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Lower Extremity Biomechanics During Weightlifting Exercise Vary Across Joint and Load

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Abstract:

The purpose of this study was to determine the effect of load on lower extremity biomechanics during the pull-phase of the clean. Kinematic and kinetic data of the three joints of the lower extremity were collected while participants performed multiple sets of cleans at three percentages: 65, 75, and 85% of 1-Reptition maximum (RM). General linear models with repeated measures were used to assess the influence of load on angular velocities, net torques, powers, and rates of torque development at the ankle, knee, and hip joint. The results suggest that the biomechanical demands required from the lower extremities change with the lifted load and to an extent depend on the respective joint. Most notably, the hip and knee extended significantly faster than the ankle independent of load, while the hip and ankle generally produced significantly higher torques than the knee. Torque, rate of torque development, and power at the ankle and knee joint were maximal at 85% and 75% of 1-RM, respectively, whereas torque and rate of torque development at the hip were maximal at loads above 75% and 85% of 1-RM, respectively. This study provides important novel information about the mechanical demands of a weightlifting exercise and should be heeded in the design of resistance training programs.

Key words: clean, power, rate of torque development

Introduction

Adaptations to resistance training programs are stimulus specific (9, 14). Out of the number of program design variables that determine the extent of these adaptations (e.g., sets and repetitions), the most salient factor is the magnitude of the external load (9). Variations in the magnitude of training loads elicit force- and velocity-specific adaptations (15, 18). Load-specific adaptations are perhaps best illustrated in training for maximal muscle power output (15). It is well documented that training at optimal loads – those that maximize power – are most effective in improving maximal muscle power (15, 22). The use of optimal loads during a training session is therefore highly important when specific adaptations, such as increased muscular power or strength, are a primary goal.

Although numerous training modalities are currently used to improve dynamic power or strength performance, resistance training programs that incorporate weightlifting exercises, or derivatives of these exercises, are known to elicit superior adaptations (4, 14, 21). Incorporating weightlifting methods produces greater and broader improvements in jumping and sprinting performance than traditional heavy resistance training exercise (21). Experienced weightlifters also exhibit greater fast-twitch fiber activation and more optimal timing when producing peak force and rate of force development (8). The efficacy of weightlifting exercises are thought to arise from a high degree of specicifity in that they are biomechanically similar to many explosive sports movements (4).

Previous research indicates that changes in the external load used with weightlifting exercises directly affect the biomechanical characteristics of these exercises (5, 16). In general it appears that performance associated biomechanical characteristics are maximized at submaximal loads (5, 16). Commonly analyzed variables are related to the trajectories or external kinetics associated with the barbell itself or the lifter-barbell system (5, 10-12, 16, 17, 23, 24). For example, the magnitudes of ground reaction forces and power associated with the movement of the

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barbell-lifter system differ significantly between low and high loads (16). Further, the velocity of the barbell and its trajectories are also affected by changes in the external load (23). While these variables provide important global information about the mechanics at the location of external constraints (i.e., the bar and ground), they do not provide information about the internal joint kinetics. Since specificity of training is a function of the task-inherent biomechanics, not simply the external movement characteristics (19), knowledge of internal joint kinetics would provide important descriptive information to be used in the program design process.

Lower extremity joint kinetics vary based on the external load (3, 7). Enoka (7) showed that absolute magnitudes of joint power production differ to accommodate changes in external loads. While this study also examined lower extremity joint angular velocities and net joint torques, these variables were not included in the analysis and not reported. It thus remains to be seen how changes in the external load may affect lower extremity kinematics and kinetics. In addition to joint velocities, net torques and power, research also suggests that the ability to rapidly generate torques (i.e. rate of torque development) may be a particularly important variable related to functional performance (1). Collectively, an understanding of how these variables change across loads at each of the lower extremity joints would facilitate the design of specific resistance programs that incorporate weightlifting exercises. However, surprisingly little is known about the load-dependent biomechanics of the lower extremity during weightlifting exercise. Therefore the purpose of this study was to determine the effect of changing external loads on hip, knee, and ankle joint biomechanics during the pull-phase of the clean.

