A Biomechanical Analysis of the Squat Between Competitive Collegiate, Competitive High School, and Novice Powerlifters

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A Biomechanical Analysis of the Squat Between Competitive Collegiate, Competitive High School, and Novice Powerlifters

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Abstract

Miletello, WM, Beam, JR, and Cooper, ZC. A biomechanical analysis of the squat between competitive collegiate, competitive high school, and novice powerlifters. *J Strength Cond Res* 23(5): 1611–1617, 2009—The purpose of this study was to measure and analyze kinematic differences between competitive collegiate (CLG, $n = 9$) powerlifters, competitive high school (HS, $n = 9$) powerlifters, and novice (NV, $n = 11$) powerlifters during a maximal squat to determine the effect of skill level on performance. All powerlifters performed 3 squats, with the final squat being their 1 repetition maximum. Kinematic data (descent, ascent, total lift times, knee angle magnitude, knee angular velocity, and knee angular acceleration) was measured using 2-dimensional motion analysis equipment. Differences in mean peak kinematic values between the 3 groups were analyzed using a 1-way multivariate analysis of variance, $p \leq 0.05$. Differences were found between the NV and HS in the time to ascent, the total lift time, the normalized time to peak (NTTP) in knee angular velocity from the "sticking point" to the "lockout," and the NTTP in knee angular acceleration during the ascent. A difference was found between the CLG and HS in the peak knee angular velocity between the bottom of the lift and the sticking point. Differences were also found in the rate of acceleration upward after coming out of "the hole" between the CLG and NV and CLG and HS. A difference was found in the rate of peak deceleration upward to the sticking point between the CLG and NV. To avoid injury and to achieve optimum results in powerlifting, lifting technique must be optimized. The HS and NV accumulated several significant differences in NTTP during the ascending phase. However, the major finding between the 3 groups was in the rate of acceleration upward after coming out of the hole. Coaches should focus their training programs on increasing strength in unskilled powerlifters for the purpose of increasing acceleration from the bottom of the lift.

Key Words powerlifting, biomechanics, technique, motion analysis, skill level

Introduction

The squat is a powerful movement that measures an individual's lower body and trunk strength (5) and is used in training programs of athletes from various sports (2). Strength, power, and precision are necessary for maximal performance when performing the squat in competitive powerlifting competitions and as part of a strength training regimen. Previous literature in the area of powerlifting focuses on knee mechanics because an elevated risk of injury to this area exists (3,10). Mechanical effectiveness is related to an individual's experience and can be determined with a biomechanical analysis among groups with different skill levels (4,8,9). Squat technique may determine victory in a powerlifting competition and may predispose an athlete to injury. Therefore, providing knowledge of the differences in technique due to skill level during the squat may be useful. The purpose of this study was to measure and analyze kinematic differences between competitive collegiate (CLG) powerlifters, competitive high school (HS) powerlifters, and novice (NV) powerlifters during a squat performed at maximum weight for 1 repetition to determine the effect of skill level on performance.

Methods

Experimental Approach to the Problem

The purpose of the current study was to determine the effect of skill level on performance of the squat in powerlifting. Kinematic variables were chosen to measure the powerlifting technique while performing the squat. Observation of the kinematic variables was conducted at the knee joint and used to quantify skill level among the groups: NV, HS, and CLG powerlifters. Mechanical effectiveness may be determined by observing timing, velocity, and accelerations of selected body segments or joints.

