7-1-2012

Kinematic and Kinetic Synergies of the Lower Extremities During the Pull in Olympic Weightlifting

Kristof Kipp
University of Michigan

Josh Redden
USA Weightlifting

Michelle Sabick
Boise State University

Chad Harris
LaGrange College

Journal of Applied Biomechanics, 2012, 28, 271-278

Kinematic and Kinetic Synergies of the Lower Extremities During the Pull in Olympic Weightlifting

Kristof Kipp,[1] Josh Redden,[2] Michelle Sabick,[3] and Chad Harris[4]
[1]University of Michigan; [2]USA Weightlifting; [3]Boise State University; [4]LaGrange College

The purpose of this study was to identify multijoint lower extremity kinematic and kinetic synergies in weightlifting and compare these synergies between joints and across different external loads. Subjects completed sets of the clean exercise at loads equal to 65, 75, and 85% of their estimated 1-RM. Functional data analysis was used to extract principal component functions (PCF's) for hip, knee, and ankle joint angles and moments of force during the pull phase of the clean at all loads. The PCF scores were then compared between joints and across loads to determine how much of each PCF was present at each joint and how it differed across loads. The analyses extracted two kinematic and four kinetic PCF's. The statistical comparisons indicated that all kinematic and two of the four kinetic PCF's did not differ across load, but scaled according to joint function. The PCF's captured a set of joint- and load-specific synergies that quantified biomechanical function of the lower extremity during Olympic weightlifting and revealed important technical characteristics that should be considered in sports training and future research.

Keywords: weightlifting biomechanics, functional data analysis, principal component analysis, movement patterns

Olympic weightlifting techniques for the snatch and clean and jerk are characterized by an initial barbell displacement, which is referred to as the *pull*, from the floor to waist height (Enoka, 1979). Researchers that have examined lower extremity joint function during weightlifting movements have noted that the most commonly used technique to accomplish the pull is the so-called *double-knee bend* that is characterized by a dynamic interaction between the hip, knee, and ankle (Baumann et al., 1988; Enoka, 1988; Garhammer, 1981, 1985; Gourgoulis et al., 2000; Kauhanen et al., 1984). The movement transition during the double-knee bend also further divides the pull into a distinct first and second pull. Success in weightlifting events relies in large part on optimal biomechanics during the pull phases. In particular, optimal coordination between lower extremity joints appears necessary to successfully lift the heaviest weight possible (Baumann et al., 1988; Bottcher & Deutscher, 1999; Hakkinen et al., 1984). Few studies, however, focus on the coordination between joints during the pull in weightlifting and do not consider the interdependent nature between multiple joint degrees of freedom.

While previous studies have provided general information about discrete and global biomechanical characteristics associated with weightlifting movements, this information may provide limited insight for two reasons. First, discrete peak values provide only partial information about continuous time-series data, because differences between these data are often not sufficiently characterized purely by simple global peak magnitudes. Second, discrete variables do relatively little in addressing the interaction between the multiple degrees of freedom of the lower extremity joints that need to be controlled during weightlifting movements. In light of these limitations it becomes evident that different methods may be needed to fully account for the biomechanical characteristics of a movement with the complexity of the clean.

Functional data analysis (FDA) provides a means to explore data where observations arise from continuous functions or curves, such as time-series biomechanical data (Ramsay & Silverman, 1997). A commonly used technique to quantify the characteristics of time-series data is functional principal components analysis (fPCA). This technique extends traditional principal component analysis, which uses single and discrete variables, in that the input data comprises entire time series and the output captures information about the time-series data. A further variant of fPCA (i.e., multivariate fPCA) uses different time-series curves from multiple joints as input data to reduce complex multijoint movements into a smaller

Kristof Kipp *(Corresponding Author)* is with the Department of Physical Medicine and Rehabilitation, University of Michigan, Ann Arbor, MI. Josh Redden is with USA Weightlifting, Colorado Springs, CO. Michelle Sabick is with the Department of Mechanical and Biomedical Engineering, Boise State University, Boise, ID. Chad Harris is with the Department of Exercise Science, LaGrange College, LaGrange, GA.

set of shared principal component functions (PCF's) that capture interjoint coordination synergies across entire movements (Mah et al., 1994; St-Onge & Feldman, 2003; Vernazza-Martin et al., 1999). For example, Vernazza-Martin et al. (1999) used this approach to study multijoint kinematic synergies of the hip, knee, and ankle during trunk bending with different loads and found that a single dominant PCF (i.e., synergy) captured the coupling between the angular changes of all joints and loads. From an applied standpoint, a reduced set of common synergies that capture salient aspects of interjoint coordination during a weightlifting movement would be of great benefit because such synergies would offer coaches and sport scientists pertinent technical cues or characteristics to consider in training or future research.

