

Original Article

The Effect of Three Work-Equivalent Whole-Body Vibration Protocols on Acute Neuromuscular Performance in Highly Trained Adolescent Soccer Players

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Abstract

Objectives: The study compared acute neuromuscular responses to three work-equivalent whole-body vibration (WBV) protocols in highly trained adolescent soccer players. **Methods:** Thirteen male soccer players (16.2 ± 0.3 years, $BMI = 24.5 \pm 1.5 \text{ kg/m}^2$) completed a counterbalanced crossover study, performing on separate visits three WBV protocols: (P1) 1 x 3 min, (P2) 3 x 1 min, and (P3) 6 x 30 s. Knee extension maximal voluntary isometric contraction (MVIC) and vastus lateralis EMG (root-mean-square, RMS) were measured at baseline and at 2, 5, and 15 min post-WBV, followed by two CMJ trials at baseline (best retained) and one CMJ trial post-WBV. Time-to-peak torque (TPT), rate of torque development (RTD), and neuromuscular efficiency (NME) were also evaluated. **Results:** No significant main effects of protocol or protocol-by-time interactions were observed across outcomes. Non-protocol effects were observed for EMGRMS normalized to baseline (%) (time, period, and carryover) and for carryover in RFD_{0-80} and CMJ power. Estimated effects were small, with wide confidence intervals. **Conclusions:** Among highly trained adolescent soccer players, a 3-min, work-equivalent WBV exposure administered as 1 x 3 min, 3 x 1 min, or 6 x 30 s did not produce clear protocol-dependent changes in knee extensor isometric performance, neuromuscular indices, or CMJ performance within 2-15 min post-intervention. Any effects appear minimal relative to inter-individual variability.

Keywords: Elite, Football, Post-Activation Performance Enhancement, Post-Activation Potentiation, Vibration Training

Introduction

The ability to produce maximal strength, rapid force development, and large impulse are critical for athletic performance in sports like soccer, where sprinting, jumping, and rapid changes of direction are essential¹. Enhancing

neuromuscular function through acute conditioning activities, such as heavy resistance exercises, whole-body vibration (WBV), and maximal voluntary isometric contractions (MVIC), has been a focus of research aiming to improve acutely athletes' performance through the mechanism of either post-activation potentiation (PAP) or post-activation performance enhancement (PAPE)²⁻⁶. PAP refers to a short-term enhancement of muscle contractile force following intense activation, typically due to myosin regulatory light chain phosphorylation, which increases the sensitivity of actin-myosin cross-bridges^{2,4}. This mechanism results in greater force output at submaximal stimulation and improved twitch responses immediately after conditioning efforts³. In contrast, PAPE describes the improvement in voluntary performance (maximal

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strength, power, speed) that often occurs several minutes after the conditioning activity, usually peaking 6–10 minutes after activation². Importantly, PAP is primarily a mechanistic construct typically demonstrated using twitch or electrically evoked responses, whereas PAPE is a performance-based phenomenon observed during voluntary tasks; therefore, most applied WBV studies.

WBV has emerged as a potentially effective conditioning stimulus to induce acute performance changes consistent with PAPE, potentially by enhancing neuromuscular efficiency (NME) through physiological mechanisms proposed in the literature, such as the tonic vibration reflex, upregulation of muscle spindle sensitivity, increased motor unit recruitment, and elevation of muscle temperature^{7,8}. However, these mechanisms are rarely measured directly in applied studies and should be considered hypothesis-generating, especially in adolescent athletes. WBV has been particularly noted for its ability to enhance performance in power-based tasks such as jumping, with evidence suggesting optimal reflex responses to be observed at lower frequencies (30 Hz) compared to higher frequencies (40–50 Hz)⁹. In soccer players, WBV performed during recovery between sets of repeated-sprints seems to improve performance or delay the onset of muscle fatigue^{10,11}. Additionally, under specific half-time protocols and in selected populations, WBV has been found to attenuate soccer-specific speed, power, and dynamic strength deterioration during half-time. Furthermore, in adult or mixed-age cohorts, these performance metrics can be maintained if a WBV protocol applied during half time¹².

Despite promising findings, research on WBV's acute effects on neuromuscular performance remains inconsistent, with outcomes varying according to protocol characteristics, performance task, timing of assessment, and athlete population¹³. Jump performance, for example, often shows no meaningful improvement after WBV-based PAPE protocols^{14,15}, whereas positive effects have been reported for knee-extensor peak isometric force¹⁶, for cycling sprint performance¹⁷, and for limiting fatigue-related declines in repeated sprint ability^{10,11}. However, these effects are not consistently reproduced across studies. This inconsistency may be attributed to athletes' status and variations in protocol characteristics, including vibration frequency, duration, as well as due to the different post WBV time selection of performance evaluations^{16,18,19}. Furthermore, most studies have focused on adult athletes, with limited exploration of PAP/PAPE effects in adolescent populations. Notably, PAP effects have been shown to be significantly greater in adults compared to pre-adolescent boys and girls, suggesting potential age-related differences in responsiveness to conditioning stimuli^{20,21}. In addition to chronological age, growth and maturation are associated with changes in muscle-tendon structure and neuromuscular function, such as increases in muscle size and tendon stiffness, improved activation and reflex control, and reduced electromechanical delay

and co-contraction. These factors can influence the balance between potentiation and fatigue, as well as the expression of rapid force production in youth athletes^{22,23}.

While PAP and PAPE have been widely examined in adult athletes, there is a lack of data about the acute effects of WBV protocols in highly-trained adolescents²⁴. Additionally, previous studies on soccer players have primarily employed either unilateral or bilateral conditioning activities without assessing their combined effect on athletes' performance. Also, while existing studies on WBV have demonstrated performance improvements following PAP/PAPE interventions, optimal intervention duration remains uncertain²⁵. Therefore, the primary objectives of this study were to: (1) examine the acute effects of three work-equivalent WBV protocols (1 set x 3 min, 3 sets x 1 min, 6 sets x 30 s) on knee extension MVIC and CMJ performance in highly-trained adolescent male soccer players, and (2) explore the time course of performance changes at 2, 5, and 15 minutes post-WBV. We hypothesized that work-equivalent WBV would induce small, time-dependent changes in neuromuscular performance within 2–15 minutes post-exposure, with protocol-specific variations in response.

