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A Review of Power Output Studies of Olympic and Powerlifting: Methodology, Performance Prediction, and Evaluation Tests

John Garhammer

Biomechanics Laboratory, Department of Physical Education, California State University, Long Beach, California 90840.

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ABSTRACT

Total energy expenditure and rate of energy expenditure (power output) are important considerations for exercise programs and training programs. Mechanical power output generated during competitive lifts in both weightlifting (WL) and powerlifting (PL) is large in magnitude and can be measured accurately using standard biomechanical analysis equipment. Power tests do not appear to have predictive value for performance capability in PL. However, athletes in WL produce power outputs in vertical jump tests that are similar to those they produce in selected phases of the competitive lifts. This fact and related data have led to research that may result in simple power test protocols useful for estimating the training and performance potential of weightlifters and other athletes in power oriented sports, as well as for measuring a power component in standard fitness testing packages. Thus the purposes of this paper are to (a) review what is known about power output during the competitive lifts of WL and PL and the methods used to evaluate it, (b) review what is known about power tests in relation to performance prediction in WL and PL, and (c) suggest applications of this knowledge to related fields of study.

Key Words: power tests, weightlifting, vertical jump

Introduction

Energy expenditure during work or exercise and rate of energy expenditure (power output) have long been of interest to biomechanists and exercise physiologists. This interest relates in part to the connection these parameters have with understanding muscle performance capabilities and metabolic processes. In addition, in many sport, work, and recreational activities power output has some relationship to performance (1, 36).

Mechanical power output generated during execution of the competitive lifts in weightlifting (WL) and powerlifting (PL) is large in magnitude and can be measured accurately using standard biomechanical analysis equipment. Insights into the kinesiological characteristics of these lifts and related power tests, and the methods used to evaluate them biomechanically, can be of value to sport scientists, medical professionals, coaches, and fitness instructors. Thus, the purposes of this paper are to (a) review what is known about power output during the competitive lifts of WL and PL and the methods used to evaluate it, (b) review what is known about power tests in relation to performance prediction in WL and PL, and (c) suggest applications of this knowledge to related fields of study. Basic terminology will be presented first, followed by methodological considerations that include detailed examples. Simple power tests and practical applications are discussed in the final sections of the paper.

Terminology

Mechanical work is defined as the scalar product of the net force applied to an entity with the resulting displacement (sum of each applied force multiplied by the corresponding distance moved in the direction of that force) (47). Mechanical power is simply the rate of doing mechanical work or work done per unit time (47). Metabolic work is the energy used and released by the body during the chemical breakdown of substrates such as glucose and fat. Metabolic power is the rate of metabolic work (metabolic work per unit time).

In aerobic events power is generally measured via oxygen utilization rate and is therefore directly related to metabolic power. In anaerobic events the metabolic mechanisms that supply energy are more complex than during steady-state aerobic activity, and mechanical measures of external power output are the most practical and accurate methods to employ. As a result, metabolic power estimates during short-term anaerobic events are usually four or more times the mechanical power output, due to inefficient coupling of internal metabolic energy release with external work performed (1, 8).

Olympic style lifting, officially called weightlifting (WL), is composed of two overhead lifts, the snatch and the clean and jerk. Research has shown WL to involve very high mechanical power outputs for both men and women (28). Powerlifting (PL), which is composed of the squat, bench press, and deadlift, is thought by many to also involve large power outputs due to the very heavy weights lifted. Limited data on power output during PL has been published, but available data indicate that the values are approximately half those for WL (19).

Methodology—General Considerations

Due to the magnitude of the loads lifted in WL and PL, work done in raising these loads against gravity during any of the competitive lifts is by far the major component of the total work done. Elevation of the athlete's center of mass, which occurs in a range of less than 1/2 meter during all but the bench press lift, also contributes a large factor to the total work performed. These and smaller factors are discussed below with estimates of measurement error effects. All analyses are considered to be performed in two dimensions.

Vertical Work in Lifting a Barbell

During the competitive lifts in WL and PL, a barbell is raised vertically against gravity. In almost all cases the range of vertical motion is between 0.2 and 0.8 m (considering the clean and jerk to consist of three distinct lifting movements: the clean, a front squat, and the jerk). Variations between athletes for a given lift are due to both body segment length and lifting technique differences. Work done in lifting the barbell upward in the gravitation field can easily be calculated from the relationship $W = \Delta ME$, where W is the work done against gravity and ΔME is the change in the barbell's mechanical energy. Mechanical energy is the sum of an object's kinetic (KE) and potential energy (PE), where $KE = mv^2/2$ and $PE = mgh$, with m being the mass of the object, v its velocity, h its height above an arbitrary reference level, and g the acceleration of gravity near the earth's surface (9.8 m/s^2).

The velocity (v) of a barbell in WL and PL has a very small horizontal component, compared to the vertical component, at any time during a lift when KE would be determined for a work-done calculation. Thus, in the KE formula v can be assumed to be equal to the vertical velocity of the barbell. In the examples presented it will be clear that $\Delta PE = mg\Delta h$ is the single largest factor in any work-done calculation. Note that Δh would typically be determined as the difference of two vertical bar position coordinates obtained by digitization of a film or video record of the lift being analyzed.

Horizontal Work in Lifting a Barbell

Work done by moving the barbell horizontally during a lift must be calculated from the basic definition of mechanical work presented above. In practice the net applied force (F_x) in the horizontal direction during a given time interval is determined from the corresponding horizontal bar acceleration value using Newton's second law, $F_x = ma_x$. The average horizontal acceleration (a_x) for each analysis interval (for example, 0.02 s for 50 fps film, or 0.0167 s for 60 fields/s video) would be calculated from horizontal bar velocity changes, which are determined from horizontal position changes.

These accelerations are then multiplied by barbell mass (m) and the absolute value of the corresponding horizontal barbell displacement to determine the work done during that time interval. These work values are then summed for the lifting movement being analyzed (14). Determination of barbell acceleration requires two differentiations of the position data obtained by film or video digitization. Horizontal work terms are usually small for WL (20, 23) but are not always negligible. Some Olympic style lifters generate rather large horizontal barbell accelerations at the beginning of the second pull for a snatch or clean lift (the total pulling motion during the snatch or clean can be divided into first pull, transition, and second pull phases) (18). During the jerk the horizontal work term can almost always be neglected.