Subjects

Nine competitive CLG powerlifters, 9 competitive HS powerlifters, and 11 NV powerlifters participated in this study. The mean mass, height, age, and years of experience of

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Table 1. Participant characteristics: CLG ($n = 9$) vs. HS ($n = 9$) vs. NV ($n = 11$).*

Variables	Mean ± *SD*		
	CLG	HS	NV
Age (y)	19.78 ± 1.39	17.22 ± 0.67	20.09 ± 1.38
Experience (y)	3.00 ± 1.42	2.00 ± 1.25	<0.50
Weight (kg)	77.42 ± 21.85	66.50 ± 11.81	74.71 ± 11.61

*CLG = collegiate; HS = high school; NV = novice.

the powerlifters were recorded (Table 1). The CLGs were considered elite with 1 male national champion, 5 national champion runner-ups (4 women and 1 man), 3 male third place national champions, 2 fifth place national champions (1 woman and 1 man), and 1 male seventh place national champion at the U.S. Collegiate National Championships in 2006, Miami, FL. In addition, these powerlifters had 2 world runner-ups, 1 third place winner, and 1 sixth place winner at the world championships in 2005, Fort Wayne, IN. There were 7 athletes who placed in the top 10 in the Louisiana State High School Powerlifting Meet (3 men and 4 women), 5 who placed at a regional meet (2 men and 3 women), and 7 who placed in a district meet (2 men and 5 women) in Louisiana in 2006. The NV had no more than 6 months of experience at performing the squat. The University Institutional Review Board at Louisiana Tech University in Ruston, LA, approved this study. Written and informed consent was obtained from each participant. In addition, a parental approved informed consent was obtained from each parent of the HS powerlifters.

Squat Procedure

The coaches of the CLG and HS powerlifters provided approximate 1 repetition maximums (1RMs) of their athletes. The NV powerlifters participated in a weight training program for 10 weeks, and a powerlifting coach obtained approximate 1RMs after the completion of the program. All powerlifters performed the squat raw (without squat suits or wraps) and barefoot. After a warm-up (repetitions at <50% of their 1RM), each participant performed 3 trials with the final trial representing their 1RM. The bar (20 kg) was placed on a squatting rack, which was on a wooden platform and slightly anterior to a force plate. Each participant rested 10 minutes before each trial. A U.S.A. Powerlifting–Certified Judge determined if each squat met the squat criteria of the International Powerlifting Federation Technical Rules (11). The judge determined which of the 3 trials constituted the best trial and that trial was used for analysis.

Instrumentation

A 4-point wooden calibration frame was used for the camera calibration. A 5-point spatial model was used with markers placed on bony landmarks in the lower extremity: the greater trochanter, the lateral epicondyle of the femur, the lateral malleolus of the fibula, the calcaneous, and the fifth metatarsal, respectively. Kinematic data were obtained using a Panasonic PV-GS55 60 Hz Digital Camcorder (Secaucus, NJ) and an optical capture system. The markers used in detecting movement were point-sized markers with radii of approximately 1 cm. They were covered with reflective tape to help detect movement using videographic principles. All data were processed using the Peak Motus System version 8.5 (Vicon, Centennial, CO).

Frames were automatically digitized (169–181 per trial) for the powerlifters. Cubic spline interpolation was used to generate missing coordinates of the markers, and a recursive Butterworth Low-Pass Digital Filter with a cutoff frequency of 6 Hz was used to filter the data. After data smoothing, transformed data were examined for differences among the groups. Kinematic data were examined for prominent peaks

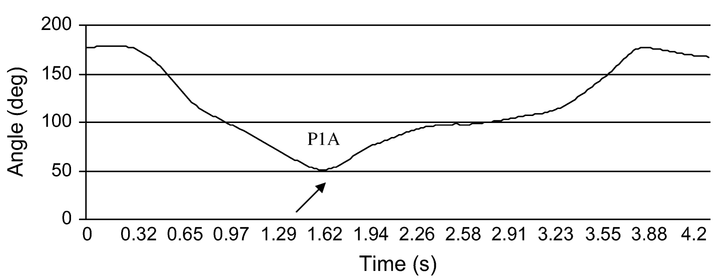

Figure 1. Knee angles.