Methods

Subjects

An interventional, repeated-measures, cross-over study was conducted among adolescent male soccer players from a professional first-division Greek team. Of the 25 athletes on the team, three goalkeepers were excluded due to distinct training regimens, two were unavailable because of serious injuries, and three had sustained recent muscle injuries leading to prolonged absences. An additional three athletes could not participate due to time or travel constraints. Thus, 14 players were initially recruited, and 13 completed all pre- and post-tests for the three WBV protocols (mean age = 16.2 ± 0.3 years, BMI = 24.5 ± 1.5 kg/m²; Table 1 & Figure 1). Participants visited our laboratory four times, spaced one week apart. Sessions were separated by one week to align with the team's weekly microcycle and to account for the short-lived nature of acute WBV effects. The first visit was dedicated to anthropometric and body composition assessments and familiarization with the laboratory environment and equipment (isokinetic dynamometer, WBV device, force platform for jump tests). The subsequent three visits involved the application of one of the three WBV protocols (P1, P2, or P3) in a counterbalanced crossover design. During visits number two to four, after a short warm up, baseline assessments (MVIC with concurrent EMG evaluation, followed by two CMJ trials) were performed. Immediately afterward, one of the three WBV protocols (P1, P2, or P3) was performed. Post-intervention measurements were taken at 2, 5, and 15 minutes following each WBV protocol, in the same

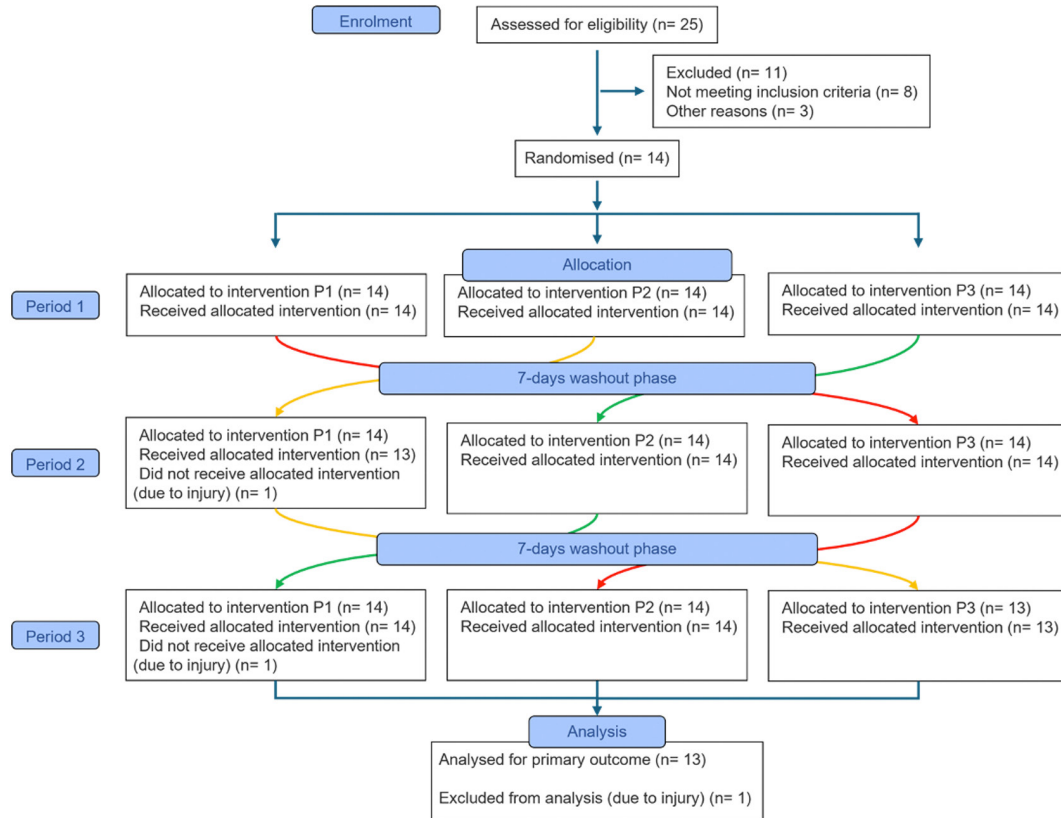


Figure 1. Participants flow diagram.

sequence as baseline (MVIC with EMG, then one CMJ trial). At baseline, two CMJ were performed (best retained) to ensure familiarization and a stable estimate; at 2-, 5-, and 15-min post-WBV, a single CMJ was performed to minimize additional fatigue and delay that could confound transient potentiation responses. A schematic representation of the study design is presented in Figure 2. All measurements were performed in a high-performance assessment laboratory (Sports Excellence Center, “ATTIKON” University Hospital, Athens, Greece) under controlled environmental conditions (24 °C, 60% relative humidity). Data collection sessions were scheduled on Wednesdays between 14:00 and 17:00, aligning with the team’s competition schedule (Sundays) and rest day (Tuesdays).

Participants were assigned to one of the six possible protocol sequences (P1→P2→P3; P1→P3→P2; P2→P1→P3; P2→P3→P1; P3→P1→P2; P3→P2→P1), using a pragmatic approach based on alphabetical order and researcher/athlete availability (2-3 athletes per visit). The first author generated the sequence lists, enrolled participants, and assigned sequences according to a rotating template (e.g., first group P1→P2→P3, next group P1→P3→P2, etc.). No allocation concealment was

Table 1. Anthropometric characteristics (n = 13).

Variable	Mean (SD)
Age, years	16.2 (0.3)
Height, cm	176.4 (8.7)
Body mass, kg	66.9 (6.9)
BMI, kg/m ²	24.5 (1.5)
Fat, %	15.5 (2.1)
Muscle mass, kg	
Total	53.6 (5.2)
Dominant leg	9.8 (1.3)
Non-dominant leg	9.4 (1.2)
Thigh muscle CSA, cm ²	77.4 (7.0)

used. Blinding of participants and testers to condition order was not feasible; pre-specified data-processing rules were applied uniformly. Period (visit order) and carryover (previous protocol) were modeled explicitly for further

