Effects of jump training on power, strength, balance and aerobic performance in non-exercising young adults

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Abstract

Physical inactivity is a major risk factor for noncommunicable diseases and associated mortality worldwide. A specifically tailored jump training has proven to be an efficient exercise countermeasure that can maintain health resources despite two months of otherwise complete inactivity. In the present study, we tested the effects of such a training program under real-life conditions. Seventy-five young adults (38 female, age 23 ± 3 years) were randomly assigned to either a training or a control group. The training group underwent an 8 week jump training with 15 min of jump exercises, 3 days per week. Before and after the 8-week period as well as another 8 weeks later we tested jump performance in countermovement jumps (CMJ) and hops, balance performance during one leg stance, maximal isometric strength of leg extensor muscles, stair climb performance, gait analysis, and peak oxygen uptake in a cardiopulmonary exercise test. We observed training specific increases (8 ± 9 %) in CMJ height that were explained by an optimized movement technique during the jump. We did not observe any generic improvements of anaerobic or aerobic power, strength or balance performance after the training. Solely for peak oxygen uptake, participants exhibiting low baseline levels appeared to benefit from the jump training. As the effectiveness of such training on several physiological systems had been demonstrated previously during bed rest, it is reasonable to hypothesise that the training load employed in the present study was sub-threshold for more generic adaptations in non-exercised but otherwise active participants.

Introduction

There is clear evidence that physical activity comes along with huge benefits on health and longevity (Argentieri et al., 2025; Saqib et al., 2020). Notwithstanding such evidence and decades of tremendous political endeavours to increase physical activity in the population, a large and still increasing proportion of people is insufficiently active (Guthold et al., 2018). A recent meta-analysis on studies using wearable devices indicated a downward trend in physical activity in the order of −600 steps per day per decade for adults and −1500 steps per day per decade for adolescents since 1995 (Conger et al., 2022). The consequences are disastrous: physical inactivity will continue to increase in significance as a major risk factor for non-communicable diseases (Lee et al., 2012), leading to an ever-increasing economic burden (Ding et al., 2016) and mortality rate (World Health Organization, 2022).

A seamless alternative to programs that aim at increasing physical activity are exercise programs which have the inherent potential to counteract the negative consequences of physical inactivity (American College of Sports Medicine, 1999). The best available experimental model to study exercise countermeasures against detrimental effects of physical inactivity in a healthy population is bed rest (Bergouignan et al., 2011; Gruber et al., 2019). Since decades a large number of potential exercise programs to mitigate the effects of bed-rest on the cardiovascular, the neuromuscular and the skeletal system, have been tested. However, most of the tested countermeasures were specifically targeting only one of those physiological systems (Swain et al., 2021). Recently we developed and implemented a jump exercise countermeasure during a 60-day bed-rest, designed to address all physiological systems in an integrative exercise approach (Kramer, Kümmel, et al., 2017).

The follow-up to this study has clearly shown that such a training significantly mitigated the effects of bed rest on the cardiovascular system (Koschate et al., 2018; Koschate et al., 2021; Kramer, Gollhofer, et al., 2017; Maggioni et al., 2018; Rabineau et al., 2020) and was even more effective in preserving bone and muscle mass (Kramer, Kümmel, et al., 2017), muscle structure, phenotype and myofiber oxidative capacity (Blottner et al., 2019) as well as muscle power (Kramer et al., 2018) and strength (Kramer, Gollhofer, et al., 2017). In addition, the jump training demonstrated its potential as an integrated countermeasure as it prevented declines in postural control, gait characteristics and functional mobility (Ritzmann et al., 2018). With regard to the generic and significant effects despite the short duration of only 15 min of training during 5 days a week, high impact exercises can be considered most efficient in counteracting inactivity related degradations in physical performance (Gruber et al., 2019).

In the present study, the training program was transferred from the bed rest model to a real-life scenario. We tested the effects of a jump training program on healthy non-exercising young adults, a cohort that is usually characterized by low physical activity and performance levels. With only 3 training sessions of 15 minutes per week, but at high to maximal intensity, we tried to provide a sufficient stimulus for training adaptations. As our primary outcome, we hypothesized to find increases in jump performance in the training group vs. our control group. As secondary outcomes we looked at a variety of physical performance measures, to identify potential effects on power, strength, balance, functional motor performance, and aerobic capacity.

Methods

Participants

The study focused on adults who were not involved in an exercise program at the time of recruitment. Further exclusion criteria were any acute injuries, physical illnesses, mental illnesses, medication use, and any other medical conditions that did not allow jump exercises at the start of the study. The training study was part of a larger study in which the participants carried out further experiments for which additional exclusion criteria were set (e.g. no tattoos due to MRI requirements). Thus, out of the 890 individuals who completed an online screening, 75 were enrolled and 65 completed the Post + 0 measurements and were therefore included in further analysis (see Figure 1 for details).

