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Weightlifting Performance is Related to Kinematic and Kinetic Patterns of the Hip and Knee Joints

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Abstract

The purpose of this study was to investigate the correlations between biomechanical outcome measures and weightlifting performance. Joint kinematics and kinetics of the hip, knee, and ankle were calculated while 10 subjects performed a clean at 85% of 1 repetition maximum (1RM). Kinematic and kinetic time-series patterns were extracted with principal components analysis. Discrete scores for each time-series pattern were calculated and used to determine how each pattern was related to body mass–normalized 1RM. Two hip kinematic and 2 knee kinetic patterns were significantly correlated with relative 1RM. The kinematic patterns captured hip and trunk motions during the first pull and hip joint motion during the

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movement transition between the first and second pulls. The first kinetic pattern captured a peak in the knee extension moment during the second pull. The second kinetic pattern captured a spatiotemporal shift in the timing and amplitude of the peak knee extension moment. The kinematic results suggest that greater lift mass was associated with steady trunk position during the first pull and less hip extension motion during the second-knee bend transition. Further, the kinetic results suggest that greater lift mass was associated with a smaller knee extensor moments during the first pull, but greater knee extension moments during the second pull, and an earlier temporal transition between knee flexion-extension moments at the beginning of the second pull. Collectively, these results highlight the importance of controlled trunk and hip motions during the first pull and rapid employment of the knee extensor muscles during the second pull in relation to weightlifting performance.

Keywords: biomechanics, movement patterns, principal components analysis, technique

Introduction

Performance and success in the sport of weightlifting is dictated by the mass a competitor can lift under the task constraints and strict rules of the events (i.e., the snatch and clean and jerk). Given these restrictions, large variations in the lifting technique are generally not to be expected (11). Although most lifters use similar technical styles of lifting (9), several differences in barbell trajectories and kinematic or kinetic characteristics exist between lifters with diverse experience or skill levels (1,3,5,7,9,10,11).

Distinct differences in weightlifting biomechanics have been observed between skilled and novice lifters. For example, Burdett (3) reported greater peak extension motions of the hip and knee for highly skilled world class lifters compared with skilled collegiate lifters during the first and second pull phases. Similarly, elite weightlifters also extend their knee and ankle joints more rapidly during these phases than do adolescent weightlifters (10). In turn, the relative barbell power outputs generated by adult weightlifters are significantly greater than those from adolescent weightlifters (10). In addition, Kauhanen et al. (11) reported significant differences in ground reaction force-time curves during weightlifting movements of elite and district level weightlifters. Furthermore, joint kinetics of skilled lifters are not only characterized by greater magnitudes of average joint power but also by more appropriate temporal organization of power production and absorption (5). In all, these studies demonstrate distinct experience-

based between-group differences in spatial and temporal biomechanical variables associated with weightlifting performance.

Few studies, however, have examined the correlation between biomechanical variables and performance within a group of weightlifters. Kauhanen et al. (11) reported a significant correlation between the maximal relative (i.e., body mass–adjusted) ground reaction force during the first pull of the clean movement and performance level (i.e., maximal mass lifted). Although ground reaction forces provide knowledge about the overall force-time profile of the lifter-barbell system, the most detailed information about weightlifting performance comes from the combined dissemination of joint kinematics and kinetics (1). Baumann et al. (1) examined the correlation between the total mass of the lifter-barbell system and internal joint moments. These authors (1) found strong to moderate correlations between the lifter-barbell system mass and the overall peak hip and the second peak knee extension moment. Unfortunately, Baumann et al. (1) did not normalize the lifter-barbell system mass to account for weight classes, nor did they normalize the joint moments to account for anthropometric differences. Consequently, it still remains to be determined how biomechanical variables (e.g., joint kinematics or kinetics) relate to weightlifting performance (i.e., body mass–adjusted lift mass).

A knowledge of the correlations between joint biomechanics and lift mass would certainly be of great applied interest to expedite focused training efforts and improve competitive performance. The purpose of this study was therefore to identify the correlations between biomechanical variables and weightlifting performance. To best account for the dynamic time-varying nature of biomechanical variables during weightlifting movements a functional principal components analysis (fPCA) was used to extract biomechanical patterns that capture joint motion or moment profiles across entire movements. Because fPCA also provides practically relevant technical information about weightlifting performance, the analysis was deemed appropriate given the applied purpose of the study. We hypothesized that the analysis would identify a distinct set of biomechanical patterns that could be correlated to weightlifting performance.