In PL the horizontal work can be neglected for the squat and deadlift due to very low accelerations. In fact, even vertical accelerations may be negligible for many analyses (5, 45). In the bench press, horizontal work can also be neglected in most cases due to the very small horizontal accelerations, even though there is a large horizontal range of barbell motion, compared to vertical (40, 46) (ratio of about 1:4), compared to the other lifts.

Work in Lifting the Body's CM

Work done in elevating the athlete's body mass is calculated from changes in his or her center of mass (CM) position. This requires the use of some values for segment CM locations. Although such values are available for various general populations, there may not be an appropriate set of such values for the body build of athletes in WL and PL. However, only differences in CM positions are used in work calculations (work = $mg\Delta h$), where m is body mass and Δh is CM position change). Thus, different sets of body segment parameters would likely produce very small differences in work done. Horizontal work and KE changes are neglected due to the very small velocity and acceleration values for body CM during the lifts and, in particular, when the CM position is determined during an analysis (see the examples below).

Body CM Elevation During Weightlifting

Body stature for elite men in a given body weight division in WL is very consistent (57). As a result of this consistency, it is possible to accurately estimate the elevation of an athlete's CM during WL movements based on values directly measured for world champions of typical stature. Table 1 provides data to make such estimates. Observations by coaches at women's World WL Championships since 1987, and work by Stoessel et al. (51), indicate that this body stature consistency also holds for elite women lifters, although there are two lighter body weight divisions for women (44 and 48 kg), and the heaviest division includes any women greater than 82.5 kg.

When errors of a few percent are acceptable in determining total average power output during any of the competitive lifts in WL, CM elevation data from Table 1 can be used to estimate work done in lifting the mass of the body. Use of Table 1 and standard home video equipment can permit coaches and athletes to make useful biomechanical measurements with no special analysis equipment (25, 27).

Power Output Calculations

The following examples contain a detailed discussion and presentation of power output calculations for the competition lifts of WL and PL. In the first example, using real data for a 125-kg male, relative power output averaged over the entire pull of the clean phase of a 260.5-kg clean and jerk lift (0.72 s) was found to be 33.5 W/kg. When only the second pull of the same lift was analyzed (0.12 s), the relative power output was 55.8 W/kg. The effects of measurement error are discussed and it is concluded that the average power output calculated for a complete pull should be accurate to within 2% of the true value.

Measurement error is likely to have a greater effect on second pull power values, due primarily to the short time intervals involved. Increasing the sampling rate for data collection to 100 Hz or more can improve accuracy for these calculations. Methodology for power calculations of the snatch lift are exactly the same as for the clean.

Table 1
Typical Changes in Elevation of a Weightlifter's Body CM* During Selected Lifts

Movement	52–60 kg div.	67.5–90 kg div.	100–110+ kg div.
Snatch			
Lift-off—max vel.	0.40 m	0.42 m	0.46 m
Second pull	0.12 m	0.13 m	0.15 m
Clean and jerk			
Lift-off—max vel.	0.32 m	0.34 m	0.36 m
Second pull	0.09 m	0.10 m	0.11 m
Jerk drive	0.14 m	0.16 m	0.18 m

Example: Power output of a 75-kg weightlifter, due to elevation of his or her body's CM, during a (complete) clean pull lasting 0.7 s, equals 357 W.
*Male or female.

Analysis of the Clean

Example 1—Power Analysis of a Clean Lift. The athlete (A.P.) is a 125-kg male attempting a 260.5-kg clean and jerk for a world record (in 1983). His total power output for the clean phase of the lift was determined as follows (2-D analysis):

1. The position of the center of the bar was digitized from film every 0.02 s (film taken at 50 fps) from two frames before any upward barbell movement from the lifting platform was seen until two frames after the bar began to descend from its maximum height (athlete moving under the bar to catch it at his shoulders). This procedure permitted evaluation of the bar trajectory during the pulling phase of the lift. Most of the calculations below end at the frame where the barbell reaches maximum vertical velocity, since this is the point in the pulling movement where force applied to the bar begins a rapid decrease toward zero (18).

2. A 5-point moving arc smoothing technique was used to determine the bar trajectory and its velocity and acceleration components from the raw digitized data (34) (see Table 2).

3. Body segment endpoints were digitized to determine the elevation of the athlete's CM (using the segmental method) in Frame 1, in the frame in which the second pull began, and in the frame in which maximum vertical bar velocity was reached (18) (see discussion below).

4. Using data from Paragraph 2 above (Table 2), work done while lifting the barbell vertically was determined from change in ME. In Frame 1, ME = 0 since KE = 0 and PE = 0 (bar center position in Frame 1 is defined to be the zero PE reference level). In Frame 37 the bar reached a maximum vertical velocity of 1.61 m/s at an elevation of 0.76 m above that of Frame 1. Thus, the ME at Frame 37 is $(260.5 \text{ kg} \cdot 9.8 \text{ m/s}^2 \cdot 0.76 \text{ m}) + (0.5 \cdot 260.5 \text{ kg} \cdot [1.61 \text{ m/s}]^2) = (1940 \text{ J}) + (338 \text{ J}) = 2278 \text{ J}$.

Table 2
Kinematic Data for the Analysis of a 260.5-kg Clean (Example 1)

Frame	X-coord	Y-coord	X-vel	Y-vel	X-accel	Y-accel
1	0	0	0	0	0	0
2	0	0	0	39	0	0
3	0	1	0	50	0	353
4	0	2	0	54	0	231
5	0	3	0	57	0	157
6	0	5	0	59	0	229
7	0	6	0	63	0	242
8	0	7	0	74	0	310
9	0	9	0	74	0	337
10	0	10	4	85	187	319
11	0	12	11	91	158	402
12	0	14	14	97	131	326
13	0	16	15	108	−58	366
14	0	18	15	109	−119	333
15	1	20	5	122	−74	213
16	1	23	7	123	56	161
17	1	25	12	122	252	50
18	1	28	18	125	249	91
19	2	30	25	126	172	170
20	2	33	26	131	44	277
21	3	36	25	137	−104	342
22	3	38	22	148	−165	340
23	4	42	16	152	−79	130
24	4	45	13	157	76	−188
25	4	48	21	145	156	−435
26	4	51	27	132	−69	−648
27	5	53	25	121	−644	−552
28	6	55	5	105	−1194	−413
29	6	57	−32	104	−1461	−229
30	5	59	−64	100	−1269	−41
31	3	61	−87	100	−692	−8
32	1	63	−95	102	−36	140
33	−1	65	−85	102	653	323
34	−3	67	−68	113	1119	586
35	−4	70	−35	127	1237	772
36	−4	72	−8	148	1008	605
37	−4	76	8	161	465	67
38	−3	79	11	156	31	−737
39	−3	83	2	130	−145	−1350
40	−3	85	−2	90	−16	−1464
41	−4	86	0	60	230	−1137
42	−3	87	11	45	370	−720
43	−3	88	19	39	363	−565
44	−3	88	26	29	253	−686
45	−2	89	29	11	185	−945
46	−1	89	31	−10	123	−1238
47	−1	89	35	−37	91	−1472
48	0	88	35	−71	1	1
49	1	86	36	−105	1	1