In addition, knowledge of how interjoint coordination synergies during weightlifting movements are modified in response to changes in external loads would also facilitate a better biomechanical understanding that could improve performance (Enoka, 1988; Hakkinen et al., 1984). While relatively little is known about load-dependent changes in lower extremity coordination, it would be of interest to determine if weightlifters use a few "robust" interjoint coordination synergies across loads and whether they scale these synergies in response to task demands. The purpose of this study was thus twofold: (1) to identify lower extremity kinematic and kinetic synergies during weightlifting exercise and (2) to compare these synergies across lower extremity joints and external loads. To this end we used fPCA to extract shared PCF's between the lower extremity joints during the pull phase of the clean and compared how PCF's differed between the hip, knee, and ankle joint across a range of external loads.

Methods

We recruited 10 subjects (nine males, one female) to participate in 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). At the time, all subjects were participating in a training program that involved weightlifting exercises. Further, all subjects were deemed technically competent and representative of collegiate-level lifters by a national USA Weightlifting coach. All subjects provided written informed consent approved by the University's Institutional Review Board for Human Subjects Research.

Subjects completed a brief warm-up that included lifting light loads up to 50% of their self-reported one 1-RM for the clean exercise. After the warm-up, subjects performed 2–3 repetitions at 65%, 75%, and 85% of 1-RM with approximately 2–3 min rest between each set. Kinematic and kinetic data were collected during each set and processed based on a three-dimensional rigid-link segment model with custom-written MatLab software. Kinematic data were calculated from a total of 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 2nd metatarsal. The positions of the reflective markers were recorded with a 6-infrared camera VICON 460 Motion Capture System that sampled at 250 Hz. Kinetic data were collected at 1,250 Hz from two Kistler model 9281A force plates that were built into an 8′ × 8′ weightlifting platform. The raw kinematic and kinetic data were filtered with a fourth-order Butterworth filter at 6 and 25 Hz, respectively. Three-dimensional Euler angle rotation sequences were used to calculate ankle, knee, and hip joint angles from the filtered kinematic data. Kinematic and kinetic data were combined with anthropometric data and used to solve for net internal ankle, knee, and hip joint moments of force with a conventional inverse dynamics approach. Moments were normalized to body height and weight. Data were calculated for right leg sagittal-plane variables and time normalized to 100% of the pull phase of the clean (i.e., from the time the barbell left the platform to the time the vertical ground reaction force fell below 10 N at the end of the second pull phase of the clean). The normalization of the time scale was performed because the duration of the pull phase varied slightly between subjects and loads.

For each of the three joint rotations and joint moments of force, the time-normalized waveforms for the three sets of clean trials from each individual were subjected to an fPCA (Mah et al., 1994; Ramsay & Silverman, 1997; St-Onge & Feldman, 2003; Vernazza-Martin et al., 1999). The input to the fPCA for the kinematic and kinetic analysis comprised the time-normalized waveforms for all subjects, joints, and loads (i.e., 10 subjects × 3 joints × 3 loads = 90 waveforms). Pooling all kinematic and kinetic time-series data therefore produced a 90 × 100 matrix for the joint rotations and moments of force, respectively. PCF's were extracted from the covariance matrix of the two original data matrices with an eigenvector decomposition method. Since the extraction method uses a covariance matrix that includes data from all joints, the PCF's account for the fact that the kinematics and kinetics of individual joints are linked and covary during movement, and therefore capture multijoint synergies common to all joints (Mah et al., 1994; Vernazza-Martin et al., 1999). Only PCF's (i.e., synergies) that explained nontrivial proportions (>3% explained variance) of the waveforms were retained for analysis. Each retained PCF was magnitude normalized and multiplied with the original kinematic and kinetic waveform data. The sum of the resulting multiplication products over the entire lift phase gave a set of PCF scores for all PCF's that were extracted from each individual's joint rotations and joint moments of force for every load. Since each PCF represents a kinematic or kinetic synergy, the associated PCF score captures how much each synergy contributes to the motion or moment of force at each joint and for each load. Group comparisons between PCF scores could then be used to test how and to what extent the PCF's differed between joints and/or across loads.

Separate 3 (joint) × 3 (load) repeated-measure ANOVAs were used to test for differences in PCF scores for the joint rotations and moments of force. Huynh–Feldt adjustments were made when assumptions of sphericity were not met. The α-level for statistical significance was set at 0.05. In the absence of significant interactions, data were pooled across joints and/or loads for post hoc testing and compared with Bonferroni-adjusted paired *t* tests.

