.174	0.212	Bivariate association attenuated after adjustment
Δ BDNF	Δ Trail Making Test B	-0.596	< .001	0.289	0.036	Exploratory peripheral signal requiring caution
Δ C-reactive protein	Δ N-back	-0.731	< .001	-0.303	0.028	Exploratory inflammatory signal requiring caution
Accumulated internal load	Δ Estimated 1RM	0.374	0.021	NA	NA	Dose-response signal within resistance training groups
Accumulated internal load	Δ Countermovement jump	0.255	0.122	NA	NA	Weak dose-response tendency

Note. Δ = posttest minus pretest. Negative correlations with Stroop or Trail Making Test B indicate that greater change in the predictor is associated with greater reduction in time. Partial correlations were adjusted for group, age, and sex. Associations involving biomarkers should be interpreted as exploratory and not as mechanistic proof.

Several bivariate associations were strong. For example, change in estimated 1RM was positively associated with change in N-back accuracy ($r = .705, p < .001$) and negatively associated with change in Trail Making Test B ($r = -.759, p < .001$), indicating that greater strength gains were associated with better working memory and cognitive flexibility performance. Change in muscle mass was also negatively associated with change in Trail Making Test B ($r = -.774, p < .001$). In addition, change in C-reactive protein was negatively associated with N-back accuracy ($r = -.731, p < .001$), suggesting that greater reductions in systemic inflammation were associated with greater improvements in working memory accuracy.

However, most associations were substantially attenuated after adjustment for group, age, and sex. For instance, the association between change in estimated 1RM and N-back accuracy decreased from $r = .705$ to partial $r = .159$ ($p = .256$), and the association between change in estimated 1RM and Trail Making Test B decreased from $r = -.759$ to partial $r = -.054$ ($p = .702$). Two exploratory adjusted associations remained statistically relevant: BDNF with Trail Making Test B (partial $r = .289, p = .036$) and C-reactive protein with N-back accuracy (partial $r = -.303, p = .028$).

This attenuation is analytically important. It suggests that much of the bivariate relationship between physical and cognitive change was explained by group allocation rather than by a direct individual-level association independent of intervention conditions. Therefore, the association analyses should not be used to claim mediation or mechanism. Their main value is to identify candidate pathways for future trials with larger samples, stronger mechanistic measures, and preregistered mediation models.

CONCLUSIONS

This randomized pilot trial supports the feasibility, safety, and preliminary analytical stability of implementing a 12-week university-based resistance training protocol with two distinct periodization models in young university students. Retention, adherence, intervention fidelity, and data completeness were high across groups, and no serious adverse events were observed. These findings indicate that



supervised linear and undulating resistance training programs can be implemented in a university setting with acceptable methodological control and participant engagement.

Both resistance training groups showed favorable preliminary changes in executive function outcomes, physical performance, body composition, and selected peripheral biomarkers when compared with the active control condition. Improvements were observed in inhibitory control, working memory, cognitive flexibility, estimated maximal strength, handgrip strength, countermovement jump, muscle mass, and body fat percentage. The peripheral biomarker profile also showed favorable exploratory changes in BDNF, cathepsin B, IGF-1, IL-6, and C-reactive protein. However, these biomarker findings must be interpreted as peripheral systemic signals and not as direct evidence of central neuroplasticity, neurogenesis, or causal brain-level adaptation.

The comparison between linear and undulating periodization suggested that both models are viable and capable of producing preliminary adaptive responses. The undulating model showed numerically larger changes in several executive, neuromuscular, morphological, and biomarker outcomes, whereas the linear model showed a slightly stronger response in handgrip strength. This pattern does not justify a definitive superiority claim. Instead, it suggests that future trials should examine whether the temporal organization of resistance training load influences specific outcome domains when total exposure, supervision, and adherence are adequately controlled.

Exploratory association analyses indicated that changes in strength, body composition, internal load, and peripheral biomarkers were associated with changes in executive function in bivariate models. Nevertheless, most associations were attenuated after adjustment for group, age, and sex. This finding reinforces the need for mechanistic caution. The observed cognitive and biomarker changes should be interpreted as preliminary signals linked to intervention exposure, not as evidence that any single physiological marker mediated executive function improvement.

Overall, the study provides a coherent pilot foundation for a future definitive randomized controlled trial. The next phase should include a larger sample size, preregistered primary cognitive endpoints, stricter control of sleep, stress, diet, caffeine, and external physical activity, improved expectancy monitoring, and standardized preanalytical procedures for biomarker collection. If feasible, future studies should incorporate complementary neurophysiological or neuroimaging measures to test



mechanistic pathways more directly. Until then, the present findings should be understood as evidence of feasibility and promising preliminary multidomain adaptation rather than confirmatory evidence of efficacy or central neurobiological causation.

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