Note. Frame interval = 0.02 s; Coordinates in cm; Vel in cm/s; Accel in cm/s/s. Raw data was smoothed and differentiated using a 5-point moving arc technique. (Table values rounded to nearest whole number. For smoothing method, see chap. 4 in C.R. Wylie, *Advanced Engineering Mathematics*, 3rd ed., 1966, McGraw Hill.)

Error Analysis. Note that the PE term is more than five times as great as the KE term. The only measurement error in the PE term would be in determining the vertical position of the bar. Practical experience with multiple digitizations of a given lift by one analyst, and digitization of a given lift by two analysts, indicates that maximum bar height seldom differs by more than 0.01 m (1 cm) from trial to trial. This difference would result in a change of ±25.5 J or 1.3% (25.5/1940) in the PE analysis. A variation of 1 cm is greater than the error estimate made by McLaughlin et al. (43) for digitizing points that would be comparable to digitizing the end of a bar during any of the lifts in WL and PL. Data smoothing techniques result in almost no change from raw position data (34) and are not needed if only bar position information is required.

Note that if the camera recording a lift from a side view is positioned close (less than 10 m) to the lift, the protrusion of the bar from the weight plates toward the camera can cause measurement error. If the optical axis of the camera lens is horizontal and passes 1 m above the lifting platform, the bar end will appear as a point representing the true center of the barbell mass only when the bar is also 1 m above the lifting platform and directly in line with the camera. When the bar is above or below this level, or forward or back from the lens axis, the protrusion of the bar (which could be as much as 30 cm for a barbell with only one weight disk) could result in the center of the barbell (represented by the end of the bar) appearing higher, lower, forward, or backward from the true position.

If the camera is far from the lift and a long lens is used, the image of the lifter and barbell will be flattened, resulting in little or no measurement error, due to this perspective effect. However, a simple way to eliminate this effect is to mark two spots on opposite ends of the largest diameter weight plate facing the camera. For each picture, digitize these two spots and define the center of a line connecting them as the barbell mass center. This method may even be possible in major competitions if loaders and officials are cooperative. Bending (flexion) of the bar itself may be a related source of error. This effect is dependent mainly on the amount of weight being lifted, but also on the type of bar (steel) used.

5. The above work of 2278 J was performed in 0.72 s ([Frame 37 − Frame 1] · 0.02 s per frame). Thus the average power output due to vertical work in lifting the barbell from the floor to the maximum vertical velocity position is 3164 W (2278 J/0.72 s).

6. Summation of the horizontal work terms for each 0.02-s interval, as described in the section

on horizontal work in lifting a barbell, resulted in a total horizontal work value of 249 J. This contributes another 346 W (249 J/0.72 s) to the total average power output in lifting the barbell from the floor to maximum vertical velocity position.

Error Analysis. There is a potential for error in this calculation since accelerations must be obtained by double differentiation of smoothed position data. However, since 36 intervals were used in the horizontal work calculation, the average acceleration value for each interval can be expected to oscillate above and below the true value, resulting in some error cancellation and low net error. Also, the horizontal work is generally a small factor in the total work done in lifting the barbell. In this example it is 10% of the total (249 J/[2278 J + 249 J]). This is a considerably higher percentage than found for lifters in lighter body weight divisions in which less than 5% of the total work in lifting the barbell is horizontal work (20, 23). Thus, in most cases errors in horizontal work calculations result in very small changes to the total work and power output values.

7. During this same time interval (0.72 s) the athlete also raised his CM about 0.40 m from the initial position of Frame 1. The velocity of the CM is essentially zero in both Frames 1 (start) and 37 (top pulling position, due to reversal of body motion from upward to downward to catch the bar) (18), so the work done was calculated as the change in potential energy of the CM, which equaled 490 J (mgh = 125 kg · 9.8 m/s^2 · 0.4 m). This resulted in a contribution to the total power output of 681 W (490 J/0.72 s).

8. The total average power output of the athlete while lifting the barbell from the floor to maximum vertical velocity position was 4191 W (3164 W + 346 W + 681 W).

9. The relative power output during this lifting movement is the total average power output divided by the mass of the athlete and equaled 33.5 W/kg (4191 W/125 kg).

In WL it is of value to determine the power output during the second pull for snatch and clean lifts. This is a very high power phase of the pull for a clean or snatch lift and relates well biomechanically to the jerk lift (see Example 2) and to vertical jumping (16, 18, 30). Second pulls begin after the bar has cleared knee height and the lifter has shifted his or her hips forward to keep the bar as close to the body as possible (18). Second pulls are of very short duration, typically between 0.10 and 0.20 seconds (18, 20, 23, 28).

10. In the current example, the athlete began the second pull at Frame 31. This was determined both from kinematic data (the bar was at a local minimum in vertical velocity and the vertical acceleration was changing from negative to positive—see Table 2) and visual inspection of body position and movement pattern from the film. At Frame 31 the vertical height and velocity of the barbell were 0.61 m and 1.0 m/s, respectively. The ME at this frame is (260.5 kg · 9.8 m/s^2 · 0.61 m) + (0.5 · 260.5 kg · [1.0 m/s]^2) = (1557 J + (130 J) = 1687 J. Again, the PE term is much larger than the KE term.

11. In Paragraph 4 above, ME at the end of the pull (Frame 37) was found to be 2278 J. Thus the vertical work done during the second pull (Frames 31–37) was 591 J (2278–1687 J). Duration of the second pull was 0.12 s (Frames 37–31 = six frames at 0.02 s per frame). Vertical work power output was 4925 W (591 J/0.12 s).

12. Similar to Paragraph 6 above, summation of the horizontal work terms for each 0.02-s interval from Frames 31 to 37 resulted in a total horizontal work value of 112 J. This contributes another 933 W (112 J/0.12 s) to the total average power output during the second pull.