Results

The kinematic ensemble averages of all three joints for all subjects at 85% of 1-RM are shown in Figure 1. The analysis extracted two PCF's from the pooled kinematic data of the hip, knee, and ankle joint (Figure 2). The first PCF accounted for 88.6% of the total variance in the entire kinematic data and captured a general flexion-to-extension motion. The second PCF accounted for 6.2% of the variance in the entire kinematic data and captured an extension-flexion-extension motion. Collectively, these two PCF's accounted for approximately 95% of the variance in the entire kinematic time-series data.

The statistical analysis of the kinematic PCF scores indicated main effects for both PCF's (Table 1). More specifically, the scores for the first PCF were greater for the hip and knee than the ankle. In addition, scores for the second PCF differed between all joints, but were greatest for the knee, intermediate for the ankle, and smallest for the hip. Figure 3 depicts the effects of changing the magnitudes of the PCF scores on the kinematics of the knee joint. Although not shown, it should be noted that changes in PCF scores also capture differences between the kinematic joint ensemble averages (e.g., a greater PCF 2 score for the knee compared with the hip indicates that the effect of the second PCF is more prominent in the ensemble-average of the knee, has greater extension-flexion-extension motion, and therefore looks more like the (+)-curve in Figure 3b).

The kinetic ensemble averages of all three joints for all subjects at 85% of 1-RM are shown in Figure 1. The analysis extracted four PCF's from the pooled kinetic data of the hip, knee, and ankle joint (Figure 2). The first PCF accounted for 73.2% of the total variance in the entire kinetic data and captured a general extension moment of force during the first half of the movement. The second PCF accounted for 12.6% of the variance in the kinetic data and captured a peak in the extension moment of force during the final phase the movement. The third PCF accounted for 6.4% of the variance in the kinetic data and captured a temporal (i.e., horizontal) shift

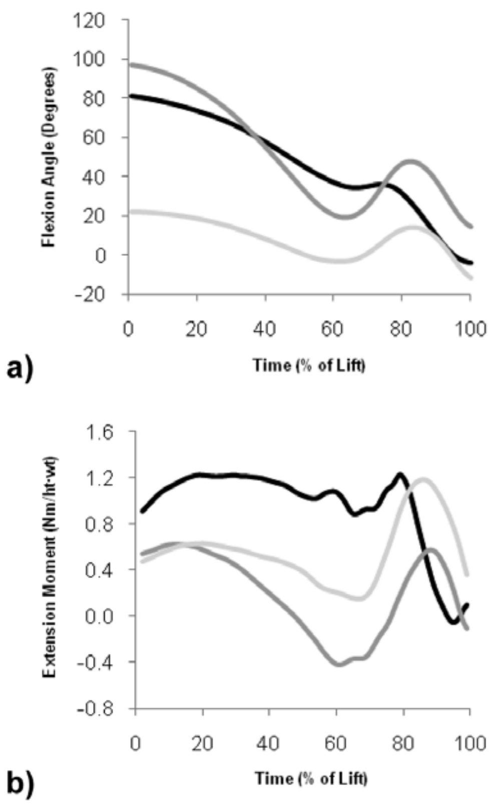

Figure 1 — Ensemble average of (a) joint angles and (b) joint moments of force of the lower extremities during the pull phase of the clean at 85% of 1-RM (black line = hip, dark gray line = knee, light gray line = ankle).

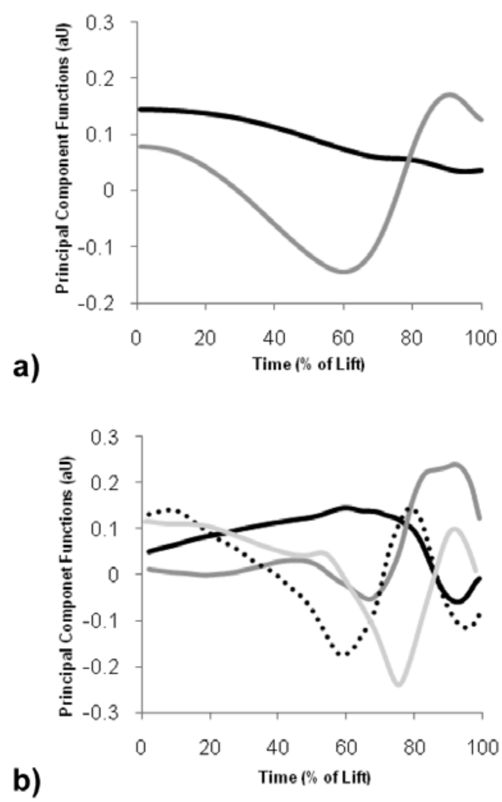

Figure 2 — Principal component functions (PCF—in arbitrary units [AU's]) for (a) joint angles and (b) joint moments of force of the lower extremity during the pull phase of the clean (black line = PCF 1, dark gray line = PCF 2, light gray line = PCF 3, dotted black line = PCF 4).