Methods

Experimental Approach to the Problem

The purpose of this study was to identify the correlations between weightlifting performance and biomechanical variables. The rationale was that understanding the relations between weightlifting performance and biomechanical variables would facilitate the technical and physical training of weightlifters. We hypothesized that the analysis would extract and identify a distinct set of biomechanical patterns that would be correlated to estimates of 1-reptition maximum (1RM), which served as a proxy for weightlifting performance. To identify the correlations between biomechanical patterns and weightlifting performance, we measured kinematic and kinetic data of the hip, knee, and ankle joints while the participants lifted 85% of their respective 1RM. Functional principal components analysis was used to extract kinematic and kinetic time-series patterns. Both joint kinematic and kinetic data were used because these provide the most detailed information about movement performance (1).

Subjects

Ten subjects (9 men, 1 woman) were recruited for this study (mean ± SD height: 1.84 ± 0.09 m; mass: 97.3 ± 18.0 kg; 1-repetition maximum [RM] clean: 120.5 ± 24.3 kg; Relative 1RM clean: 1.21 ± 0.10 kg/kg). All the subjects actively engaged in resistance training programs that involved weightlifting exercises and were deemed technically competent and representative of collegiate-level weightlifters by a national U.S. Weightlifting coach. All the subjects who participated were tested during an 'off'-week during their preseason training phase. All the subjects signed an institutionally approved written informed consent document before the collection of any data.

Procedures

Data Collection. After performing a brief warm-up, the subjects performed 2–3 repetitions at 65, 75, and 85% of their self-reported 1RM for the clean exercise. Approximately 2–3 minutes of rest was allowed between each set. Although kinematic and kinetic data were acquired during all sets, only data from the final set at 85% of 1RM were considered for analysis in this study. Because the weightlifting

technique stabilizes at loads >80% of 1RM, the 85% load was used as a proxy for competitive weightlifting performance (13).

Data Processing. A 6-camera infrared motion capture system (Vicon 460, Vicon, Los Angeles, CA, USA) was used to record the trajectories from 16 reflective markers attached bilaterally to the anterior and posterior superior iliac spines of the pelvis, medial and lateral epicondyles of the knee, medial and lateral malleoli of the ankle, and the subjects' heel and second metatarsal at 250 Hz (12). Two force plates (Kistler model 9281A, Kistler Instrument Corp., Amherst, NY, USA) that were built into an 8' × 8' weightlifting platform were used to collect kinetic data at 1,250 Hz (12). A fourth-order Butterworth filter was used to filter kinematic data at 6 Hz and kinetic data at 25 Hz. Euler angle rotation sequences were used to calculate 3-dimensional hip, knee, and ankle joint angles (19). Anthropometric data from each subject were combined with kinematic and kinetic data and used to solve for net internal hip, knee, and ankle joint moments of force with a conventional inverse dynamics approach based on a 3-dimensional rigid-link segment model (19). Moments were normalized to body height and mass. A custom-written MATLAB software program (MatLab, The Mathworks, Inc., Natick, MA, USA) was used for all calculations. Although these procedures generated joint angles and moments for both legs and in 3 planes of motion, only data from the right leg and in the sagittal-plane were used for further analysis. Pilot testing showed that all variables had high reliability (intraclass correlation coefficient > 0.90).