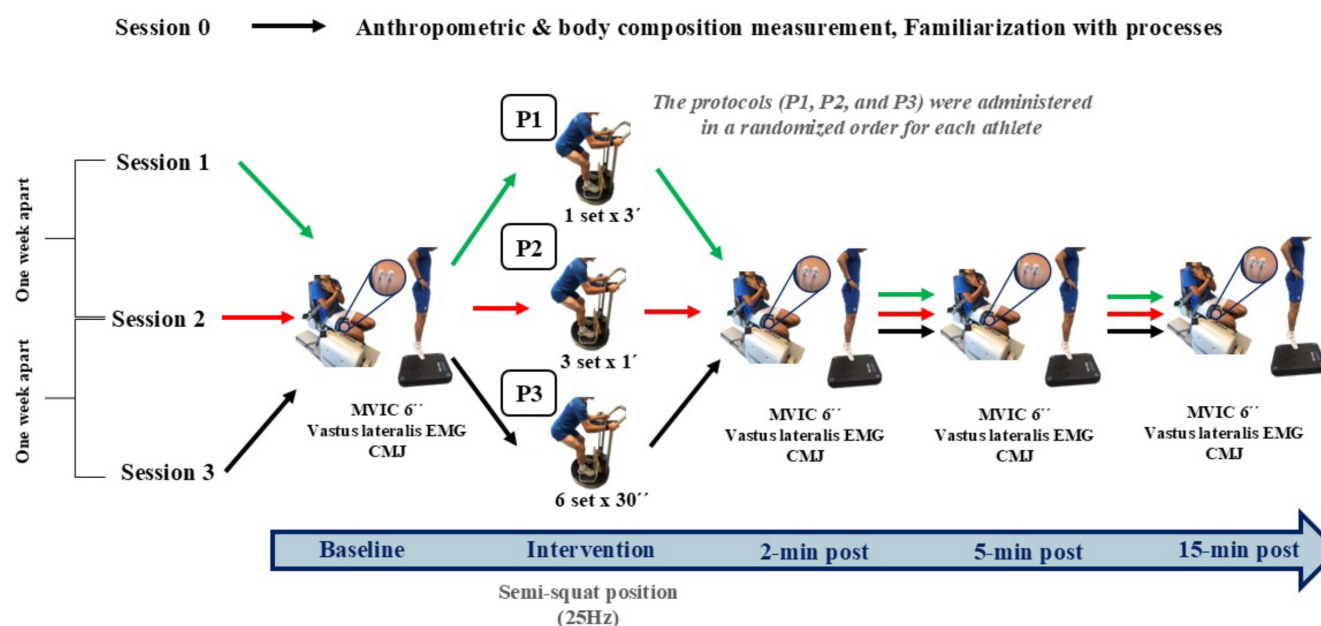


Figure 2. Study design protocol.

analysis. The study was not prospectively registered. Data collection occurred from 15 October 2022 to 4 November 2023.

Procedures

Anthropometric and body composition

Standing height was measured to the nearest millimeter using a wall-mounted tape (Seca 206, Hamburg, Germany). Body composition was assessed via bioelectrical impedance analysis (BIA; MC-780MA, Tanita Co., Tokyo, Japan). Per the manufacturer's prerequisites, participants were well-hydrated, abstained from eating or drinking for at least 3 hours, refrained from vigorous physical activity for at least 24 hours before the assessment, and removed any metallic objects (e.g., jewelry, belts). The BIA provided estimates of fat mass, fat-free mass, and total body water. Body mass index (BMI) was computed from standing height and body mass. To estimate thigh muscle cross-sectional area (CSA) using the Housh, Housh²⁶ equation, the mid-thigh circumference was measured with a flexible measuring rod (Seca 201, Hamburg, Germany), and the anterior thigh skinfold was measured using a Lange Skinfold Caliper (Beta Technology, Santa Cruz, CA, USA). Skinfold assessments were conducted by practitioners with more than ten years of experience.

Familiarization

During the first laboratory visit, each athlete performed a familiarization session of 30 repetitions on an isokinetic dynamometer (System 4 Pro™, Biodex Medical Systems, NY) at 300 deg/s, with a subjective exertion level of approximately 60%. They also performed five countermovement jumps (CMJ) on a force platform (Quattro Jump – Type 9290DD, Kistler Group, Winterthur, Switzerland). They were introduced to the WBV device (Galileo® 900, Novotec Medical GmbH, Pforzheim, Germany) by completing one 30 s set in a half-squat position. In subsequent visits, an 8-minute warm-up on a stationary bike at light-to-moderate intensity (Borg RPE 9-13) with a cadence target of 70-80 rpm was performed before baseline assessments. The selected resistance and cadence were recorded and replicated across all sessions.

Whole-body vibration

A side-alternating WBV device (Galileo® 900, Novotec Medical GmbH, Pforzheim, Germany) set to 25 Hz was employed for all protocols. This frequency was chosen as it is within the recommended 25-40 Hz range¹³ and was considered practical and well tolerated by adolescent athletes. Participants stood in a half-squat (~90° knee flexion; visually monitored) with a shoulder-width stance, wore shoes, and held the handrail for balance. Platform

amplitude was fixed at 2.5-3.0 mm (5-6 mm peak-to-peak displacement). Each athlete completed three WBV protocols –P1, P2, and P3– in a counterbalanced order (protocol *per session*, one session per week). Specifically, P1 consisted of 1 set x 3 minutes, P2 of 3 sets x 1 minute (1-minute standing rest off-vibration), and P3 of 6 sets x 30 seconds (30-second standing rest off-vibration). Exposure time was recorded after the platform reached steady-state 25 Hz (ramp-up/ramp-down not included).

Knee extension maximal voluntary isometric contraction

Knee extension MVIC was assessed on an isokinetic dynamometer (Biodex System 4 Pro™, Biodex Medical Systems, Shirley, NY). Participants were seated with the hips flexed at 90° while the seat orientation (90°) and seatback tilt (80°) were adjusted so that the knee could exert torque at 90° of flexion. The torso was stabilized by double belts, and the arms were crossed over the chest. For the baseline measurement (pre-intervention), athletes performed three isometric contractions: two submaximal efforts (~50% and ~75% of maximal effort) as a warm-up, followed by one 6 second MVIC. Only the final maximal contraction was retained for analysis. At each post-WBV time point (2, 5, 15 min), one 6-s MVIC was collected and analyzed. Variables calculated from the force-time curve included the MVIC, the time to peak torque (TPT), and the rate of torque development (RTD). All outcomes were analyzed as torque (Nm). Signals were gravity-corrected at 30° knee flexion per manufacturer instructions. The lever arm was set with the pad proximal to the malleoli; the device internally computes torque from force x lever arm. MVIC (as the highest peak on the torque curve) and RTD at 80, 150, and 250 ms from the onset of muscle contraction, were calculated according to the following equation: $RTD (Nm/s) = \Delta Torque \times \Delta Time^{-1}$. Contraction onset was identified on the raw torque–time trace as the first consistent rise from the pre-contraction baseline that progressed to the torque peak; this was performed by the same analyst for all files, with no additional filtering. TPT was the time from onset to peak torque. Processing was performed in Microsoft Excel using custom spreadsheet formulas. The ICC for MVIC and RTD were: ICC = 0.90 (95% CI: 0.86, 0.96) and ICC = 0.92 (95% CI: 0.80, 0.98)²⁷⁻³⁰.