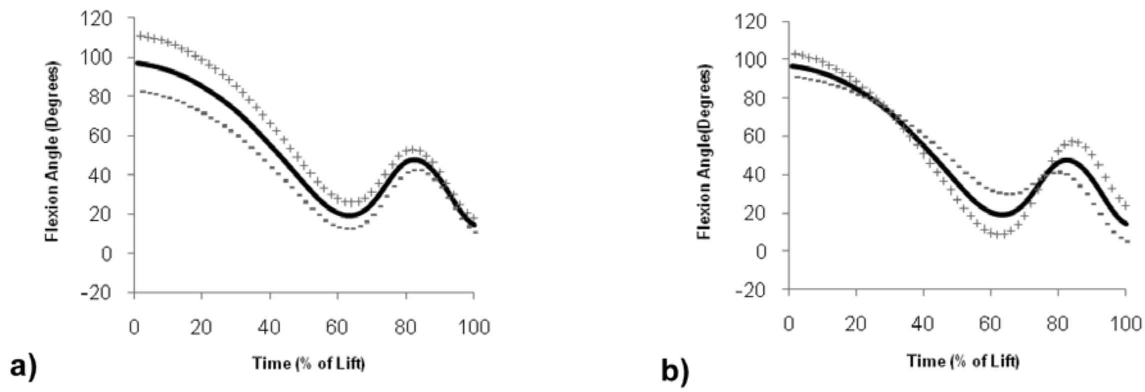

Figure 3 — Effects of increasing (+) and decreasing (–) the score of the (a) first and (b) second kinematic principal component function (PCF) on knee joint angles during the pull-phase of the clean at 85% of 1-RM. (*Note.* Changes in the score of the first PCF affect the range of extension motion at the beginning of the movement; changes in the score of the second PCF affect the amount of extension-flexion-extension motion during the latter part of the movement).

Table 1 Kinematic and kinetic principal component function (PCF) scores for each joint and load

		Kinematic		Kinetic			
Joint	**Load**	**PCF1**	**PCF2**	**PCF1**	**PCF2**	**PCF3**	**PCF4**
	65	534.9 ± 97.2*	–16.5 ± 31.8*†	87.3 ± 19.7*†	18.0 ± 16.7	18.2 ± 15.8	17.1 ± 5.7
Hip	75	530.0 ± 115.0*	–38.7 ± 29.0*†	94.5 ± 22.5*†	20.7 ± 16.2	13.9 ± 15.9	17.5 ± 3.9
	85	525.3 ± 122.8*	–25.7 ± 36.0*†	92.9 ± 21.0*†	24.5 ± 21.9	17.6 ± 15.3	18.9 ± 3.9
	65	570.5 ± 153.8*	111.4 ± 25.6*‡	2.6 ± 11.9*‡	20.7 ± 13.2	21.7 ± 11.9	22.6 ± 11.3*
Knee	75	570.0 ± 142.4*	105.7 ± 29.6*‡	6.6 ± 16.1*‡	23.9 ± 17.2	25.4 ± 9.4	21.9 ± 10.0*
	85	572.9 ± 129.1*	114.6 ± 32.1*‡	5.6 ± 10.5*‡	19.2 ± 14.9*	22.0 ± 6.4	25.1 ± 9.7*
	65	98.8 ± 38.6†‡	41.8 ± 17.5†‡	28.9 ± 9.0†‡	34.9 ± 6.9	8.9 ± 5.9	10.9 ± 10.8†
Ankle	75	112.0 ± 47.5†‡	40.5 ± 16.9†‡	30.8 ± 10.0†‡	36.3 ± 7.4	14.0 ± 4.5	11.1 ± 8.5†
	85	106.0 ± 38.3†‡	43.6 ± 17.3†‡	34.6 ± 11.6†‡	46.1 ± 8.4†	11.3 ± 7.8	12.8 ± 7.5†

*$p < .05$ vs. ankle; †$p < .05$ vs. knee; ‡$p < .05$ vs. hip.

Note. The principal component function scores only indirectly reflect joint motion or moment of force. Rather, the scores act as a scaling factor, which, if multiplied with the respective principal component function reconstructs the original joint motion or moment of force for each joint or load.

in the moment of force peak during the final part of the movement. The fourth PCF accounted for 4.0% of the variance in the kinetic data and captured an extension-flexion-extension moment of force transition also during the middle part of the movement. Collectively, these four PCF's accounted for approximately 96% of the variance in the entire kinetic data.

