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Review Article

Good Practice Rules for the Assessment of the Force-Velocity Relationship in Isoinertial Resistance Exercises

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Abstract

The mathematical relationship between the force and the velocity as determined during isoinertial progressive resistance strength tests is being extensively used for the assessment of neuromuscular qualities and for a targeted resistance training. The reliability of this relationship depends on the reliability of the collected force and velocity values. This reliability can be jeopardized by several factors such as: 1) an erroneous movement execution; 2) an improper load assignment; 3) a useless number of performed repetitions; 4) an inadequate rest interval between sets of repetitions; 5) an improper use of the measurement device and of the relevant computing methods. The aim of this contribution is to provide the operator with a list of good practice rules retrieved from the specific scientific literature concerning the instrumented assessment of muscle strength during isoinertial resistance exercises.

Keywords: Strength Testing, Isoinertial, Force-Velocity, Best Practice

1. Introduction

Several studies have analyzed the in-vivo relationship between the force applied to the external resistance and the lifting velocity of the external resistance during the so-called "isoinertial resistance exercises" (1). Such mechanical quantities are typically retrieved by means of draw wire encoders (2-7) or, less commonly, inertial sensors (8, 9). These devices can be used, indeed, to track the kinematics of the external resistance during exercising. Load, force and velocity can be paired and represented on a graph in different ways depending on the purpose, and their relationship can be represented by first- or second-degree polynomial models used to fit the data. For instance, a second-degree power-load curve has been used for determining the load that maximizes power production (i.e., optimal load) (3-5, 10). A first-degree velocity-load curve (6, 7) and a combination of second-degree force-velocity and load-velocity curves (8) have been used for predicting the one-repetition maximum (1RM). Force, velocity and power values obtained from draw wire encoders and accelerometers during isoinertial strength testing have been showed to present a high inter-trials and inter-sessions repeatability (9, 11). However, the reliability of the obtained force, velocity and power values and, hence, the reliability of their mathematical relationships can be jeopardized, though, by several factors such as: 1) an erroneous movement execution; 2) an improper load assignment; 3) a useless number of performed repetitions; 4) an inadequate rest interval between sets of repetitions; 5) an improper use of the measurement device and of the relevant computing methods. Aim of this report is to provide the operator with a list of good practice rules retrieved from the scientific literature concerning the instrumented assessment of muscle strength during isoinertial resistance exercises. This list contains some basic principles that are usually well respected in scientific researches but often neglected in practical settings. Methodological approaches for the determination of force-velocity and related curves during loaded vertical jump tests (11-17) will be not intentionally discussed in this paper.

2. Movement Execution

The prerequisite of any strength test is to make sure that the subject performs the test with maximal voluntary effort. This condition, easier to obtain in isokinetic and isometric modality (because the subject is not asked to control the movement since the latter is either guided or performed against a fixed resistance, respectively), is less controllable for isoinertial strength testing. The reliability of a force-velocity relationship as determined during isoinertial strength testing relies on the fact that the lifting velocity decreases as the lifted load increases so that Hill's principle could take place. Nevertheless, in resistance training exercises, this basic principle can be compromised by the subject's erroneous execution. Errors related to movement execution are, of course, exacerbated in case the subject is not familiar with the exercise or the equipment. As an adequate level of familiarization is a prerequisite for performing strength testing (18, 19), the following recommendations are addressed to those whose movement familiarization is no longer an issue. Note that "familiarization" requires several sessions of practice and cannot be accomplished in the same session of testing (18, 19). In particular, two things are the sources of errors that are related to movement execution and may jeopardise the natural inverse relationship between the load and the velocity.

2.1. Lifting Velocity

This first source of error is related to the fact that the subject has not put in the maximal voluntary effort when lifting lighter loads (where the term "maximal voluntary effort" means lifting the load at a maximal voluntary velocity). This is a concrete risk when performing strength tests by means of isoinertial resistance exercises. Since a submaximal load can be either lifted more slowlyor faster, the maximal voluntary effort for any given load is required, otherwise results can be very different. Electromyographic observations have showed, indeed, a significantly lower concentric force when a submaximal load is intentionally lifted at a slower velocity (20). The concrete risk is that, as the load gets heavier, the subject may naturally increase his effort in lifting it. In the totality of the studies concerning the assessment of force-velocity and related curves in isoinertial resistance strength testing, subjects are asked to perform the lift (i.e. repetition) as fast as possible (2-10).

