**Altitude alters the effects of a power-oriented resistance training on the force-velocity relationship of elite judokas**

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**Running head:** Force-velocity relationship and altitude training

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**Altitude alters the effects of a power-oriented resistance training on the force-velocity relationship of elite judokas**

**Abstract**

This study investigated the effects of a 3-week power-oriented resistance training program performed at moderate altitude on the lower-limb maximal theoretical power and force-velocity (F-V) imbalance of elite judokas. Twenty-two elite male judokas were randomly assigned to either a hypobaric hypoxia or normoxia group. Mechanical outputs from an incremental loaded countermovement jump test were assessed at sea level, before and after training, and 1 week later. Results indicated an increase in the maximal theoretical force and a reduction in the F-V imbalance both at moderate altitude and sea level. Altitude training induced additional benefits when compared to sea level for F-V imbalance (8.4%; CI: 0.3, 17.3%), maximal theoretical power (2.09 W·kg-1; CI: 0.13, 4.52 W·kg-1) and force (1.32 N·kg-1; CI: -0.12, 2.96 N·kg-1), jump height (3.24 cm; CI: 2.02, 4.80 cm) and optimal maximal theoretical force (1.61 N·kg-1; CI: 0.06, 3.60 N·kg-1) and velocity (0.08 m·s-1; CI: 0.00, 0.17 m·s-1) after the training period. The hypoxia group achieved their best results immediately after the training period, while the normoxia group achieved them one week later. These results suggest that a power-oriented resistance training program carried out at moderate altitude accelerates and improves the gains in leg push capacity while minimizing lower-limb imbalances. Therefore, it seems appropriate to compete immediately after the return to sea level and/or use altitude training as a tool to improve muscle power levels of athletes without tapering goals, especially in highly trained power athletes, since their window of adaptation for further power enhancement is smaller.

**Highlights**

* A 3-week power-oriented resistance training program improved explosive leg extension capacity of elite judokas both at moderate altitude and sea level.
* Furthermore, training at moderate altitude increases and accelerates these gains, reducing athletes’ imbalances.
* It may be optimal for judokas to compete immediately after the return to sea level and/or use altitude training as a tool to improve muscle power levels of athletes without tapering goals, especially in highly trained power athletes, since their window of adaptation for further power enhancement is attenuated.

**Keywords:** *judo, hypoxia, altitude training camp, force-velocity relationship.*

**Introduction**

Judo is a complex sport that requires a number of specific athletic characteristics to achieve a high level in competition. One of these characteristics is known to be leg muscle power (Bonitch-Domínguez et al., 2010; Franchini et al., 2011), mainly due to small time windows to apply high levels of strength during performance. Elite judokas show enhanced jumping performance compared to non-elite practitioners (Detanico et al., 2016; Zaggelidis & Lazaridis, 2013). Furthermore, findings related to the effect of combat on leg power (Bonitch-Domínguez et al., 2010; Detanico et al., 2015; Julio et al., 2018) in conjunction with time-motion analysis (Marcon et al., 2010; Miarka et al., 2014) seem to suggest that explosive leg actions employed to perform the attacks occur sporadically, likely with sufficient time between them to recover energy supplies and dissipate fatigue. Therefore, one of the main aims of the resistance training programs in judo is to improve leg power capacity.

Maximal muscular power of athletes is determined by the maximal neuromuscular capabilities, which can be assessed by the force-velocity (F-V) relationship (Cormie et al., 2011a). Jumping performance has been widely tested to assess the lower-limb F-V relationship (Samozino et al., 2014). In particular, the countermovement jump is the most commonly used exercise in sports training and testing (Morin & Samozino, 2018). According to Jiménez-Reyes et al. (2017; 2019) and Simpson et al. (2021), training programs to improve ballistic performance should be specifically designed to increase the individual maximal theoretical power and to reduce the F-V imbalance (i.e., to increase the maximal theoretical force or velocity component of an individual’s F-V profile in order to achieve the optimal profile).