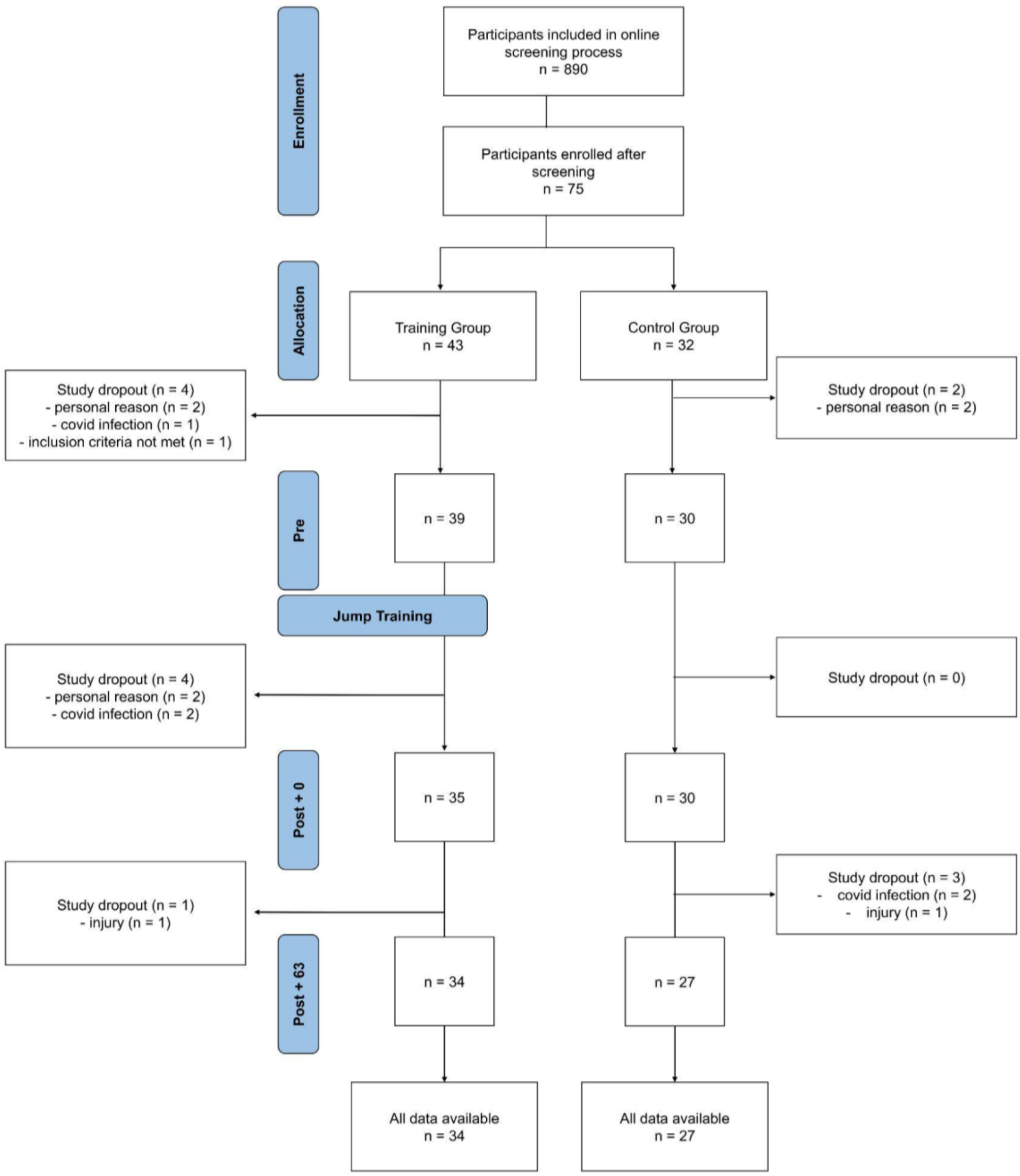

Figure 1. The flowchart illustrates the enrollment, allocation, and follow-up process of participants in the study. Physical performance was tested before the training (Pre), directly after the 8-week training program (Post + 0) and another 8 weeks later (Post + 63). Please note that dropouts occurred at various stages due to different reasons, which were all unrelated to the study itself.

The study was approved by the Ethics Committee of the University of Konstanz (No. 31/2022) and conducted in accordance with the latest revision of the Declaration of Helsinki. At Pre, the 65 participants (34 females, age 23 ± 3 years, body height 173 ± 8 cm, body mass 71 ± 12 kg, resting heart rate 78 ± 13 min^{-1}, systolic blood pressure 125 ± 13 mmHg, diastolic blood pressure 83 ± 10 mmHg) signed an informed consent form, after we provided detailed verbal and written information about the study design and procedures, exclusion criteria and potential risks.

We randomly assigned participants to either a training group (n = 35; 18 females, age 23 ± 3 years, body height 172 ± 8 cm, body mass 70 ± 10 kg, resting heart rate 78 ± 13 min^{-1}, systolic blood pressure 125 ± 15 mmHg, diastolic blood pressure 84 ± 11 mmHg) or a control group (n = 30; 16 females, age 23 ± 2 years, body height 173 ± 9 cm, body mass 73 ± 14 kg, resting heart rate 78 ± 13 min^{-1}, systolic blood pressure 124 ± 11 mmHg, diastolic blood pressure 82 ± 9 mmHg) using a computer-generated randomisation sequence. As we assumed a higher drop-out rate in the training group, we initially assigned 30 per cent more participants to this group compared to the control group. The participants in the training group performed high-intensity jump training 3 times a week for 8 weeks. At Pre, we administered a battery of tests to assess the physical baseline performance of all participants. After 8 and 16 weeks (Post + 0 and Post + 63, respectively), we reassessed all participants using the same set of tests with the identical order as in the Pre session. We measured body mass and height at the beginning of each test session. Afterwards, participants performed a warm-up consisting of 30 seconds of jumping jacks, 30 seconds of CMJs, and 30 seconds of high knee running. All exercises were demonstrated once by the experimenter before the warm-up started. The rest between tasks was 30 seconds and we instructed participants to perform all tasks of the warm-up with submaximal effort.

Performance tests

After the warm-up, we assessed CMJ performance, hopping performance, and static balance of participants using a Leonardo Mechanograph® GRFP force plate (Novotec Medical GmbH, Pforzheim, Germany) operating at 800 Hz. First, participants performed 3 maximal CMJs with their hands on their hips. We instructed them to stand still until they heard a loud beep, after the beep, they should perform the CMJ with the aim of jumping as high as possible while keeping the legs straight during the flight phase. Participants had a 1-minute break between each jump. We used custom written MATLAB© scripts (MathWorks, Natick, MA, USA) to analyse all force traces off-line and conducted all analyses according to previous methodology (Ruggiero et al., 2022; for details see also Supplementary Material S1). For in depth analysis of jump kinetics we chose specifically the following variables (see Ruggiero et al., 2022; Twible et al., 2024): jump height [m], absolute [kW] and relative (to body mass) [W kg^{-1}] peak power, absolute [kN] and relative [N kg^{-1}] force at zero velocity, upward movement range [m], and upward and braking movement duration [ms]. Jump height was calculated using the impulse-momentum method. For comparability with previous literature using field-based methods (Wade et al., 2020), jump height was also calculated using flight time; results are reported in the Supplementary Material S1. For statistical comparisons, we calculated the average of the 3 CMJs for each variable.

Following the CMJs, participants performed 2 sets of 10 reactive hops with the instruction to hop as high as possible and to keep ground contact time as short as possible. From each hopping trial, hops 4 to 8 were retained for further analysis. The following variables were calculated, and averaged across the 5 selected hops, and the two trials, to obtain representative values per participant per session: contact and flight time [ms], reactive strength index (ratio of flight to contact time), hop height [m], absolute [kN] and relative [N kg^{-1}] peak force. The calculations were performed using previously reported methods and algorithms (Kramer, Kümmel, et al., 2017). Further details of the analysis can be found in Supplementary Material S2.

Thereafter, participants performed a single-leg standing test to assess static balance. We instructed participants to stand as still as possible on their dominant leg (determined as the leg used to kick a ball) and keep their hands on their hips for 15 seconds. We measured the change in position of the centre of pressure (CoP) on the force plate and derived an ellipse with the area covering 95% of the CoP path [cm^2].