All kinematic and kinetic data were time normalized to 100% of the pull phase of the clean (i.e., from the time the barbell broke contact with the platform to the time the vertical ground reaction force fell <10 N at the end of the second pull phase of the clean) to facilitate between-subjects comparisons because the duration of the pull phase varied slightly between subjects. The time-normalized joint angle and moment time-series data from each individual's hip, knee, and ankle joint were then entered into an fPCA (14–16). The input for each fPCA consisted of a 30 × 100 data matrix (i.e., 30 rows = 10 subjects × 3 joints; 100 columns = 100 time points). In all, 4 fPCAs were performed; 2 for the normal angle and moment time-series data and 2 for the standardized angle and moment time-series data. To standardize the angle and moment time-series data, each matrix row had its mean subtracted and was then divided by its SD (15,16). The

standardization procedure was performed to account for the fact that a larger variation for a given time series (e.g., hip) may dominate the results and overemphasize its importance with respect to the other time series (16). Principal component functions (PCFs) were then extracted from the covariance matrix of each of these 4 matrices. Only PCFs that explained nontrivial proportions (>5% explained variance) in the time-series data were retained for further analysis. The retained PCFs were then projected back onto the original kinematic and kinetic waveform data. The sum of the projections across the lift phase gave a set of PCF scores for each extracted PCF. Because the extraction of PCFs comes from the covariance matrix the pooled kinematic or kinetic hip, knee, and ankle data the extracted PCFs account for the fact that these joints are linked and covary during movement and therefore capture multijoint patterns common to the entire lower extremity (14,16,18). Subsequently, each PCF represents a kinematic or kinetic pattern, and the associated PCF score captures how much each pattern contributes to the motion or moment at each joint. Ordinary statistical methods could then be used to test how PCF scores correlate to body mass–normalized lift mass and provide details on which kinematic or kinetic patterns are most important to lifting performance.

Statistical Analyses

Simple linear regression analyses were used to test for correlations between all extracted PCF scores and body mass–normalized lift mass (i.e., relative 1RM). The criterion for statistical significance was set at 0.05. All statistical analyses were performed in SPSS 17.0 (IBM Corporation, Somers, NY, USA).

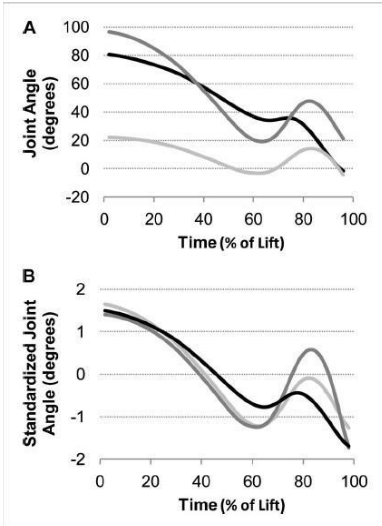

Figure 1. Ensemble averages of hip, knee, and ankle joint angles (degrees) across the duration of the lift for (A) normal kinematic data and (B) standardized kinematic data (hip = black line, knee = dark gray, ankle = light gray).

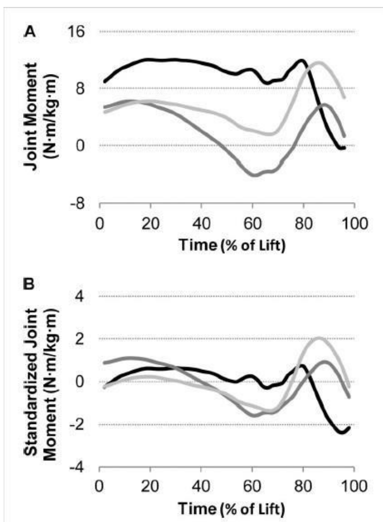

Figure 2. Ensemble averages of hip, knee, and ankle joint moments (newton meter per kilogram meter) across the duration of the lift for (A) normal kinetic data and (B) standardized kinetic data (hip = black line, knee = dark gray, ankle = light gray).

Results

Functional Principal Component Analysis

The fPCA extracted 2 PCFs for the normal and 3 PCFs for the standardized angle data. For the normal angle data, the first and second PCFs accounted for 88.1 and 6.8% of the variance, respectively. For the standardized angle data, the first, second, and third PCFs accounted for 67.3, 20.7, and 6.5% of the variance, respectively (Figure 1).

The analysis extracted 3 PCFs for the normal and 3 PCFs for the standardized moment data. For the normal moment data, the first, second, and third PCFs accounted for 71.2, 20.7, and 6.5% of the

variance, respectively. For the standardized moment data the first, second, and third PCFs accounted for 62.1, 17.9, and 6.3% of the variance, respectively (Figure 2).