The statistical analysis of the respective PCF scores indicated main effects for the first and fourth kinetic PCF's (Table 1). More specifically, the scores for the first kinetic PCF differed between all joints and were greatest for the hip, intermediate for the ankle, and smallest for the knee joint. The scores for the fourth kinetic PCF, however, differed only between the knee and the ankle in that they were greater for the knee joint. Further, an interaction indicated that the scores for the second kinetic PCF were greater for the ankle than the knee at the 85% load only. Figure 4 depicts the effects of changing the magnitudes of the kinetic PCF scores on the moments of force at the knee joint. As stated in the kinematic results section, changes in PCF scores also capture differences between the kinetic joint ensemble-averages (e.g., a greater PCF 2 score for the ankle compared with the knee indicates that the effect of the second PCF is more prominent in the ensemble-average of the knee, has greater extension moment of force during the final part of the movement, and therefore looks more like the (+)-curve in Figure 4b).

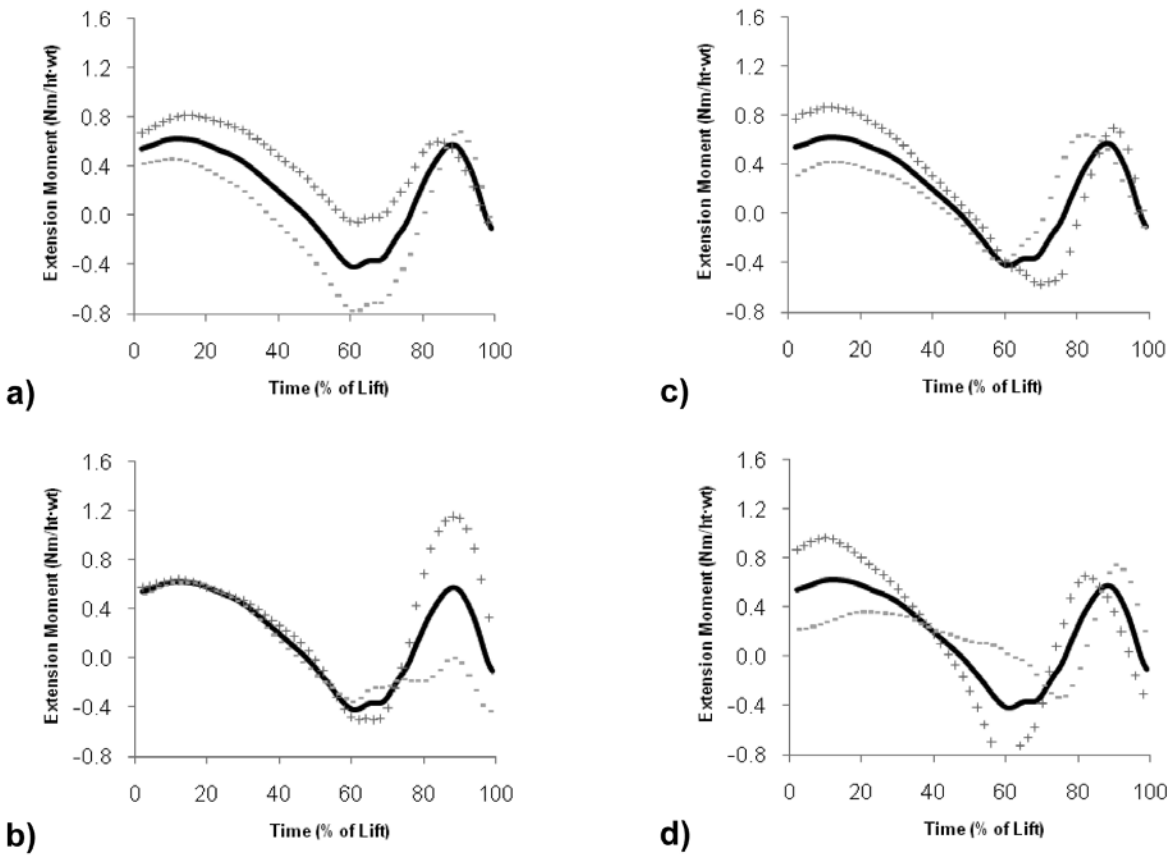

Figure 4 — Effects of increasing (+) and decreasing (–) the score of the (a) first, (b) second, (c) third, and (d) fourth kinetic principal component function (PCF) on knee joint moments of force during the pull phase of the clean at 85% of 1-RM (*Note.* Changes in the score of the first PCF affect the magnitude at the beginning of the movement; changes in the score of the second PCF affect the magnitude during the final part of the movement; changes in the score of the third PCF affect the timing of the peak during the final part of the movement; changes in the score of the fourth PCF affect amount of extension-flexion-extension transition).

