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Influence of Isoinertial-Pneumatic Mixed Resistances on Force–Velocity Relationship

Simon Avrillon, Boris Jidovtseff, François Hug, and Gaël Guilhem

Purpose: Muscle strengthening is commonly based on the use of isoinertial loading, whereas variable resistances such as pneumatic loading may be implemented to optimize training stimulus. The purpose of the current study was to determine the effect of the ratio between pneumatic and isoinertial resistance on the force–velocity relationship during ballistic movements. ***Methods:*** A total of 15 participants performed 2 concentric repetitions of ballistic bench-press movements with intention to throw the bar at 30%, 45%, 60%, 75%, and 90% of the maximal concentric repetition with 5 resistance ratios including 100%, 75%, 50%, 25%, or 0% of pneumatic resistance, the additional load being isoinertial. Force-, velocity-, and power-time patterns were assessed and averaged over the concentric phase to determine the force–velocity and power–velocity relationships for each resistance ratio. ***Results:*** Each 25% increase in the pneumatic part in the resistance ratio elicited higher movement velocity (+0.11 ± 0.03 m/s from 0% to 80% of the concentric phase) associated with lower force levels (–43.6 ± 15.2 N). Increased isoinertial part in the resistance ratio resulted in higher velocity toward the end of the movement (+0.23 ± 0.01 m/s from 90% to 100%). ***Conclusions:*** The findings show that the resistance ratio could be modulated to develop the acceleration phase and force toward the end of the concentric phase (pneumatic-oriented resistance). Inversely, isoinertial-oriented resistance should be used to develop maximal force and maximal power. Resistance modality could, therefore, be considered an innovative variable to modulate the training stimulus according to athletic purposes.

Keywords: variable resistance, constant load, exercise modality, maximal power

Resistance training has long been performed through the application of an external load on targeted muscle groups.[1] The determination of the optimal load for enhancing muscle capacity requires a knowledge of the fundamental force–velocity relationship that determines power-generating capacity of the muscle and the force-velocity levels involved during specifi sport tasks.[2–4] This relationship is classically established by measuring force and associated movement velocity under various constant isoinertial loads.[5] The slope of this relationship provides valuable information about the individual balance between force and velocity capabilities.[6]

Isoinertial loading elicits muscle contractions similar to those observed during daily-life tasks in which the muscle exerts a force to accelerate a mass. As such, the magnitude of the force required to generate movement depends on inertia. Light loads are thus used to generate similar movement velocities than those observed during explosive performance. In the absence of load projection, an extended deceleration phase is needed, which ultimately leads to a decreased velocity toward the end of the movement.[7–9] Overall, contractions under isoinertial load are effective for generating maximal force during the initiation of the movement.[10,11] However, the ability to generate force decreases with the increase in velocity of the displaced load. Therefore, constant loading does not provide an appropriate training stimulus to generate force at high velocity.[8,10]

Pneumatic resistance is one alternative that has been developed to overcome the aforementioned limitations associated with the use of isoinertial load. Pneumatic loading consists of generating variable resistance resulting from air compressed in a cylinder.[12] Using this technique (pneumatic resistance), the only inertia that needs to be overcome is related to the mass of the mobilized body segments, limiting the amount of force required to initiate the movement.[13,14] As a consequence, higher velocities can be reached as the decrease in force is limited toward the end of the concentric phase,[13] therefore allowing maximization of the velocity component of the force–velocity relationship. Inversely, isoinertial exercise (being ballistic or not) results in higher force levels toward the initial phase of the movement. It is, therefore, likely that the optimal trade-off between isoinertial and pneumatic loading (ie, in percentage of the total resistance) should change as a function of the required neuromuscular adaptations.[15] Although recent studies investigated the force and velocity patterns elicited by pneumatic and isoinertial loading during the concentric displacement,[13,14] the effect of the ratio between both resistances on the force– and power–velocity relationships is still unknown.

The purpose of the current study was to determine the effect of the ratio between pneumatic and isoinertial resistance on movement patterns and force–velocity–power relationships during bench press. We hypothesized that isoinertial resistance would affect the force–velocity relationship toward a force component, whereas pneumatic resistance would affect the slope of the relation toward a velocity-oriented profi The knowledge gained by this study will provide crucial information for coaches to adapt a ratio for specifi athletic purposes.

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Methods

Subjects

A total of 15 healthy males (mean ± SD age 25 ± 1 y, height 179 ± 5 cm, body mass 74 ± 10 kg) with no previous history of upper-limb injury volunteered to participate in this study. Each participant was engaged in physical activity and had previous resistance training experience (3.9 ± 4.3 y, 1-repetition maximum [1RM] 77.2 ± 17.6 kg). They were informed regarding the nature, aims, and risks associated with the experimental procedure before they gave their written consent to participate. The study was approved by the local ethical committee and conducted in accordance with the Declaration of Helsinki.