We used a dynamometer (Isomed 2000, D&R Ferstl GmbH, Nuremberg, Germany) to determine maximum isometric leg press strength (iMVC). Participants were positioned in a leg press module with 60° hip flexion, 90° knee flexion and 90° ankle plantarflexion. The leg press was equipped with a force plate to measure ground reaction forces during the maximal leg extension trials (Dirnberger et al., 2013; Siebert et al., 2016; Zöger et al., 2025). Participants were instructed to “push themselves off as hard as possible from the force plate”. Each trial lasted 3 s, and we repeated it 3 times, with 30 s rest between trials. The positioning data for each participant was then stored in the dynamometer, but technical issues led to incorrect standardization for some participants. As a result, we needed to exclude leg press data from 14 training group participants at Pre and Post + 0, and 15 at Post + 63. In the control group, we needed to exclude 18 at Pre and Post + 0, and 17 at Post + 63. Thus, we ended up with 31 participants in total who were included in the final analysis of leg press data. We took the maximum force value from each trial and determined the isometric MVC for each participant as the mean of the maximum force values of the 3 trials.

To assess potential transfer effects in activities of daily living, we conducted a 14-step stair climb and a gait test. The 14-step stair climb was performed at habitual speed. Prior to the stair climb, we asked participants to stand still for two minutes. Immediately, after the 2 min we measured their heart rate [min^{-1}] by a sports watch (Polar Vantage 2©, Polar OY, Kempele, Finland) with a chest strap and a heart rate monitor (Polar M10 HR-monitor©, Polar OY, Kempele, Finland). Thereafter, the participants climbed up the stairs and we assessed the climbing time [s] with a stopwatch. Then participants stood still again, and we measured the heart rate peak [min^{-1}] within a 30s-window after the stair climb test. Following the stair climb test, we conducted 8 gait test trials using the OptoGait© system (Microgate©, Bolzano, Italy) over a 10 m corridor. We instructed participants to walk at an "everyday pace, as if walking calmly to the bus stop". We extracted gait variables from the proprietary OptoGait© software (Lienhard et al., 2013), which gives the mean plus standard deviation for stride time [s], stride length [m] and mean walking speed [ms^{-1}] of the 8 trials for each participant.

Lastly, we performed a cardiopulmonary exercise test (CPET). Participants laid down for 5 minutes and we determined resting heart rate [min^{-1}] (Polar M10 HR-monitor©, Polar OY, Kempele, Finland) and blood pressure (Boso medicus X©, BOSCH + SOHN GmbH u. Co. KG, Jungingen, Germany). Thereafter, participants performed an incremental ramp test on a cycle-ergometer (Ergoline GmbH, Bitz, Germany) while we measured heart rate and breath-by-breath respiratory gas exchange with an Ergostik© gas analyzer (Geratherm Respiratory GmbH, Bad Kissingen, Germany) and the Blue Cherry© diagnostic platform. The test started with a 5-minute warm-up at 35 W, during which we instructed participants to "ride straight ahead for 5 min on a flat road at a comfortable everyday pace as if taking a leisurely Sunday stroll". After the 5min warm-up, power output increased by 3 W every 12s (15 W per minute) and participants kept their cadence between 70 and 80 min^{-1}. We determined exhaustion when participants could no longer maintain 60 min^{-1}, or until they could go no further. Further, we determined $\dot{V}O_{2peak}$ [ml $kg^{-1}min^{-1}$] as the peak value of a 30-second moving average of breath-by-breath oxygen uptake. We determined peak power [W] and peak heart rate [min^{-1}] as the maximum values that were achieved during the test. During off-line analysis we identified artifacts in O_2 and CO_2 breath-by-breath data that affected $\dot{V}O_{2peak}$ detection, likely due to equipment failure or incorrect mask positioning. In total we needed to exclude five measurements, which led to a further drop-out of five participants specifically for the CPET (3 control, 2 training).

Jump training protocol

The participants of the training group performed jump training sessions of 15 minutes on 3 days a week for 8 weeks. We instructed the participants of the control group to maintain their normal daily routine for 8 weeks and they did not receive any training or any other intervention during this time. For the training group, we gradually increased the intensity and volume of the training, with a minimum of 24 hours rest between 2 sessions. We instructed the training group to perform 3 sessions per week, with 1 session taking place under controlled laboratory conditions at the Human Performance Research Centre (HPRC), University of Konstanz. We fully explained and instructed the participants on how to perform the remaining 2 weekly sessions, after which they were performed at home. Each training session consisted of 4 parts: a standardized warm-up (30 seconds jumping jacks, 30 seconds submaximal CMJs, and 30 seconds high knee running), hoppings, CMJs and high-intensity CMJ training (HIT). After the warm-up, in the main section of the training session, we varied CMJs and hops in number of repetitions and length of rest to progressively increase the training effort throughout the training program (see Supplementary Material S3 for information about the training programming per session). We thoroughly explained all parts of the training during the first training session, which was held at the HPRC. We further provided a detailed training plan to the participants (see Supplementary Material S4) containing video links that allowed participants to review the warm-up and exercises at home.

We provided all participants with a sports watch (Polar Vantage 2©, Polar OY, Kempele, Finland) to store and track their training units. The watch expertly guided the participants through each training session, automatically indicating the start and end of each exercise, as well as the duration, number of repetitions and length of breaks. Jump training adherence was defined as the number of recorded jump training sessions lasting longer than 10 minutes, expressed relative to the prescribed total of 24 sessions. Peak training intensity was calculated as the peak heart rate achieved during each session, expressed as a percentage of the individual's peak heart rate determined during the CPET at Pre.

Statistical analysis

We conducted all statistical analyses in R (version R4.2.2) and created figures using ggplot2 or MATLAB© (TheMathworks, Natick, USA). To test for baseline differences between participants of the training and the control group, we ran independent t-tests for all dependent variables at Pre using the R stats package. To examine the effects of training over time, we computed linear mixed effects models using the lmer function (lme4 package). We treated performance measures as dependent variables, with fixed effects for time (Pre, Post + 0, Post + 63), group (training, control), and their interaction (time × group). We added a random intercept for participants to account for within-subject variability and evaluated model significance by type III ANOVA using the Anova function (car package). In case of significant group x time interaction effects, we executed post-hoc pairwise comparisons with estimated marginal means (emmeans) using the Bonferroni correction. We calculated effect sizes as Cohen's d for pairwise comparisons and partial eta squared (η^2) for ANOVA main and interaction effects.

To gain more detailed insights into the observed changes in CMJ technique, we applied functional principal component analysis (Warmenhoven et al., 2021) to the normalized relative force-time traces, which is an unsupervised learning technique used to identify the functions explaining the greatest variance in relative force from pre-training to Post + 0. Details on this procedure are provided in Supplementary Material S5.

To explore relationships between baseline scores and changes in CMJ and aerobic performance, we calculated pre-post delta scores for CMJ height and $\dot{V}O_{2peak}$, e.g. $\dot{V}O_{2peak}$ changes as (($\dot{V}O_{2peak}$ post - $\dot{V}O_{2peak}$ pre) / $\dot{V}O_{2peak}$ pre*100)). We used Pearson's correlation coefficients for analyses and visualized the relationships with scatter plots. Furthermore, we fitted linear regression models to the delta plots and plotted confidence intervals using geom_smooth in ggplot2.