2.2. Range of Motion

This second source of error is related to the fact that the subject, as the load increases, reduces the range of motion (ROM) of the involved joint and, hence, the vertical excursion of the external resistance. This is also a natural strategy adopted with heavier loads to prevent muscles from working within those articular ranges where lever arms get small and disadvantageous. This typically results in null or non significant velocity decrements as the load increases. If the movement is eccentric-concentric, ROM should be controlled by using electro-goniometers (21) or, when using draw wire encoders, by controlling the vertical excursion of the external resistance which is strictly related to the ROM of the involved joints. In this regard, the bench-press exercise is characterized by a high reproducibility as the chest behaves as an anatomical restraint to ROM (22) but, on the other hand, care must be taken in avoiding bounces of the barbell that might alter the measurements reliability. If lifts are concentric-only, ROM can be controlled more easily since the movement can restart as the subject reaches the desired initial joint position. Concentric-only movements are, indeed, generally used when assessing the force-velocity relationships during isoinertial resistance exercise (2-10).

2.3. Further Remarks on Movement Execution: Guided vs. Non-Guided Movements

Another important role in this regard is played by the equipment used for strength testing. From a strictly mechanical point of view, guided equipment (such as a Smith machine or a leg-press) allows the user to easily standardize the ROM, especially in concentric-only exercises. Moreover, as the movement is restricted to a vertical-only plane, machines may help those less familiar with the exercise typology. For this same reason (movement restriction corresponds to higher movement stability), however, free weight exercises require a higher neuromuscular demand with respect to guided exercises. It has been proved, in fact, that both squat and bench-press exercises performed by using barbells employ a higher muscle activity than those performed at a Smith machine (23, 24). Since a force-velocity profile is generally used for training prescription and eventually for real-time training monitoring, the equipment used for testing must reflect the equipment normally used for training. For example, a force-velocity profile assessed at a Smith machine should not be used for training prescription and monitoring in a free weight squat exercise. With regard to the studies discussed in the present paper and strictly related to the assessment of power-load, load-velocity and force-velocity relationships, most of them (seven out of nine) made use of machines (2, 3, 5, 7-10). One study made use of a barbell (6) while one study performed the assessment both in a guided and non-guided conditions (4).

3. Load Assignment

This is another quite crucial point for a proper construction of the curves of interest. Load assignment is easier if the coach knows his athlete. In any case, load assignment should be based on the subject's 1RM. Of course, since these curves rely on polynomial fitting of the experimental data, the richer the dataset is, the better will be the fit. However, despite the fact that the resolution of the curve fitting would be very high, a high number of lifted loads would share the same drawbacks of the direct determination of the 1RM: a time-consuming testing procedure that may expose the subject to a fatigue-related injury risk (25, 26). Pearson and colleagues, for instance, collected their force and their power data using loads ranging from 10% to 100%, at 10% intervals, of the 1RM. This was for describing the power-load relationship in bench-press and bench-pull exercises, by using a draw wire encoder (3). Lund and colleagues collected their power data using 30%, 40%, 50%, 60%, 70%, and 80%, of an indirect 1RM, by using a machine-embedded dynamometer for describing the power-load relationship in a leg-press exercise (10). Bosquet and colleagues used a draw-wire encoder to collect force, velocity, and power data, starting from 10 kg, with increments of 5 kg, until a significant power decrease. They used a total of ten different loads for estimating the 1RM in a bench-press exercise by means of a commercially available software with a factory algorithm for the estimation of the 1RM (2). Jidovtseff and colleagues recommended the use of three or four incremental loads for constructing a velocity-load relationship for the estimation of the 1RM, according to their proposed methodology in a bench-press exercise (6). Picerno et al. used the 50%, 65% and 80% of the actual 1RM for determining the force-velocity and the load-velocity curves during a chest-press and leg-press exercise (8). Loads do not have to be too close to each other in order to avoid small velocity decrements. Generally, since the method relies on the fitting of experimental data, the reliability of the curve increases if the latest available data is collected as close as possible to the 1RM. As a reference ending point of the protocol, several authors suggested that the latest used load should not be beyond 80% of the 1RM (6, 8, 27) so that the curve can be assumed to represent a good description of muscles' performance throughout a sufficient range of loads without the risk of getting close to the 1RM. Finally, it has to be said that a strong contribution of the coach's experience is required for a proper load assignment, which often turns out into an in-itinere process throughout the test.

4. Number of Lifts to Perform

The force-velocity and power-velocity relationships need to be constructed by using the maximal velocity that the subject can express for any used load. From this point of view, fatigue is the main factor to avoid, since it is responsible for any velocity loss (28-30). A high correlation has been proven, indeed, between mechanical (decrease of lifting velocity) and metabolic (blood lactate concentration) measures of fatigue during a bench-press exercise using loads ranging from 70% to 90% of 1RM lifted at the maximal voluntary velocity (29).