Experimental Design

Participants attended 2 familiarization sessions to become accustomed to the testing procedures and 1 test session. Bench-press movements were performed on a bench positioned in the center of a rack (Rack 3111, Keiser, Fresno, CA, USA). Isoinertial resistance was calculated by adding the mass of the barbell and the bumper plates that were weighted before the experiment. Pneumatic resistance was produced by a compressor (1022, Keiser) regulating the pressure of compressed air into pneumatic cylinders. This load was applied to the barbell by cables and pulleys provided by the manufacturer (Figure 1[A]).

Procedures

Quantification of Pneumatic Load. The relationship between pneumatic and isoinertial load was determined during a pilot session. Using a strain gauge (Enertec Schlumberger, Montrouge, France), the amount of pneumatic force applied to the barbell was measured at 8 different levels of pneumatic resistance as provided by the device (4.9, 10, 20, 30, 40, 60, 80, and 92.8 kg). For each measure, we divided the measured force value by the gravitational component (9.81 N/kg) to obtain a theoretical mass (m_i, in kg). A linear regression (Equation [1], R^2 = .99) between the theoretical mass (m_i) and the pneumatic mass (m_p) provided by the device was used to determine the amount of displayed pneumatic resistance required to impose a targeted resistive force:

$$m_p = 0.9184 \times m_i + 0.8057 \qquad (1)$$

Bench-Press Movement. The bench-press movement was standardized to ensure the reproducibility of our measurements during each session. Participants' feet were consistently in contact with the floor, and hands were placed on the barbell with the elbow angle at 90° (0° = full elbow extension). For each attempt, the participants lowered the barbell to a minimal distance of 1 cm over the chest, immobilized the barbell for 1 second, then pushed the barbell. The position of hands, shoulders, back, and feet were marked with tape, and the distance between the barbell and the chest was controlled by a piece of plastic foam attached to the bar.

The assessment of the force–velocity relationship requires that maximal ballistic contractions are performed. In addition, ballistic actions maximize power output during concentric-only contractions. Therefore, participants pushed the bar maximally throughout the range of motion with the intention to throw the bar when possible.

Familiarization. During the familiarization session, participants were accustomed to the resistance modalities and experimental procedures. The maximal load that participants were able to lift