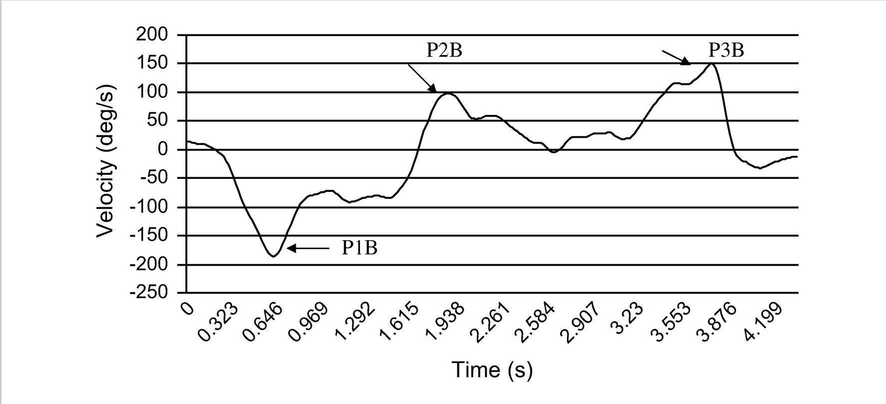

Figure 2. Knee angular velocities.

in the magnitude and timing of angular displacement, velocity, and acceleration for the knee.

Data Collection and Analysis

The data analysis involved creating events within the squatting phase to predict differences in squatting technique within each phase. The squat was divided into 3 phases: (a) the beginning of the lift to the bottom of the lift, (b) the bottom of the lift to the "sticking point," and (c) the sticking point to the end of the lift. The phases were further termed according to common terminology used in the sport of powerlifting. The point from the beginning of the lift to the bottom of the lift is termed the "controlled dive bomb." The bottom of the squat is also known as "the hole." The act of maximally contracting the musculature from the hole to the sticking point, which is represented by the decrease in velocity that occurs mid-ascent (9), is commonly referred to as "firing out of the hole." The final phase occurs from the sticking point to the end of the squat, and it is termed the "lockout."

The total lift time, the descent time, and the ascent time were calculated. These phases of the squat were normalized to the same time frame for all groups and included 20 frames before the descent was initiated and 20 frames after the ascent was terminated. To normalize the time of the descent, the difference between the time at the bottom of the squat and the time at the start of the squat was determined. To normalize the time of ascent, the difference between the time at the end of the squat and the time at the bottom of the squat was determined. Finally, to normalize the total lift time, the difference between the time at the end of the squat and the time at the start of the squat was determined.

The magnitude of knee angle, knee angular velocities, knee angular accelerations, and their corresponding normalized time to peak (NTTP) were considered for each predominant peak in curve values. This resulted in 1 peak (P1A) in knee angle, which was the minimum knee angle achieved (Figure 1). Three peaks in knee angular velocity were found, with peak 1 (P1B) representing the peak in knee angular velocity during the descent, peak 2 (P2B) representing the peak in knee angular velocity during the ascent and before the sticking point, and the third peak (P3B) representing the knee angular velocity after the sticking point but before the lockout (Figure 2).

Six peaks were found for knee angular acceleration, with peak 1 (P1C) representing the acceleration downward, peak 2 (P2C) representing the deceleration downward before the hole, peak 3 (P3C) representing acceleration upward, peak 4 (P4C) representing deceleration in the upward direction to the sticking point, peak 5 (P5C) representing acceleration beyond the sticking point, and peak 6 (P6C) representing the deceleration before the lockout (Figure 3). The NTTP for each of the peaks was the difference between the time of the peak and the time the lift was started. Each NTTP is denoted by NTTP#*, where # is the corresponding number of the peak and * is the corresponding letter of the peak.

