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## Abstract

The purpose of this study was to investigate correlations between biomechanical outcome measures and weightlifting performance. Joint kinematics and kinetics of the hip, knee, and ankle were calculated while ten subjects performed a clean at 85% of 1-RM. 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 1-RM. Two hip kinematic and two knee kinetic patterns were significantly correlated with relative 1-RM. The kinematic patterns captured hip and trunk motions during the first pull and hip joint motion during the movement transition between the first and second pull. 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, as well as 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 lifting technique are generally not to be expected (11). While most lifters use similar technical styles of lifting (7), several differences in barbell trajectories and kinematic or kinetic characteristics exist between lifters with diverse experience or skill levels (1, 3, 4, 6, 7, 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 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 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 (4). In all, these studies demonstrate distinct experience-based between-group differences in spatial and temporal biomechanical variables associated with weightlifting performance.

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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). While 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 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).

Knowledge of the correlations between joint biomechanics and lift mass would certainly be of great applied interest in order 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. In order to best account for the dynamic time-varying nature of biomechanical variables during weightlifting movements a functional principal components analysis was used to extract biomechanical patterns that capture joint motion or moment profiles across entire movements. Since functional principal components analysis 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 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 (RM), which served as a proxy for weightlifting performance. In order to identify correlations between biomechanical patterns and weightlifting performance we measured kinematic and kinetic data of the hip, knee, and ankle joints while participants performed lifted 85% of their respective 1-RM. 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 (nine males, one female) 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 1-RM clean: 1.21±0.10 kg/kg). All 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 USA Weightlifting coach. All subjects participated were tested during an 'off'-week during their pre-season training phase. All subjects signed an institutionally approved written informed consent document before collection of any data.

### Procedures

*Data Collection.* After performing a brief warm-up, subjects performed 2-3 repetitions at 65%, 75%, and 85% of their self-reported 1-RM for the clean exercise. Approximately 2-3 minutes of rest were allowed between each set. While kinematic and kinetic data were acquired during all sets, only data from the final set at 85% of 1-RM were considered for analysis in this study. Since weightlifting technique stabilizes at loads above 80% of 1-RM, the 85% load was used as a proxy for competitive weightlifting performance (13).

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*Data Processing.* A 6-camera infra-red motion capture system (VICON 460, Vicon, Los Angeles, CA, USA) was used to record the trajectories from 16 reflective markers attached bi-laterally 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 at 250 Hz (12). Two force plates (Kistler model 9281A, Kistler Instrument Corp, Amherst, NY, USA) that were built into an 8'x8' 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 three-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 three-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 three-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 (ICC > .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 below 10 Newton's 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 individuals' hip, knee, and ankle joint were then entered into a functional principal components analysis (fPCA) (14-16). The input for each fPCA consisted of a 30x100 data matrix (i.e. 30 rows = 10 subjects x 3 joints; 100 columns = 100 time-points). In all, four fPCA's were performed; two for the normal angle and moment time series data, and two 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 standard deviation (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 (PCF's) were then extracted from the covariance matrix of each of these four matrices with a singular value decomposition method. Only PCF's that explained nontrivial proportions (>5% explained variance) in the time-series data were retained for further analysis. The retained PCF's 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. Since the extraction of PCF's comes from the co-variance matrix the pooled kinematic or kinetic hip, knee, and ankle data the extracted PCF's account for the fact that these joints are linked and co-vary during movement, and therefore capture multi-joint 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 Analysis

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

## Results

*fPCA.* The fPCA extracted 2 PCF's for the normal and 3 PCF's for the standardized angle data. For the normal angle data, the first and second PCF's accounted for 88.1% and 6.8% of the variance, respectively. For the standardized angle data the first, second, and third PCF's accounted for 67.3%, 20.7%, and 6.5% of the variance, respectively.

*Insert Figure 1 about here*

The analysis extracted 2 PCF's for the normal and 3 PCF's for the standardized moment data. For the normal moment data the first, second, and third PCF's accounted for 71.2%, 20.7 and 6.5% of the variance, respectively. For the standardized moment data the first, second, and third PCF's accounted for 62.1%, 17.9%, and 6.3% of the variance, respectively.

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*Insert Figure 2 about here*

*Correlation Analysis.* The correlation analysis revealed significant correlations between relative lift mass and the scores of four of the extracted PCF's: the second normal kinematic PCF for the hip (HA-PCF2; r = .870, p = 0.011), the first standardized kinetic PCF for the hip (HA-sPCF1; r = .854, p = 0.015), the second normal kinetic PCF for the knee (KM-PCF2; r = .766, p = 0.044), and the second standardized kinetic PCF for the knee (KM-sPCF2; r = .858, p = 0.014).