Results

The groups did not differ significantly on any of the measured variables in the pre-test. Participants of the training group recorded an average of 22 ± 4 jump training sessions, corresponding to a mean adherence rate of 92% ± 17%. The relative peak intensity across all training sessions was 92% ± 5%.

There were no main effects for group nor time but significant group x time interaction effects for all analysed variables of the CMJ (Table 1). Post-hoc analysis showed an increase in jump height (8 ± 9 %), higher absolute (4 ± 8 %) and relative peak power (5 ± 7 %) as well as a greater upward movement range (16 ± 17 %) and upward movement and braking duration (19 ± 21 %; 31 ± 36 %) from Pre to Post + 0 for the training group, while absolute (-8 ± 12 %) and relative forces at 0 velocity (-8 ± 11 %) were decreased. All changes were maintained at Post + 63, except absolute and relative peak power, which did not significantly differ at Post + 63 compared to Pre or Post + 0. We did not find any changes in the control group for none of the analysed variables. We then analysed correlations between changes of jump height from Pre to Post + 0 and jump height at Pre for the training (Figure 2A) and the control group (Figure 2B). Increases in jump height after training were not correlated with baseline levels of jump height in the training group (Figure 2A).

Functional principal component analysis on CMJ relative force-time traces revealed that the scores of the first and third component significantly decreased and increased, respectively, from Pre to Post + 0 in the training group only (Figure S5). These changes indicated reduced relative force throughout the movement after training, except at higher velocities near takeoff, where relative force increased.

The effect of these changes in the kinetic variables of CMJs for the training group, or lack of them for the control group, is shown in Figure 3, where velocity-displacement, relative force-time, and relative force-velocity traces are reported for all testing sessions. As shown by the mean velocity-displacement traces, participants increased the depth of the countermovement after training, exhibiting greater negative displacement values. This resulted in a longer duration of braking and upward movement and a greater range of upward movement, as shown by the shift to the right for the start of the relative force-time curve in the Post + 0 and Post + 63 sessions compared to Pre.

Flight time, contact time, reactive strength index, jump height and absolute and normalized peak force during hops remained unchanged over the measurements at Pre, Post + 0 and Post + 63 (see Table 1). Moreover, there were no significant effects of time, group or group x time interaction for absolute nor relative MVC in the leg press test. We found the same result, no interaction effects, for the one-leg stance, gait, and stair climb tests, while a main effect of time was observed for stride length during gait and stair climb time with shorter stride lengths and shorter stair climb times at Post + 0 and Post + 63 vs. Pre (see Table 1).

When we looked at maximal aerobic capacity, we did not observe a group x time interaction effect for $\dot{V}O_{2peak}$ nor one for absolute and normalized maximal load during the incremental CPET (see Table 1). However, we found a significant main effect of time for absolute and relative maximal load, with higher values at Post + 0 and Post + 63 compared to Pre. We also saw a correlation between changes in $\dot{V}O_{2peak}$ between Pre and Post + 0 and baseline levels of $\dot{V}O_{2peak}$ at Pre, only in the training group with the confidence interval indicating a potential increase in $\dot{V}O_{2peak}$ after training for participants with Pre baseline values lower than 37 ml $kg^{-1}min^{-1}$ (Figure 2C and 2D).

Table 1. Overview on the type 3 ANOVA for mixed models results for all performance variables. The first column subdivides the table into the different tests with the independent variables listed in the second column. Descriptive values are presented as Mean ± SD for the training (t) and control (c) groups and for Pre, Post + 0 and Post + 63, respectively. ANOVA results are reported using Chi-square (χ^2), p-value, and Eta-square (η^2). Post-hoc analyses were performed only for variables that demonstrated statistically significant group x time interaction effects and are presented with p-values and Cohen's d. Significance levels are indicated as follows: $p < .05$*, $p < .01$**, $p < .001$***.

