Measurement of Elastic-Like Behaviour in the Power Squat

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Because traditional procedures of evaluating elastic-like behaviour have yielded mixed results, the purpose of this work was to explore two methods of measuring elastic-like behavior in the power squat. The entire concentric time method was based on traditional procedures. The initial concentric time method was developed to examine elastic-like behavior for the beginning 0.2 s of concentric movement. The present study compares a power squat performed maximally by nine subjects at 70% of their 1 repetition maximum. Squats were performed with rebound (REB) and without rebound (NRB). For the entire concentric time method only concentric time was significantly greater (p < 0.05) in the NRB than the REB. For the initial concentric time method the relative displacement, velocity, net work, & peak power of the center of mass were significantly greater (p < 0.05) in the REB than the NRB. Some subjects had theoretically infeasible negative results for elastic enhancement in the entire concentric time method, but not the initial concentric time method. It seems that measuring elastic-like behavior near the end of the movement can be confounded by the constraints of the task. Based on its success, the initial concentric time method appears to be more appropriate for measurement of elastic-like behavior in lifting.

Elastic-like behaviour in human movement has been documented for many activities with rebound. In these studies numerous variables and procedures have been used to reflect the benefits of performing with a rebound. Many questions, however, remain unanswered. One limitation of understanding elastic-like behavior has been the variation in the methods of its measurement.

The typical scenario of gaining elastic benefit was summarized by Cavagna (1977): "In some exercises, kinetic and/or gravitational potential energy of the body are absorbed by contracted muscles while they are forcibly stretched. This mechanical energy is wasted more or less completely as heat if the muscle is kept active at the stretched length or if it is allowed to relax after stretching. On the contrary, if the mechanics of the exercise is such that shortening of the muscle immediately follows stretching, an appreciable recovery of the work done on the muscle can take place" (p. 125). This recovery of work is believed to be particularly influential in the initial moments of the concentric phase of movement (Chapman, Caldwell, & Selbie, 1985).

Many different sports and movements have been used to examine the elastic-like benefits gained from a rebound. The most commonly used task has been the vertical jump (Asmussen & Bonde-Peterson, 1974a; Hudson & Owen, 1985; Komi & Bosco, 1978). Other tasks that involve the lower extremity include running...
(Asmussen & Bonde-Peterson, 1974b; Cavagna, Citterio, & Jacini, 1981), repetitive deep knee bending (Thys, Faraggiana, & Margaria, 1972), knee extensions (Bober, Putnam, & Woodworth, 1987), and plantar flexion of the ankle (Shorten, 1987). Upper extremity tasks include pushing a pendulum with the arms (Bober, Jaskolski, & Nowacki, 1980), elbow flexions (Poussin, Van Hoecke, & Goubel, 1990), forearm rotations (Chapman, 1980; Chapman et al., 1985), and the bench press (Wilson, Elliott, & Wood, 1991).

Regardless of the task, the advantages gained from moving with a rebound have been assessed from the differences in the kinematic or kinetic variables of similar motions performed with and without rebound. Although the concentric, or shortening, phase of the activity was typically superior when performed with rebound, it was partly dependent on the methods and variables used. Previous methods have included measures of elastic energy, elastic enhancement, and efficiency. Variables used to evaluate elastic-like behavior include velocity (Bober et al., 1980; Chapman, 1980; Thys et al., 1972), work (Chapman, 1980; Thys, Cavagna, & Margaria, 1975; Wells, 1967), power (Thys et al., 1972; Wilson et al., 1991), force (Bosco, Tihanyi, Komi, Fekete, & Apor, 1982; Thys et al., 1975; Wilson et al., 1991), and energy (Asmussen & Bonde-Peterson, 1974b; Hudson & Owen, 1985; Komi & Bosco, 1978).

Methods of calculating elastic-like benefit in any given task have also varied. When evaluating elastic energy, researchers typically used the ratio of the difference in concentric energy (with and without rebound) to eccentric energy for the chosen variable (Asmussen & Bonde-Peterson, 1974a; Hudson & Owen, 1985; Komi & Bosco, 1978). For elastic enhancement, researchers typically used the ratio between the concentric values (with and without rebound) for the chosen variable (Thys et al., 1972; Wilson et al., 1991).