Correlation Analysis

The correlation analysis revealed significant correlations between relative lift mass and the scores of 4 of the extracted PCFs: the second normal kinematic PCF for the hip (HA-PCF2; $r = 0.870$, $p = 0.011$), the first standardized kinematic PCF for the hip (HA-sPCF1; $r = 0.854$, $p = 0.015$), the second normal kinetic PCF for the knee (KM-PCF2; $r = 0.766$, $p = 0.044$), and the second standardized kinetic PCF for the knee (KM-sPCF2; $r = 0.858$, $p = 0.014$).

Interpretation of Principal Component Function and Correlation Results

Because the second normal kinematic PCF (HA-PCF2) for the hip captured a relative constant amount of joint angular extension during the first pull and rapid extension during the second pull, the significant positive correlation between this PCF and relative lift mass indicates that less hip extension motion during the first pull and rapid extension during the second pull is significantly correlated to relative lift mass (Figure 3A).

The first standardized kinematic PCF (HA-sPCF1) for the hip captured the magnitude of angular extension between the first pull and second pulls. The significant positive correlation between this PCF and relative lift mass indicates that a smaller hip joint excursion during the transition between the first pull and second pull is significantly correlated to relative lift mass (Figure 3B).

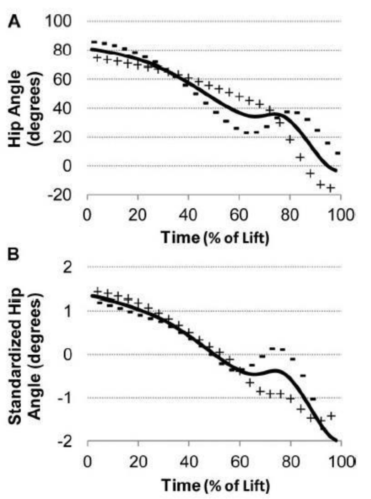

Figure 3. Effects of increasing ('+' symbol) or decreasing ('-' symbol) PCF scores on (A) hip joint angle (depicts the influence of HA-PCF2 scores) and (B) standardized hip angle (depicts the influence of HA-sPCF1 scores). Note: Because correlations between lift mass and PCF scores were positive, these effects indicate that lifters with greater 1 repetition maxima (1 RMs) exhibited kinematic time series that followed the '+' symbol time series, whereas lifter with smaller 1RMs followed the '-' symbol time series. PCF = principle component function; HA-sPCF1 = the first standardized PCF for hip angle, HA-PCF2 = the second normal PCF for hip angle.

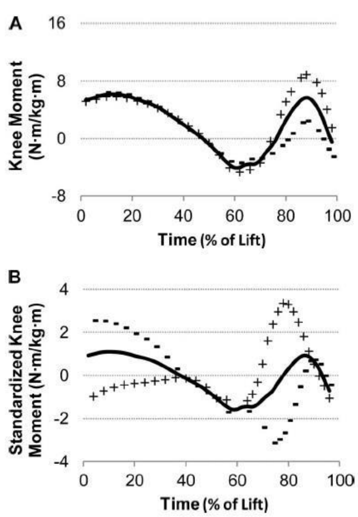

Figure 4. Effects of increasing ('+' symbol) or decreasing ('-' symbol) PCF scores on (A) knee joint moment (depicts the influence of KM-PCF2 scores) and (B) standardized knee joint moment (depicts the influence of KM-sPCF2 scores). Note: Because correlations between lift mass and principal component scores were positive, these effects indicate that lifters with greater 1 repetition maxima (1 RMs) exhibited kinetic time series that followed the '+' symbol time series, whereas lifters with smaller 1 RMs followed the '-' time series. PCF = principal component function; KM-sPCF2 = the first standardized PCF for knee moment, KM-PCF2 = the second normal PCF for knee moment.

As the second normal kinetic PCF (KM-PCF2) for the knee captured the amount of joint extensor moment during the second pull, the significant positive correlation between this PCF and relative lift mass indicates that a greater extension moment during the second pull is significantly correlated to relative lift mass (Figure 4A).