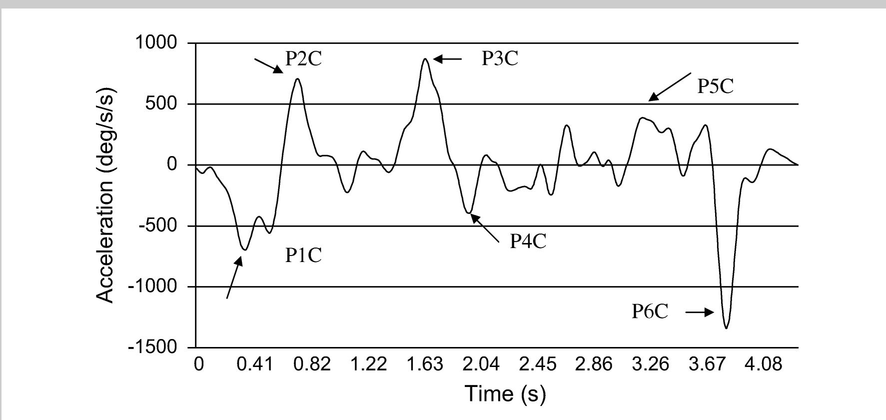

Figure 3. Knee angular accelerations.

Table 2. The peak knee angular velocities.*

	Mean ± *SD* (°·s^{-1})			
Variable	CLG	High school	NV	Combined
P1B	−133.16 ± 31.17	−149.02 ± 26.86	−139.47 ± 29.06	−140.48 ± 28.75
P2B	101.57 ± 37.13†	76.88 ± 26.60	73.50 ± 14.14†	83.26 ± 28.73
P3B	152.77 ± 26.37	169.70 ± 64.52	182.38 ± 38.33	169.26 ± 45.47

*CLG = collegiate; NV = novice.
†Significant difference ($p < 0.05$) between P2B of the CLG and NV powerlifters.

Statistical Analyses

To determine the effect of skill level on technique between the NV, HS, and CLG powerlifters, a 1-way multivariate analysis of variance was conducted on mean peak knee kinematic values. Pairwise differences were analyzed using a Fisher's least significant difference. A mean strength quotient (SQ = weight lifted [kg] × body mass [kg]$^{-1}$) for the 3 groups was analyzed in terms of mean and *SD*s for the purpose of data interpretation.

Results

The most important findings can be found in Tables 2 and 3 and Figures 4 and 5. Statistically significant differences were found between the NV and HS in NTTP in knee angular velocity from the sticking point to the lockout and the NTTP in knee angular acceleration during the ascent. A statistically significant difference was found between the CLG and HS in the peak knee angular velocity between the bottom of the lift and the sticking point. Statistically significant differences were also found in the rate of acceleration upward after coming out of the hole between the CLG and NV and the CLG and HS. A statistically significant difference was found in the rate of peak deceleration upward to the sticking point between the CLG and NV.

The descent time, the ascent time, and the total lift time for each group were analyzed for statistical significance. The NV descended (1.53 ± 0.31 seconds) faster than the CLG (1.61 ± 0.50 seconds) and HS (1.77 ± 0.34 seconds). The NV also ascended (1.76 ± 0.38 seconds) faster than the CLG (2.10 ± 0.33 seconds) and HS (2.62 ± 0.76 seconds). The NVs completed their ascent and total lift (3.28 ± 0.53 seconds) significantly faster than the HSs completed their ascent and total lift (4.38 ± 0.88 seconds). The NV achieved the greatest depth (66.17 ± 7.44 °) at the bottom of the squat, with the CLG not far behind (68.33 ± 11.95 °). The HS achieved the greatest knee angles (72.55 ± 5.35 °) at the bottom of the squat. An analysis was conducted on the strength quotient, where the weight lifted to body mass relationship was examined among the groups. CLG and HS mean and *SD*s were compared (1.76 ± 0.39 vs. 1.55 ± 0.56) and resulted in marginal differences. However, both CLG and NV and (1.76 ± 0.39 vs. 1.16 ± 0.22) and HS and NV (1.55 ± 0.56 vs. 1.16± 0.22) mean and *SD*s were compared and a large difference existed.