Although the gains from rebound movements are thought to occur early in concentric motion, most of the previously mentioned studies evaluated benefits at the end of the concentric phase. For movements such as a vertical jump, an evaluation of the chosen variable(s) at the end of the concentric phase was appropriate because peak velocity occurred at or near the end of a brief thrust phase and at or near full extension of the joints. For movements with a different purpose, such as weight lifting activities, a different approach may be needed. For example, Wilson et al.'s (1991) study of the decay of elastic benefit in the bench press used a finite amount of time based on the power generated during the lift. An initial, finite time interval may be applicable for lifting types of activities because they require greater time for the range of motion (ROM) to be completed and peak velocities are reached well before the end of the ROM.

The power squat has not been previously used for the evaluation of elastic-like behavior. It is an appropriate task for study because it can be performed with and without rebound. In addition, we can use this task to advance our understanding of elastic-like behavior through the manipulation of load. Eventually, we may provide insight for the many athletes who train with the power squat.

The purpose of this work was to explore two methods of measuring elastic-like behavior in the power squat. The entire concentric time method was based on previous procedures used to study the jump. The initial concentric time method was developed to examine elastic-like behavior in the early stages of concentric movement.
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**Methods**

**Subjects**

Nine skilled college-age weight lifters (mean mass $\pm$ S.D. of 77.45 ± 9.56 kg and height of 1.75 ± 0.07m) participated in this study. All subjects were in good apparent health, with no reported history of chronic or recent acute back, knee, or leg injuries. All lifters signed informed consent in accordance with the approved standards set forth by the university. Each subject was allowed to perform preferred stretching activities and warm-up lifts. The hip (greater trochanter), knee (lateral epicondyle), and ankle (lateral malleolus) joints were marked on the left side of the body with reflective tape. The bar center also was similarly marked with reflective tape.

**Task**

Each subject performed a power squat with the bar placed on the superior, posterior trunk in the area of the spines of the scapulae. In keeping with standard practice, each subject used a weight belt in performing all lifts. No other devices used to enhance the lifter's capabilities, such as knee wraps or lifting suits, were allowed. All lifters were encouraged to rest adequately between lifts to avoid fatigue.

All lifters performed a squat with a rebound (REB) and a squat without a rebound (NRB). The REB condition has both eccentric and concentric motions and the NRB condition has only concentric motion. The REB and NRB conditions were controlled to ensure that the thrust distances were as similar as possible. An adjustable safety bar was positioned within a standard power rack to represent the lowest position of the crouch. In this way, the ROM of the knee joint was limited in all lifts to reach a minimum of 90° of flexion.

The REB was performed to a depth consistent with the adjusted bar. For the NRB the lifters performed a downward movement from an upright position, as in a normal squat, but were allowed to rest the bar on the rack without changing body position or stance. This was done to minimize muscle fatigue that would result from holding the isometric position at the bottom position under load. Based on the findings of Wilson et al., the bottom position was held between five and six seconds to ensure that stretch benefits would be dissipated as heat (Wilson et al., 1991).

Each lifter performed from one to three lifts with a rebound to determine their one repetition maximum (1RM) in the power squat. After a sufficient recovery time, the lifters performed the power squat at 70% of their 1RM (mean 70% mass: 118.3 ± 37.1 kg) for both REB and NRB conditions, the order of the lifts being randomly determined. Both of the REB and NRB conditions were performed at maximum effort. That is, the subject was asked to perform the lift with as much force and velocity as possible in both the REB and the NRB. This request was consistent with procedures used by Wilson et al. (1991). Because lifters often perform submaximal lifts at submaximal velocities, an acclimation period was used during warm-up.

**Data Collection and Reduction**

Subjects were videotaped with a Panasonic camcorder (model PV-330D) at a rate of 60 Hz. Blur was eliminated through the use of a 2000.s⁻¹ high-speed shutter. The camera was positioned perpendicular to the sagittal plane of the subject.