A low number of repetitions will minimise the effects of fatigue on the strength data and will decrease the injury risk. In this regard, Garcia-Ramos and colleagues explored the effects of fatigue over fifteen consecutive lifts performed at a maximal velocity in a bench-press exercise by using a draw wire encoder. They found no significant velocity loss until the 7th lift at 30% and at 40% of the 1RM and until the 5th lift at 50% of the 1RM (30). Baker and Newton analyzed power output using a draw wire encoder during a high-repetition set of bench-throw exercise performed at the maximal voluntary velocity recommending to perform two or three lifts between 45% and 60% of 1RM, and three to six lifts between 30% and 45% of 1RM (31). With regard to the assessment of power-load, load-velocity and force-velocity relationships, a certain degree of heterogeneity results from the approaches present in the literature: Pearson and colleagues used a single lift (3); Lund and colleagues used three lifts (10); Jidovtseff and colleagues used four lifts from 30% to 40% of the 1RM, three lifts from 50% to 70% of the 1RM, and two lifts from 80% to 95% of the 1RM (6); Rontu and colleagues used five lifts (27); Bosquet and colleagues used two lifts (2); and, finally, Picerno and colleagues used three sets of 5 - 6, 4 - 5 and 3 - 4 repetitions at 50%, 65% and 80% of the 1RM, respectively (8). This is pretty much in line with what was concluded by Legaz-Arrese and colleagues in their revision about the optimal repetition numbers to maintain the maximum exerted power: 4-5 repetitions with a load corresponding to 10-12 RM, 3 repetition with a load corresponding to 7-9 RM, 2-3 repetitions with a load corresponding to 6 RM (32). Certainly, the choice of using a single lift should be avoided because the output might be mystified in case that single lift is affected by execution errors. Actually, since measurement devices are able to stream data in real-time, there could be no need to assign a fixed number of repetitions since the subject can be stopped as soon as the coach identifies a significant decrease of lifting velocity (e.g., < 10% of the highest value collected until then) (30, 32).

5. Rest Period Between Sets of Repetitions

Generally, the duration of the rest between sets of repetitions during a maximal strength test should aim at ensuring the restoration of the muscle's creatine phosphate (ATP) reserve to allow the muscle to express its maximal power during the next set of repetitions. In this regard, muscle physiology teaches us that ATP takes from 2.5 to 3 minutes to fully recover from a set of intense exercise (18) whereas mechanical and electrical voluntary muscle contraction properties are not recovered within 3 minutes of rest (33). Based on empirical evidence, indeed, both position stands and systematic reviews agree in recommending 3 to 5 minutes as the rest interval that allows for greater repetitions over multiple sets when training with loads between 50% and 90% of 1RM performed at a fast contraction velocity (34, 35). Both these two characteristics are close to the aforementioned requirements of strength testing. Finally, with regard to the studies discussed in the present paper and strictly related to the assessment of power-load, load-velocity and force-velocity relationships, a 3 minutes rest interval was used by Bosquet and colleagues (2), Sanchez-Medina and colleagues with "light and medium loads" (5), by Picerno and colleagues (although not specified in the paper) (8), and by Jidovtseff and colleagues for loads ranging from 75% - 90% of 1RM (9). A 2-minute rest was used by Pearson and colleagues (3) and by Meylan and colleagues (7). Finally, 90 seconds were used by Jidovtseff and colleagues for loads ranging from 45% - 60% of 1RM (9) and up to 5 minutes were used by Thomas and colleagues (4) and by Sanchez-Medina and colleagues "for the heaviest loads" (5). Two studies did not report this information (6, 10). The average value of the rest intervals adopted by the abovementioned studies is 183 seconds (about 3 minutes).

6. Data Managing

6.1. Over the Repetition: Average vs. Peak Value

One might ask why the average of the collected instantaneous mechanical quantities is considered for performing the curve fitting instead of its peak value. The totality of the studies concerning strength assessment by means of isoinertial resistance exercises makes use of the average value of the instantaneous force and velocity over the duration of the lift. When assessing muscle strength by means of such typology of exercising the average value is to be preferred to the peak value of the instantaneous signal (9, 29). It has been demonstrated, indeed, that mean values are more stable and reliable than peak values during the propulsive phase of lifting (5). Since the muscle force varies within the ROM of the involved joint during the execution of the movement, a peak may correspond to the movement portion where muscles have an advantageous lever arm. Even lifting a heavy load may be, thus, characterised by a sudden high peak of velocity, which does not reflect the real effort that is exerted during most part of the movement, but represents only the result of a mechanical advantage carried by a greater muscle's lever arm. Moreover, from a strictly mathematical point of view, the total displacement of an object moving with a non-uniform rectilinear motion (e.g., the external resistance during the lift) is computed by using the average velocity rather than by its peak value. Average values can be, hence, assumed as more representative of the total mechanical work performed by external forces to lift the external resistance.