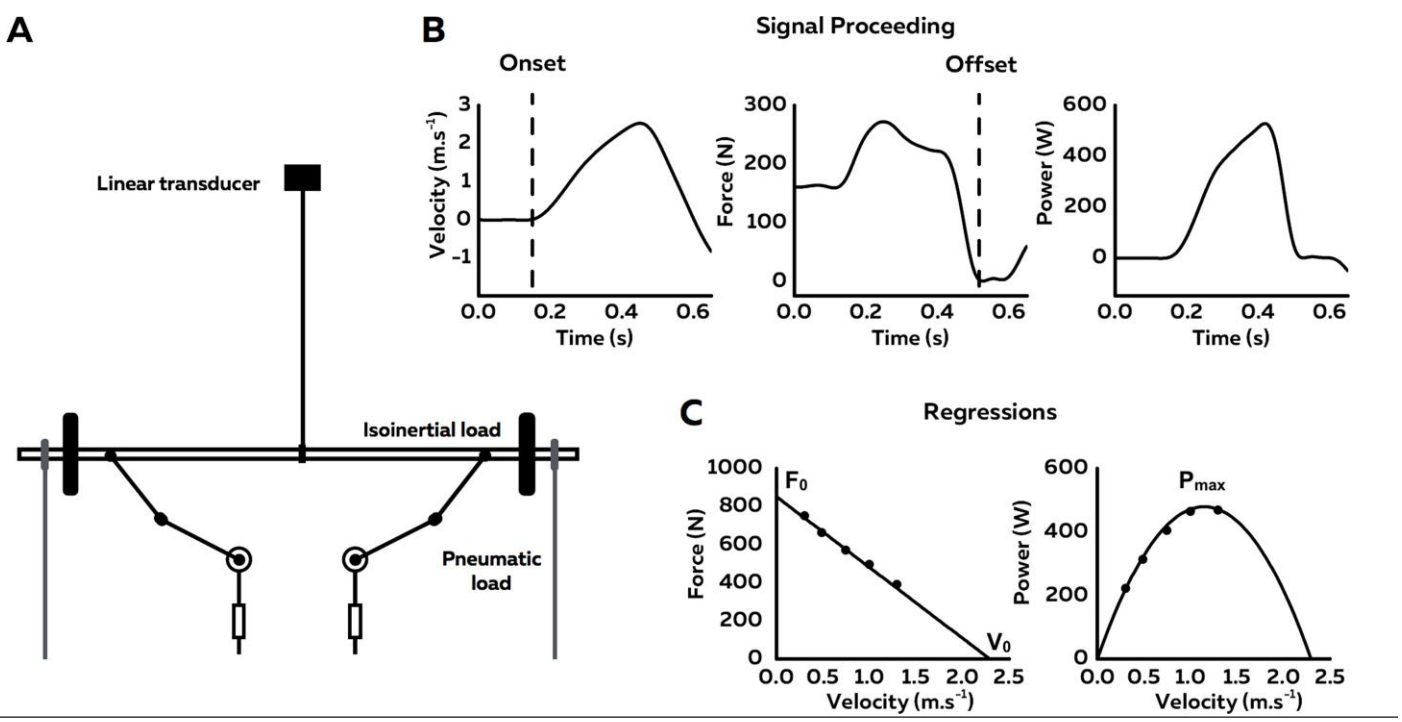

Figure 1 — Overview of data acquisition and processing. (A) Experimental setup. (B) Velocity, force, and power patterns and detection of the onset and offset (dashed lines) of the concentric phase. (C) Mean values were calculated after averaging force, velocity, and power output between the onset and the offset of the concentric phase at all intensities (30%–90% 1RM). These mean values were used to build force–velocity and power–velocity relationships obtained with linear and polynomial regression, respectively. The x-intercept corresponds to maximal theoretical velocity (V_0), and y-intercept corresponds to maximal theoretical force (F_0) of the force–velocity relationship. Maximal power (P_{max}) corresponds to the peak of power–velocity relationship.

once during a concentric bench press (1RM) was also determined. After a standardized warm-up, they were instructed to complete 3 repetitions at 15%, 30%, 45%, and 60% of their estimated 1RM in the considered modality and 2 repetitions at 75% and 90% 1RM with 3 minutes of rest between sets. Then, they performed 1 attempt with 2.5-kg increments until they reached their 1RM. The 1RM was defined as the last load lifted by the participants over the entire range of motion.

Test Session. The test session aimed to assess the force–velocity relationship during 5 conditions that differed in their ratio between pneumatic and isoinertial resistance: 100% pneumatic to 0% isoinertial (100P), 0% to 100% (100I), 25% to 75% (25P75I), 50% to 50% (50P50I), and 75% to 25% (75P25I). Standardized warm-up included 5 minutes of rowing at 100 W, 2 sets of 10 repetitions at 30% 1RM, and 1 set of 6 repetitions at 60% 1RM. Then, for each condition, participants had to perform 2 repetitions at 30%, 45%, 60%, 75%, and 90% 1RM in a randomized order to limit the effect of fatigue. The duration of the rest period was adapted to the amount of external load displaced (ie, 1 min at 30% 1RM, 1 min 30 s at 45% 1RM, 2 min at 60% 1RM, 2 min 30 s at 75% 1RM, and 3 min at 90% 1RM).

Data Collection and Processing

Barbell displacement was measured with a linear transducer (PT5A-150, Celesco, Chatsworth, CA, USA) that was vertically positioned over the barbell. The signal was digitized at 1000 Hz using a 12-bit analog to digital converter (DT 9804, Data Translation, Marlboro, MA, USA). All analyses were performed using a custom written script (Origin 2015, OriginLab Corp, Northampton, MA, USA). Position was low-pass filtered (10 Hz, third-order Butterworth). The vertical displacement (d_Z) of the barbell was differentiated to calculate instantaneous velocity (v_Z). Velocity was then differentiated to calculate instantaneous acceleration (a_Z). Force was calculated using Equation (2):

$$F = m(a_z + g) + F_{PNE} \qquad (2)$$

where m is the external mass (barbell + plates in kg), and g is the gravitational acceleration (in $m \cdot s^{-2}$). Pneumatic force (F_{PNE}, in N) was measured during the concentric phase using proprietary software (A420 Keiser, Keiser, Fresno, CA, USA) as follows:

$$F = P \times A \qquad (3)$$

where P is the air pressure (in Pa), and A is the area through which the air is compressed (in m^2). The excellent reproducibility of the measurements was previously demonstrated by Frost et al.[13]

Power output (P_0 in W) was then calculated as the product between force and velocity.