Methods

Experimental Approach to the Problem:

We hypothesized that the external load lifted during the pull portion of the clean exercise significantly influences the biomechanical demands of the lower extremity. The rationale for this investigation was that a more precise understanding of these biomechanical demands at each lower extremity joint will facilitate proper design of resistance programs that incorporate weightlifting exercises. In order to determine the effect of load on lower extremity biomechanics during the pull-phase of the clean we measured kinematic and kinetic data of the hip, knee, and ankle joints while participants performed sets of cleans at 65, 75, and 85% of their respective 1- Reptition Maximum (RM). The chosen biomechanical variables were joint angular velocities, net torques, power, and rate of torque development based on their mechanical relationship to lower extremity performance.

Subjects:

A basic power calculation indicated that in order to detect moderate within-group and between-group differences with statistical power of at least .80 at $\alpha < .05$, a minimum of 10 subjects per group would be required. We thus recruited 10 subjects (9 male and 1 female) to participate in this study. All subjects indicated that they participated in a training program that involved weightlifting exercises. All subjects were deemed technically competent and representative of collegiate-level lifters by a national USA Weightlifting coach. Subject characteristics are presented in Table 1. All subjects signed an informed consent from approved by the University's Institutional Review Board.

Procedures:

Prior to commencement of data collection, all subjects completed a brief warm-up that included lifting light loads up to 50% of their estimated one repetition maximum (1-RM) for the clean exercise. After the warm-up, subjects performed 2-3 repetitions at 65%, 75%, and 85% of 1-RM. Each subject was given 2-3 minutes rest between each set. Kinematic and kinetic data were collected during each of the three sets.

Kinematic and Kinetic Data Analysis:

During data collection session, subjects performed the clean exercise while standing on 2 force platforms that were built into an 8x8 foot weightlifting platform. The force plates were mounted flush with the top of the platform. During the execution of each of the lifts, the positions of reflective markers attached to the subjects' body were recorded with a 6-camera motion capture system (Vicon 612; Vicon Peak, Lake Forest, CA). Kinematic data were collected at 250 Hz and filtered at 6 Hz. Kinetic data were collected at 1,250 Hz from the two force plates (Kistler) and filtered at 25 Hz. In order to establish a neutral anatomical position, a single static calibration trial was

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performed. Kinematic and kinetic data were exported and processed with custom software in MATLAB. Euler angle rotation sequences were used to calculate ankle, knee, and hip joint angles, which were numerically differentiated to obtain the respective joint angular velocities. Kinematic and kinetic data then were combined with published anthropometric data and used to solve for ankle, knee, and hip joint torques with an inverse dynamics approach in 3 planes of motion. Calculated joint torques represent net internal torques and thus reflect the net influence of all anatomical structures crossing a joint. Joint powers were calculated as the products of velocity and torque. Net joint torques were numerically differentiated to calculate rates of torque development. Only positive peak joint kinematic and kinetic variables were extracted for analysis and represent peak angular extension velocity, extensor torque, extensor rate of torque development, and extensor power generation. All peak variables were averaged between right and left leg and submitted to statistical analysis. Although the analysis used 3-D joint segment models and yielded variables in all 3 planes of motion, only sagittal-plane variables were analyzed since the pull-phase of the clean primarily involves muscles in said plane.