Measurement	Variable	Group	Pre	Post + 0	Post + 63	Group	Time	Group x Time	Post hoc tests		
									Pre to Post + 0	Pre to Post + 63	Post + 0 to Post + 63
Counter Movement Jump Test	Jump height [m]	t	0.34 ± 0.07	0.37 ± 0.08	0.36 ± 0.08	$\chi^2(1) = 0.45, p = .501, \eta^2 = 0$	$\chi^2(2) = 1.42, p = .492, \eta^2 = 0.11$	$\chi^2(2) = 27.68, p = .000***, \eta^2 = 0.18$	p = .000***, d = -1.53	p = .000***, d = -1.19	
		c	0.35 ± 0.07	0.35 ± 0.07	0.35 ± 0.06						
	Peak power absolute [kW]	t	2.73 ± 0.74	2.84 ± 0.77	2.80 ± 0.76	$\chi^2(1) = 1.32, p = .251, \eta^2 = 0.01$	$\chi^2(2) = 0.88, p = .643, \eta^2 = 0.03$	$\chi^2(2) = 9.21, p = .010*, \eta^2 = 0.07$	p = .002**, d = -0.85		
		c	2.97 ± 0.95	2.94 ± 0.95	2.93 ± 0.84						
	Peak power normalized [W kg⁻¹]	t	39.0 ± 7.1	40.8 ± 8.0	40.1 ± 7.7	$\chi^2(1) = 0.54, p = .462, \eta^2 = 0$	$\chi^2(2) = 1.99, p = .370, \eta^2 = 0.03$	$\chi^2(2) = 15.74, p = .000***, \eta^2 = 0.11$	p = .000***, d = -1.04		
		c	40.3 ± 7.3	39.7 ± 7.0	39.9 ± 6.0						
	Force at 0 velocity absolute [kN]	t	1.39 ± 0.25	1.27 ± 0.25	1.30 ± 0.25	$\chi^2(1) = 0.7, p = .402, \eta^2 = 0.05$	$\chi^2(2) = 2.42, p = .298, \eta^2 = 0.14$	$\chi^2(2) = 9.5, p = .009**, \eta^2 = 0.07$	p = .000***, d = 1.2	p = .000***, d = 0.96	
		c	1.45 ± 0.32	1.42 ± 0.33	1.46 ± 0.34						
	Force at 0 velocity normalized [N kg⁻¹]	t	20.0 ± 2.2	18.4 ± 2.4	18.7 ± 2.2	$\chi^2(1) = 0, p = .998, \eta^2 = 0.03$	$\chi^2(2) = 3.16, p = .206, \eta^2 = 0.15$	$\chi^2(2) = 8.8, p = .012*, \eta^2 = 0.07$	p = .000***, d = 1.21	p = .000***, d = 1	
		c	20.0 ± 2.6	19.5 ± 2.7	20.0 ± 3.1						
	Upward range [m]	t	0.39 ± 0.08	0.45 ± 0.07	0.44 ± 0.07	$\chi^2(1) = 0.12, p = .724, \eta^2 = 0.07$	$\chi^2(2) = 1.5, p = .472, \eta^2 = 0.2$	$\chi^2(2) = 19.9, p = .000***, \eta^2 = 0.14$	p = .000***, d = -1.56	p = .000***, d = -1.43	
		c	0.38 ± 0.08	0.39 ± 0.08	0.38 ± 0.08						
	Upward duration [ms]	t	292 ± 56	342 ± 54	338 ± 54	$\chi^2(1) = 0.18, p = .669, \eta^2 = 0.09$	$\chi^2(2) = 3.31, p = .191, \eta^2 = 0.22$	$\chi^2(2) = 14.15, p = .001**, \eta^2 = 0.1$	p = .000***, d = -1.52	p = .000***, d = -1.38	
		c	286 ± 49	301 ± 66	288 ± 65						
	Braking duration [ms]	t	200 ± 78	249 ± 68	245 ± 65	$\chi^2(1) = 0.01, p = .941, \eta^2 = 0.04$	$\chi^2(2) = 1.6, p = .448, \eta^2 = 0.15$	$\chi^2(2) = 8.53, p = .014*, \eta^2 = 0.07$	p = .000***, d = -1.19	p = .000***, d = -1.1	
		c	199 ± 69	212 ± 81	200 ± 88						
Hop Test	Contact time [ms]	t	233 ± 34	228 ± 39	224 ± 34	$\chi^2(1) = 0.37, p = .543, \eta^2 = 0.03$	$\chi^2(2) = 1.24, p = .538, \eta^2 = 0.02$	$\chi^2(2) = 1.25, p = .536, \eta^2 = 0.01$			
		c	239 ± 42	243 ± 47	234 ± 36						
	Flight time [ms]	t	338 ± 63	346 ± 53	348 ± 69	$\chi^2(1) = 1.21, p = .272, \eta^2 = 0.04$	$\chi^2(2) = 0.05, p = .974, \eta^2 = 0.01$	$\chi^2(2) = 0.36, p = .837, \eta^2 = 0$			
		c	320 ± 70	322 ± 65	329 ± 72						
	Reactive strength index	t	1.49 ± 0.34	1.56 ± 0.34	1.60 ± 0.43	$\chi^2(1) = 1.12, p = .290, \eta^2 = 0.04$	$\chi^2(2) = 0.43, p = .809, \eta^2 = 0.04$	$\chi^2(2) = 1.9, p = .387, \eta^2 = 0.02$			
		c	1.38 ± 0.39	1.39 ± 0.43	1.46 ± 0.45						
	Hop height [m]	t	0.15 ± 0.05	0.15 ± 0.04	0.15 ± 0.06	$\chi^2(1) = 1.07, p = .301, \eta^2 = 0.03$	$\chi^2(2) = 0.13, p = .938, \eta^2 = 0.01$	$\chi^2(2) = 0.36, p = .835, \eta^2 = 0$			
		c	0.13 ± 0.05	0.13 ± 0.05	0.14 ± 0.06						
	Peak force absolute [kN]	t	3.31 ± 0.59	3.30 ± 0.61	3.39 ± 0.60	$\chi^2(1) = 0.01, p = .941, \eta^2 = 0$	$\chi^2(2) = 0.51, p = .774, \eta^2 = 0.03$	$\chi^2(2) = 0.61, p = .736, \eta^2 = 0.01$			
		c	3.32 ± 0.80	3.31 ± 0.82	3.37 ± 0.82						
	Peak force normalized [N kg⁻¹]	t	47.7 ± 6.2	47.8 ± 6.5	49.2 ± 7.5	$\chi^2(1) = 1.47, p = .225, \eta^2 = 0.04$	$\chi^2(2) = 0.4, p = .820, \eta^2 = 0.03$	$\chi^2(2) = 1.31, p = .519, \eta^2 = 0.01$			
		c	45.6 ± 6.2	45.4 ± 7.3	46.4 ± 7.1						
Leg Press Test	MVC absolute [N]	t	1771 ± 425	1898 ± 494	1730 ± 382	$\chi^2(1) = 1.72, p = .190, \eta^2 = 0.07$	$\chi^2(2) = 2.58, p = .275, \eta^2 = 0.12$	$\chi^2(2) = 0.97, p = .616, \eta^2 = 0.02$			
		c	1976 ± 378	2089 ± 489	2007 ± 266						
	MVC normalized [N kg⁻¹]	t	25.9 ± 4.6	27.8 ± 5.8	25.8 ± 5.1	$\chi^2(1) = 0.51, p = .475, \eta^2 = 0.02$	$\chi^2(2) = 1.43, p = .489, \eta^2 = 0.1$	$\chi^2(2) = 1.3, p = .522, \eta^2 = 0.02$			
		c	27.2 ± 4.5	28.3 ± 5.7	27.0 ± 3.0						
One-leg Stance Test	CoP area [cm²]	t	4.00 ± 3.02	3.82 ± 2.72	3.43 ± 1.77	$\chi^2(1) = 0.24, p = .621, \eta^2 = 0.02$	$\chi^2(2) = 1.77, p = .412, \eta^2 = 0.02$	$\chi^2(2) = 0.83, p = .662, \eta^2 = 0.01$			
		c	3.73 ± 2.80	3.02 ± 1.38	3.28 ± 1.85						
10m Gait Test	Velocity [m s⁻¹]	t	1.73 ± 0.25	1.60 ± 0.24	1.65 ± 0.26	$\chi^2(1) = 1, p = .317, \eta^2 = 0.01$	$\chi^2(2) = 5.19, p = .074, \eta^2 = 0.12$	$\chi^2(2) = 0.72, p = .698, \eta^2 = 0.01$			
		c	1.67 ± 0.23	1.58 ± 0.23	1.61 ± 0.26						
	Stride length [cm]	t	83.5 ± 9.1	80.3 ± 7.7	80.9 ± 8.5	$\chi^2(1) = 0.28, p = .595, \eta^2 = 0.01$	$\chi^2(2) = 14.76, p = .001**, \eta^2 = 0.16$	$\chi^2(2) = 0.81, p = .668, \eta^2 = 0.01$			
		c	82.4 ± 8.7	78.5 ± 7.6	78.6 ± 8.4						
Stair Climb Test	Time [s]	t	8.17 ± 0.84	8.14 ± 1.00	8.00 ± 0.90	$\chi^2(1) = 1.37, p = .242, \eta^2 = 0$	$\chi^2(2) = 17.25, p = .000***, \eta^2 = 0.11$	$\chi^2(2) = 5.76, p = .056, \eta^2 = 0.04$			
		c	8.42 ± 0.90	7.95 ± 0.67	7.77 ± 0.76						
	Heart rate increase [%]	t	18.4 ± 9.2	24.2 ± 13.3	21.3 ± 11.0	$\chi^2(1) = 0.01, p = .941, \eta^2 = 0$	$\chi^2(2) = 5.77, p = .056, \eta^2 = 0.08$	$\chi^2(2) = 0.66, p = .717, \eta^2 = 0.01$			
		c	18.6 ± 13.2	24.6 ± 14.4	18.8 ± 8.8						
Cardiopulmonary Exercise Test	$\dot{V}O_2$peak [ml kg⁻¹ min⁻¹]	t	33.4 ± 6.8	35.3 ± 7.1	35.6 ± 6.6	$\chi^2(1) = 1.83, p = .176, \eta^2 = 0.05$	$\chi^2(2) = 2.4, p = .302, \eta^2 = 0.11$	$\chi^2(2) = 1.82, p = .403, \eta^2 = 0.02$			
		c	30.8 ± 7.2	31.7 ± 8.6	32.0 ± 9.3						
	Max. load absolute [W]	t	213 ± 50	222 ± 49	224 ± 52	$\chi^2(1) = 1.27, p = .260, \eta^2 = 0.02$	$\chi^2(2) = 11.47, p = .003**, \eta^2 = 0.18$	$\chi^2(2) = 0.52, p = .773, \eta^2 = 0$			
		c	199 ± 46	205 ± 49	213 ± 57						
	Max. load normalized [W kg⁻¹]	t	3.07 ± 0.62	3.22 ± 0.59	3.24 ± 0.58	$\chi^2(1) = 2.91, p = .088, \eta^2 = 0.06$	$\chi^2(2) = 8.65, p = .013*, \eta^2 = 0.17$	$\chi^2(2) = 1, p = .607, \eta^2 = 0.01$			
		c	2.79 ± 0.67	2.88 ± 0.74	2.98 ± 0.80						