Data were reduced from video to digital horizontal and vertical coordinates
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<table>
<thead>
<tr>
<th>Variable</th>
<th>REB Mean (±S.D.)</th>
<th>NRB Mean (±S.D.)</th>
<th>Repeated Measures ANOVA of REB vs. NRB p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentric Time (s)</td>
<td>0.593 (0.186)</td>
<td>0.793 (0.106)</td>
<td>0.013*</td>
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<td>Relative Displacement of COM(%)</td>
<td>71.08 (6.131)</td>
<td>75.31 (3.470)</td>
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<td>Maximum Velocity of COM (m·s⁻¹)</td>
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<td>0.968 (0.171)</td>
<td>0.489</td>
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<tr>
<td>Net Work by Four Segment Model (J)</td>
<td>635.9 (176.1)</td>
<td>624.6 (174.0)</td>
<td>0.893</td>
</tr>
<tr>
<td>Peak Power of Four Segment Model (W)</td>
<td>1947 (655.6)</td>
<td>1808 (515.7)</td>
<td>0.627</td>
</tr>
</tbody>
</table>

* = significant at alpha = 0.05 level

Table 1: Means, standard deviations, and p-values for entire concentric time results. REB values represent the squat with rebound and NRB values represent the squat without rebound. The ANOVA results are based on the comparison of the variable for the REB and NRB conditions.

representing relevant joint and bar landmarks via a Peak Performance Motion Analysis System. Data were digitized with both an automatic digitizing program and manual manipulation of a cursor. Points digitized were top of head, shoulder, elbow, wrist, hip, knee, ankle, toe, and bar center. In the event of a marker not being located, the point was manually digitized for that field. Several points, such as the top of the head, elbow, and shoulder were digitized manually because marker placement was impractical or impossible. The location of the shoulder was estimated based on the orientation of the lifter with respect to the bar. Digitized data were adjusted to a fixed origin within the field to eliminate frame shifting and vibration errors inherent to the camera and data collection procedure.

Variable Calculation

A four segment model was used to represent the rigid link system of the human body (Plagenhoef, Evans, & Abdelnour, 1983). Segments in this model were: (1) the head, neck, trunk, and arms; (2) the thighs; (3) the shanks and feet; and (4) the bar. This model was used for calculation of the radii of gyration and moment of inertia for each segment as well as the center of mass (COM) of the subject. A quintic spline program was incorporated for eliminating random errors in the digitized coordinates (Woltring, 1986). Effectiveness of the spline routine was assessed through visual examination of the second derivative and the residual pattern of the difference between the raw and smoothed data points (Zernicke, Caldwell, & Roberts, 1976). Sufficient filtering of the data resulted in a residual plot without pattern and a second derivative with a definite pattern. The desired contour of the second derivative pattern was neither "too smooth" nor "too coarse". Input parameters of the spline routine were adjusted manually or iteratively until consistent results were found from digitized point to digitized point, trial to trial,
and subject to subject. The number of knots used and the mean square error were monitored for all trials and subjects to assess consistency.

Output from the spline routine was used to calculate position, velocity, and acceleration data of all coordinates (including the COM). All subsequent variables were calculated from these data. The eccentric phase was defined as beginning at peak negative vertical velocity of the COM and ending at zero velocity. The concentric phase was defined as beginning at zero vertical velocity of the COM and ending at peak velocity. The relative displacement of the COM was calculated as the amount of vertical displacement of the COM at the end of the concentric phase relative to the total vertical displacement of the COM during the entire upward motion. Work was calculated as the net change in mechanical energy of the four segment model. Power was calculated as work divided by time. Peak values for all variables were used for analyses. Elastic enhancement was calculated as the ratio of the REB energy over the NRB energy.

The entire concentric time was defined as the time from the initiation of upward movement of the COM until peak velocity of the COM. The initial concentric time was defined as the time from the initiation of upward movement of the COM until 0.2 s later. The duration of 0.2 second was selected because it was less than the briefest concentric time for all subjects and conditions. Further, this time is consistent with the methods and finite times used in previous work (Chapman et al., 1985; Wilson et al., 1991).

Statistical Methods

Statistical analyses were performed on each variable for both the entire concentric and initial concentric time periods. Statistics were computed via SAS program on a VAX mainframe computer. A repeated measures ANOVA was used to test main effects for conditions (REB or NRB). All tests for significance were performed at the alpha = 0.05 level.