The second standardized kinetic PCF (KM-sPCF2) for the knee captured a complex spatiotemporal pattern in the joint moment profile. Greater positive scores for this PCF were associated with a smaller extension moment during the first pull, a greater extension moment during the second pull, and shift in the timing when the knee transitioned from a flexion moment to an extension moment at the beginning of the second pull. The significant positive correlation between this PCF and relative lift mass indicates that a greater relative lift mass is significantly correlated to smaller extension moments during the first pull, and greater extension moments during the second pull, and an earlier transition from flexion to extension moment at the beginning of the second pull (Figure 4B).

Discussion

The purpose of this study was to identify correlations between weightlifting biomechanics and performance. To best characterize the dynamic time-varying nature of weightlifting biomechanics at the joint level, an fPCA was used to extract biomechanical patterns that captured joint motion and moment profiles across the entire weightlifting movement. The results indicated that greater lift mass was associated with less hip extension motion during the first pull and second-knee bend transition, a smaller knee extension moment during the first pull, and a greater a knee extension moment during the second pull. In addition, an earlier temporal transition from knee flexion to extension moment at the beginning of the second pull was also associated with higher lift mass. These results highlight the importance of optimal hip and trunk motion along with knee extension moments in relation to weightlifting performance.

Two kinematic patterns were significantly correlated with weightlifting performance (i.e., relative 1RM). Surprisingly, both patterns were related to hip motion characteristics, even when joint motions were standardized to account for magnitude-variance differences between joints. The first of these kinematic patterns captured a relative constant amount of hip joint extension motion during the first pull and rapid extension during the second pull. The correlation between this pattern and relative 1RM indicated that steady and controlled hip motion during the first pull, followed by rapid extension during the second pull is related to greater relative lift mass. It has been suggested that proper weightlifting technique necessitates

a constant trunk angle with respect to the horizontal during the first pull (2). A relatively constant trunk angle likely enables the generation of large amounts of muscular work in that the absence of large angle changes facilitates low angular velocities, which would favor conditions of high force production during the first pull, where the employment of hip extensor muscles is dominant (2). The hip angle measured in this study, however, represents the relative angle between the trunk and thigh segment and therefore does not exclusively represent solely trunk motion. Regardless, a relatively small change in the hip angle during the first pull may reflect a constant trunk angle if the change in the hip angle is driven by an increase in the knee angle rather than the trunk angle. Furthermore, the second aspect captured by this kinematic pattern (i.e., rapid hip extension during the second pull) is also in agreement with reports that emphasize powerful triple extension of the lower extremity during the second pull as an important contributor to success in weightlifting (6,8,10). The observed correlation between the described patterns of hip and trunk motion relative to lift mass therefore corroborates previous technical reports of successful weightlifting technique (2).

The second kinematic pattern that was correlated to relative lift mass captured the amount of standardized hip joint motion between the first pull and second pull. The correlation between this pattern and relative 1RM therefore indicates that a smaller amount of hip joint motion during the transition between the first pull and second pull is significantly correlated to greater relative 1RM. Although the repositioning of the trunk with respect to the barbell during the second-knee bend transition appears essential to optimize employment of the back extensor muscles during the second pull (4), it is likely that too much hip flexion during this phase, as captured by this pattern, is also detrimental because too much hip flexion-extension motions may lead to excessive 'hipping' of the barbell and cause undesirable barbell trajectories associated with unsuccessful weightlifting attempts (17).

In addition to the 2 kinematic patterns, 2 kinetic patterns were also significantly correlated with relative 1RM. The first of these kinetic patterns captured a peak in knee extensor moment during the second pull, which indicated that a larger knee extension moment during the second pull is correlated to greater relative 1RM. Although a large involvement from knee extensor muscles makes practical sense as a

correlate to lifting performance, this is an interesting finding because several studies have questioned the importance of the magnitude of knee extensor moments during weightlifting as related to performance (1,12). For example, Kipp et al. (12) reported that the peak knee extensor moment does not increase linearly with external load across a range of submaximal weights. Similarly, Baumann et al. (1) suggested that low correlations between total system mass and knee moments occur because skilled lifters are able to better control the moment arm of the ground reaction force (i.e., the mechanical advantage) about the knee and therefore require a smaller joint moment for a given lift mass. Nevertheless, the lack of normalization of joint moments in the previously reported studies (1,12) or the different method used in this study (i.e., fPCA as opposed to traditional peak variables) may also contribute to the discrepancy in findings.