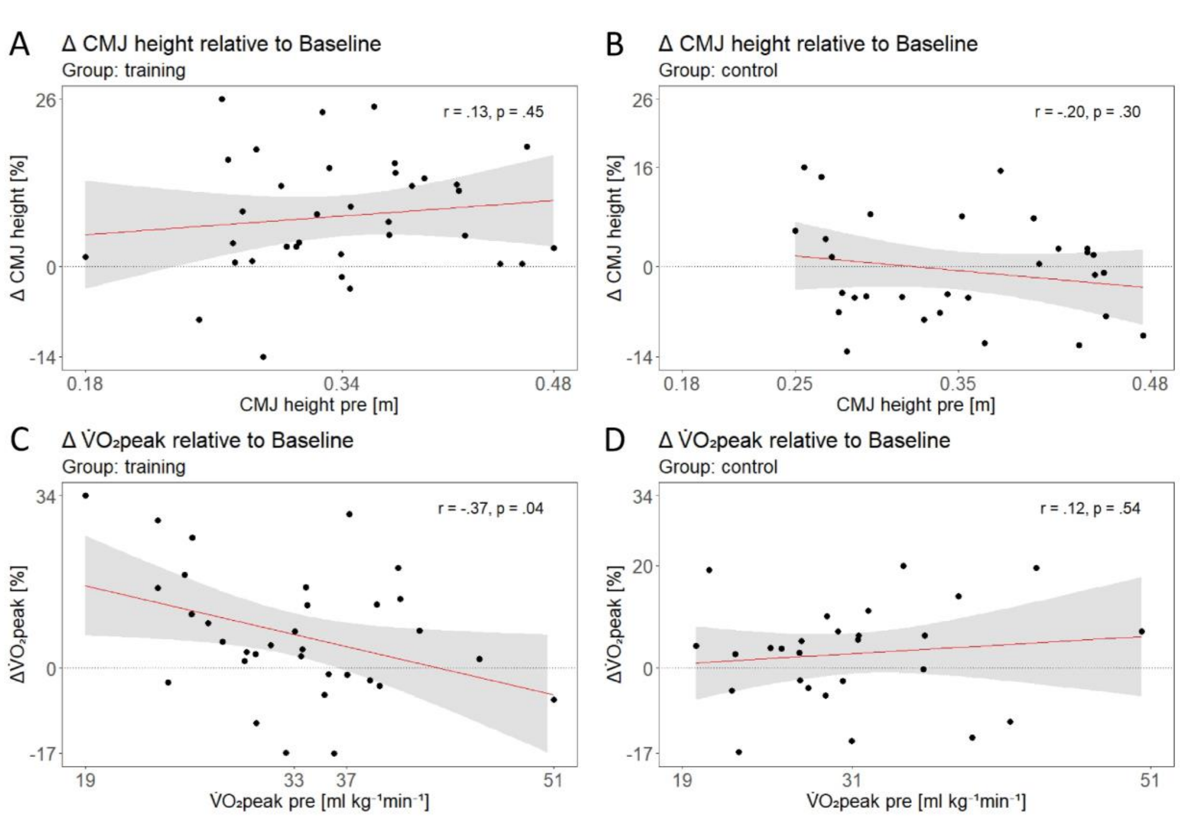

Figure 2. Pre to Post + 0 differences in CMJ height for the training (A) and control (B) groups as well as Pre to Post + 0 $\dot{V}O_{2peak}$ differences for both groups (C, D) are displayed. The solid lines represent fitted linear regression models, with shaded bands indicating 95% confidence intervals. Y-axis ticks show 0, as well as the overall minimum and maximum values across groups; group-specific minimum and maximum values are also shown if they deviate by more than 5%. X-axis ticks represent the overall minimum and maximum values across groups and, similarly, group-specific minimum and maximum values if they deviate by more than 5%. Mean values are additionally indicated on the x-axis, with an additional x-axis tick in C (at 37) indicating the lower CI bound equaling 0.