This experimental design was previously tested during free-weight exercises and the validity of force, velocity, and power measurements obtained with a linear transducer was verified by our group and others.[16,17]

Mechanical signals were time-reversed to determine the onset of the concentric phase, as the first time point corresponding to a zero velocity, starting from the time point corresponding to the peak force value (Figure 1[B]). Then, mechanical signals were time-reversed a second time to determine the offset of the concentric phase as the minimal force produced by the subject, starting from the onset of the concentric phase (Figure 1[B]). A linear interpolation technique was used to normalize the mechanical data (force, velocity, power) as a percentage of the same concentric distance (the maximal range of motion completed in all conditions). Mean mechanical parameters were calculated over this range of motion to determine the relation between force, velocity, and power for all conditions (Figure 1[C]). A linear regression was applied to the relation between force and velocity to determine the y- and x-intercept that corresponded to maximal theoretical force (F_0 in N) and maximal theoretical velocity (v_0 in m/s), respectively (Figure 1[C]). The slope of the measured profile (S_{FV}) was calculated as follows:

$$S_{FV} = -(F_0/V_0) \qquad (4)$$

A second-degree polynomial regression was applied to determine the relation between power and velocity (Figure 1[C]). Maximal theoretical power (P_{max} in W) was determined as the peak value of the regression.

Statistical Analyses

All statistical analyses were conducted using Statistica version 7.1 (StatSoft, Tulsa, OK, USA) and Matlab (version R2015a, The Mathworks, Natick, MA, USA). Data distributions were first checked by the Shapiro–Wilk normality test. All data being normally distributed, differences in force, and velocity patterns were tested using a wavelet-based functional analysis of variance (ANOVA).[18] The advantage of this method is to reduce the number of statistical tests required without affecting statistical power. The procedure was applied using specific Matlab codes. Briefly, force and velocity patterns were transformed to the wavelet domain (third-order Coiflet wavelet, with periodic extension), and ANOVAs were performed on the individual wavelet coefficients. To evaluate significant differences across ratios (ie, wavelet coefficient corresponding to the initial F tests at significant level $\propto = .05$), we used a Scheffé post hoc test. Wavelet coefficients that were significantly different between conditions were back transformed to obtain significant difference curves (Figures 2 and 3, dashed traces). Inspection of the force–velocity and power–velocity relationships revealed that a load of 30% 1RM elicited mean power values that were the closest to P_{max} for all the ratio conditions. For the sake of clarity, the impact of resistance ratio on velocity and force patterns were, therefore, tested for 30% 1RM. Separate 1-way ANOVAs for repeated measures were used to test the potential effect of resistance ratio on F_0, V_0, S_{FV}, and P_{max}. When the sphericity assumption was violated (Mauchly test), a Geisser–Greenhouse correction was used. When a main effect or interaction was found, Bonferroni post hoc tests were performed. For all tests, the significance level was set at $P < .05$.

Results

Contrasts in the Temporal Domain Identified Across Resistance Ratios

Velocity. Visual inspection of velocity traces suggested that velocity in the middle phase of the concentric phase increased with increases in pneumatic resistance, whereas the gradual increase in isoinertial resistance elicited higher movement velocity toward the end of the movement (eg, Figure 2 [D–H], dashed trace). When considering the middle of the concentric phase, a significant lower velocity was found at 100I compared with 100P (–0.52 ± 0.28 m/s from 20% to 79% of the concentric phase) and 75P25I (–0.35 ± 0.13 m/s from 43% to 83% of the concentric phase). During the same portion of the movement, a significant higher velocity was found for 100P than 75P25I (+0.26 ± 0.28 m/s from 35% to 63%), 50P50I (+0.33 ± 0.35 m/s from 27% to 75%), and 25P75I (+0.51 ± 0.29