Discussion

We found that the FDA approach used in this study captured joint- and load-dependent kinematic and kinetic synergies of lower extremity time-series data during weightlifting. Specifically, we found that all kinematic and two out of the four kinetic synergies differed only between joints and were not affected by changes in external load. These load-independent synergies included a general extension and an extension-flexion-extension motion that captured joint-specific triple-extension and double-knee bend characteristics inherent to weightlifting movements. While the load-independent synergies did not change across loads, they differed between lower extremity joints according to specific joint function during the weightlifting movement. Conversely, only one kinetic synergy exhibited more complex behavior in that it differed across joints as the external load increased. This synergy captured a greater relative increase in moment of force during the second pull at the ankle than at the knee as the load increased from 75% to 85% of 1-RM. Collectively, the kinematic and kinetic synergies captured general biomechanical characteristics and provided technical perspectives on lower extremity joint function during weightlifting exercise across a range of external loads.

The analyses revealed that the prominent kinematic and kinetic synergies during the pull phase of the clean are a general flexion-to-extension motion and a general net extension moment of force, respectively. In addition, it should be noted that the effects of both kinematic and kinetic synergies on the extension motion and moment of force were most prominent during the first pull of the clean. The kinematic aspect of these findings is well in line with literature that characterizes weightlifting movements by a general triple-extension of all three lower extremity joints (Baumann et al., 1988; Bottcher & Deutscher, 1999; Garhammer, 1981; Gourgoulis et al., 2000; Hakkinen et al., 1984). This synergy was more prominent at the hip and knee than at the ankle, which is likely due to the fact that during the pull phase of the clean, the hip and knee joint move through a larger range of motion (Bottcher & Deutscher, 1999; Gourgoulis et al., 2000). Interestingly, adolescent lifters display smaller peak extension angles of the lower extremities during the first pull than adult lifters (Gourgoulis et al., 2004). Gourgoulis et al. (2004) hypothesized that the attenuated extension pattern during the first pull may reflect a less forceful movement, which may suggest that the general extension synergy described in the current study is influenced by the skill or physical condition of each lifter. As for the kinetics, the magnitude of the net extension moment of force captured by the most prominent kinetic synergy displayed a distinct hierarchy between joints and was largest at the hip, intermediate at the ankle, and smallest at the knee. In combination, a general extension motion and a net extension moment of force indicate that positive mechanical work is produced. Indeed, previous researchers have reported large amounts of mechanical work performed on the barbell during the first pull (Gourgoulis et al., 2004). Therefore, the greater degree to which the primary kinematic and kinetic synergies were present at the hip joint likely signifies a relatively larger requirement of mechanical work from the hip extensor muscles and underscores the respective mechanical and technical importance of these muscles during the first pull phase of the clean.

The analysis also extracted an extension-flexion-extension synergy that was present in the latter part of both kinematic and kinetic time-series data. With respect to the kinematic synergy, the results revealed a distinct hierarchy between joints in that the extension-flexion-extension motion was most prominent at the knee, intermediate at the ankle, and smallest at the hip. Similarly, the extracted extension-flexion-extension kinetic synergy was greater at the knee than at the ankle. In general, the kinematic and kinetic extension-flexion-extension synergies reflect the second knee bend that occurs between the first and second pull of the clean during weightlifting (Baumann et al., 1988; Enoka, 1988; Garhammer, 1981; Gourgoulis et al., 2000; Hakkinen et al., 1984; Kauhanen et al., 1984). Since discrete angular variables associated with a more pronounced second knee bend (e.g., greater peak knee flexion angle during second knee bend) have been reported in male compared with female lifters and in adult compared with adolescent lifters it may be of interest to consider other external influences, beyond the effect of load, on this synergy in future studies (Gourgoulis et al., 2002). Although the presence of the extension-flexion-extension synergy in the kinematic and kinetic data would imply that the second knee bend during weightlifting is important, this synergy appeared to contribute relatively little to the overall variance in the time-series data. The second knee bend is traditionally considered an important aspect of the double-knee bend technique by many researchers and coaches (Baumann et al., 1988; Enoka, 1979, 1988); however, future research should continue to focus on the second knee bend during weightlifting so as to delineate its ultimate importance and contribution to weightlifting performance.