13. Similar to Paragraph 7 above, during this time interval (0.12 s) the athlete raised his CM 0.11 m (position of Frame 31 vs. 37). The vertical velocity of the CM is essentially zero in both Frames 31 and 37 (18) so this work-done factor was calculated as the change in potential energy of the CM, which was 135 J (mgh = 125 kg · 9.8 · 0.11 m). This results in a contribution to the total power output of 1123 W (135 J/0.12 s).

14. The total average power output of the athlete during the second pull was 6981 W (4925 W + 933 W + 1123 W).

15. The relative power output during the second pull equaled 55.8 W/Kg (6981 W/125 Kg).

Summary of the Power Analysis. An overall error estimate for determining work done during a lift is impossible to make in general, due to anthropometric and lifting technique differences between athletes as well as the accuracy limits of various measurement and analysis equipment and skill of the analyst. In this example, note that 77% (1940 J) of the total work done in lifting the barbell (2527 J = 1940 J + 338 J + 249 J), and 64% of the total work done by the athlete (3017 J), during the clean pull was due to a change in the PE of the barbell. The error in this PE value should be very small as discussed in Paragraph 4 above. The second largest factor (490 J = 16%) in the total work done by the athlete was due to elevation of his CM. Measurement errors in this term are associated with determining the *difference* in vertical CM position rather than absolute position, and are therefore likely to be small.

An exact overall error estimate is difficult to make even for this specific lift due to the many contributing factors. A 1-cm error in bar elevation determination would change the total work done during the lift by ±0.8% (25.5/3017). A 1-cm error in determining the change of the athlete's CM elevation during the lift would result in a change of ±0.4% (12.2/3017) in the total work done.

Horizontal work and KE terms are usually the smallest in magnitude but may have a larger percent error associated with their determination. However, it is difficult to imagine how a careful analysis of a quality film or video record could yield errors in these terms that would result in greater than ±0.5% changes in the total work done. Thus, total average power output (work/time) during a lifting movement like the clean can be determined with low total error (<2%) as long as the time interval measurement between images is accurate. Use of internal timing lights in film cameras or electronically controlled video cameras provide very accurate time measures.

Accurate analysis of a second pull is more difficult than that for a complete pull, due to uncertainty in determining the exact image representing the start of this movement. The time interval used for second pull power calculations is of very short duration. In the current example, an error of one image (0.02 s) would result in a power output decrease, due to vertical work, of almost 7% (from 4925 W to 4586 W). This large change is due primarily to a large percent increase in the time interval from 0.12 s to 0.14 s (17%). The ME change from Frame 31 to 30 is only 51 J (1687 J to 1636 J), due to a lower barbell elevation (0.61 m to 0.59 m, see Table 2). Changes in horizontal power and power associated with lifting the athlete's CM would also be large due to the time interval increase. Using a sampling rate of 100 Hz or more can improve accuracy in this type of calculation.

Analysis of a Snatch Lift

Work and power output analyses of a snatch lift are, methodologically, exactly the same as for a clean. For a given skilled athlete, the weight lifted in a maximum snatch lift is about 80% of that lifted in a maximal clean. The starting position of the lifter's CM is slightly lower than for a clean, due to the wider handgrip used. Maximum barbell and body CM elevation during each phase of the snatch are usually higher than for a clean, due to a greater average and peak vertical velocity during the pulling motion and greater range of motion for some body segments. Total average power output values, however, tend to be very similar for a given athlete for snatch and clean movements (18, 20, 23, 28). Force-velocity considerations relative to muscle function may be important when making detailed kinematic and kinetic comparisons between snatch and clean movements (17, 21, 26).

Analysis of a Jerk Lift

Power analysis methodology for the jerk phase of the clean and jerk lift is somewhat different than that for the clean and snatch pulls, and is presented below as Example 2. Elastic energy storage in the musculoskeletal system and lifting bar are unaccounted for sources of error in the calculations. For a given athlete, power output values for the jerk are usually very similar to those found for second pulls in the clean and snatch (20, 23, 28). However, in the example given, the jerk power value was lower than expected. Possible reasons for this low value are given at the end of the example.

Example 2—Analysis of the Jerk Phase of the Clean and Jerk Lift. Work and power output analyses of the jerk phase of the clean and jerk lift are dependent on ME changes of the barbell and the athlete's CM. Horizontal bar movement during the jerk thrust is negligible for skilled lifters (20, 23). The jerk starts with the athlete standing erect and holding the barbell across the shoulders. The athlete then rapidly "dips" by flexing the knee and hip joints (usually less than 90° of flexion at the knee) while keeping the torso vertical. This downward movement is immediately followed by a rapid and forceful extension of the same joints and elevation of the shoulder girdle to thrust the barbell vertically upward. Vertical force application to the bar rapidly drops toward zero as the knee joints reach full extension This corresponds to the barbell reaching maximum vertical velocity during the jerk thrust. Thus, work and power analyses begin at the lowest point of the jerk dip (ME = 0 for both the barbell and the athlete's CM) and end when the barbell achieves maximum vertical velocity.

For the 260.5-kg clean analyzed in Example 1, the corresponding jerk was analyzed as follows:

1. The lowest point of the jerk dip occurs when the vertical bar velocity equals zero or changes from negative to positive. The vertical bar coordinate is then noted.

2. The end of the jerk drive occurs when the vertical bar velocity reaches maximum. For this example lift the value was 2.06 m/s. The total bar elevation during the jerk thrust was 0.27 m. Thus, for the barbell, $\Delta ME = (260.5\ kg \cdot 9.8\ m/s^2 \cdot 0.27\ m) + (0.5 \cdot 260.5\ kg \cdot [2.06\ m/s]^2) = 689\ J + 553\ J = 1242\ J$. Note that in this case the PE and KE terms are similar in magnitude.

3. The jerk thrust lasted 0.32 s (16 film frames @ 50 fps), so the power output due to work done on the barbell is 3881 W (1242 J/0.32 s). This duration for a jerk thrust is rather long but is found for lifters using a slower and deeper dip technique for the jerk. Generally, 0.18 to 0.24 s are more typical time intervals for jerk thrusts.

4. During this same time interval the athlete raised his CM approximately 0.18 m (see section on body CM elevation during weightlifting, and also Table 1). The corresponding work done was 220 J ($125\ kg \cdot 9.8\ m/s^2 \cdot 0.18\ m$). The resulting

power output due to lifting the body's CM was 689 W (220 J/0.32 s).