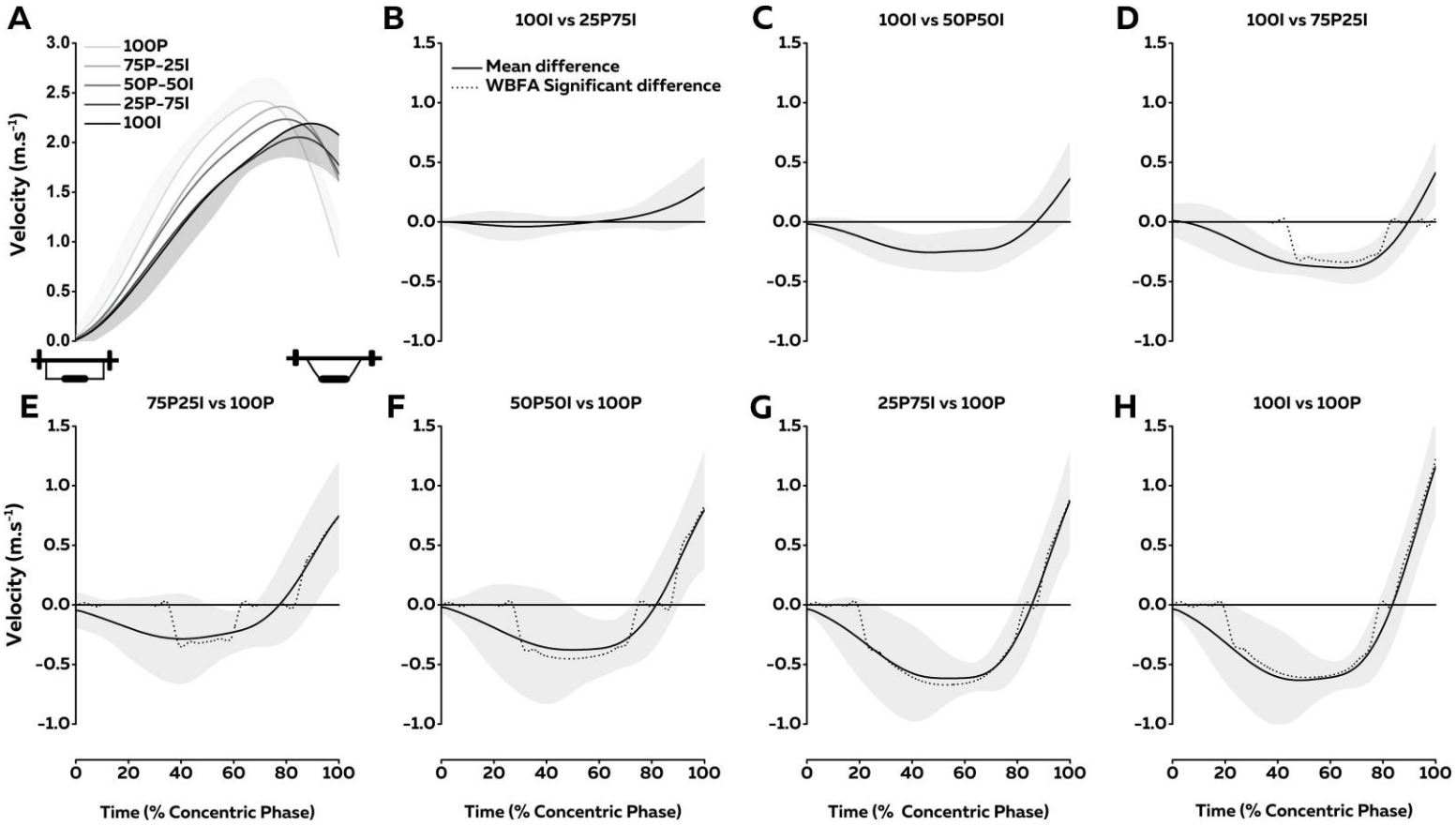

Figure 2 — Movement velocity expressed as a percentage of the concentric phase at 30% 1RM. Values are presented as mean (line) ± SD (area). Values above the horizontal axis represent the superiority of isoinertial-oriented resistance, and values below the horizontal axis represent the superiority of pneumatic-oriented resistance. Dashed lines display the inverse wavelet transform of the significant wavelets, thus indicating the statistically significant differences. Abbreviations: 100I, 0% pneumatic to 100% isoinertial ratio; 100P, 100% pneumatic to 0% isoinertial ratio; 25P75I, 25% pneumatic to 75% isoinertial ratio; 50P50I, 50% pneumatic to 50% isoinertial ratio; 75P25I, 75% pneumatic to 25% isoinertial ratio.