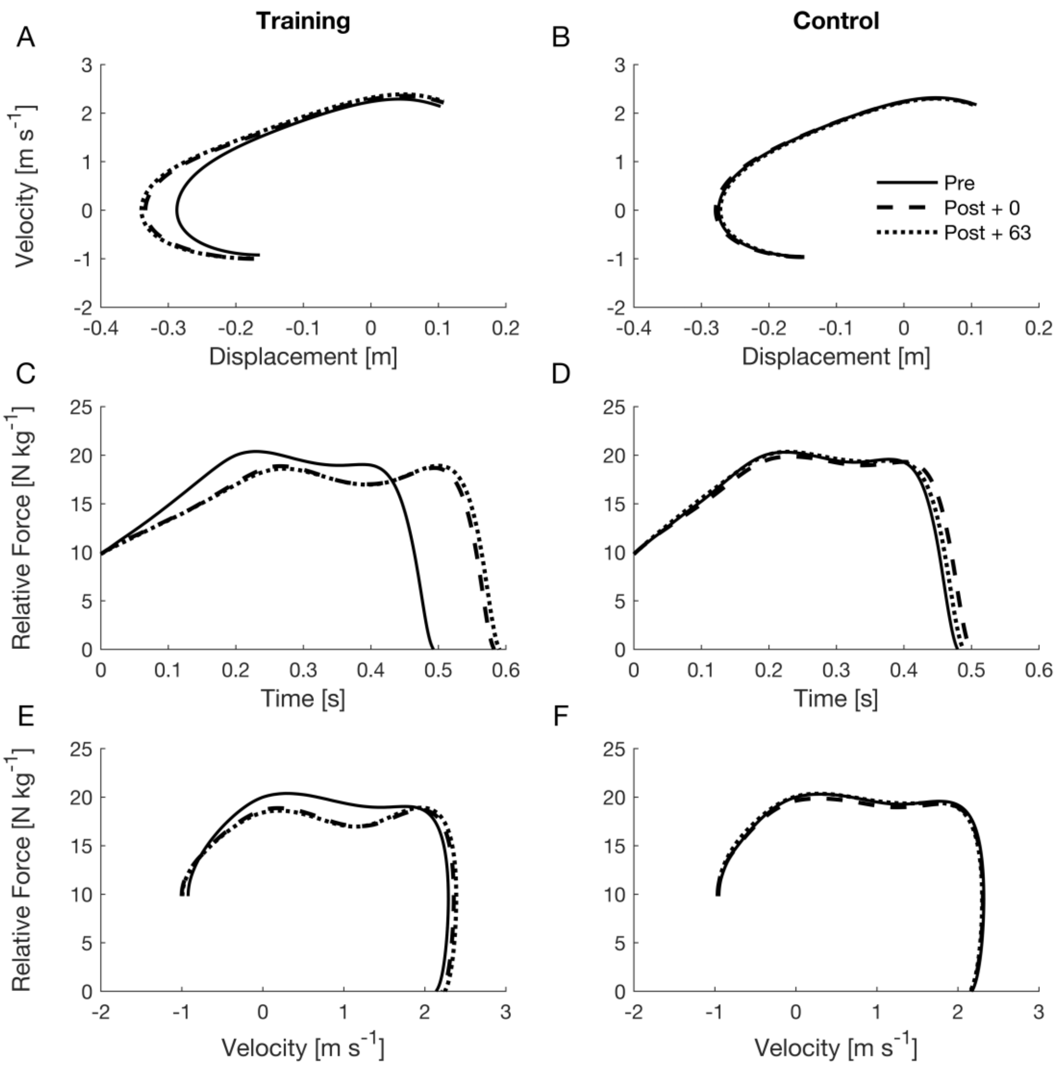

Figure 3. Mean displacement-velocity traces (A, B), relative force-time (C, D) and relative force-velocity (E, F) for the training and the control group respectively. Continuous, dashed, and dotted lines represent the results obtained during Pre, Post + 0, and Post + 63 testing. Only the braking (from peak negative velocity to 0) and upward (from 0 velocity to take off) movement phases were considered. For relative force-time curves, all jumps were interpolated to 401 data points. Piecewise linear length normalization aligned the start and end of the braking and upward movement phases. The braking phase duration across all participants and trials represented ~71% of the upward movement duration. Therefore, the braking and upward movement phases were interpolated with 167 and 234 data points, respectively. Relative force-time traces were then horizontally rescaled to represent the duration of the braking and upward movement phases. There are apparent changes in the training group between Pre (solid line) and Post +0, Post + 63 (dotted and dashed lines). Participants squatted deeper during the jump which increased displacement (A) and time (B). This strategy led to a greater impulse and ultimately to a higher take off velocity (E). No changes can be observed in the control group (B, D, F).

Discussion

The 8-week jump training induced specific adaptations that enhanced performance in CMJs. The participants in the training group learned to go lower in the first phase of the jump and used a longer acceleration path. These adjustments were long-lasting and were maintained for a follow-up period of 8 weeks. However, they remained specific and did not translate into general improvements in physical performance. The negative correlation between changes in $\dot{V}O_{2peak}$ in the training group and baseline $\dot{V}O_{2peak}$ values may be indicative of the interplay of baseline physical performance, exercise load and generic physiological adaptations of the human body after jump training (Impellizzeri et al., 2023).

Specific improvements in CMJ performance can be explained by an optimized movement technique. A longer duration and greater countermovement depth in the CMJ provided participants with more time to generate impulse (area under the relative force-time curve), ultimately increasing takeoff velocity and jump height. Interestingly, these adaptations in CMJ performance came at the expense of relative force throughout the movement. As shown in the relative force-velocity traces in Figure 3E, post-training, the training group exhibited lower relative force during both the braking and upward movement phases at most time points, except near takeoff, where relative force was higher at increased velocities. This aligns with recent findings (Pommerell et al., 2025), indicating that a deeper countermovement reduces force production at low velocities but enhances force at higher velocities, ultimately leading to an increase in jump height. As no additional instructions were given during the training sessions, improvements in movement technique cannot be attributed to external feedback.

Functional principal component analysis confirmed that training significantly reduced relative force throughout the movement, except at higher velocities near takeoff, where relative force increased (Figure S5). Notably, no changes were observed in the control group. These findings suggest that the increase in jump height in the training group was indeed primarily driven by modifications in jumping technique. Interestingly, the extent of the changes in CMJ performance did not depend on the baseline level (Figure 2A). This can be explained by neural plasticity that usually evolves early during training and leads to task specific increases in neuromuscular performance, independent of the initial performance in novices to the trained task (Giboin et al., 2018).

Interestingly, we saw no changes in the hop test, no increase in any of the variables analysed over time, and no effect of training, despite hopping being an integral part of the training programme (see Supplementary S3). We know from previous studies that it is possible to increase jump height in old adults (Hoffrén-Mikkola et al., 2015) as well as in athletes (Kubo et al., 2007). However, gains in reactive jumping have mainly been attributed to changes in the mechanical properties of the muscle-tendon complex rather than to muscle activation strategies (Gruber et al., 2019; Hoffrén-Mikkola et al., 2015; Kubo et al., 2007). This may well explain the different effects of training on CMJs compared to hops. In the present study, neuroplasticity did not influence performance in hops to a sufficient degree, and the training load was probably not high enough for the participants to induce adaptations within the muscle-tendon unit.