5. The total power output for this jerk lift was 4570 W. This is a low value compared to the clean second pull value determined in Example 1 (6981 W). Jerk and second-pull power output values are usually found to be very similar in magnitude for elite lifters in top physical condition (18, 20, 23). Possible reasons for the lower jerk power value in this example include the following: (a) body CM elevation was an estimate (see section on body CM elevation during weightlifting, and Table 1); (b) the duration of the jerk thrust was greater than usually found; and (c) the athlete may not have been in top physical condition and/or may have been fatigued (this was his last lift of the meet and the competition was an exhibition rather than a major championship).

It must be pointed out that at the bottom of the jerk dip (start of the jerk power analysis) considerable elastic muscle-tendon energy and bar flexion strain energy may exist as types of system (lifter + barbell) elastic potential energy. This potential energy can do work during the immediately following jerk thrust effort, and could invalidate to some extent the analysis assumption of zero ME at the start of the thrust movement. The magnitude of this stored elastic energy depends on (a) the weight of the barbell, (b) the type of steel used to make the bar, and (c) the speed of the jerk dip and reversal from descent to ascent. Similar concerns can be expressed for snatch and clean second pulls (17) and for the squat lift (see Example 3). This problem has not been biomechanically evaluated for the jerk, although it is well known to practitioners that less weight can be jerked overhead if a dead stop is held at the bottom of the dip than if the jerking movement is continuous. This question in general remains a challenge to sport scientists.

Analysis of the Deadlift, Squat, and Bench Press. The following examples present discussion of and power output calculations for the competition lifts of PL. The specific example for the deadlift resulted in a power value about one third as great (12.7 W/Kg) as found for the total clean pull in Example 1. Methodology for power output calculations for the squat lift are identical to those used for the deadlift. Elastic energy may be a source of calculation error in the squat. The bench press lift is considerably different than all the other lifts analyzed since it is performed while lying supine on a bench rather than while standing. Since it is primarily the upper body musculature that controls this lift, the power values are rather low. The example calculation given below resulted in a relative power output value of only 4.6 W/Kg.

Example 3—Analysis of the Deadlift. The deadlift has some movement similarities to the clean, which was analyzed in Example 1. The starting or "lift-off" position is very similar to that for a clean, but the speed of motion during the lift is considerably slower. A typical maximum vertical velocity during a clean or snatch pull would be 1.6 m/s and 2.0 m/s, respectively, while for a deadlift it would be about 0.6 m/s. No published work has been found that analyzes the deadlift pull in phases (if any can be identified), such as the first pull, transition, and second pull phases for cleans and snatches.

The range of motion of the barbell during a deadlift depends on anthropometric and technique variables, but is of the order of 0.5 m. The lift ends with the athlete standing erect, arms at the sides, and the barbell held in the hands at about midthigh height. Only one study has evaluated power output during the deadlift (19) (horizontal work done on the barbell was included) (26, 39). Values found were less than half of those found for comparable clean and snatch pulls. The following specific example illustrates how total power output during a deadlift can be accurately calculated.

Consider a 100-kg athlete deadlifting 375 kg. The movement from lift-off until finish takes 2.0 s and the barbell is elevated 0.6 m. Since the barbell and CM of the athlete are not moving at the start or finish of this lift, work done can be calculated from changes in PE only (KE = 0 at the start and finish). Work done in lifting the barbell equals $\Delta ME = mg\ \Delta h = (375\ kg \cdot 9.8\ m/s^2 \cdot 0.6\ m) = 2205$ J. Work done in elevating the athlete's CM is calculated the same way: $\Delta ME = mg\ \Delta h = (100\ kg \cdot 9.8\ m/s^2 \cdot 0.35\ m) = 343$ J. This total work of 2548 J (2205 J + 343 J) was performed in 2 seconds. Thus, the total power output was 1274 W (2548 J/2 s) and the relative power output was 12.7 W/kg. Note that this value is about one-third of that found in Example 1 for a 260-kg clean. The main reason is that the deadlift lasts about three times as long as the clean pull. Horizontal work was neglected in this example because of its very small magnitude for skilled deadlifters.

Example 4—Analysis of the Squat. The squat has received considerable attention in biomechanical analyses as reviewed by Garhammer (26). Descent and ascent phases have been characterized, as has a "sticking point" during the ascent (44, 45). Only one paper, however, has addressed the question of power output during the squat (19) (horizontal work done on the barbell was included) (26, 39). The descent phase was ignored in that analysis even though elastic muscle-tendon energy and bar flexion strain energy may be a contributing factor to the work done during ascent, as discussed in the jerk analysis in Example 2. An unpublished report (41) indicated that initiating a squat ascent from a dead stop (bar on supports) decreases the amount of weight that can be lifted and reduces the magnitude of the initial ascent velocity. This is considered a similar effect to that found for vertical jumps with versus without countermovement (2, 37).

Values found for average power output during the squat were less than half of those found for comparable clean and snatch pulls (19). Example 3 above for a deadlift analysis illustrates the exact methodology used to calculate power output during the squat exercise. At the lowest point of the descent the lifter and barbell are considered to have ME = 0, just as at the start of the deadlift (liftoff). The change in ME (= ΔPE) for the barbell and athlete's CM by the end of the ascent phase of the lift equals the work done during the lift. Even the numerical values used in Example 3 are representative for a realistic squat in competition.

Example 5—Analysis of the Bench Press. The bench press has undergone more biomechanical study than the deadlift but less than the squat and Olympic lifts (26). Three published reports have presented information about power output during this lift (40, 46, 49). It is the only lift from WL and PL in which elevation of the body's mass is not important, and in which the movement is not done while standing on the feet. Only the arms are raised during the lift, while the rest of the body is stationary and supported on a bench. By the rules of PL, the bar is to touch the chest at the end of the descent phase of the lift, and a pause is to occur before the ascent is initiated by a referee's signal. This should minimize elastic energy recovery from muscle, tendon, and rib cage recoil (60) and permit the assumption that ME for the lifter plus barbell system is zero at the start of the upward pressing motion. At the finish of the press, the barbell is motionless at arm's length about the body. Work done is considered equal to the change in PE of the barbell. Work done in raising the mass of the arms can be neglected.