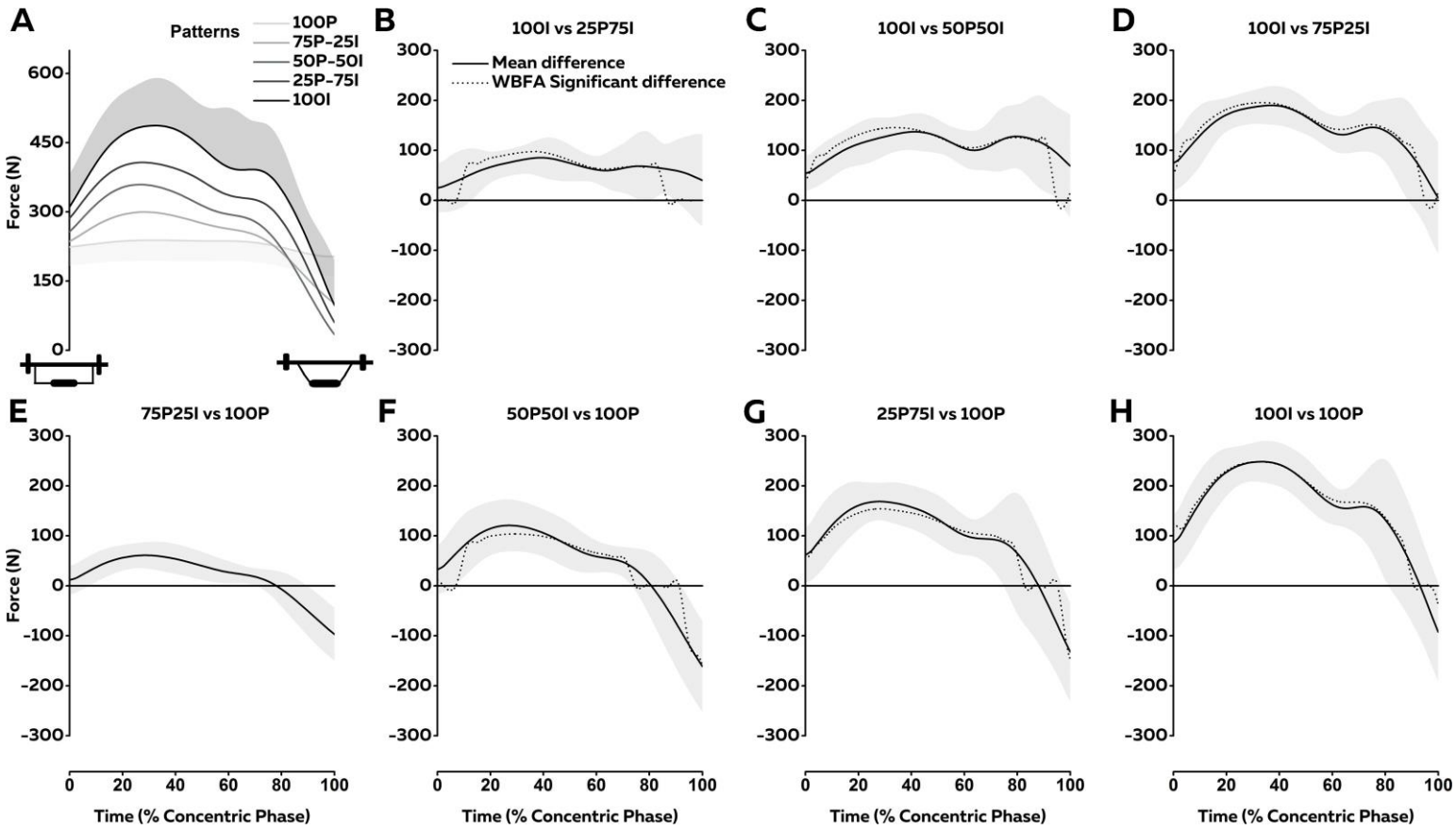

Figure 3 — Force expressed as a percentage of the concentric phase at 30% 1RM. Values are presented as mean (line) ± SD (area). Values above the horizontal axis represent the superiority of isoinertial-oriented resistance, and values below the horizontal axis represent the superiority of pneumatic-oriented resistance. Dashed lines display the inverse wavelet transform of the significant wavelets, thus indicating the statistically significant differences. Abbreviations: 100I, 0% pneumatic to 100% isoinertial ratio; 100P, 100% pneumatic to 0% isoinertial ratio; 25P75I, 25% pneumatic to 75% isoinertial ratio; 50P50I, 50% pneumatic to 50% isoinertial ratio; 75P25I, 75% pneumatic to 25% isoinertial ratio.

m/s from 19% to 80%). During the end of the concentric phase, a higher velocity was found at 100I in comparison with 100P (+0.39 ± 0.35 m/s from 83% to 100%). Pure pneumatic loading (100P) elicited slower movement velocity than 75P25I (–0.48 ± 0.44 m/s from 83% to 100%), 50P50I (–0.54 ± 0.41 m/s from 87% to 100%), and 25P75I (–0.51 ± 0.36 m/s from 87% to 100%).

Force. Mean differences in force patterns are depicted in Figure 3. Pure isoinertial loading (100I) generated higher force output than 100P (+179.9 ± 60.6 N from 0% to 90% of the concentric phase), 75P25I (+146.5 ± 49.3 N from 0% to 94%), 50P-50I (+113.3 ± 47.7 N from 0% to 94%), and 25P75I (+65.6 ± 42.4 N from 0% to 86%). During the same portion of the movement, a significant higher force output was found for 50P50I (+86.8 ± 45.6 N from 8% to 75%) and 25P75I (+124.3 ± 55 N from 0% to 82%) compared with 100P. In contrast, during the end of the concentric phase, 100P elicited higher force values than 100I (+78.5 ± 99.2 N from 97% to 100%), 25P75I (+109.7 ± 99.6 N from 95% to 100%), and 50P50I (+130.8 ± 91.6 N from 92% to 100%). No other significant differences were found between the tested conditions.