Vastus lateralis EMG

During MVIC testing, a synchronized analog EMG system (Biometrics Ltd., Newport, UK) recorded vastus lateralis activity in the dominant leg (the same leg that used for MVIC and RTD evaluations at each time point). Participants were seated with knees slightly flexed for electrode placement. The skin over the midportion of the muscle was shaved, gently abraded, and cleansed with alcohol to reduce impedance. The electrode was placed approximately two thirds of the distance from the anterior superior iliac spine (ASIS) to the lateral border of the patella, aligned parallel

to the muscle fibers. An inter electrode distance of 20 mm was maintained, and the electrodes were secured using adhesive tape. The placement point of the electrodes and the distances between them were marked and recorded, so that the electrodes will be placed exactly at the same points in every session. The sampling rate was set at 2500 Hz, and the raw EMG signal was band-passed filtered (4th-order, zero-lag Butterworth, 20-450 Hz) with a 50 Hz notch (manufacturer default setting) to suppress mains interference, then full-wave rectified and converted to root-mean-square (RMS) using a 50 ms moving window. RMS was primarily reported in raw units (μV), and we additionally analyzed EMG_{RMS} as a percentage of the day-specific baseline MVIC (%). NME was then calculated as the ratio of knee extension torque to the raw RMS of the vastus lateralis EMG signal.

Jump performance

Immediately following MVIC measurement, each athlete performed two CMJ trials at baseline and one CMJ trial at each post-WBV timepoint on the force platform (Quattro Jump – Type 9290DD, Kistler Group, Winterthur, Switzerland). Starting from an upright position with hands on the waist, participants rapidly flexed their knees and then explosively extended them to jump. The best of the two trials was used for analysis. Data from the force platform were recorded and analyzed in order to calculate jump height and maximum power. Jump height was computed from flight time detected by the force plate using the standard equation:

$$h = (g \times t_{\text{flight}}^2) / 8$$

with $g = 9.81 \text{ m/s}^2$; values are reported in cm.

Peak power (W) was obtained from the Quattro Jump software as the maximum instantaneous power:

$$P(t) = F_z(t) \times u_{\text{com}}(t)$$

where $u_{\text{com}}(t)$ is derived by the manufacturer's default integration of net vertical acceleration; no external processing was applied. CMJ_{RFD} was software-derived as the maximum rate of rise of vertical ground reaction force during the concentric phase. The best performance according to the jump height was used for further analysis. The ICCs for jump height and power were 0.87 [95% CI: 0.83, 0.95] and 0.91 [95% CI: 0.90, 0.99]^{28,30}.

Statistical Analysis

Based on a previous study investigating the effect of WBV on physical performance, which reported a large effect size ($f = 0.4$) for the CMJ performance enhancement across time points³¹, an *a priori* power analysis was conducted using G*Power 3.1.9.7 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). The analysis based on the reported effect size, an alpha level of 0.05, and a desired power ($1-\beta$) of 0.90, indicating that a total sample size of 13 participants was needed.

All results are presented as means and standard

Table 2. Estimated marginal mean differences in knee extension isometric performance metrics from pre- to post-intervention (2 min, 5 min, and 15 min) by protocol, and fixed effects p-values from the linear mixed models.

Variable	Protocol	Pre – Post 2 min	Pre – Post 5 min	Pre – Post 15 min	Fixed effects p-values				
		MD [95%CI]	MD [95%CI]	MD [95%CI]	Protocol	Time	Protocol x Time	Period	Carryover
MVIC (Nm)	P1	-17.54 [-92.92, 57.84]	-19.06 [-94.43, 56.32]	-5.66 [-81.04, 69.71]	0.370	0.277	0.994	0.682	0.065
	P2	-37.21 [-104.63, 30.21]	-23.13 [-90.55, 44.29]	-20.82 [-88.24, 46.60]					
	P3	-25.86 [-101.23, 49.52]	-36.75 [-112.12, 38.63]	-19.02 [-94.40, 56.35]					
TPT (s)	P1	1.56 [-0.42, 3.54]	0.95 [-1.03, 2.93]	1.64 [-0.34, 3.62]	0.742	0.072	0.899	0.512	0.439
	P2	0.78 [-1.00, 2.55]	0.60 [-1.17, 2.37]	0.72 [-1.05, 2.50]					
	P3	0.56 [-1.43, 2.54]	0.73 [-1.25, 2.72]	0.39 [-1.59, 2.37]					
RTD ₀₋₈₀ (Nm/s)	P1	-151.43 [-603.31, 300.46]	172.54 [-279.34, 624.43]	74.26 [-377.63, 526.14]	0.109	0.475	0.638	0.126	0.012*
	P2	101.97 [-302.21, 506.14]	28.19 [-375.98, 432.37]	49.79 [-354.39, 453.96]					
	P3	180.24 [-271.65, 632.12]	223.21 [-228.67, 675.10]	139.43 [-312.46, 591.31]					
RTD ₀₋₁₅₀ (Nm/s)	P1	-174.82 [-558.83, 209.19]	-39.06 [-423.07, 344.95]	-67.46 [-451.47, 316.55]	0.322	0.707	0.923	0.295	0.105
	P2	-146.31 [-489.78, 197.16]	-119.94 [-463.41, 223.53]	-121.56 [-465.03, 221.91]					
	P3	50.15 [-333.86, 434.16]	47.47 [-336.54, 431.48]	3.70 [-380.31, 387.71]					
RTD ₀₋₂₅₀ (Nm/s)	P1	-182.89 [-455.79, 90.00]	-69.77 [-342.66, 203.13]	-71.37 [-344.27, 201.52]	0.310	0.155	0.913	0.656	0.094
	P2	-187.79 [-431.87, 56.29]	-99.48 [-343.56, 144.61]	-106.71 [-350.79, 137.38]					
	P3	-19.21 [-292.11, 253.68]	-2.04 [-274.93, 270.86]	-33.95 [-306.84, 238.95]					
EMG _{RMS} (μV)	P1	-6.06 [-130.94, 118.82]	-25.11 [-149.99, 99.77]	-16.11 [-140.99, 108.77]	0.666	0.887	0.999	0.626	0.324
	P2	-2.10 [-113.79, 109.60]	-6.96 [-118.65, 104.73]	6.03 [-105.67, 117.72]					
	P3	-23.26 [-148.14, 101.62]	-27.81 [-152.69, 97.07]	-7.93 [-132.80, 116.95]					
EMG _{RMS} (%)	P1	-1.22 [-16.40, 13.96]	-10.91 [-26.09, 4.27]	-5.00 [-20.18, 10.18]	0.144	0.016*	0.464	<0.001*	0.002*
	P2	1.35 [-12.23, 14.93]	-2.75 [-16.33, 10.83]	6.06 [-7.52, 19.64]					
	P3	-10.92 [-26.10, 4.26]	-14.29 [-29.47, 0.89]	-3.24 [-18.42, 11.94]					
NME	P1	-0.08 [-1.01, 0.86]	0.04 [-0.90, 0.98]	0.03 [-0.91, 0.97]	0.228	0.904	0.994	0.152	0.486
	P2	-0.31 [-1.15, 0.53]	-0.12 [-0.96, 0.72]	-0.26 [-1.10, 0.58]					
	P3	0.001 [-0.94, 0.94]	-0.005 [-0.94, 0.93]	-0.057 [-1.00, 0.88]					

Negative values indicate a decrease from baseline; MVIC, maximal voluntary isometric contraction; TPT, time to peak torque; RTD, rate of torque development; EMG_{RMS}, root mean square of the electromyographic signal from the vastus lateralis muscle; NME, neuromuscular efficiency. * p-value ≤ 0.05.