Results

Means, standard deviations, and statistical results are provided for both the entire concentric time and initial concentric time methods in Table 1 and Table 2. Time can only be evaluated for the entire concentric time method because it is held constant in the initial concentric time method of examining elastic-like behavior. The time required for completion in the entire concentric time method was significantly less in the REB than in the NRB. The 0.2 s initial concentric time value represents 34% and 25% of the entire concentric time for the REB and NRB respectively.

The range of relative displacements of the COM for the entire concentric time was between 61% and 80% in the REB and between 71% and 83% in the NRB. The relative displacements were not significantly different between conditions for the entire concentric time method. The range of relative displacements of the COM for the initial concentric time was between 9% and 34% in the REB and between 3% and 12% in the NRB. The relative displacements were significantly greater in the REB condition than in the NRB condition for the initial concentric time method.

For the entire concentric time the maximum velocities of the COM ranged from 0.627 m·s⁻¹ to 1.434 m·s⁻¹ in the REB and from 0.738 m·s⁻¹ to 1.269 m·s⁻¹ in the NRB. No differences were found between conditions for the entire concentric time method. For the initial concentric time the velocities of the COM ranged from
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<td>Concentric Time (s)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Relative Displacement of COM(%)</td>
<td>21.18 (7.82)</td>
<td>6.45 (2.64)</td>
<td>0.0001 *</td>
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<tr>
<td>Maximum Velocity of COM (m·s⁻¹)</td>
<td>0.453 (0.196)</td>
<td>0.145 (0.051)</td>
<td>0.0003 *</td>
</tr>
<tr>
<td>Net Work by Four Segment Model (J)</td>
<td>140.6 (65.30)</td>
<td>38.70 (22.20)</td>
<td>0.0004 *</td>
</tr>
<tr>
<td>Peak Power of Four Segment Model (W)</td>
<td>973.7 (508.8)</td>
<td>313.9 (144.5)</td>
<td>0.0018 *</td>
</tr>
</tbody>
</table>

* = significant at alpha = 0.05 level

Table 2: Means, standard deviations, and p-values for initial concentric time results. REB values represent the squat with rebound and NRB values represent the squat without rebound. The ANOVA results are based on the comparison of the variable for the REB and NRB conditions.

0.171 m·s⁻¹ to 0.723 m·s⁻¹ in the REB and from 0.059 m·s⁻¹ to 0.219 m·s⁻¹ in the NRB. The velocities were significantly greater in the REB than in the NRB for the initial concentric time method.

Net work performed in the entire concentric time ranged from 400.4 J to 979.8 J in the REB and from 313.7 J to 940.7 J in the NRB. Net work performed during the entire concentric time was not significantly different for either REB or NRB condition. The net work performed in the initial concentric time ranged from 35.5 J to 252.6 J in the REB and from 14.1 J to 91.0 J in the NRB. Work performed in the initial concentric time, however, was significantly greater in the REB condition.

Maximum power values for the entire concentric time ranged from 1106 W to 3320 W in the REB and from 923 W to 2313 W in the NRB. Just as in net work performed, the entire concentric time had no differences in peak power produced for either condition. The power values for the initial concentric time were about 50% and 17% of peak power entire concentric time values for the REB and NRB respectively. Also similar to net work performed, the initial concentric time had significantly greater power production when a rebound was used.

Elastic enhancement for the entire concentric time had a mean and standard deviation of 3.2±14.8%. As evident by the standard deviation, some of the values were negative. Enhancement values for the initial concentric time had a mean and standard deviation of 327±213%. No negative values were present.

Discussion

Variables

As evident from the results, the entire concentric time and initial concentric time methods produced different outcomes for the respective variables. Time, which
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Figure 1: Representative COM vertical velocity vs. time graph for the rebound and no-rebound conditions. Time zero corresponds to the beginning of the concentric phase for both lifts.

was measured only for the entire concentric time method, had results consistent with those reported by others (Cavagna, Komarek, Citterio, & Margaria, 1971; Harman, Rosenstein, Frykman, & Rosenstein, 1990). Although the concentric times of the vertical jump reported by Harman et al. (1990) were about half as long as concentric times for the power squat in the present study, they found that the concentric time was about 10% greater without rebound. Cavagna et al. (1971) found that the time of positive work was 55% greater with no prestretch of the muscle. In the present study the NRB required 34% greater time than the REB. It seems that for most tasks the use of a rebound will allow the performer to complete the action more quickly than not using a rebound.