Interestingly, the second kinetic pattern that was correlated to relative lift mass also captured the characteristics related in part to the peak knee joint moment during the second pull. This pattern, however, was extracted from the standardized kinetic data and captured a more complex spatiotemporal knee joint moment pattern. Based on the qualitative assessment of this pattern, it appears that greater relative 1RMs are associated with a smaller knee extension moment during the first pull but a greater knee extension moment during the second pull. A previous report of hip and knee joint acceleration profiles identified a temporal switch or trade-off between these mechanical actions of these joints, which led to the conclusion that the hip is largely responsible for breaking the inertia and accelerating the barbell during the first pull but is then followed by overriding involvement of the knee joint in the second pull (2). The aforementioned kinematic results along with currently discussed kinetic results seem to support such a reciprocal exchange, with dominant knee function during the second pull as a primary characteristic related to greater relative lift mass. In addition, the standardized kinetic pattern also captured a temporal shift in the transition from flexion to extension moment at the beginning of the second pull. The presence of a temporal variation in knee extensor moment profile in relation to 1RM is in agreement with reports by Enoka (5) in that the technique of skilled lifters (i.e., those that lifted heavier weights) was not only characterized by greater magnitudes in joint kinetics but also by a more appropriate temporal

organization of power production and absorption during the weightlifting movement.

Although this study provides novel information about the correlations between biomechanical measures and weightlifting performance, some limitations should be considered. First, kinematic and kinetic data were acquired and analyzed while subjects lifted a submaximal load (i.e., 85% of 1RM). Technical aspects of competitive weightlifting performance, however, stabilize at loads >80% of 1RM (13), which would suggest that the chosen load and acquired biomechanical data represent a valid proxy of weightlifting performance at maximal or competition loads. Second, the kinetic results reported in this study represent the net internal joint moments, which implies that only the net effect of all muscle forces that act about a joint are considered and that the effects of muscular coactivation are ignored. Hence, a net joint extension moment only indicates that the extensor muscles are more active than the flexor muscles. To this end, future experimental designs may consider electromyographic analyses, which are basically nonexistent in the weightlifting literature, to quantify muscle activation and coactivation. Another limitation and consideration for future studies relates to the use of relative joint angles in kinematic analyses, because the results partially suggest that the use of relative angles during the analysis of weightlifting movements may not fully capture the relation between hip and trunk motion. Given these limitations, the need for additional studies seems warranted. Clearly, electromyographic analyses, musculoskeletal modeling, and expanded analysis of trunk and even upper-body motions would provide additional insight into the biomechanical performance characteristics during weightlifting.

This study provided novel information about weightlifting biomechanics and performance. The results suggest that lifting a greater mass during the pull phase of the clean is associated with steady trunk position during the first pull, attenuated hip extension motion during the second-knee bend transition, a smaller knee extension moment peak during the first pull, a greater a knee extension moment peak during the second pull, and an earlier temporal transition between a knee flexion and extension moment at the beginning of the second pull. These results underscore the importance of controlled hip and trunk motion along with knee extensor muscle function in relation to weightlifting performance.

Practical Applications

The results suggest that weighlifting performance is associated with several biomechanical patterns during the pull phase of the clean. Greater relative lift mass appears to be associated with steady trunk position during the first pull, relatively small hip motion during the second-knee bend transition, and rapid hip extension during the second pull. In addition, less involvement of the knee extensor muscles during the first pull but greater involvement of the knee extensor muscles during the second pull was also related to greater lift mass. Furthermore, a faster transition between a knee flexor and extensor muscles at the beginning of the second pull was also associated with greater lift mass. Together, these results indicate that weightlifting performance relies on optimal hip and trunk motions along with knee extensor muscle function during the pulling phases. Because the kinematic patterns represent noticeable gross motion patterns, coaches could easily observe and monitor them during technical training. Although the kinetic patterns are not as easily observed, coaches could still emphasize the patterning of knee extensor muscles across the different pull phases.

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