Table 3. Estimated marginal mean differences in countermovement jump performance metrics from pre- to post-intervention (2 min, 5 min, and 15 min) by protocol, and fixed effects p-values from the linear mixed models.

Variable	Protocol	Pre – Post 2 min	Pre – Post 5 min	Pre – Post 15 min	Fixed effects p-values				
		MD [95%CI]	MD [95%CI]	MD [95%CI]	Protocol	Time	Protocol x Time	Period	Carryover
CMJ height (cm)	P1	0.54 [-4.32, 5.40]	1.18 [-3.69, 6.04]	0.11 [-4.75, 4.97]	0.599	0.472	0.986	0.887	0.368
	P2	0.78 [-3.57, 5.12]	0.98 [-3.37, 5.33]	-0.96 [-5.30, 3.39]					
	P3	0.26 [-4.60, 5.12]	-0.46 [-5.32, 4.40]	-1.68 [-6.54, 3.19]					
CMJ power (W)	P1	-42.75 [-366.30, 280.80]	-49.00 [-372.55, 274.55]	-87.25 [-410.80, 236.30]	0.122	0.546	0.926	0.110	0.031*
	P2	-39.50 [-328.89, 249.89]	42.00 [-247.39, 331.39]	-157.30 [-446.69, 132.09]					
	P3	21.63 [-301.92, 345.17]	3.55 [-323.55, 323.55]	-11.50 [-335.05, 312.05]					
CMJ _{RFD} (N/s)	P1	-375.00 [-8000.78, 7250.78]	1476.00 [-6149.78, 9101.78]	330.00 [-7295.78, 7955.78]	0.914	0.831	0.999	0.544	0.685
	P2	-83.85 [-6904.56, 6736.86]	751.20 [-6069.51, 7571.91]	1029.85 [-5790.86, 7850.56]					
	P3	-1830.25 [-9456.03, 5795.53]	-294.88 [-7920.66, 7330.91]	-409.25 [-8035.03, 7216.53]					
Negative values indicate a decrease from baseline; CMJ, countermovement jump; RFD, rate of force development. * p-value ≤ 0.05.									

deviations (SD). The normality of residuals was examined using the Shapiro–Wilk test, along with visual inspection of Q–Q plots and histograms. To account for the counterbalanced crossover design, data were analyzed using linear mixed models (LMMs) for each outcome variable. Each LMM included fixed effects for Protocol (P1, P2, P3), Time (Pre, Post-2, Post-5, Post-15), and their interaction (Protocol x Time), as well as Period (visit order) and Previous Protocol (the treatment received in the previous session) to test for potential period and carryover effects. A random intercept was included for each subject to account for individual variability. Estimated marginal means (EMMs) were compared using Bonferroni-adjusted pairwise comparisons when appropriate. All models were fitted using restricted maximum likelihood (REML) estimation and small-sample degrees-of-freedom approximations (Satterthwaite)³². We present EMMs with 95% confidence intervals (95%CI) and interpret directional patterns as exploratory when interactions are non-significant. All analyses were conducted using a complete-case approach; only participants who completed all study visits and outcome assessments were included in the LMM, and no imputation of missing

data was performed.

MVIC and CMJ height were predefined as co-primary outcomes. All other neuromechanical and neuromuscular variables (RTD, TPT, EMG, NME, CMJ power, CMJ_{RFD}) were analyzed as secondary outcomes to provide mechanistic and functional context. All statistical analyses were performed using IBM SPSS Statistics for Windows (Version 29.0.2.0; IBM Corp., Armonk, NY), with the alpha level set at $p < 0.05$.

Results

LMM analysis indicated no statistically significant main effects of Protocol and no Protocol x Time interactions for any outcome variables (Tables 2 and 3). For knee extension MVIC, neither protocol ($p = 0.370$) nor time ($p = 0.277$) produced significant main effects, and the protocol by time interaction was not significant ($p = 0.994$) (Figure 3A). For TPT, protocol effects were not significant ($p = 0.742$), and time did not reach significance ($p = 0.072$), although a potential

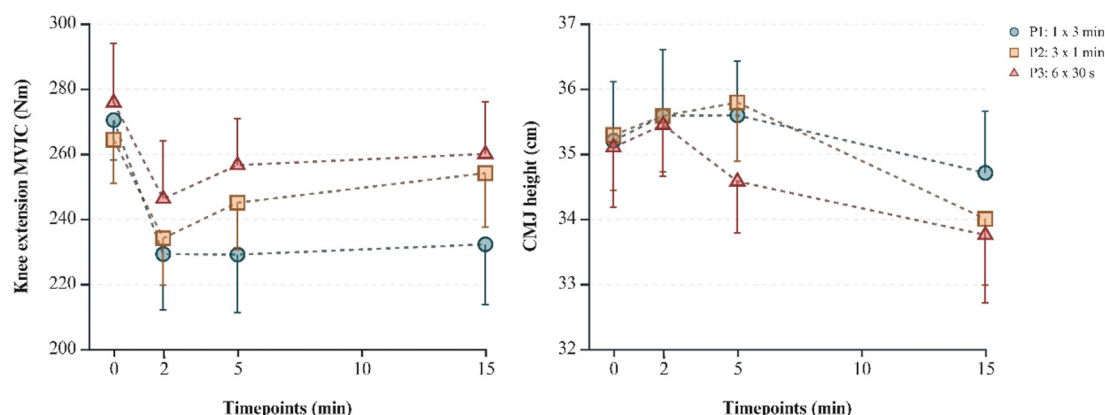


Figure 3. Changes in physical performance over time by protocol for knee extension maximal voluntary isometric contraction (MVIC; panel A) and countermovement jump height (CMJ; panel B). Data are presented as means $\pm$ standard error of the measurement (SEM). Created in <https://BioRender.com>.