Two additional kinetic synergies were extracted from the kinetic time-series data. The first captured an extension moment of force peak that was most prominent during the final part of the movement, whereas the second captured a shift in the timing of the peak moment of force during the final part of the movement. The synergy that captured the peak moment of force during the latter part of the movement likely captured the mechanism responsible for the forceful triple extension during the second pull (Baumann et al., 1988; Garhammer, 1981). The analysis indicated a relatively greater increase in the peak extension moment of force at the ankle compared with the knee as the load increased from 75% to 85% of 1-RM. Since this synergy differed only between the knee and the ankle at the 85% load, it appears that compared with the knee joint, forceful extension of the ankle joint becomes relatively more important as lift weight increases, especially during the final part of the movement (Weide, 1989). Similarly, Gourgoulis et al. (2004) reported greater peak ankle joint angles during the second pull in adult than adolescent lifters and concluded that this may reflect a more powerful lift and explain group differences in weight lifted. With respect to the final remaining kinetic synergy, it is interesting to note that this synergy did not vary across load or joint. In the absence of any load or joint differences the presence of this synergy may indicate that it captured more between-subject differences (e.g., individual variations in technique) than within-subject differences (i.e., load- or joint-dependent differences). On the other hand, the emergence of this synergy may be the by-product of the procedure used to normalize the time-scale of the input data for the fPCA. Because the normalization procedure may introduce a warping bias on the time-scale before the data are entered into the fPCA, it is conceivable that this bias is captured by one of the extracted synergies. It should be noted, however, that the timing-related synergy emerged from the kinetic data only and accounted for a relatively small (6.4%) portion of the overall variance in the data. Nonetheless, due to the clear importance of timing-related events during weightlifting movements, these issues should be addressed in future research studies.

Although this study provides novel biomechanical insights into load-dependent and joint-specific behavior of interjoint coordination during weightlifting movements, several limitations warrant discussion. First, normalization of the time-scale may affect the extraction and interpretation of movement synergies as mentioned in the previous paragraph, because normalization may attenuate timing-related differences between waveforms. Still, the number of synergies and total variance explained typically remain similar regardless of any time-scale normalization (Epifanio et al., 2008). Second, we included a fairly narrow range of external loads and it is possible that replicating this study across a greater range of external loads could provide more information about load-dependent changes (Kawamori et al., 2005; Kawamori et al., 2006). The range of loads chosen, however, represents a range commonly encountered in the training of weightlifters or those that use weightlifting exercises as part of traditional resistance training programs (Lukashev et al., 1979; Tricoli et al., 2005).

Further, technical aspects stabilize at loads above 80% of 1-RM and are representative of competition performance (Lukashev et al., 1979). Another general limitation lies in only examining net moments of force. The likely presence of coactivation and the indeterminacy of the musculoskeletal system emphasize that the kinetic data presented here simply constitutes the net output of all muscle forces that act about a joint (Baumann et al., 1988). In addition, several physiological (e.g., maximal strength) and training-related variables (e.g., training status) of an individual can significantly influence muscular performance, and would imply that the current results may not simply extrapolate to more or less trained individuals (Baker, 2002; Baker & Newton, 2006, Gourgoulis et al., 2004). Moreover, this study represents cross-sectional information and it is known that longitudinal resistance training or feedback-based interventions affect various aspects of weightlifting performance (Winchester et al., 2005, 2009). Given these limitations, the need for additional, and especially, longitudinal studies is warranted. Without a doubt, longitudinal information on interjoint coordination or movement synergies would provide interesting insight into physiological or training-related changes with regards to the biomechanical characteristics of weightlifting exercise.

The control of lower extremity interjoint coordination during weightlifting can be sufficiently characterized by a small set of principal kinematic and kinetic synergies. Since these kinematic and kinetic synergies captured general biomechanical features of weightlifting movements, they could be used by coaches for the purposes of technical training or by sport scientists as foci for future research.

Acknowledgments

We would like to thank Seth Kuhlman for help with data processing.

References

Baker, D. (2002). Differences in strength and power among junior-high, senior-high, college-aged, and elite professional rugby league players. *Journal of Strength and Conditioning Research, 16,* 581–585. PubMed

Baker, D.G., & Newton, R.U. (2006). Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-power athletes. *Journal of Strength and Conditioning Research, 20,* 541–546. PubMed

Baumann, W., Gross, V., Quade, K., Galbierz, P., & Shwirtz, A. (1988). The snatch technique of world class weightlifters at the 1985 world championships. *International Journal of Sport Biomechanics, 4,* 68–89.

Bottcher, J., & Deutscher, E. (1999). Biomechanische ergebnisse zur bewegungstechnik im gewichtheben (reißen). *Leistungssport, 29,* 55–62.