*Interpretation of PCF's and Correlation Results.* Since the second normal kinematic PCF 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 for the hip captured the magnitude of angular extension between the first pull and second pull. 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).

*Insert Figure 3 about here*

As the second normal kinetic PCF 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 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, as well as an earlier transition from flexion to extension moment at the beginning of the second pull (Figure 4b).

*Insert Figure 4 about here*

## Discussion

The purpose of this study was to identify correlations between weightlifting biomechanics and performance. In order to best characterize the dynamic time-varying nature of weightlifting biomechanics at the joint level a functional principal components analysis 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 1-RM). 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 1-RM 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

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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 hip angle during the first pull may reflect a constant trunk angle if the change in hip angle is driven by an increase in knee angle rather than trunk angle. Furthermore, the second aspect captured by this kinematic pattern (i.e., rapid hip extension during the second pull) also agrees with reports that emphasize powerful triple-extension of the lower extremity during the second pull as an important contributor to success in weightlifting (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 1-RM 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 1-RM. 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 (5), 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 two kinematic patterns, two kinetic patterns were also significantly correlated with relative 1-RM. 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 1-RM. Although 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 sub-maximal 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 the current 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 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 1-RM’s 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 1-RM agrees with reports by Enoka (4) in that the technique of skilled lifters (i.e., those that lifted heavier weights) was not solely characterized by greater magnitudes in joint kinetics, but also by a more appropriate temporal organization of power production and absorption during the weightlifting movement.

While 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 sub-maximal load (i.e., 85% of 1-RM). Technical aspects of competitive weightlifting performance, however, stabilize at loads above 80% of 1-RM (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 non-existent in the weightlifting literature, to quantify muscle activation and/or co-activation. Another limitation and consideration for future studies relates to the use of relative joint angles in kinematic analyses, since 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. Since the kinematic patterns represent noticeable gross motion patterns, coaches could easily observe and monitor them during technical training. While 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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## Figure Legends

**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 grey, ankle = light grey).

**Figure 2.** Ensemble averages of hip, knee, and ankle joint moments (N·m/kg·m) across the duration of the lift for **a)** normal kinetic data, and **b)** standardized kinetic data (hip = black line, knee = dark grey, ankle = light grey).

**Figure 3.** Effects of increasing ('+' symbol) or decreasing ('-' symbol) principal component 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: Since correlations between lift mass and principal component scores were positive, these effects indicate that lifters with greater 1-RM's exhibited kinematic time-series that followed the '+' symbol time-series, whereas lifters with smaller 1-RM's followed the '-' symbol time-series.

**Figure 4.** Effects of increasing ('+' symbol) or decreasing ('-' symbol) principal component scores on **a)** normal knee joint moment (depicts the influence of KM-PCF2 scores) and **b)** standardized knee joint moment (depicts the influence of KM-sPCF2 scores). Note: Since correlations between lift mass and principal component scores were positive, these effects indicate that lifters with greater 1-RM's exhibited kinetic time-series that followed the '+' symbol time-series, whereas lifters with smaller 1-RM's followed the '-' symbol time-series.

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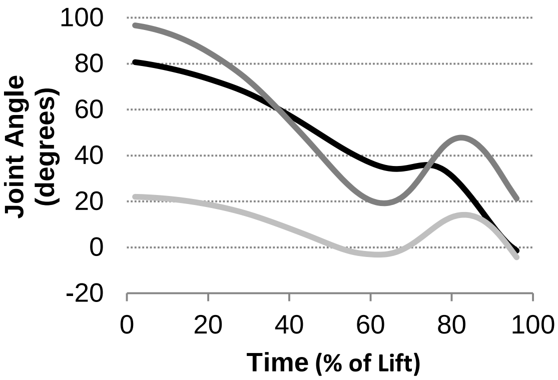

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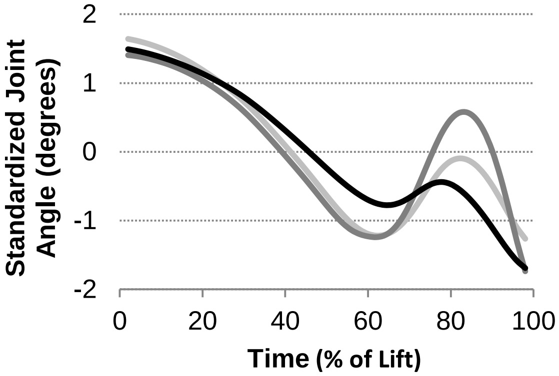