Research in the last decade supports the use of moderate altitude training to improve leg extension power capacity at sea level (Almeida et al., 2021; Feriche et al., 2017; García-Ramos et al., 2014; García-Ramos et al., 2016). However, despite emerging evidence on the importance of assessing the F-V relationship (Jiménez-Reyes et al., 2019; Samozino et al., 2012), only one study to date endeavored to explore the influence of altitude training on this relationship (Morales-Artacho et al., 2018). Therefore, the aim of this study was to assess the effect of a lower-limb power-oriented resistance training program at moderate altitude versus as sea level on the maximal theoretical power and F-V imbalance of elite judokas. We hypothesized that the training intervention at moderate altitude would: (1) improve maximal theoretical power to a greater extent than at sea level, and; (2) reduce the imbalance between the current and optimal F-V profile.

**Materials and methods**

*Experimental approach to the problem*

We employed a longitudinal design, with intra- and inter-group measurements, to compare the effect of a lower-limb power-oriented resistance training at moderate altitude (hypobaric hypoxia) versus at sea level (normoxia) on the F-V relationship of elite judokas. Participants were randomly assigned to a group that performed a 3-week training program in either hypobaric hypoxia (at the High-Performance Center of Sierra Nevada, 2320 m asl; HT; *n* = 12) or normoxia (at the High-Performance Center of Valencia, 15 m asl; NT; *n* = 10). Testing sessions were conducted under normoxic conditions at 3 timepoints: pre-training (Pre), post-training (Post-0) and one week after training (Post-1). All tests were performed at the same time of day under similar environmental conditions.

*Subjects*

Twenty-two male judokas from the High-Performance Center of Valencia (age: 21.82 ± 2.92 years; body mass: 79.92 ± 11.55 kg; height: 177.40 ± 7.57 cm; fat percentage: 10.90 ± 1.03%; relative one repetition maximum in the half squat: 2.12 ± 0.34 kg.kg-1 of body mass) participated in this study. The dataset is the same as that used in our previous study (Almeida et al., 2021). The study was carried out at the end of a special preparation mesocycle that aimed to improve muscle power (Cormie et al., 2011b) so as to improve the judokas’ performance in competition (Bonitch-Domínguez et al., 2010). All participants had experience in the loaded countermovement jump as well as in the specific protocol used in this study. They had been practicing judo for at least 10 years and all had attained the rank of black belt (from first to third Dan). All participants had been medalists in the junior or senior National Championships in Spain, Dominican Republic, or Georgia; eight of them in junior or senior European Cups; four in Continental Opens; one in Grand Prix; two in junior Continental Championships; and one in junior World Championships. All participants self-reported no chronic diseases or recent injuries that might compromise performance. Participants did not have previous altitude training experience and had not been exposed to altitudes above 1500 m for more than 3-4 consecutive days for at least two months before the study. Participants were instructed to avoid any strenuous exercise for a minimum of two days preceding the testing sessions. They also were advised to maintain their customary nutritional intake and to avoid consuming any potentially ergogenic supplements during the course of the study. They were informed about the study protocol and signed a written informed consent form prior to investigation. The study protocol was approved by the university Institutional Review Board and was carried out in accordance with the Declaration of Helsinki.

*Procedures*

*Countermovement jump test.* After a 10-min standardized warm-up (jogging, dynamic stretching, joint mobility exercises, unloaded countermovement jumps, and 5 countermovement jumps loaded with 20 kg), participants undertook an incremental loaded countermovement jump test. The protocol consisted of 2 repetitions per each loading condition (0.2, 20, 40, 60 and 80 kg), separated by 1 min of rest between repetitions with the same load and 3 min between each loading condition. A complete description of the countermovement jump technique can be found elsewhere (Almeida et al., 2018). The test was performed in a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) for all the loading conditions except for the 0.2 kg condition, which consisted of a free jump with a plastic bar to maintain the same body position. The mean values of force, velocity and power at each loading condition were calculated from the equations proposed by Samozino et al. (2008) and validated for the countermovement jump (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017). Test-retest reliability of this assessment has been previously reported (ICC > 0.98 and CV < 1.0%) (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017). The countermovement jump height used was estimated from the flight time collected by an infrared platform (Optojump, Microgate, Bolzano, Italy) at a 1000 Hz sampling rate. The highest of the 2 jumps was selected and used for analysis. The countermovement jump height with 0.2 kg was considered the jump height, indicating the jumping performance. Afterwards, the mean values of force and velocity at each loading condition were used to assess the current F-V relationship and the associated slope (Sfv = - F0/V0), maximum theoretical force (F0, force-axis intercept), velocity (V0, velocity-axis intercept) and power (Pmax = F0·V0/4) values through a linear regression. In addition, we also estimated the optimal profile (i.e., the ideal profile that would maximize jump height for a given athlete, OP-Sfv) and associated maximum theoretical force (OP-F0) and velocity (OP-V0), as well as the F-V imbalance (i.e., relative difference between individual current and optimal F-V profiles, FVimb in %). F-V imbalance was classified in accordance with the thresholds defined by Jiménez-Reyes et al. (2017) (high force deficit, low force deficit, well-balanced, low velocity deficit and high velocity deficit).{, 2017, Effectiveness of an individualized training based on force-velocity profiling during jumping} A specific spreadsheet based on the equations validated by Samozino et al. (2014; 2008; 2012) was used for all calculations (Morin & Samozino, 2017).