Table 3. Normalized time to achieve peak knee angular velocities.*

	Mean ± *SD* (s)			
Variable	Collegiate	HS	NV	Combined
NTTP1B	0.46 ± 0.38	0.43 ± 0.18	0.29 ± 0.14	0.39 ± 0.25
NTTP2B	2.08 ± 0.38	2.14 ± 0.36	1.92 ± 0.40	2.04 ± 0.44
NTTP3B	3.44 ± 0.75	3.95 ± 0.81†	2.81 ± 0.43†	3.44 ± 0.82

*HS = high school; NTTP = normalized time to peak; NV = novice.
†Significant difference ($p < 0.01$) between NTTP3B of the HS and NV powerlifters.

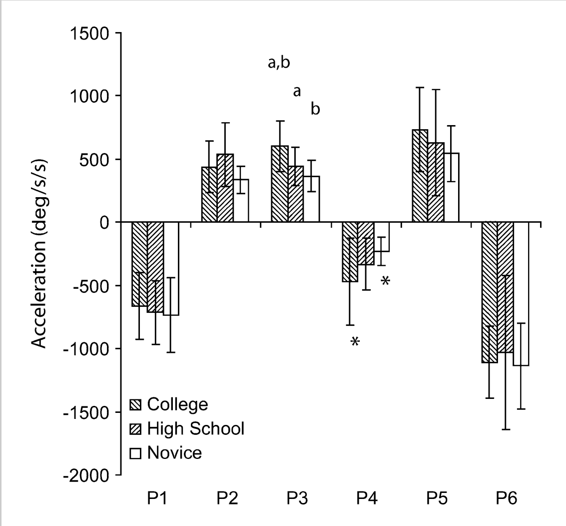

Figure 4. Graphical analysis of the peak knee angular accelerations. [a]Significant difference ($p < 0.05$) between P3C of the collegiate (CLG) and high school powerlifters. [b]Significant difference ($p < 0.01$) between P3C of the CLG and novice (NV) powerlifters. [*]Significant difference ($p < 0.05$) between P4C of the CLG and NV powerlifters.

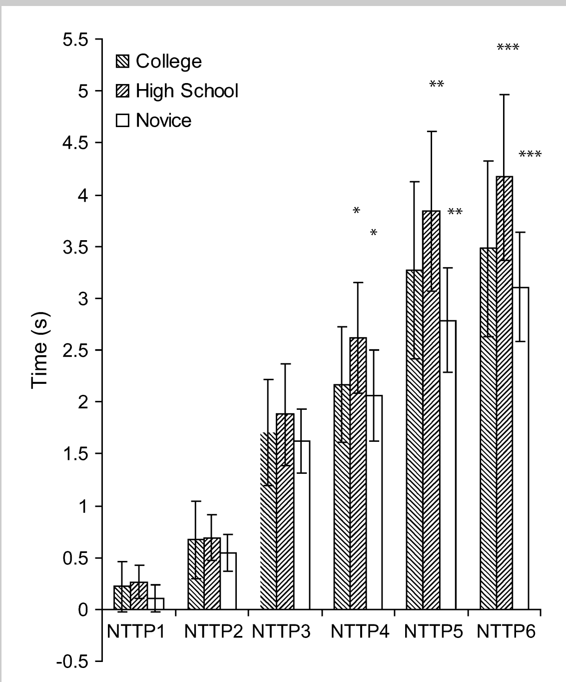

Figure 5. Graphical analysis of normalized time to achieve peak accelerations. [*]Significant difference ($p < 0.05$) between NTTP4C of the high school (HS) and novice (NV) powerlifters. [**]Significant difference ($p < 0.01$) between NTTP5C of the HS and NV powerlifters. [***]Significant difference ($p < 0.01$) between NTTP6C of the HS and NV powerlifters.