Statistical Analyses:

Peak positive kinematic and kinetic variables from three sets of cleans were analyzed: 65, 75, and 85% of 1-RM. Dependent kinematic and kinetic variables chosen for analysis were peak angular velocities, net torques, power, and rate of torque development for the ankle, knee, and hip joint. Separate general linear analysis of variance models were used to test for differences in dependent variables. Each model consisted of a 3 x 3 (load x joint) analysis to test for within-subject differences (load) and for between-subject (joint) differences. Within-subject differences (i.e. across load) were treated as repeated measures. Assumptions of the test statistic were verified with Mauchly's Test of Sphericity. Greenhouse-Geisser (GG) corrections were made when assumptions of sphericity were violated. Partial eta-squared ($\eta 2$) and power values were used to help interpret the magnitude of main and interaction effects. In the absence of a significant interaction effect, data were pooled across load to compare differences between joints. Post hoc analysis consisted of paired and independent t-tests for comparisons among between and within-subject differences, respectively. The standard of proof to show statistical significance for all analyses was set at a level of $\alpha < .05$. All statistical analyses were performed using SPSS version 17.0 (SPSS, Chicago, IL, USA).

Results

The effects of load on lower extremity joint velocities did not depend on the respective load (interaction $p=.11$, $\eta 2=.184$, power=.549; Table 2). However, joint velocities were significantly influenced by joint independently (main effect $p<.05$). Joint velocities were significantly larger for the knee and hip than for the ankle.

[Insert Table 2 about here]

Lower extremity net joint torques depended on combined effects of load and joint (interaction $p=.001$, $\eta 2=.384$, power=.961; Table 2). Specifically, hip joint torque at 65% of 1- RM was significantly smaller than at 75% and 85% of 1-RM. Knee joint torque at 85% of 1-RM was significantly smaller than at 75% of 1-RM. Ankle joint torque at 85% of 1-RM was significantly larger than at 65% and 75% of 1-RM. Further, knee joint torque was significantly lower than hip torque at all loads, but differed from ankle joint torque only at 65% and 85% of 1- RM.

Lower extremity joint powers depended on combined effects of load and joint (interaction $p=.024$ – GG correction, $\eta 2=.311$, power=.848; Table 2). Specifically, knee joint power was significantly higher at 75% of 1-RM than at 65% and 85% of 1-RM. Ankle joint power at 85% of 1-RM was significantly higher than at 65% of 1-RM. Hip joint power did not vary with load. Lower extremity power did not vary across joints.

The effects of load on lower extremity joint rate of torque development (RTD) depended on the respective joint (interaction $p=.014$, $\eta 2=.254$, power=.829; Table 2). Hip joint RTD was significantly smaller at 65% of 1-RM than at 75% and 85% of 1-RM. Knee joint RTD was significantly larger at 75% of 1-RM than at 85% of 1-RM. Ankle joint RTD was significantly smaller at 85% of 1-RM than at 75% of 1-RM. Further, joint RTD did not vary across joints.

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Discussion

The external load lifted during the pull-phase of the clean has a direct influence on biomechanics of the lower extremity. Generally load effects appeared more evident in lower extremity kinetics than kinematics. Although joint angular velocities did not change across the load-spectrum, net joint torque, power, and rate of torque development did vary with the load lifted, but in part depended on the respective joint in question. Joint velocities did, however, vary across joints in that angular velocities were higher at the hip and knee than at the ankle.

Increases in external loads generally resulted in greater task-demands imposed on the lower extremity. Ankle joint torque was significantly greater at 85% of 1-RM than at 65% and 75%, which may underscore the importance of forceful plantar-flexion during the final pull-phase of the clean as the external load increases. Hip joint torque increased from 65% to 75% of 1-RM, but appeared to plateau thereafter. Contrary to our observation that hip joint torque stabilizes once the load exceeds 75% of 1-RM, Baumann et al. (3) observed that hip joint torque during competitive weightlifting attempts increased as barbell load increased. In combination, the load-associated increase in hip and ankle torque from 65% to 75% and 85% of 1-RM compare well with studies that demonstrate higher ground reaction forces in response to elevated loads (16). Knee joint torque, however, decreased when the load was increased from 75% to 85% of 1-RM. Although, mechanically the magnitudes of the ground reaction forces are a direct reflection of the summed total of the body's net joint torques, an increase in external load may thus not always increase the functional torque or strength demands imposed on a joint. Accordingly, it has been suggested that it is not necessarily the magnitude of joint torque produced by the knee extensors during weightlifting movements that is important, but rather the control of the moment arm of the ground reaction force with respect to the knee joint center (3). However, collectively these results indicate that in order to maximize joint torque of the lower extremities and increase the demand imposed on the involved musculature, loads should generally exceed 75% and 85% for the hip and ankle joint, respectively. Maximizing knee joint torque on the other hand may be achieved with loads less than 85% of 1-RM, but may also involve more complex control.