Force–Velocity and Power–Velocity Relationships

We observed a main effect of resistance ratio on the slope of the force–velocity relationship ($P = .006$). This slope was significantly lower at 100P than 50P50I –326.5 ± 136; $P = .005$), 25P75I (–280.1 ± 87.2 vs –363.9 ± 128.7; $P < .001$), and 100I (–280.1 ± 87.2 vs 340.3 ± 112.2; $P = .007$). No significant differences in slope were found between the other conditions. There was a main effect of ratio on F_0, V_0, and P_{max} ($P < .003$). F_0 was significantly higher with 100I (788 ± 250 N) compared with 50P50I (+11% ± 10%), 75P25I (+12 ± 8) and 100P (+20% ± 23%; $P < .01$). Moreover, F_0 obtained at 100P (651 ± 202 N) was significantly lower than that obtained at 50P50I (+8% ± 18%) and 25P75I (+12% ± 28%; $P < .008$). Compared with 25P75I, a significant higher V_0 was found with 100P (+14% ± 11%, $P = .007$). P_{max} obtained with the 100I condition (472.2 ± 101.3 W) was significantly higher than the values produced under modalities that included pneumatic resistance (+18% ± 4%, +16% ± 8%, +17% ± 5%, and +18% ± 8%, compared with 25P75I, 50P50I, 75P25I, and 100P, respectively; $P < .001$). No other significant differences were obtained between the tested conditions.

Discussion

The aim of the current study was to investigate the effect of a resistance ratio between pneumatic and isoinertial resistance on movement kinetics and kinematics during bench press. On the basis of an original statistical analysis, the major finding of the study is that gradual modulation of resistance ratio influenced the amount of force and velocity generated throughout the concentric phase of a ballistic movement. The increase in pneumatic resistance resulted in higher velocity associated with lower force levels in the middle of the concentric phase. Inversely, the increase in isoinertial loading elicited higher velocity toward the end of the movement. As a consequence, the force–velocity relationship was oriented toward force (with isoinertial resistance) or velocity (with pneumatic resistance) capacity. These results are useful for determining the optimal resistance modality according to an individual profile and for training purposes.

Some methodological considerations should be kept in mind when interpreting the data. First, due to the type of the resistance and the characteristics of the movement (ballistic action), slight variations in range of motion were observed between conditions when the shoulders failed to remain in contact with the bench. In this context, the data processing employed in the current study considered the range of motion that was completed in all tested conditions. On the basis of results from a pilot experiment, we applied the same amount of total external force in each condition, regardless of the resistance ratio. This procedure was chosen to consider the effect of resistance ratio on movement mechanics in standardized conditions (ie, with the same movement amplitude and total resistive force). In a view to overcome the well-known limitations of classical statistical methods regarding the comparison of signal patterns, we used original statistical analysis[18] to consistently compare the entire force–time and velocity–time curves between loading conditions. This procedure showed differences in the shape and magnitude of force and velocity signals throughout the concentric phase without loss of temporal resolution.

Our results showed that the effect of resistance ratio on velocity and force patterns was not homogeneous throughout the movement. The amount of pneumatic resistance increased movement velocity from the beginning to the middle of the concentric phase while the level of force was higher over the same phase as part of the isoinertial load increase (Figures 2[A] and 3[A]). Of note, the present force values were smaller but consistent with the results of Frost et al[13] showing that pneumatic resistance permitted one to reach higher peak acceleration (mean difference of 177%) and mean velocity (mean difference of 23%) than ballistic isoinertial resistance. These differences among resistance ratios could be mainly related to the significant influence of inertia on movement kinetics.[19] Using isoinertial resistance, the amount of force the individual has to produce to initiate the movement must exceed the weight of the load. With pneumatic resistance, this level of force solely depends on the mass of the barbell and body segments involved during the concentric phase. The progressive inclusion of pneumatic loading in the current study gradually reduced the influence of inertia and limited the magnitude of initial force required to displace the barbell.[11,12,14] As a consequence, in the initial part of the movement pneumatic resistance favored accelerative high-velocity movements, whereas an isoinertial load elicits a higher amount of force.

In contrast, when considering the end of the concentric phase, pure isoinertial and pure pneumatic modalities were the most effective means to induce a high level of force, with slightly higher values with pneumatic resistance (Figure 3 [F–H]). This outcome resulted from 2 different mechanical schemes. In line with the literature, isoinertial resistance permitted one to reduce the deceleration phase by throwing the barbell into free space.[7,9,20] This extension of the acceleration phase limited the effect of momentum over the end of the movement compared with nonballistic actions.[21,22] Inversely, pneumatic resistance is not related to the inertia and momentum of the load, theoretically limiting the effect of velocity variations.[12] Resistive force resulting from the application of pneumatic resistance is, thus, relatively constant throughout the movement, as reflected by the highest amount of force in the last moments of the concentric phase obtained in the current study.