Discussion

The rate and timing of acceleration values were the key kinematic variables in determining the effect of skill level on technique during the descent. In particular, the rate and timing of peak acceleration values may indicate how the movement was controlled. In powerlifting, lower rates of acceleration are desirable during the descent and higher rates of acceleration are desirable during the ascent. The CLG maintained the most control during the descent with overall smaller acceleration values when compared with the HS. The CLG strength quotient was the largest (weight lifted/body mass), yet the group exhibited the most control during the descent. The HS ranked third in terms of control of movement during the descent. This may be attributed to a larger strength quotient than the NV, yet less skill than the CLG. Interestingly, the NV had the lowest rate of deceleration before the hole. This may be attributed more to their lower strength quotient rather than a higher skill level.

The most significant finding of this study was the difference in acceleration values among the groups during the ascent. A higher skill level was best demonstrated by a higher rate of acceleration after coming out of the hole and before the sticking point. Powerlifters typically refer to this phenomenon as firing out of the hole. Interestingly, all groups achieved their highest rate of acceleration when firing out of the hole with similar timing (0.10 seconds). The CLG ascended at a higher velocity and achieved this velocity closer to the sticking point when compared with the other groups. Overall, CLG had the highest velocity and acceleration during this phase of the movement. In addition, they spent the most time in this phase of the movement. Therefore, the effect of skill level on performance is most evident during this phase of the movement.

The NV lacked control when terminating the movement with a higher rate of acceleration to the lockout. The effect of skill level on technique was less pronounced after the sticking point. Overall, the HS spent more time performing the squat than the other groups, especially during the ascent. This may be explained by a larger strength quotient compared with the NV but less skill compared with the CLG.

The current study revealed that patterns of performance differ among groups with different skill levels. McLaughlin et al. (9) substantiated these patterns in prior research. The authors proposed that a model of performance of highly and less skilled powerlifters should be determined to have a better understanding on how to maximize performance for competition and to determine "typical" errors for various skill levels for improved safety. These authors compared elite powerlifters (ranked with a top 10 performance in the world) to highly skilled powerlifters (competing at a world-class level, but not ranked with a top 10 performance). After an extensive analysis of kinematic performance factors, vertical bar velocity exhibited similar patterns among the group regardless of weight lifted. Furthermore, vertical bar velocity also represented the effect of muscular force exerted by the athlete on the bar (i.e., the end result). Vertical bar velocity was indicative of subject technique and therefore was considered the most meaningful parameter regarding performance. The results found for the less skilled group were higher vertical bar velocities and greater trunk lean on descent. The group with less skill approached the lowest position faster, and they also exhibited a lower bar velocity on ascent when compared with the elite group.

In the current research project, findings were similar with a faster descent and a slower ascent for the group with less skill (i.e., HS). However, the knee joint angular velocity for the descent and ascent was examined, rather than vertical bar velocity. In addition, McLaughlin et al. (9) found that trunk, hip, and knee horizontal displacements were greater in the less skilled group. In the current research, relative knee angular displacement was considered, and the less skilled group had a greater knee angular displacement when compared with the highly skilled group.

Biomechanical analysis of the knee joint during powerlifting maneuvers has been conducted due to the incidence of injury (4,6,7,10). For the younger and inexperienced athletes (less than 1 year of training), the knee joint is the site with the second most incidences of injury and pain, not only during workouts but also immediately after and between workouts (1). In previous literature, bar acceleration values were used to assess differences between groups of varying skill levels (4,5). Escamilla et al. (5) related bar acceleration information to acceleration and force values for the knee and hip. A greater deceleration magnitude for the bar was associated with greater tibiofemoral shear and compressive forces during the descent. In the current study, knee angular accelerations varied between the groups. High school athletes had acceleration values greater in magnitude when compared with CLG athletes during the descent phase. The results of the current study are similar to McLaughlin et al. (9) and Escamilla et al. (5), where greater accelerations of the bar occurred for the less skilled group during the descent phase. Escamilla (4) also determined the rate of increase in compressive forces during knee flexion and found that compressive forces are higher when the knee flexion angle was larger. As the knee flexion angle decreased to a smaller value, a lower magnitude of knee compressive force was found. In the current study, the less skilled athletes had larger knee angles during the squat, which over long periods of time of heavy training could be problematic.