*Training program.*The 3-week training program included a physical conditioning session in the morning and a judo session in the afternoon, taking place from Monday to Saturday morning. The physical conditioning training was designed and supervised by the research team and included 8 power-oriented resistance sessions (Table 1) alternated with 7 metabolic sessions. The training load displaced during all countermovement jumps (~35-40% 1RM) was estimated from the load linked to 1.2 m·s-1 of the mean propulsive velocity from the individual load-velocity relationship (Pérez-Castilla et al., 2020). For this, a linear regression model from a three-load incremental test was fitted each Monday after the warm-up and used to estimate the new weekly external load corresponding to a barbell mean propulsive velocity of 1.2 m·s-1. The training load on Wednesdays and Fridays was estimated during pre-training, which allowed the participants to improve the velocity, as their explosive leg extension capacity increased in both study conditions. A linear velocity transducer (T-Force System, Ergotech, Murcia, Spain) at 1000 Hz sampling rate attached to the bar was used to measure the mean propulsive velocity. After the training camp there was 1 training-controlled week, during which both groups trained together in the High-Performance Center of Valencia, completing 5 judo sessions and 5 physical conditioning sessions. Both groups showed similar RPE values in the physical conditioning sessions during the training program (6.05 ± 0.57 in hypoxia group vs. 5.94 ± 0.45 in normoxia group; p = 0.62) and the training-controlled week (5.74 ± 0.58 in hypoxia group vs. 6.40 ± 0.96 in normoxia group; p = 0.06).

[Insert Table 1 near here]

*Statistical analyses*

All analyses were performed in R (version 4.0.2) (R Core Team, 2020). For each outcome, a linear mixed-effects model with time (Post-0 and Post-1), altitude (hypoxia group and normoxia group), and their interaction was created, and baseline scores were included as a covariate of no interest (Bates et al., 2015); varied intercepts were permitted by treating subject as a random effect. This model was built for the variables of the lower-limb F-V relationship (maximal theoretical power, current and optimal slope, maximal theoretical force and velocity, as well as F-V imbalance and jump height). Since we were principally interested in the between-group average treatment effects of the intervention (altitude), we calculated a contrast for each timepoint based on the estimated marginal means from the linear mixed-effects model (Lenth, 2020). Residuals were qualitatively examined for heteroscedasticity. We calculated 90% compatibility intervals (CIs) of the adjusted effects using the bias-corrected and accelerated bootstrap with 500 replicates, resampled on the subject level (Canty & Ripley, 2019; Davison & Hinkley, 1997; Efron, 2012). Standardized mean differences (ES) were calculated to complement the inferential statistics, by dividing the between-group adjusted effect by the pooled baseline standard deviations. P-values were calculated using Satterthwaite degrees of freedom.

Similar to previous work (Almeida et al., 2021), we used an estimation-based approach to draw inferences from our data. Specifically, we interpreted each effect and its precision continuously (Gardner & Altman, 1986), rather than relying on null hypothesis significance testing and drawing binary conclusions as to the presence of an effect or no effect (Amrhein et al., 2019).

**Results**

Table 2 and Figure 1 display within-group descriptive statistics and change scores for current and optimal mechanical outputs of the F-V relationship and jump height at the 3 timepoints, in addition to between-group adjusted effects and their respective 90% CIs, p-values and ES.