temporal trend was observed. For RFD from 0 to 80 ms (RFD_{0-80}), no significant main effects were observed for protocol ($p = 0.109$), time ($p = 0.475$), or their interaction ($p = 0.638$). Similarly, for RFD_{0-150} , protocol ($p = 0.322$), time ($p = 0.707$), and interaction effects ($p = 0.923$) were not significant. In RFD_{0-250} , neither protocol ($p = 0.310$), time ($p = 0.155$), nor the interaction ($p = 0.913$) reached statistical significance. CMJ height showed no significant main effects of protocol ($p = 0.599$) or time ($p = 0.472$), and the interaction was also not significant ($p = 0.986$) (Figure 3B). For CMJ power output, protocol ($p = 0.122$), time ($p = 0.546$), and interaction ($p = 0.926$) effects were not significant. No significant main effects or interactions were found for maximum RFD, EMG amplitude (RMS), or NME. However, EMG_{RMS} normalized to baseline (%) showed a main effect of time ($p = 0.016$) with no protocol or Protocol $\times$ Time effects, while period and carryover terms were significant ($p < 0.001$ and $p = 0.002$). Absolute values for all outcome variables at each timepoint and protocol are presented in Supplementary Table S1 to complement model-based estimates.

To assess potential bias introduced by the crossover design, LMM were conducted with period (visit order) and carryover (previous protocol) included as fixed effects. A significant period effect was observed only for EMG_{RMS} normalized to baseline, whereas all other outcomes showed non-significant period effects ($p > 0.05$). In contrast, significant carryover effects were identified in RFD_{0-80} ($p = 0.012$), baseline-normalized EMG_{RMS} ($p = 0.002$), and CMJ power output ($p = 0.031$). All other outcomes showed non-significant carryover effects ($p > 0.05$), supporting the adequacy of the washout period for most variables.

Discussion

The primary purpose of this study was to examine the acute effects of three work-equivalent WBV protocols on knee extension MVIC and CMJ performances in highly trained adolescent soccer players. In this counterbalanced three-period crossover study, LMMs identified no significant main effects of Protocol and no Protocol $\times$ Time interactions for MVIC, TPT, RTD (0–80/150/250 ms), EMG_{RMS} , NME, or CMJ outcomes. Consequently, protocol-specific interpretations have been omitted in favor of focusing on estimation (EMMs with 95% CIs), uncertainty, and within-subject variability. No period (visit) effects were observed for most outcomes. Carryover effects were detected for RFD_{0-80} and CMJ power and are best interpreted as potential sources of noise rather than evidence of systematic bias. A period effect was identified for baseline-normalized EMG_{RMS} (%), and carryover effects were also detected for baseline-normalized EMG_{RMS} (%). Overall, the configuration of a work-equivalent 3-min WBV exposure (1x3 min, 3x1 min, or 6x30 s) did not produce measurable changes in the acute neuromuscular profile in this cohort.

Because we did not collect direct mechanistic measures (e.g., muscle temperature, reflex/twitch responses, tendon stiffness), any physiological explanations are presented as hypotheses rather than causal interpretations. Despite using three distinct, but equal as for their total time set configurations for WBV, knee extension MVIC did not exhibit a clear protocol-dependent difference. Point estimates indicated small decreases from baseline over time regardless of protocol; however, these changes were not significant in the LMM and confidence intervals were

wide. Typically, PAP or PAPE studies reporting an increase in MVIC post-conditioning highlight the principle that high-intensity or impulsive muscle activity can acutely sensitize contractile properties^{2,4}. This may reflect that rather than enhancing isometric torque in the short term, our WBV protocols might have induced a mild fatigue that outweighed potential PAP benefits. Prior research on adolescent athletes shows that balancing potentiation and fatigue can be challenging²⁰. In the present study, the null to negative shifts may reflect limited fast-twitch recruitment capacity or incomplete recovery within the first 2 to 5 minutes after WBV interventions⁷. Moreover, while a frequency of 25-40 Hz is recommended for acute neuromuscular responses¹³, a 25 Hz may be slightly below the “optimal” WBV frequency –often reported around 30-60 Hz in adults^{33,34}. Although a consistent reduction might be considered contrary to typical PAP responses, it is possible that younger athletes respond differently, with the partial gains to be masked by the WBV induced acute increases of metabolic or neuromuscular fatigue.

Contrasting with the MVIC decrements, estimates for TPT tended to be higher following WBV. However, this effect was not statistically significant and showed high inter-individual variability. Although this pattern could be compatible with altered torque-time characteristics following WBV, we did not collect mechanistic measures and therefore cannot attribute the observed TPT variability to specific neuromuscular or contractile processes. However, while the model suggested a possible time effect ($p = 0.072$) with no protocol effect ($p = 0.742$), confidence intervals were wide and do not support firm inferences. A longer TPT would generally indicate slower force expression and is therefore more consistent with a potentially detrimental or non-beneficial change in rapid force production rather than a desirable neuromuscular adaptation. One interpretation is that muscle contractile or reflex properties changed from the vibration –potentially raising muscle compliance or introducing a slight delay in early cross-bridge formation^{15,35}. Alternatively, partial postural fatigue or decreased synergy in the isokinetic setting might inflate TPT. Interestingly, an increase in TPT does not necessarily contradict PAP³⁶; if an athlete eventually achieves the same or similar peak torque but needs longer time to achieve it, it could reflect a negative shift of neuromuscular functionality and performance. This phenomenon warrants further study focusing on the interplay between the WBV induced changes in muscle functionality, mechanics, motor unit recruitment patterns, and muscle temperature.