The following specific example illustrates how total power output can be calculated accurately for a competition bench press: Consider a 75-kg athlete bench pressing 200 kg. The barbell is raised 0.35m in 2 seconds during the ascent phase of the lift. For the barbell, the work done is $\Delta ME = \Delta PE = mg\,\Delta h = (200\text{ kg} \cdot 9.8\text{ m/s}^2 \cdot 0.35\text{ m}) = 686$ J. This work occurred in 2 seconds, so the power output was 343 W. The relative power output is 4.6 W/Kg (343 W/75 Kg).

Power Output During WL and PL

In both WL and PL the total absolute power output for a given lift will almost always be greater for elite athletes in heavier versus lighter weight classes (19, 20, 23) as expected. This trend in power output seems to occur for women as well as men (28). Thus it is often advantageous to discuss relative power output (watts per kg body mass) so as to take body weight into account when comparing athletes. Average relative power output values of about 34.3 W/kg for elite male athletes during the entire snatch or clean pulling movements have been published. The corresponding value for elite women is 21.8 W/kg (about 63% that of the males). For the second pull during snatches and cleans, and during jerks, the average values for men and women are 52.6 and 39.2 W/kg (about 74% that of the males), respectively (28).

Higher values in the range found for men are comparable to estimates of 54.9 W/Kg (59) and 64.3 W/Kg (42) as the maximal power output capability for humans in exertions of less than 1 second duration. Note that these measured values for second pulls and jerks are average values over a 0.1- to 0.2-second interval. Peak power output during a lifting movement is higher (see discussion below in connection with vertical jump testing).

In PL much less data on power output has been published, and none was found for women. However, from world record lift data for women in PL, and the methodology illustrated in Examples 3–5, estimates of their power outputs during the lifts can be made. For elite males performing the squat or deadlift, relative power outputs are about 12 W/Kg (19). For the bench press, relative power outputs are about 4 W/Kg (46) (much lower due to the small percent of total body muscle mass involved in this lift). Estimates indicate that the corresponding values for women are 60 to 70% as great. In both WL and PL the heaviest athletes sometimes have lower than average relative power outputs, due to higher percentages of body fat compared to lighter athletes.

It is well established that power output during the WL and PL events increases as the weight lifted decreases from a maximal (1-RM) effort (19, 26, 49). This is particularly true for the power lifts, in which power output may be twice as great for a 90% versus 100% effort (19). This is primarily due to a large decrease in the time required to complete a lighter squat, bench press, or deadlift. It has not been established at what percent of a 1-RM effort maximal power output occurs, but indications are that efforts of about 80% will result in near maximal power production (26). These facts are very important in the planning of strength and power development as well as other types of training programs.

Applications

Snatch and clean lifts, and related movements such as power snatch, power clean, and high pulls, not only require high power production if executed properly but also involve a large muscle mass and multiple joint movements that relate well to everyday work, recreational, and sport activities. Thus, by specificity of training, these lifting exercises result in adaptations that transfer well to improve performance in other common movement activities, as well as sports requiring high power output. In addition, the caloric cost can be very high. Consider an athlete using clean grip high pulls (lifting the barbell as in the clean but only pulling it as high as possible before returning it to the floor without catching it at the chest) for three sets of 10 repetitions after warm-up.

If the work rate during each repetition averages 30 W/kg, and the athlete's body mass is 90 kg, the total work done for the 30 pulls (averaging 1 s per pull for a total of 30 s of lifting work) is 19.4 Kcal (1000 W = 0.239 Kcal/s). If the efficiency of converting metabolic energy to mechanical energy is 25% (1, 8), the pulls alone have a caloric cost of almost 80 Kcal. Work during warm-up, eccentric work while lowering the barbell between repetitions, and recovery energy expenditure between sets results in a very large caloric cost for one exercise that may take 15 minutes of a total workout lasting an hour or more. Postworkout recovery also maintains one's metabolic rate well above basal levels for at least several hours (11).

The above example relates to WL movements. Similar arguments can be made for the squat and deadlift from PL. These exercises involve a large muscle mass and multiple joint movements. The power output may be lower, but not as much lower as the competition lift values stated in the section on power output during WL and PL. In general training, when 5 to 10 repetitions per set are performed, the weight used may be 70 to 85% of the 1-RM. Thus the power output may approach twice the value for a competition 1-RM, or near 24 W/kg. The caloric cost of a squat or deadlift workout designed like the clean pull workout above could have a caloric cost 70 to 80% as great. Thus, although the PL events are heavily dependent on strength rather than power for competition performance, they may be performed at a very high work rate in training (if desired) by using lighter weights. For example, jumpers, throwers, and sprinters who use squatting as part of their conditioning program would likely squat heavy (primarily) during a strength development phase of their program, but squat mainly with lighter weights for power development during the training phases close to competitions.

The above energy cost considerations indicate that many individuals primarily concerned with fitness improvement could benefit by incorporating some of the above mentioned lifts in their exercise programs. The large muscle mass, multijoint involvement, and coordination requirements of these types of lifts also make them desirable for workers who need to improve their strength levels to reduce injury risk or more easily satisfy job demands, such as heavy or repetitive lifting, pushing, and pulling.

Performance Prediction and Evaluation

Powerlifting

In PL, power output has been found to decrease considerably as the weight lifted increases, that is, as performance improves. This is due to the fact that as an athlete lifts more and more weight, closer to his or her maximum, the movement speed decreases (consider the force-velocity relationship for skeletal muscle) and the time factor in the denominator of the power formula increases, often substantially. Thus there is an inverse relationship between power output and performance in competitive PL, and it seems unlikely that any type of power test (e.g., vertical jump) would be useful for performance prediction in PL. However, such tests have not been performed and correlated to performance with powerlifters.

This does not mean that powerlifters should never do lighter lifts with substantially higher work rates in training. Monotonous low-repetition heavy weight training, over periods of weeks or months, can result in maladaptation symptoms grouped under the term overtraining (54). Variation in the training program, such as periodic use of higher repetition training with lighter weights, is one method for reducing the risk of overtraining (12, 24, 33, 55, 56).

Weightlifting

In WL, power output testing has more potential as a tool for predicting performance than in PL. Although power output does decrease as the weight lifted approaches the 1-RM maximum, the decrease is much smaller in magnitude and percentage than in PL. This is due to the fact that during the snatch and clean and jerk several kinematic values, including time, must fall in a rather narrow range (minimum *and* maximum) for a given athlete in order for the lifts to be successful and be performed with proper technique. As the weight lifted increases from about 95% to a maximal effort (1-RM), parameters such as maximum barbell velocity and pull height decrease only a few percent.