6.2. Over the Set: Best Repetition vs. Mean of the Nth Repetitions

Most of the studies (five out of nine) related to the assessment of power-load, load-velocity and force-velocity relationships considered in the present review made use of the mean values of force, velocity and power output collected over the set of repetition for constructing, for any given load, the relevant curves (6-10). Three studies considered, instead, the best performed lift over the set of repetitions (2, 4, 5) and one study used the solely performed single repetition (3). Besides the fact that the best value over the set of repetitions may be an outlier related to an erroneous execution of the lift, since there is no empirical evidence proving which is the best choice between the two approaches, the use of the mean value over the set of repetitions should be preferred at least on the basis that, between the two, this approach is the most used so far. Provided, of course, there is no significant decrease of velocity between the performed repetitions.

7. Measurement Techniques

Finally, a paragraph will be dedicated to the measurement techniques available for achieving these quantities. The instantaneous lifting velocity of the external resistance and the instantaneous force applied to the external resistance during a resistance training exercise can be estimated in two different ways. This can be achieved by measuring the instantaneous displacement of the external resistance or by estimating its instantaneous acceleration. These two approaches imply the use of two different measurement techniques/technologies: a draw wire encoder (i.e. linear position transducer or simply linear encoder) in the first case and a linear accelerometer in the second case. While accelerometers are completely wireless, draw-wire encoders still need cables for power supply and communication, although draw wire encoders with Bluetooth data transmission have recently become commercially available. From the instantaneous vertical displacement of the external resistance that is measured by a draw wire encoder, the lifting velocity and the acceleration can be estimated by the first and the double numerical differentiation of the vertical displacements, respectively. The force that is applied to the external resistance can then be obtained by multiplying the acceleration of the external resistance, added with the gravitational acceleration, multiplied by the mass of the external resistance (11, 36). The force applied to the external resistance can be directly measured using accelerometers fixed on the barbell or on the weightstack (8, 27, 37, 38), while instantaneous vertical velocity of the external resistance can be computed by numerical integration of the vertical acceleration. In dynamic conditions, an accelerometer sensor measures the sum of the gravitational acceleration and the acceleration due to the force impressed to the sensor along its sensitive axis. Prior to compute linear velocity through numerical integration, the acceleration due to gravity has to be removed from the sensor's readings. This means that the use of a uniaxial accelerometer fixed on the external resistance implies an accurate manual alignment of the sensor's sensitive axis along the vertical line in order to both easily subtract the contribution due to gravity (i.e., 9.81 m/s^2) and to fully sense the vertical acceleration produced by the force applied to the external resistance. The use of a triaxial accelerometer allows to overcome such limitations as the vertical acceleration can be computed through simple trigonometry as long as the orientation of the accelerometer remains constant during the movement of the external resistance (37). This condition is, for instance, satisfied when the accelerometer is fixed on a weightstack. Conversely, when this condition cannot be ensured (e.g. when using barbells), the orientation in space of the accelerometer has to be known so that the 3D acceleration vector can be rotated from the sensor-embedded to a global fixed system of reference. In turn, when the sensor's orientation is known, the accelerometer can be fixed with an arbitrarily orientation on the barbell or on the weightstack and no manual alignment is required. For this reason, accelerometers are typically used in a combination with gyroscopes becoming Inertial Measurements Units (IMU). IMU's orientation is computed through so called "sensor fusion" algorithms (39). Commercially available IMU's generally come with an on-board algorithm that returns the absolute vertical acceleration. Finally, both approaches present errors due to numerical calculus. The force and the velocity that are estimated by using encoders are affected by high frequency errors related to the numerical differentiation (40), while the velocity that is estimated by using accelerometers is affected by a low drift that is introduced by the numerical integration (41). Errors due to numerical integration affect the accuracy of the computed linear velocity more than those related to the numerical differentiation. In fact, linear encoders have been found to be more accurate that IMUs in estimating the barbell's vertical velocity during a squat exercise performed at a Smith machine (42). In this same study, velocity has been proved to be more reliable than power. As power is the algebraic product of the linear velocity of the external resistance and the force applied to the external resistance, this mechanical quantity carries errors related to the computation of force when using linear encoders and errors related to the estimate of velocity when using IMUs. For this reason, a combination of a draw-wire encoder and an accelerometer, as adopted by Jidovtseff and colleagues (9), may be the suitable measurement solution to solve the previously mentioned computational issues and obtaining a reliable determination of force, velocity and power data. It can be concluded that draw-wire encoders should be preferred to accelerometry when the force-velocity profile assessment has to be pushed towards very high loads as it has been shown how the reliability of accelerometers decreases approaching 90% of the 1RM (43). This is because the acceleration of the external resistance would be close to the gravitation acceleration in case of very slow movements and the accelerometer would not be able to sense any variation of velocity.