Enoka, R.M. (1979). The pull in olympic weightlifting. *Medicine and Science in Sports, 11,* 131–137. PubMed

Enoka, R.M. (1988). Load- and skill-related changes in segmental contributions to a weightlifting movement. *Medicine and Science in Sports and Exercise, 20,* 178–187. PubMed doi:10.1249/00005768-198820020-00013

Epifanio, I., Avila, C., Page, A., & Atienza, C. (2008). Analysis of multiple waveforms by means of functional principal component analysis: Normal versus pathological patterns in sit-to-stand movement. *Medical & Biological Engineering & Computing, 46,* 551–561. PubMed doi:10.1007/s11517-008-0339-6

Garhammer, J. (1981). Biomechanical characterisitics of the 1978 world weightlifting champions. *International Series on Biomechanics, 3,* 300–304.

Garhammer, J. (1985). Biomechanical profiles of olympic weightlifters. *International Journal of Sport Biomechanics., 1,* 122–130.

Gourgoulis, V., Aggelousis, N., Mavromatis, G., & Garas, A. (2000). Three-dimensional kinematic analysis of the snatch of elite greek weightlifters. *Journal of Sports Sciences, 18,* 643–652. PubMed doi:10.1080/02640410050082332

Gourgoulis, V., Aggeloussis, N., Kalivas, V., Antoniou, P., Christoforodis, C., Mavromatis, G., ... (2002). Comparative 3-dimensional kineamtic analysis of the snatch in elite male and female greek weightlifters. *Journal of Strength and Conditioning Research, 16,* 359–366. PubMed

Gourgoulis, V., Aggeloussis, N., Kalivas, V., Antoniou, P., & Mavromatis, G. (2004). Snatch lift kinematics and bar energetics in male adolescent and adult weightlifters. *Journal of Sports, Medicine, and Physical Fitness, 44,* 126–131. PubMed

Hakkinen, K., Kauhanen, H., & Komi, P.V. (1984). Biomechanical changes in the olympic weightlifting technique of the snatch and clean & jerk from submaximal to maximal loads. *Scandinavian Journal of Sports Sciences, 6,* 57–66.

Kauhanen, H., Hakkinen, K., & Komi, P.V. (1984). A biomechanical analysis of the snatch and clean & jerk techniques of finnish elite and district level weightlifters. *Scandinavian Journal of Sports Sciences, 6,* 47–56.

Kawamori, N., Crum, A.J., Blumert, P.A., Kulik, J.R., Childers, J.T., Wood, J.A., ... (2005). Influence of different relative intensities on power output during the hang power clean: Identification of the optimal load. *Journal of Strength and Conditioning Research, 19,* 698–708. PubMed

Kawamori, N., Rossi, S.J., Justice, B.D., Haff, E.E., Pistilli, E.E., O'Bryant, H.S., ... (2006). Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *Journal of Strength and Conditioning Research, 20,* 483–491. PubMed

Lukashev, A.A., Medvedev, A.S., & Melkonian, A.A. (1979). Snatch technique of weightlifters executing repetitions with 80 percent of maximum. *Teoriya I Praktika Fizicheskoi Kultury, 12,* 13–15.

Mah, C.D., Hulliger, M., Lee, R.G., & O'Callaghan, I.S. (1994). Quantitative analysis of human movement synergies: Constructive pattern analysis for gait. *Journal of Motor Behavior, 26,* 83–102. PubMed doi:10.1080/00222895.1994.9941664

Ramsay, J.O., & Silverman, B.W. (1997). *Functional data analysis*. New York, NY: Springer Verlag.

St-Onge, N., & Feldman, A.G. (2003). Interjoint coordination in lower limbs during different movements in humans. *Experimental Brain Research, 148,* 139–149. PubMed

Tricoli, V., Lamas, L., Carnevale, R., & Ugrinowitsch, C. (2005). Short-term effects on lower-body functional power development: Weightlifting vs. Vertical jump training programs. *Journal of Strength and Conditioning Research, 19,* 433–437. PubMed

Vernazza-Martin, S., Martin, N., & Massion, J. (1999). Kinematic synergies and equilibrium control during trunk movement under loaded and unloaded conditions. *Experimental Brain Research, 128,* 517–526. PubMed doi:10.1007/s002210050874

Weide, U. Mathematische modellierung und simulation in der sportart gewichtheben: Ein beitrag zur weiteren vervollkommnung der biomechanischen begründung der sollbewegungsstruktur für die wettkampfübung reissen, Leipzig, 1989.

Winchester, J.B., Erickson, T.M., Blaak, J.B., & McBride, J.M. (2005). Changes in bar-path kinematics and kinetics after power-clean training. *Journal of Strength and Conditioning Research, 19,* 177–183. PubMed

Winchester, J.B., Porter, J.M., & McBride, J.M. (2009). Changes in bar path kinematics and kinetics through use of summary feedback in power snatch training. *Journal of Strength and Conditioning Research, 23,* 444–454. PubMed doi:10.1519/JSC.0b013e318198fc73