While TPT was predominantly higher, RTD results varied. Across both early (0-80 ms) and later (0-150/250 ms) windows, average changes were small; neither Protocol nor Protocol x Time effects reached significance. RTD_{0-80} changes ranged between -7% and +29% (with high SD), lacking main effects for protocol or time. The same was observed for RTD_{0-150} and RTD_{0-250} . Although not statistically significant, participants in P2 and P3 had

smaller negative changes (-10% to -20%) than P1 at certain time points or lower reduction compared to baseline values. This suggests that for late RTD (≥ 150 ms), distributing the WBV stimulus into multiple shorter sets (3×1 min or 6×30 s) may lead to lower RTD decrements. Early RTD, mostly rely on the function of neural system and muscle stiffness, as in cases such as the well-trained power athletes in the percentage cross sectional area (%CSA) of Type IIx muscle fibers³⁰, while late RTD seems to be affected mostly by the size of muscles-muscle fibers and cross-bridge cycle efficiency^{2,37,38}. Our data imply that beyond 150 ms, physiological parameters that determine late RTD, and thus the late RTD performances may benefit from repeated but short-termed WBV bouts (such as P2, P3) instead of long-termed bouts (such as the P1). However, these observations should not be interpreted as performance enhancement, rather they may reflect small differences in the magnitude of decline within the uncertainty of the estimates. Similar findings in adult populations highlight that set configuration are crucial for the possible WBV's effects, probably by mitigation of WBV induced fatigue¹². However, in all cases in the present study, the WBV's effects on RTD performances were negative, indicating that all protocols lead to reduction of RTD performance, with the only difference to be at the magnitude of the protocol induced reductions. A plausible explanation is that adolescents are still developing their neuromuscular system and functionality, thus they cannot respond to a WBV stimuli, in the same way as adults²¹. However, under the current exposure parameters and timings, set distribution did not meaningfully influence RTD in this population. Apparent between-protocol differences in raw means are considered non-confirmatory due to the non-significant interaction and wide confidence intervals.

Raw EMG_{RMS} values (μV) and NME did not show significant effects. EMG_{RMS} changes were modest (-7% to +10%) and mostly non-significant. NME (torque-to- EMG_{RMS}) also showed small negative shifts (range: -12% to -1%), but did not reach statistical significance. In PAP studies, an increased torque-to-EMG ratio indicates more force per unit neural drive. The lack of such an increase might reflect partial fatigue overshadowing the PAP/PAPE positive effects⁴. Alternatively, participants might have already been near their maximal voluntary activation, giving little room to show an EMG-based improvement. The data align with reports that adolescent athletes may require more optimized stimuli to exhibit robust PAP/PAPE or efficiency gains^{21,39}. Moreover, due to substantial inter-individual amplitude variability in surface EMG, EMG_{RMS} was also examined after normalization to the day-specific baseline MVIC. This normalization revealed a time effect for EMG_{RMS} only; however, this is interpreted cautiously as a change in activation proxy rather than performance, and it does not affect the null protocol findings.

CMJ height and power demonstrated no significant model effects. Exploratory trajectories suggested slight early increases followed by later declines, but with broad

confidence intervals and no protocol differentiation. For CMJ height, the changes were generally small (-3.7% to +1.5%) and inconsistent. From pre- to post-2 min or 5 min, changes ranged around 1% for P1 and P2. However, at 15 minutes, a reduction in some of the CMJ parameters were observed (-3.7%). This pattern suggests that if there was a short-term jump improvement, it faded away shortly. Also, these differences may be of similar magnitude to the typical within-session measurement error. Accordingly, any apparent early 'improvement' should be interpreted cautiously and regarded as hypothesis-generating rather than a clear potentiation effect. In other PAP/PAPE studies, lower limb power performances peaking around 5 minutes after a conditioning activity^{2,25}. Also, in young adults, after anterior cruciate ligament reconstruction, a single bout of WBV does not improve jumping performance¹⁴. Our results show no differences among the three WBV protocols, implying that total "work" matters more than set distribution for the acute WBV's induced changes in jumping performance at this age group. In other words, all protocols may have comparable effects on neuromuscular system and jumping performance. By 15 minutes, performance tended to drop below baseline values, suggesting that there is a short time-window for the possible PAP/PAPE phenomenon to took place in adolescents.

Given the negative or minimal net changes in isometric torque, it is plausible that the metabolic cost of sustained half-squats during each WBV protocol overshadowed the potential potentiation of athletes' performances. The modest, although non-significant, short-term improvement in jump performance suggest the presence of a low-level PAP/PAPE response, peaking around at 15 minutes in specific performance variables. The mechanical oscillations of WBV may be less beneficial for stretch-shortening cycle performance (e.g., a jump) than pure isometric contraction¹⁸. However, up to date, it remains inconclusive which approach elicits the largest effects for each athletic task²⁵. Although unmeasured mechanisms such as changes in muscle temperature or reflex excitability are sometimes proposed to explain WBV responses, our data cannot confirm these pathways. This outcome aligns with broader findings in youth soccer contexts, where Annino, Manzi¹⁰ showed that adding WBV during repeated-sprint training in adolescent players can reduce performance drop-off, presumably by maintaining muscle activation and readiness. Similarly, Lovell, Midgley¹² noted that a short WBV bout helped mitigate half-time performance losses in adult soccer. Our participants seem to follow that pattern to a smaller extent, indicating partial synergy between PAP and warm-up benefits for ballistic tasks. However, given the small magnitude of CMJ changes and wide CIs, any early directional trends should be interpreted cautiously and considered hypothesis-generating.

One aim of distributing three minutes of WBV into different set patterns was to see if shorter, repeated bouts

minimize fatigue while maximizing potentiation. Although RTD_{0-150} and RTD_{0-25} exhibited protocol effects, the other variables (MVIC, TPT, CMJ) generally did not. One explanation is that RTD in the later phases might be more sensitive and reliable to subtle differences in how the muscle is pre-activated⁴⁰. Repeated shorter sets (P2, P3) may allow brief rests that mitigate local muscle fatigue, leading to less negative RTD changes than a continuous 3-minute set (P1). Meanwhile, for global performance measures like MVIC and CMJ, the differences were small or overshadowed by other factors. Another factor is timing: our first post-test was at 2 minutes, which might be too early for some participants to benefit from a more distributed protocol. Indeed, adult-based PAPE literature typically uses 2.5-11.0 minutes of rest for optimal performance gains²⁵. Adolescents with lower absolute strength might be fatigued faster and recover faster, complicating the time course^{39,41}. Thus, small differences in set structure may not fully manifest at 2, 5, or 15 minutes but potentially appear at intervals in between. If future studies add multiple interim time points (e.g., 3 or 8 minutes), we might see a clearer advantage for one protocol.