8. Conclusion

The reliability of force-velocity and related curves as determined during isoinertial strength testing may be jeopardized by several factors. Best practice for strength testing has been retrieved from the specific scientific literature to help strength training coaches in determining the force-velocity curve in a reliable manner (Table 1).

Primarily, subjects involved in the test have to be familiar with the equipment and exercise typology. A force-velocity profile should not be assessed on novices. During testing, the operator has to ensure that lifts are performed at the maximal voluntary effort and without modifying the ROM of the involved joints between consecutive lifts. As a force-velocity profile is meant for training prescription, testing should be accomplished by using the same exercise performed at the same equipment intended to be used during training. A targeted load assignment is fundamental for preventing useless efforts that can dramatically extend the duration of the test leading the subject to fatigue. The operator should conclude the protocol within three or four loads, sufficiently far from each other and ranging from 45% to 80% of the 1RM. Initial load assignment can rely on a first approximation of the 1RM as estimated using any regression-based approach. Coach's experience and knowledge of his athlete's should do the rest for a proper load progression. The number of lifts to perform at any given load must reflect muscles' maximum power capabilities avoiding the rise of fatigue. This can be easily monitored since an instrumented isoinertial strength test normally included the use of a device to measure the velocity with which the external resistance is being lifted. In any case, the number of repetitions should decrease linearly as the load increases. As a general rule, six repetitions can be considered enough with the lowest load (e.g. 50% of 1RM) whereas, for the sake of statistics, at least a couple of repetitions should be concluded at the highest load used (e.g., 80% of 1RM). Rest intervals should not be below 3 minutes. About data managing prior to curve fitting: (a) for every single lift, the arithmetic mean of the instantaneous force and velocity signal relative to the concentric phase of the movement has to be preferred to peak

Table 1. Issues That Might Jeopardize the Reliability of a Force-Velocity Profile Assessed at Isoinertial Resistance Exercises. A Summary of the Relevant Best Practices is Also Reported.

No.	ISSUE	Best Practice
1	Movement execution	a) perform lifts at the maximal voluntary effort
		b) ROM of the involved joints has to remain constant between consecutive repetitions
2	Load assignment	testing should be concluded within 3 - 4 loads (i.e., sets) sufficiently far from each other and ranging from 45% - 50% to 80% - 85% of 1RM
3	Number of lifts within a set	linear decreasing trend from 6 - 7 lifts with the lowest load and at least 2 lifts with the highest load; alternatively, velocity could be monitored in real time so that lifts can be stopped after a significant decrease of velocty
4	Rest intervals between sets	3 minutes
5	Data managing	(a) For every single lift, the average the instantaneous force and velocity signal relative to the concentric phase of the movement should be preferred to peak values
		(b) Mean power has to be computed as the average of the instantaneous power signal
		(c) Force, velocity and power values used for constructing the relevant curves have to represent the mean values of the Nth (N = number of lifts) average force, velocity and power values obtained over a single set of repetitions
6	Measurements techniques	Draw wire encoders should be preferred to IMUs

values; (b) mean power has to be computed as the arithmetic mean of the instantaneous power signal rather than as the algebraic product of the mean force and mean velocity values; (c) force, velocity and power values used for constructing the relevant curves have to represent the average values of the Nth (N = number of lifts) mean force, velocity and power values obtained over a single set of repetitions rather than values relative to the best performed lift. Care must be taken in excluding outlying values. Finally, with regard to the measurement technique: considering the computation complexity related for retrieving force and velocity data from an inertial sensor and if cables are not an issue, draw wire encoders should be preferred to IMUs for tracking the lifting velocity of the external resistance.

Footnotes

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Implications: A list of good practice rules is provided for helping strength training coaches in determining the force-velocity curve in a reliable manner.

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