These differences in velocity–time and force–time curves subsequently affect the shape of the force–velocity relationship. Our fi showed that force and power output were systematically higher under only-isoinertial ratio. Constant external loading, therefore, seems to remain the more appropriate mechanical stimulus to maximize muscle power when movement is performed as a ballistic action (Figure 4[A]). Moreover, the slope of the force–velocity relationship measured in pure pneumatic conditions exhibits a profile oriented toward velocity capabilities when com-

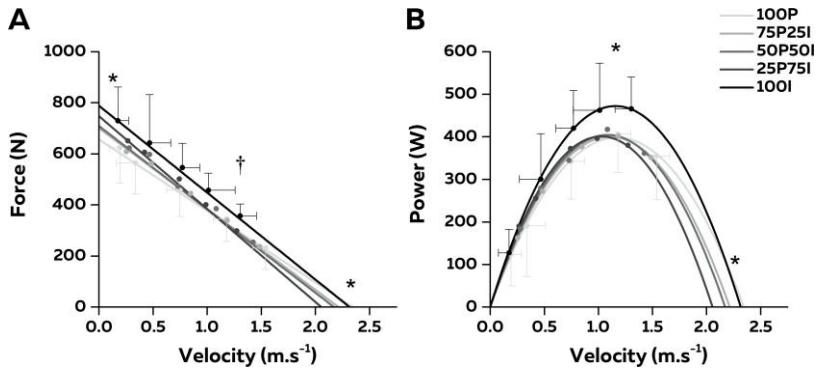

Figure 4 — Effect of resistance ratio on (A) force–velocity and (B) power–velocity relationships. The x-intercept corresponds to maximal theoretical velocity (V_0) and y-intercept corresponds to maximal theoretical force (F_0) of the force–velocity relationship. Maximal power (P_{max}) corresponds to the peak of the power–velocity relationship. For the sake of clarity, only the main effect of resistance ratio was indicated. *Significant effect of resistance ratio on F_0, V_0, or P_{max} ($P < .05$). †Significant effect of resistance ratio on S_{FV} ($P < .05$). Abbreviations: 100I, 0% pneumatic to 100% isoinertial ratio; 100P, 100% pneumatic to 0% isoinertial ratio; 25P75I, 25% pneumatic to 75% isoinertial ratio; 50P50I, 50% pneumatic to 50% isoinertial ratio; 75P25I, 75% pneumatic to 25% isoinertial ratio.

pared with resistance modalities that include isoinertial resistance. For the same amount of external resistance, movement velocity was consistently higher as the amount of the pneumatic part in total resistance increased. This is corroborated by the fact that the velocity measured under pure pneumatic loading at 30% 1RM (1.54 m/s on average) was remarkably superior to that produced with a larger part consisting of isoinertial loading (1.30 m/s with a pure constant load). Thus, the inclusion of pneumatic resistance appears to be the most conducive means to allow the production of force at high movement velocities.

Conclusions and Practical Applications

Numerous studies have investigated the power-load spectrum to determine an optimal load to maximize mean power output.[7,23–26] According to the specificity of resistance training, muscular adaptations may be maximized at the movement velocity involved during the exercise.[27] On the basis of our results, exercises including pneumatic resistance could contribute to training velocity-generating capacity, especially in the initial part of the movement. This resistance modality seems appropriate to stimulate the velocity component of the force–velocity relationship and potentially changes the orientation of the slope toward velocity capabilities. Conversely, the use of isoinertial resistance in ballistic actions could allow for development of velocity capacity toward the end of the movement. Regarding the force component of the relation, our findings confirm that the greater the isoinertial load in total resistance, the higher the amount of produced force. Constant external loading, therefore, will be more prone to modify the slope of the force–velocity relationship toward the force-generating capacity.

A recent approach suggests that an optimal ratio exists between force and velocity, which can contribute to maximizing ballistic performance.[28,29] On the one hand, given that our findings demonstrate the significant impact of resistance ratio on force and movement velocity, the type of resistance modality can be considered as an interesting exercise variable that can be adjusted to induce the targeted gains in force or velocity. On the other hand, for athletes with similar maximal power capability, a significant imbalance between force and velocity capacities can negatively impact their respective ballistic performance.[30] Consequently, practitioners may adapt mechanical stimulus (ie, resistance modality) based on an athlete's athletic capacities and on-field requirements.

Acknowledgments

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