Table 3 presents representative data for a number of elite weightlifters completing two progressive lifts of a given type at a single competition (also see Table 2 of Ref. 23). In almost all cases the power output for an entire lift and for the second pull, and the maximum velocity and pull height, decrease slightly for the heavier lift. Conversely, the pull

Table 3
Typical Effects of Increased Load on Barbell Kinematics and Power Output in WL

Athlete	Lift (kg)	Eff.(%)	V(cm/s)	T1(s)	Y(cm)	T2(s)	P1(W)	P2(W)	T3(s)
H.X. (47)	1S-65	98	222	0.72	105	0.98	1147	1970	0.22
China [28]	3S-75	99	199	0.74	96	0.96	1118	1891	0.22
D.A. (67)	1C-152	97	146	0.72	87	0.90	2103	2986	0.14
USA [22]	4C-163	97	128	0.76	85	0.92	2034	2954	0.12
K.C. (98)	1C-197	93	169	0.72	96	0.92	2991	4775	0.12
USA [22]	2C-205	96	153	0.76	91	0.98	2676	4418	0.12
	1J-197	100	203	–	–	–	–	5022	0.20
	2J-205	100	199	–	–	–		3924	0.26
C.W. (82)	1S-140	94	179	0.74	105	0.96	2370	3919	0.14
USA [22]	3S-150	94	168	0.74	101	0.98	2335	3905	0.12
V.S. (97)	1C-200	95	191	0.72	89	0.92	2853	6077	0.12
USSR [22]	2C-215	96	166	0.78	87	1.00	2627	5393	0.12
	1J-200	100	194	–	–	–	–	4860	0.10
	2J-215	100	185	–	–	–	–	4587	0.10
J.M. (112)	3S-185	94	204	0.84	122	1.10	3128	6772	0.14
USA [22]	4S-188	97	196	0.84	119	1.10	2982	6185	0.14
K.O. (51)	2S-100	97	202	0.64	97	0.88	1701	2686	–
USSR [20]	3S-105	95	192	0.68	94	0.90	1619	2784	0.14
Y.R. (67)	1C-170	96	148	0.68	83	0.84	2355	2892	–
Bulg. [20]	4C-180	96	137	0.70	80	0.86	2149	2762	0.12
R.U. (74)	1S-147	95	219	0.64	107	0.86	2821	4252	–
Cuba [20]	3S-155	95	190	0.62	101	0.88	2675	3892	0.14
Y.V. (81)	1S-157	96	219	0.58	108	0.80	3382	4891	–
USSR [20]	3S-171	95	199	0.60	100	0.84	3057	4765	0.12
	1C-195	96	168	0.58	90	0.76	3242	3906	–
	4C-210	96	161	0.66	84	0.86	2858	4630	0.10
Y.Z. (109)	1C-220	90	173	0.64	91	0.80	3877	4387	0.16
USSR [20]	3C-238	94	157	0.70	85	0.88	3413	5164	–

Note. Athlete (body mass)/country [reference no.]; Eff-vertical work/total work on barbell; V-max pull velocity; T1-time to V; Y-max pull height; T2-time to Y; P1-average power during T1; T3-duration of second pull or jerk thrust; P2-average power during T3.

duration is almost always a few 100ths of a second longer for the heavier lift. From one competition to another, for an elite athlete, the trend is for higher power outputs in the competition in which performance was at a higher level (13, 22, 23).

The change in power output capacity and weight lifted may be large over a period of years for developing athletes, but smaller from year to year and competition to competition for elite level athletes. However, the associated barbell kinematics change little over a period of years once basic lifting technique has been established (48, 50). For example, the maximum pull height during (1-RM) competition cleans for an elite lifter may fluctuate a few percent (2 or 3 cm) over several years while the weight lifted and power output may increase in the range of 10 to 20%. Thus, for a given athlete the major change as performance increases over time will be in power output capability, not in kinematic parameters associated with the lifts.

Comparison of weightlifters across skill levels also shows higher power output as a characteristic of better performance (15, 22, 52, 53). Power output for male and female athletes in WL, and other power oriented sports, has been shown to be greater than for athletes in endurance oriented sports and for untrained controls (51, 52).

Power Tests—The Vertical Jump

The following discussion relates to the use of power tests to detect fluctuations in lifting power output capability within training cycles during the year and just prior to competitions. Simple nonexhaustive tests are desirable so that they can be given quickly and often without contributing to the potential for overtraining, as would frequent tests using maximal attempts in the competitive lifts.

A maximal-effort standing vertical jump is a common physical fitness test used to indicate explosive power capability, as opposed to a test like the 12-min run, which is used to measure endurance and cardiovascular fitness. A vertical jump test is an obvious choice in trying to predict ability in WL due to biomechanical similarities between the activities, as observed by coaches (18) and sensed by athletes, as well as quantified through analysis (6, 7, 16, 21, 30). Power output during a vertical jump test can be calculated by the "Lewis formula" or by film or video analysis.

The Lewis Formula

Power [kg–m/s] = {Body mass (kg) · [4.9 · Jump Height (m)]$^{0.5}$}. Note that this power value must be multiplied by the acceleration of gravity (9.8 m/s^2) to obtain the standard power unit of watts. The Lewis formula assumes that work done during the jump equals the work done in lifting body mass a height equal to the jump height. The time factor to determine power is set equal to the time it would take a point mass to fall from rest a distance equal to the jump height. This is not generally related to the actual time of propulsion to generate the take-off velocity for the jump The more massive a person and the higher the jump, the greater the calculated work. However, a higher jump, compared to a lower one, results in a larger time factor which reduces the calculated power. As a result, the Lewis formula is not an accurate method for determining power output, but it may still differentiate higher versus lower power outputs among a group of subjects.

If a given subject is tested on two different occasions and jumps higher the second time at a lighter body weight, he or she may register an erroneous lower power output for the second test due to the larger time factor, even if the work done (body weight × jump height) for each jump remained constant. Thus, results obtained using the Lewis formula must be interpreted with caution. Some historical considerations related to the Lewis formula's development, and errors involved in using it, have recently been presented by Harman and co-workers (38).