Lower extremity joint torque-time curve characteristics, as assessed through rate of joint torque development, were also influenced by changes in external loads. This finding is contrary to previous research where load has little influence on the rates of ground reaction force development (16). This discrepancy illustrates the importance to consider internal kinetics when evaluating task-inherent biomechanics. Ankle joint rate of torque development was significantly greater at 85% of 1-RM than at 75%, whereas knee joint torque was greater at 75% of 1-RM than at 85%. Hip joint rate of torque development increased linearly and reached a maximal point at 85% of 1-RM. These results generally match those reported for joint torques. Knee joint torque and rate of torque development were both greater at 75% of 1-RM than at 85%. Similarly, both ankle joint torque and rate of torque development were greater at 85% of 1-RM than at 75%, whereas hip joint torque and rate of torque development were greater at 75% of 1-RM than at 65%. Although we did not measure movement time, the total time of the pull-phase of weightlifting movements does not change significantly as load increases (13). Therefore, in order to achieve higher torques with a constant time interval it becomes necessary to increase the rate at which the torque is developed. Consequently, in much the same way that joint torques were maximized at specified loads, the rate at which at these torques were developed followed a similar load-dependent pattern.

In addition to observing load-dependent behavior for joint torque and rate of torque development, the power generated at the ankle and knee joint was also significantly influenced by load. Ankle joint power was higher at 85% of 1-RM than at 65% of 1-RM, while power at the knee joint was maximal at 75%. These results compare well to previous findings that show power output associated with either the barbell or barbell-lifter system is maximized between 70- 80% (5, 16). Since joint power is the product of the joint torque and joint angular velocity it may be a more sensitive variable to examine load-dependent changes in lower extremity biomechanics during the clean. In general it appears that joint velocities are less subject to change as resistance is increased (13). Accordingly, joint angular velocities did not vary across the load ranges used in this study. As joint velocities remained constant, the observed differences in power at the ankle and knee joint may be associated with higher torques. Although we did not extract the joint angular velocity and joint torque at the instant of maximal power, qualitative analyses of the time-histories indicate that maxima for knee and ankle torques, rate of torque development and power all occurred towards the end of the pull-movement (i.e. the second pull). External power outputs, derived from barbell kinematics, are also highest during this phase (10, 11). Load-dependent changes in maximal lower extremity biomechanics may thus result from the interplay among the kinetic variables and display temporal patterns similar to those observed externally.

Apart from the load-dependent changes in lower extremity biomechanics during the pull-phase, some differences were joint-dependent. Most notably, joint angular velocity was smaller at the ankle than at the knee and hip. The hip and knee joint undergo greater joint angular excursions than the ankle during the pull-phase of the clean. A greater range of motion may necessitate greater velocities, especially if the time of the movement remains constant. Joint torques, on the other hand, were generally larger at the hip and ankle than at the knee. The difference between the torque at the knee and the other joints can be interpreted similarly to the load-dependent change in knee joint torque in that the control of the moment arm about the knee joint is a greater determinant of joint torque than the external load. Likewise, hip joint torque during weightlifting movements may largely be determined by the lever arm of the ground reaction forces about the hip joint, because as the torso assumes a more erect position during the latter phase of the pull, hip joint torque progressively declines even though ground reaction forces are highest during this phase. Although the idea that the control of the moment arm in joint function during weightlifting is not new, few studies have examined this in the literature. In light of the important technical implications associated with the control of joint torques during movement, it may be prudent to focus on this biomechanical aspect in future weightlifting research.