The adjusted between-group effect for the jump height favored the hypoxia group at Post-0 (3.24 cm; CI: 2.02, 4.80 cm) and also at Post-1 (1.51 cm; CI: -0.06, 3.02 cm), although at this timepoint the CI showed a negligible change in favor of the normoxia group and an appreciable change in favor of the hypoxia group. Compared to pre-training, the hypoxia group displayed the best performance in jump height earlier, at Post-0 (9.0 ± 6.5%), while normoxia group achieved peak performance at Post-1 (2.0 ± 5.9%).

The maximal theoretical power showed an adjusted effect at Post-0 that favored hypoxia group (2.09 W·kg-1; CI: 0.13, 4.52 W·kg-1).

The point estimate of the adjusted effect for the maximal theoretical force favored the hypoxia group at Post-0 (1.32 N·kg-1), with CI estimates ranging from a 0.12 N·kg-1 benefit to the normoxia group to a 2.96 N·kg-1 benefit to the hypoxia group. Conversely, at Post-1 the adjusted effect favored the normoxia group (1.45 N·kg-1), with CI estimates ranging from a 3.20 N·kg-1 benefit to the normoxia group to a 0.60 N·kg-1 benefit to the hypoxia group. Compared to pre-training, the hypoxia group displayed the best performance in maximal theoretical force at Post-0 (12.0 ± 10.6%), while the normoxia group achieved peak performance at Post-1 (9.3 ± 9.4%).

Adjusted effects for both optimal maximal theoretical force (1.61 N·kg-1; CI: 0.06, 3.60 N·kg-1) and velocity (0.08 m·s-1; CI: 0.00, 0.17 m·s-1) favored the hypoxia group at Post-0.

F-V imbalances observed in both groups at each timepoint indicate a high/low force deficit (from ~56 to 73% of the optimal F-V profile). The adjusted effect for the F-V imbalance showed a greater reduction of this imbalance in the hypoxia group compared to the normoxia group at Post-0 (8.4%; CI: 0.3, 17.3%).

[Insert Table 2 near here]

[Insert Figure 1 near here]

**Discussion**

The aim of this study was to analyze the influence of a moderate altitude power- oriented resistance training program on lower-limb maximal theoretical power and F-V imbalance of elite judokas. The 3-week training period improved maximal theoretical force and reduced the F-V imbalance, regardless of the altitude condition. The reduction in the F-V imbalance was more pronounced in the hypoxia group, although the F-V relationship in both groups at all timepoints displayed low values of maximal theoretical force, high values of maximal theoretical velocity and a general imbalance of the F-V profile when compared to the optimal predicted values. The hypoxia group also showed notably greater improvements in maximal theoretical power and force, jump height and optimal maximal theoretical force and velocity after the training period. These results suggest that a power-oriented resistance training at moderate altitude accelerates and improves the gains in leg push capacity, minimizing athletes’ imbalances.

Emerging evidence supports the use of moderate altitude resistance training to improve leg extension power capacity at sea level (Almeida et al., 2021; Feriche et al., 2017; García-Ramos et al., 2014; García-Ramos et al., 2016). Almeida et al. (2021) investigated the effect of resistance training at moderate altitude on leg power-related variables in elite judokas and found superior results in peak velocity and jump height in the hypoxia group compared to training in normoxia. These findings are consistent with our results, further highlighting the benefits of training at moderate altitude for power-sports like judo.

From a mechanistic standpoint, training at altitude, apart from the reduction in air resistance (Levine et al., 2008), seems to accelerate neuromuscular adaptations by increasing the recruitment of type II fibers (Melissa et al., 1997; Schoenfeld, 2013; Scott, Slattery, Sculley, et al., 2014), the spinal excitability (Amann et al., 2013; Delliaux & Jammes, 2006; Tomazin et al., 2016) and/or the twitch contractile properties due to an upregulation of excitation-contracting coupling (Tomazin et al., 2020). However, Tomazin et al. (2021) found that elite judokas that trained at moderate altitude showed impaired neuromuscular adaptations compared to those who trained at sea level. These results must be considered in the context that the post-training measurement was only taken one week after the 3-week power-oriented training period and, at that time, the neuromuscular adaptations of the judokas that trained at altitude may have already decreased after an earlier peak in performance. This phenomenon would be consistent with what we observed in the present study, since the hypoxia group achieved their best results immediately after training and performance declined 1 week later, while the normoxia group demonstrated a delayed response, achieving their best results 1 week after the end of the training period.