Although peak power during CMJs increased in the training group at Post + 0, no improvements were observed for maximal isometric leg extension strength and in habitual functional measurements, specifically in the one-leg stance test, the 14-step stair climb, and the 10 m gait test (Table 1). Since the optimization of movement technique can be explained by neural adaptations specific for CMJs, increases in performance outcomes also remained task-specific, without substantial transfer to other tasks such as leg press, balance, walking or stair climbing. This aligns with previous findings showing that improvements in jump performance do not necessarily translate to enhanced neuromuscular performance in unrelated motor tasks (Cormie et al., 2011). Moreover, it seems plausible that baseline levels in those tests were already at a very high level, reducing the potential for further measurable improvements. Functional tests such as balance tests, walking or stair climbing are widely reported to suffer from ceiling effects in young, healthy populations, as high baseline performances, leave little room for measurable gains (Gagliano-Jucá et al., 2020; Halliday et al., 2020; Springer et al., 2007). Unlike bed rest studies, where inactivity induces rapid functional decline that can be mitigated even by minimal exercise (Kramer, Kümmel, et al., 2017) participants in this study were not subjected to such physiological constraints. This may have further masked transfer effects of training adaptations into more functional improvements.

In gait analysis, we observed a decrease in stride length and gait velocity from Pre to Post + 0 in both groups. Given that no group-by-time interaction was found, it is likely that these changes reflected familiarization effects. As participants became more accustomed to the lab environment, they may have adopted a more relaxed walking style during post-testing compared to the pre-test session. Similar patterns have been observed in gait tests, where test-related psychological factors changed velocity and stride length (Mennella et al., 2024). In line with this argument, participants of both groups reduced their stair climb time during the Post + 0 and Post + 63 tests.

A further indication that the training load was probably too low to induce more general adaptations could be seen in the aerobic capacity. In fact, when we looked at aerobic performance during cycling, we saw a significant negative correlation for $\dot{V}O_{2peak}$ changes over baseline $\dot{V}O_{2peak}$ for the training group (Figure 2C). Participants with low $\dot{V}O_{2peak}$ increased their $\dot{V}O_{2peak}$, whereas this wasn´t the case in participants with moderate or high $\dot{V}O_{2peak}$ baseline levels. There was no such correlation for the control group. The correlation seen in participants of the training group might be the result of a fundamental concept in exercise science, the training principle of overload. The overload principle posits that to achieve physiological adaptations, the physiological system that is supposed to adapt, must be subjected to a load which is greater than the load it is accustomed to (Burton & McCormack, 2021; Fairman et al., 2017; Impellizzeri et al., 2023). Only a small part of our training was tailored towards adaptations of aerobic capacity (see Supplementary Material S3). Exactly 10 sessions included a segment with continuous jumps lasting 3 min or more in absolute volume to resemble a high intensity interval jump training protocol (Venegas-Carro et al., 2023). Notwithstanding, high intensity interval training can be considered superior to moderate continuous training in improving $\dot{V}O_{2peak}$ in non-exercising adults (Poon et al., 2021) and is supposed to play a crucial role in the dose–response relationship between training and aerobic capacity (Reuter et al., 2023), such a relationship has not been established in jump training yet (Lievens et al., 2021). As basic proof for the efficacy of jump training to target $\dot{V}O_{2peak}$, we have recently demonstrated the effect of a jump training protocol as a countermeasure against declines in aerobic capacity during bed rest (Kramer, Kümmel, et al., 2017). With only 15 min of training on 5-6 days per week, the detrimental effect of 60 days of bed rest on $\dot{V}O_{2peak}$ could be largely counteracted (Kramer et al., 2018). The training protocol of the present study was designed following the program that we used in the bed rest study, however, with only 3 training sessions per week the load was considerably lower. Moreover, activity levels of the participants in the present study were not confined in contrast to activity levels of participants during bed rest. Taken together, this might suggest that the load on the cardiorespiratory system induced by the jump training protocol in the present study was subthreshold for the majority of participants and potentially only above threshold for those with very low baseline $\dot{V}O_{2peak}$ levels, which then well explains the negative correlation for $\dot{V}O_{2peak}$ changes and baseline $\dot{V}O_{2peak}$ in the training group. The threshold value for baseline $\dot{V}O_{2peak}$ of 37 ml kg^{-}

^{1}min^{-1} can be estimated from the confidence interval of the correlation analysis (Figure 2C). However, this must be treated with great caution as the correlation analysis was exploratory and not hypothesis-driven.

Looking at the results at a glance, the jump training caused only specific adaptations in counter movement jumps, but not general improvements in physical performance. This result cannot be explained by low adherence or insufficient training intensity in the training sessions carried out at home. With a mean adherence rate of 92% and a peak heart rate that was at 92% of the maximal heart rate for all participants over all training sessions, the jump training was implemented very well. Based on our bed rest results (Kramer, Gollhofer, et al., 2017; Kramer, Kümmel, et al., 2017; Kramer et al., 2018), we have tailored a jump training programme that should lead to adjustments in physical performance in untrained but otherwise active people. As we wanted to make the training program scalable, so that it could be applied to larger populations, we used a low dosage of only 15 minutes per session and three sessions per week. Since it has already been shown that jump training can improve anaerobic and aerobic performance in untrained participants (Deng et al., 2024), this study cannot fundamentally question its effectiveness. The baseline levels of our participants in CMJ height and $\dot{V}O_{2peak}$ were in line with study results on sedentary participants (Dyrstad et al., 2016; Eriksen et al., 2016; Sööt et al., 2005; Souza et al., 2023; Srivastava et al., 2024) and considerably lower compared to physically active or generally trained participants (Dyrstad et al., 2016; Eriksen et al., 2016; Gruber et al., 2022; Moir et al., 2008; Sööt et al., 2005; van der Steeg & Takken, 2021; Walsh et al., 2007). Thus, our results indicate that for untrained or even sedentary young adults the training load that we have offered in the present study was too low to induce general adaptations and increases in physical performance. In future studies, there are several practicable options for increasing the training load. As the intensity was already at 100% from the first week onwards (see Table S1), training time seems to be the best way to increase the overall load. This can be achieved by steepening the progression and offer more sessions per week (4 or 5) or longer sessions (20, 25, 30 min) or a combination of both. Another and complementary option is to take into account the individual baseline levels of the participants and to tailor the training program to their specific needs, e.g. anaerobic vs. aerobic capacity.

Conclusion

The 8-week jump training was feasible for a non-exercising population and effectively improved CMJ performance. Despite improvements in peak power during jumping, no significant transfer effects were observed for either maximal isometric or reactive strength tasks or functional tasks such as balance, walking or stair climbing. Although the training protocol showed a negative correlation between changes in $\dot{V}O_{2peak}$ and initial $\dot{V}O_{2peak}$ level, suggesting that participants with low baseline aerobic capacity benefited, the overall aerobic effect was limited, probably due to insufficient training volume. These findings highlight the specificity of jump training adaptations and the importance of tailoring the training load to the individual needs of participants if broader performance improvements are to be obtained.

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