Efforts have been made to maintain the simplicity of the Lewis formula test methodology while estimating a more accurate absolute power output (29, 31, 32). The multiplication coefficient needed to convert Lewis formula power in watts to true power output, as determined by methods discussed below, increases with skill level (height of jump) (29), for example, from about 2 to 2.3 for unskilled to skilled female jumpers and 2.2 to 2.5 for lower to higher skilled male athletes. A "highly skilled" jump for a male was considered to be one greater than 0.75 m, and greater than 0.60 m for a female. This increase of coefficient with skill level agrees with the effect pointed out above, that a higher jump results in a larger time interval in the Lewis formula power calculation and a reduced power value.

Film or Video Analysis

Elevation of the body's CM is determined at (a) its lowest point during the countermovement (or at the start position for a static jump), (b) take-off just as the feet lose contact with the ground, and (c) its highest point during the jump. Duration of the propulsive effort is the time interval from (a) to (b), and is used for the power output calculation. Work done is equal to the change in PE of the body's CM from (a) to (c); KE is assumed to be zero at both (a) and (c). As discussed earlier, in connection with analyses of various lifting movements, only differences in CM position are used in this work calculation. This minimizes any error effect that could be caused by the use of inappropriate body segment parameters in the segmental method determination of CM position from digitized landmarks on the body. Power output for the jump is calculated as the work done divided by the time of propulsion.

The major problem with this method of determining power output during a vertical jump is the short time interval for propulsion (typically 0.2 to 0.3 seconds, and similar to the duration of second pulls and jerk thrusts in WL). Just as with power analyses of second pulls and jerks (discussed in Examples 1 and 2), an error of one frame of film or one video field when determining the start or finish of a movement phase causes a large percent change in the time interval used in the power formula. For example, at 50 fps one frame is equal to a 10% change in a 0.2-s propulsion interval, and a similar percent change in the power output calculated.

Thus, when comparing power outputs for vertical jumps, jerks, and second pulls, small timing errors in one or more of the activities may mask true similarities or differences. Increasing data sampling rates to 100 Hz or more can reduce this type of error. Keeping this potential problem in mind, data indicate that differences of 10% or less in power output for the above activities are typically found for skilled weightlifters (29, 31, 32), as discussed below.

An additional problem with this method of calculating power output for a countermovement vertical jump is that ME is not truly zero at the start of the propulsion phase (lowest point of the countermovement). The arms are rotating rapidly enough to cause blurring of the hands if a nonshuttered video camera (60 fields/s) is used for data collection. This rotational kinetic energy is used by skilled jumpers to increase jump height (37). At the apex of a jump, the body continues to have rotational kinetic energy due to rotation of the legs and one arm (the other arm is reaching upward to register touch height).

No data on the exact distribution of rotational energy during such jumps has been found. Thus, although there will generally be some change in rotational KE from the start to the finish of the jump, the major system (body) ME change (work done) is still in PE of the CM. Stored elastic energy in hip and knee joint musculature is another unaccounted for source of energy at the start of a countermovement jump, as discussed for the jerk in Example 2. These two energy considerations indicate possible advantages of using static start vertical jumps with hands held on the hips for performance capacity evaluation. However, the lifting movements a jump test may be related to are not static and do likely involve elastic energy (21).

One possible method of determining power output during vertical jump tests with greater accuracy than that of film or video analysis involves the use of a force plate and methodology similar to that used by Davies and Rennie (10) and others (8, 9). The need for this type of equipment is not desirable for practical field tests of power output. A comparison of force plate and film or video methods for measuring power output during lifts or jumps has not been found. However, Harman and co-workers (38) have compared force plate and Lewis formula methods of power output determination for vertical jumps. They reported considerable differences in the values obtained by the two methods and generated regression equations from the force plate data to calculate power output from jump height and body mass for *static start* vertical jumps. Their subjects were not good jumpers and the regression equation power values do not agree well with those determined using the Lewis formula and a multiplication factor for more skilled jumpers.

Other power tests, such as the Margaria stair test and Wingate ergometer test, do not result in as large a magnitude of relative power output as vertical jump tests (4) and do not relate as well biomechanically to lifting movements (e.g., single vs. double leg propulsion).

Recent work has indicated that the power output of a given skilled weightlifter in a maximal vertical jump is similar to that for his or her snatch and clean second pull, and jerk thrust (29, 31, 32). Differences in power output between these activities was generally less than 10%. This is not a large difference, considering the above mentioned potential for measurement error. However, using a maximal vertical jump test to predict one's state of readiness for competition or continued heavy training is questionable when a 10% fluctuation up or down in calculated power output is possible due to measurement uncertainties. As an alternative, peak and average height of multiple jumps have been suggested for use as prediction criteria for the performance and training capability of weightlifters (58). Fifteen jumps, evenly distributed over 1 minute, were measured and results were correlated to the athlete's ability to continue a training program at a prescribed level of loading. This 60-s protocol has some similarities to that of a power test developed by Bosco and co-workers (4) which was shown to be useful in predicting leg extensor muscle fiber composition (3).

In the future it may be possible to correlate results in tests of this type to blood levels of selected "stress" hormones and metabolites, which in turn may be related to training state (35, 58). In any case, a pivotal consideration will be how accurate and sensitive the power test used will be, and whether it will be of the simple Lewis formula type or a more involved biomechanical procedure. The issue is not whether a power test can be a useful predictor for WL performance, but what is the appropriate test and how can it best be administered?

Finally, it should be emphasized that the mechanical power output values discussed above are average values over time intervals ranging from about 0.1 s to about 0.8 s. As the interval decreases, the absolute and relative power output during the corresponding lifting movement for a given athlete increases. I have calculated "instantaneous" power outputs for 0.02-s intervals (film analysis at 50 fps) and found values higher than 60 W/kg, which were found for some male weightlifters during entire second pulls and jerk thrusts (20, 28). If film analyses were conducted at 100 fps (0.01-s intervals) "instantaneous" values of 70 to 80 W/kg would be likely. This is comparable to instantaneous power output values of 60 to 75 W/Kg reported for vertical jumps of sedentary men to elite high jumpers (8, 9, 10).

This information further supports the vertical jump as a performance predictor for WL. Note that elite weightlifters produce these large relative power outputs while accelerating body mass plus loads of two to three times body mass (during competitive lifts). They also produce these high power outputs when only accelerating body mass, as in vertical jump tests (e.g., 110-kg male weightlifter performing a standing countermovement vertical jump of 1.01 m). In order to gain insight into muscle force-velocity and power-velocity adaptations caused by intense weight training, it would be beneficial to determine how power output in a jump test varies as a function of load for weightlifters as well as power oriented and endurance oriented athletes.

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