Time is an important variable because other variables are dependent on it or influenced by it. Elastic-like behavior itself is dependent on time because of its transient characteristics (Aruin, Prilutski, Raitsin, & Savel'ev, 1978; Hill, 1961; Wilson et al., 1991). If too much time elapses between the eccentric prestretch and the concentric contraction of the muscle, the elastic energy stored is dissipated as heat (Hill, 1961).

In the present movement the use of a rebound may help reduce concentric time under moderate load by aiding the musculature in overcoming inertia at the beginning of the lift. This is one reason for the use of a time factor for the measurement of elastic benefit near the beginning of the concentric phase. The use of a finite time interval may allow gains from a rebound to be more accurately reflected both in this task and perhaps other tasks as well. Time was also consequential for this task because the concentric phase typically ended well before the upward thrust ended.

For the entire concentric time method, the relative displacement of the COM did not differ by condition. Although the range of values for the different conditions indicated that the NRB had a tendency to go slightly higher, it was not statistically significant. Unlike the entire concentric time method, the initial concentric time
method did differ by condition. The greater relative upward movement of the lifter in the REB for the initial concentric time method may indicate how elastic-like behavior is evident near the beginning of concentric movement, where the probable recoil of elastic elements occurs. The greater relative displacement of the COM in the REB may be due once again to the rebound helping the musculature overcome inertia at the beginning of the concentric phase and provide additional displacement in the same amount of time.

On the average, the lifters achieved the same velocity in the REB as they did in the NRB for the entire concentric time. The maximum velocity in the NRB, however, occurred after a longer concentric interval. (See Figure 1 for a representative graph of COM velocity.) Unlike these results, the findings for the initial concentric time indicated that the early velocities were higher for the REB condition. This was consistent with relative displacement results. The advantages of the rebound seemed more apparent when a finite time interval was used and benefit was measured closer to when it likely occurred. Later in the ROM, the advantages gained from elastic-like behavior seemed to be obscured by task limitations. That is, in the squat the lifters reach maximum velocity well before completing the upward movement. The slowing (perhaps prematurely) of the lifters' motion near the end of knee and hip extension may confound the measurement of benefits gained early in the concentric phase.

If the task had different requirements, such as maximum velocity at the end of the thrust phase (as in a vertical jump), then the benefit from elastic-like behavior would be evident at that time as well. Presumably, the performers of those types of tasks are able to continue to add to the greater early velocities and therefore achieve greater end results. Also, while jumping with maximum velocity is not unusual, lifting for maximum velocity at a given load is unusual. Lifters usually perform submaximal lifts with submaximal velocities. Lifting with maximal velocities is not unprecedented, but is different and in need of some acclimation by the performer for safety reasons.

Because of these task differences, procedures used in an entire concentric time method, which are adequate for measuring elastic-like behavior in the jump, may not be appropriate for the power squat. In particular, the entire concentric time method may not be sensitive to the elastic contributions created near the beginning of the thrust. Therefore, the initial concentric time method might better reflect the benefits of elastic-like behavior.

As with the previous two variables, the net work performed during the entire concentric time did not differ between the REB and NRB, but net work performed during the initial concentric time was significantly greater in the REB condition. Other research (Cavagna et al., 1971) has suggested that net work would be 10% greater with prestretch. Presently, the net work in the entire concentric time method was 2% greater with prestretch and net work in the initial concentric time method was 350% greater with prestretch.

Net work performed was influenced by the mass of the system (which was the same for each condition), time (which was not limited for the entire concentric time, but was for the initial concentric time), relative displacement (which had results similar to net work), and velocity (which also had results similar to net work). The results for the work performed within the initial concentric time method suggest that rebound benefits work as it does other variables. In the beginning of the concentric phase the elastic-like behavior allows greater net work
as a result of greater velocities and displacements. These greater values for net work are believed to be the result of elastic elements and contractile elements working together to produce greater results than the contractile elements independently.