Possible explanations for a more effective performance among the CLG athletes may include the developmental aspects of the athlete. The age of the athlete is directly related to their anatomical and physiological development. In addition, technical maturity of the athlete improves with the more years of training (8). The HS powerlifters in the current study were from many programs in the state of Louisiana and therefore represented a variety of training programs. The type of training program may be a factor that should be controlled for in subsequent research. Many questions still exist regarding differences in technique among athletes with different skill levels in powerlifting. More research on technical errors, which occur more often in less skilled powerlifters, is needed to help coaches teach their athletes how to properly perform the powerlifting squat. Therefore, injuries may be reduced and performance may improve.

Practical Applications

When coaching unskilled athletes, coaches should be aware that these athletes may not have a controlled descent when compared with more skilled athletes. The coaches should focus their training programs on timing of movement during the descent and ascent. Another concern for coaches is the ability of the athlete to accelerate from the bottom of the lift or “fire out of the hole.” Coaches should focus their training programs on increasing strength for the purpose of increasing acceleration from the bottom of the lift in unskilled powerlifters. Powerlifters of lower skill level may have the tendency to end the lift with high rates of acceleration or not to control the termination of their lift. Coaches should be aware of the detrimental effects of terminating a lift with high rates of acceleration on the knee joints and should train lifters of lower skill levels to control the lift when approaching a fully extended knee joint. In addition, coaches should teach athletes lifting with heavier weights to improve speed of movement through sport-specific power training. This study provided data that revealed that NV powerlifters had the tendency to drop too low, which may have detrimental effects on the knee joints due to an increase in sheer forces at the knee. Conversely, the HS powerlifters were not dropping low enough and should be taught to drop lower. Because dropping too low or not dropping low enough when performing a squat may lead to a less than optimal length-tension relationship, coaches should train powerlifters to optimize the length-tension relationship.

References

1. Brown, EW and Kimball, RG. Medical history associated with adolescent powerlifting. *Pediatrics* 72: 636–644, 1983.
2. Chandler, J and Stone, M. The squat exercise in athletic conditioning: A review of the literature. *J Strength Cond Res* 13: 52–60, 1991.
3. Chandler, J, Wilson, D, and Stone, M. The effect of the squat exercise on knee stability. *Med Sci Sports Exerc* 21: 299–303, 1989.
4. Escamilla, RF. Knee biomechanics of the dynamic squat exercise. *Med Sci Sports Exerc* 33: 127–141, 2001.
5. Escamilla, RF, Fleisig, GS, Lowry, TM, Barrentine, SW, and Andrews, JR. A three-dimensional biomechanics analysis of the squat during varying stance widths. *Med Sci Sports Exerc* 33: 984–998, 2001.

6. Escamilla, RF, Fleisig, GS, Zheng, N, Lander, JE, Barrentine, SW, Andrews, JR, Bergemann, BW, and Moorman, CT III. Effects of technique variations on knee biomechanics during the squat and leg press. *Med Sci Sports Exerc* 33: 1552–1566, 2001.
7. Flanagan, SP and Salem, GJ. The validity of summing lower extremity individual joint kinetic measures. *J Appl Biomech* 21: 181–188, 2005.
8. Kreighbaum, E and Barthels, K. *Biomechanics: A Qualitative Approach for Studying Human Movement.* Needham Heights, MA: Benjamin Cummings, 1995.
9. Mclaughlin, TM, Dillman, CJ, and Lardner, TJ. A kinematic model of performance in the parallel squat by champion powerlifters. *Med Sci Sports Exerc* 9: 128–133, 1977.
10. Souza, AL and Shimada, DS. Biomechanical analysis of the knee during the power clean. *J Strength Cond Res* 16: 290–297, 2002.
11. The International Powerlifting Federation Technical Rules Book, 2007. Available at: http://www.powerlifting-ipf.com. Accessed April 24, 2007.