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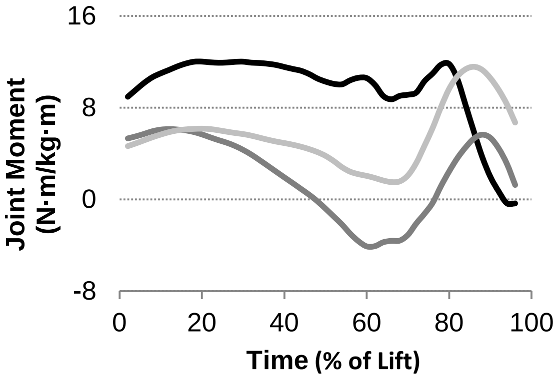

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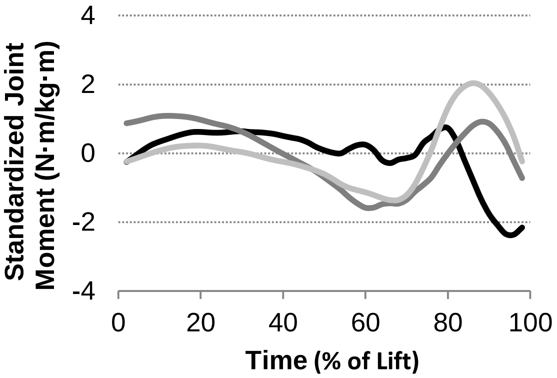

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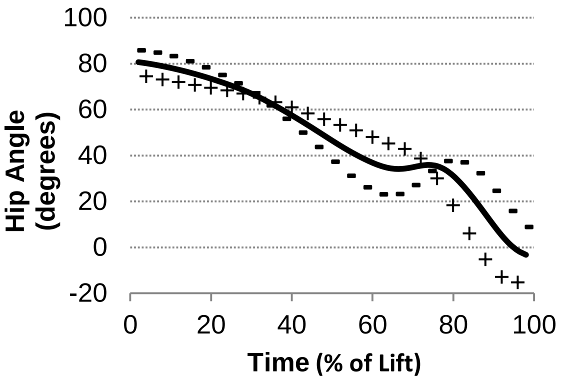

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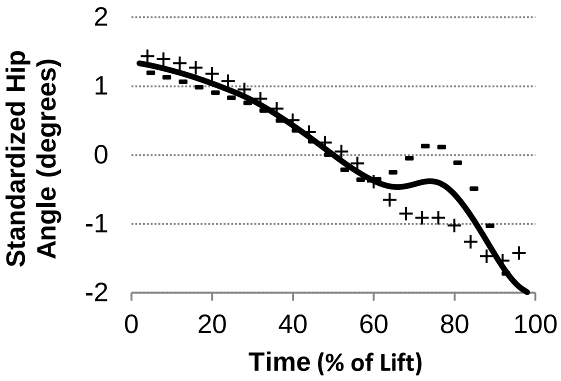

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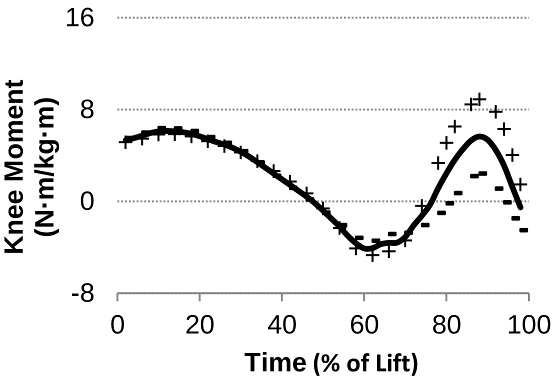

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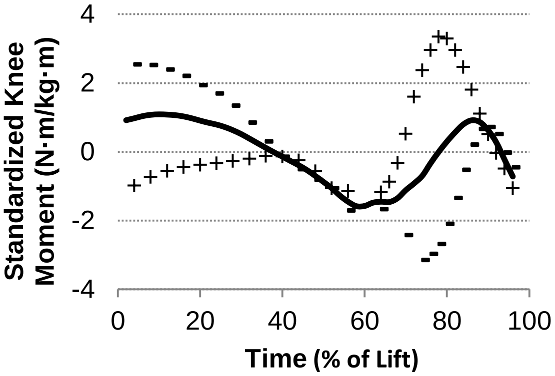

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