While this study provides novel biomechanical insights, the results should be interpreted with caution. First, the subjects in this study were all of similar experience level. An individual's training status can significantly influence load-dependent expression of muscular performance (2, 6, 20). Extrapolating and applying these results to either more or less trained individuals may result in erroneous exercise prescription and should thus be done with caution. Second, the results from this study provide only a cross-sectional perspective of load-associated changes in lower extremity mechanics. Since resistance training or feed-back based programs may influence characteristics associated with the loading spectrum, the need for continuous assessment is warranted (23, 24). These limitations indicate that lower extremity kinetics should be constantly monitored and suggest a need for longitudinal studies. Nonetheless, the results provide an important step to a better understanding of the biomechanical demands of weightlifting exercise and should prove useful in the program design process.

The results of this investigation suggest that the external load significantly affects lower extremity kinetics, while differences in lower extremity kinematics appear to be more joint-dependent. Together the examination of joint torque, rate of torque development, and power indicated that lower extremity kinetics follow a load-dependent pattern. In general the mechanical behavior at a joint was maximized through high rates of torque development which allowed for the generation of high joint torques. In the absence of load-associated changes in joint velocities the increased joint torques served to maximize joint power. This pattern was most apparent at the ankle and knee joint, where joint kinetics were maximized at 75% and 85% of 1- RM, respectively.

Practical Applications

The rationale for this study was that facilitating a better understanding of the biomechanical demands at each lower extremity joints would assist proper design of resistance programs that incorporate weightlifting exercises. For example, selecting and training at external loads that maximize either joint torque/power would be expected to result in superior strength/power performance and adaptation at that joint. Based on these rationales, if the goal of a weightlifting-based resistance training program is to maximize either joint torque, rate of torque development, or power of the ankle plantar-flexors and the knee extensors, loads consisting of 85% and 75% of 1-RM should be chosen. If hip joint torque and rate of torque development are program goals, loads above 75% and 85% of 1-RM should be targeted, respectively. Further, it is suggested that resistance training programs allow for sequential progression in order to maximize joint and load-dependent training adaptations. Training status and adaptations, however, should be closely considered and monitored when applying the findings of this study.

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Table 1. Subject characteristics

Variable	Mean±SD
Height (m)	1.84±0.09
Weight (kg)	97.3±18.0
1-RM (kg)	120.5±24.3

Table 2. Mean±SD lower extremity joint angular velocities (degrees/second), net torques (N·m) powers (W) rates of torque development (RTD) (N·m/s) for the hip, knee, and ankle joint at loads of 65, 75, and 85 percent of one-repetition maximum.

		Variables			
Joint	Load	Angular Velocity	Torque	Power	RTD
Hip	65	302.1±67.1*	248.4±73.5†	846.1±337.4	2248.0±1196.4
	75	286.0±65.1*	272.0±70.0†‡	896.5±339.7	2788.6±1175.4‡
	85	268.5±47.7*	266.3±66.8†‡	876.3±246.9	3316.4±1085.0‡
Knee	65	334.26±70.9*	154.7±42.5	765.2±337.0	3247.4±1687.2
	75	339.7±80.9*	175.0±67.2	854.3±421.1‡	3521.7±2123.0
	85	347.2±82.3*	148.0±54.2§	700.1±411.5§	2050.8±980.8§
Ankle	65	153.1±31.5	197.2±59.2†	648.4±327.8	2576.3±1714.7
	75	155.4±27.8	196.8±62.2	696.1±306.7	2050.8±980.8
	85	165.0±28.0	241.0±63.4†§‡	843.1±349.8‡	2697.5±1263.5§

Joint-effects: * p<.05 vs. Ankle, † p<.05 vs. Knee

Load-effects: ‡ p<.05 vs. 65, § p<.05 vs. 75