Some study limitations should be considered. Our study includes a modest sample size from a single academy (n=13) of male adolescent soccer players, which may reduce the generalizability. Also, we lacked a control group without WBV, relying on the baseline as our reference. Even so, the crossover design ensures that the same accuracy as a parallel design may be obtained with fewer individuals. At the same time, the intervention effect is compared within a subject since each subject serves as his or her own control, removing in this way the inter-subject variability from the comparison between groups and the effect of covariates can be reduced⁴². Another potential limitation is that we used only 25 Hz vibration, though frequencies near 30 Hz are often cited more frequently in the literature. However, a recent systematic review indicates that a range between 25 and 40 Hz is sufficient to elicit a positive neuromuscular response¹³. Also, surface EMG was recorded only from the vastus lateralis. Vastus lateralis was selected because it has been classified among the most suitable lower-limb muscles for surface EMG recordings, showing high signal quality and relatively consistent innervation-zone location across subjects⁴³. However, the absence of multi-site quadriceps recordings (e.g., rectus femoris, vastus medialis) limits the generalizability of EMG/NME inferences across tasks and sessions. Moreover, the isometric force tests preceded CMJ attempts, so any MVIC test-induced additional PAP or fatigue could blur the results. Another limitation is that some pre-post changes might not have reached statistical significance owing to the conservative Bonferroni correction for multiple comparisons. This correction helps avoid type I errors but can increase type II errors, potentially masking subtle protocol or time differences⁴⁴. Some of the strengths, apart from our within-subject

crossover design where each athlete experienced all protocols, include also the breadth of outcome measures: lower limb isometric torque (MVIC), power and dynamic performance (CMJ), and neuromuscular parameters (RTD, TPT, EMG, NME). Moreover, focusing on highly trained adolescents fills a gap in PAP/PAPE research, which mostly centers on adults. Our data thus offer practical insights for youth soccer coaches considering WBV as a warm-up strategy. Last, this study was not prospectively registered because it was conducted as part of an MSc thesis under fixed academic timelines, and prospective registry submission was not required at our institution for single-centre, minimal-risk laboratory crossover studies led by students. Nevertheless, the study received prior ethics approval, and written informed consent was obtained. We acknowledge that preregistration enhances transparency.

In conclusion, under the current frequency, amplitude, and total exposure conditions, set configuration (1 x 3 min, 3 x 1 min, or 6 x 30 s) did not yield significant protocol effects or protocol by time interactions. The observed changes were minimal, transient, and varied among individuals, indicating limited potential for robust acute potentiation within this cohort. Therefore, WBV may function as a potentiation stimulus for youth soccer players, although the overall effect may be minor or inconsistent without careful attention to frequency, rest intervals, and the athletes' readiness. For practical application, coaches aiming for acute performance improvements might find slight benefits from a brief bout of WBV before competition or training, but the effect lasts only about 2 to 5 minutes. Future research should investigate various frequencies and include additional interim time points to optimize WBV protocols for adolescent populations, clarifying the best ways to utilize PAP/PAPE in youth soccer settings.

Ethics Approval

The study was approved by the Scientific Committee of the "ATTIKON" University Hospital (Α' ΟΡΘΟΠ, ΕΒΔ3/5-1-2022). All study procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki (2013 revision).

Consent to Participate

Written informed consent to participate in this study was provided by the participants or their legal guardians.

Authors' Contributions

PA, SM, PK and CT conceived and designed the study. PA, AZS, SM, PK and CT developed the methodology. PA, GP, AT and CT carried out the experiments. AZS and GP performed formal analysis; AZS and AT prepared the visualisations. PA, GP and AT curated the data. PA, AZS and SM drafted the manuscript. GP, AT, PK and CT critically reviewed and edited the manuscript. CT and PK supervised and administered the project. All authors read and approved the final manuscript.

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Supplementary Table S1. Absolute values (means $\pm$ SD) of all outcome variables at baseline and at each post-intervention timepoint (2, 5, and 15 min) for each WBV protocol.

Protocol	Time		MVIC (Nm)	TPT (s)	RTD80 (Nm/s)	RTD150 (Nm/s)	RTD250 (Nm/s)	CMJ (cm)	CMJ power (W)	CMJRFD (N/s)	EMGRMS (μ V)	EMGRMS (%)	NME
P1: 1x3 min	Pre	Mean	270.37	1.42	920.64	1028.02	843.79	35.20	1896.69	11750.69	193.26	100.00	1.61
		SD	44.02	1.12	227.04	188.76	125.01	3.27	348.49	7129.29	82.88	-	0.64
	Post-2	Mean	229.21	2.81	874.07	863.20	653.62	35.58	1851.92	12794.23	185.45	99.56	1.38
		SD	61.61	1.80	402.07	416.94	264.00	3.65	322.30	8559.55	68.18	19.40	0.61
	Post-5	Mean	229.04	2.38	1028.24	915.77	705.05	35.59	1836.62	12311.46	173.98	93.42	1.43
		SD	64.44	1.44	342.22	294.24	233.79	3.01	302.30	5447.66	65.58	18.47	0.51
	Post-15	Mean	232.20	2.94	907.35	838.58	665.89	34.71	1811.15	10796.08	186.02	100.72	1.36
		SD	66.96	1.72	357.51	292.91	210.24	3.42	373.54	4134.01	64.04	22.40	0.55
P2: 3x1 min	Pre	Mean	264.33	1.63	970.93	1053.55	851.47	35.29	1918.08	10882.35	176.43	100.00	1.86
		SD	48.23	1.05	251.21	242.03	162.29	3.07	276.71	4144.72	107.23	-	0.78
	Post-2	Mean	234.08	2.49	1034.59	894.23	675.56	35.58	1947.08	10575.62	175.98	101.72	1.60
		SD	52.36	1.68	330.48	229.74	162.73	3.09	236.69	4133.30	100.96	14.83	0.67
	Post-5	Mean	245.00	2.09	993.85	918.28	747.37	35.79	1996.85	10536.58	174.74	99.73	1.73
		SD	52.39	1.28	300.46	221.82	165.70	3.26	250.34	4851.11	102.66	18.37	0.71
	Post-15	Mean	254.09	2.74	1018.74	945.97	763.42	34.00	1829.62	10947.69	192.21	110.82	1.60
		SD	59.84	2.02	384.85	292.22	214.76	3.66	254.46	6779.46	107.20	19.74	0.65
P3: 6x30 s	Pre	Mean	275.77	1.80	975.73	1040.46	836.63	35.10	1893.38	11615.46	188.88	100.00	1.70
		SD	65.66	1.12	292.79	312.65	235.72	3.32	250.42	7424.90	80.04	-	0.75
	Post-2	Mean	246.20	2.42	1057.78	1012.61	719.17	35.44	1911.69	10061.54	172.05	92.96	1.60
		SD	64.46	1.70	357.70	260.30	249.22	2.84	259.20	3144.23	66.77	11.19	0.64
	Post-5	Mean	256.54	2.32	1127.16	1035.71	820.71	34.58	1898.38	11273.69	165.76	88.97	1.76
		SD	51.38	1.73	279.06	211.96	173.32	2.87	228.18	6233.28	66.89	10.71	0.69
	Post-15	Mean	259.97	2.43	1004.87	951.17	760.70	33.75	1887.38	10975.08	181.27	96.38	1.72
		SD	57.46	1.48	412.33	314.12	202.18	3.75	238.67	3543.21	82.36	20.16	0.82