Power values were consistent with values hypothesized and found in previous research by Wilkie (1960) and Garhammer (1980). A study by Cavagna et al. (1971) found that average power was 70% greater with prestretch, but that instantaneous power was not different. The present results indicated that the REB condition had greater peak power on the order of 7% for the entire concentric time method and 310% for the initial concentric time method. Maximum power produced in the entire concentric time did not differ by condition, but at the end of the initial concentric time the power produced by the lifter was greater in the REB than in the NRB.

It is possible that the lack of significance of entire concentric time power values was because of the “maximum effort” required of the lifters. Using this effort may suggest they generate maximum power. As a reflection of the interaction between time, relative displacement, velocity, and work, power is an indication of the relative intensity for the overall performance of the lifters. At the end of the initial concentric time, however, the inability of the lifters to produce similar power values in the NRB may be an indication of how rebound aids in producing powerful movements. The initial increases in power output may be due to the increased speed of the entire muscle shortening and consequently the speed of the concentric movement (Thys et al., 1972). Had the movement context been different, such as a vertical jump, then the additional power resulting from the elastic-like behavior in the initial stages of concentric motion may have continued to build to greater values.

The elastic enhancement results were unusual. Some negative values were found for elastic enhancement in the entire concentric time method. These results were theoretically infeasible. The negative values occurred as a result of the net changes in the energies of the NRB being larger than the net changes in the energies of the REB. Results for the entire concentric time method using previously described procedures involving eccentric energy with the respective concentric energies also would have revealed negative results for the same subjects. The negative results were another indication of the confounded variable measures for the entire concentric time method. Similar calculations for the initial concentric time method resulted in no negative values. Values for the initial concentric time had a large variance, but were not inconsistent with the variance found in other studies (Hudson & Owen, 1985).

**Measurement Duration**

In the present study of the power squat different results were found for each of the methods designed to measure elastic-like behavior. The traditional method of using the entire concentric time was not successful or effective in reflecting the elastic-like behavior of musculature in any manner except concentric time. The initial concentric time method, however, was much more successful and consistent in reflecting the benefits of using a rebound within the initial moments of the concentric phase.

In general, quick movements may be better suited for traditional measurements of elastic-like behavior. This may be particularly true for those movements which
require maximum speed near the end of the thrust phase, as in a vertical jump. In the present task the amount of displacement of the COM in the concentric phase relative to the displacement of the COM for the entire thrust was free to vary by condition and subject. This variability is impossible to control in this task because of the risks involving the lack of integrity between the lifter and the weighted bar. If the lifter were not concerned about the bar leaving the stable resting spot on the posterior, superior trunk (or worse yet returning to the same position after projection) then the relative displacement would be closer to that of a vertical jump type of task.

Another difference between squat and vertical jump requirements was the need to stop all motion at the end of the thrust phase in the squat, but not in the jump. This limitation regarding the constraints of the lift and the safety concerns of the lifter requires slowing upward motion prior to the end of the upward thrust. The differences in the lifters' performance for the entire concentric time method may be due to this constraint. Each lifter may have varied slightly between conditions with respect to where they began slowing, thus confounding benefits produced by elastic-like behavior. In a jump the range through which work can be performed and energy produced remains similar for conditions with and without rebound, but in a squat slight variations in range may produce large variations in energy produced due to the large potential energy values, thus confounding energy measures for the entire concentric time method.

As stated previously, the use of the entire concentric time method in a power squat type of task may confound the benefits resulting from rebound. The use of a finite time interval for enhancement measures is one method that avoids this problem. For instance, a time interval may be superior to a displacement interval because when a finite time is used the potential energy and kinetic energy can each vary according to the performance differences in the conditions (with or without a rebound). Moreover, the initial concentric time method can be used to compare any two tasks performed with and without a rebound.

When deciding on a time interval several factors should influence the chosen value. The factors include the purpose of the movement, the concentric time typically used, and the data collection frequency. The interval used in any movement should be brief enough to allow all subjects to perform the task without undue influence from any factor (e.g., fear or risk of injury) that might affect subsequent variable measures. Depending on the movement, time limits should be long enough to allow elastic-like behavior to be clearly shown, yet not so short as to distort benefit measures. Previous research has related the amount of time to power (Wilson et al., 1991). It can also be determined relative to the time of the thrust phase or it can be a constant value. In the present study a constant value of 0.2 seconds seems to be effective in representing the elastic benefits of the power squat.

References