Only one previous study explored the influence of altitude training on the lower-limb F-V relationship (Morales-Artacho et al., 2018). Contrary to our findings, the authors reported similar results between an intermittent moderate altitude training strategy and at sea level after a 4-week leg power-oriented resistance training program. Conceivably, the hypoxic dose-response under an intermittent hypoxia exposure (Scott, Slattery, & Dascombe, 2014) was not sufficient to produce an additional stimulus to sea-level training as was observed in our study.

Apart from the altitude training effect, only two longitudinal studies have investigated the effect of a strength/power training period on the muscle power of judokas (Franchini et al., 2015; Marques et al., 2017). Neither study observed changes in leg muscle power after the training intervention, possibly because they used unloaded jumps to assess the muscle power changes; notably, both these studies were carried out under normoxic conditions. On the contrary, the jump test employed in our study was assessed with a wide range of loads (25 to 100% of the body mass). The discrepancy between studies thus may be explained by the fact that strength training responses are load and task-specific (Cormie et al., 2010).

Individualized training based on the F-V imbalance has shown to be efficient at improving jumping performance even in trained subjects (Jiménez-Reyes, Samozino, Brughelli, et al., 2017; Jiménez-Reyes et al., 2019; Simpson et al., 2021). In this regard, the training program in our study was designed to enhance explosive muscle performance (Cormie et al., 2011b), primarily by including a velocity-based training component (Gonzalez-Badillo et al., 2017; Pareja-Blanco et al., 2014) and a contrast training component (Alves et al., 2010; Cometti, 1998; Sale, 2002) in each session. Readjusting the countermovement jump training load to maintain the mean propulsive velocity of 1.2 m·s-1 at the corresponding condition every Monday helped to focus the resistance training program on strength enhancement on one of the three weekly training days, while using the countermovement jump pre-training load on the other two days helped to focus the program on velocity enhancement. Moreover, including a contrast training component with moderate to high-load exercises allowed participants to improve their maximal theoretical force and consequently reduce their F-V imbalance. This training design is consistent with the recommendations of Cormie et al. (2010) to use explosive type strength training with medium-light loads and heavy loads to change the high-velocity and high-force portions of the F-V relationship, respectively.

At all timepoints, both groups displayed notable F-V imbalances, due to lower current values in maximal theoretical force and higher values in maximal theoretical velocity compared to the optimal expected values. Considering that judokas have to move high loads (opponent’s body mass) in order to accomplish throws (Bonitch-Domínguez et al., 2010), this force deficit should be addressed as quickly as possible. Moreover, it conceivably would be preferable to improve their maximal strength levels before focusing on power training to potentiate results in the latter variable (Cormie et al., 2010). In this regard, the training program employed in this study improved the maximal theoretical force and reduced the F-V imbalance as mentioned before, with greater and faster improvements in the hypoxia group. Similarly, Nishimura et al. (2010) observed a faster improvement in muscle strength after resistance training under normobaric hypoxia than under normoxia (3 vs. 6 weeks).

To date, Almeida et al. (2021) is the only study that focused on post-altitude muscle power adaptations. Likewise, the best results in our study were reached the day participants returned to sea level, with subsequent decreases in the studied variables. Indeed, it is possible that judokas that trained at altitude reached their peak performance before the end of the training program, although this cannot be confirmed because we did not assess outcomes at mid-intervention. Further research is warranted to better understand the temporal responses to resistance training at altitude and help coaches determine the most suitable program duration to optimize increases in muscle power specific to individual goals.

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**Declaration of interest statement**

The authors have no conflicts of interest to disclose.

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**Figure captions**

Figure 1. Altitude training effect on jump height (A), maximal theoretical power (B) and force (C) and force-velocity imbalance (D). Pre, pre-training; Post-0, post-training; Post-1, one week after training. PE, adjusted between-group difference [i.e., the estimated marginal mean of the difference between hypoxia and normoxia groups (hypoxia group – normoxia group) at time Post-0 or Post-1 after adjusting for baseline differences]; ES, effect size between hypoxia group and normoxia group; p-value of the adjusted between-group difference. WB, well-balanced; LFD, low force deficit; HFD, high force deficit.