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Correlations Between Internal and External Power Outputs During Weightlifting Exercise

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Abstract:

Identifying loads that maximize mechanical power is important because training at such loads may optimize gains in dynamic athletic performance. The purpose of this study was to examine correlations between measures of external mechanical power output and internal mechanical joint power output across different loads during a weightlifting exercise. Ten subjects performed three sets of the clean exercise at 65, 75, and 85% of 1-RM. Peak external mechanical power output was calculated with four commonly used methods, whereas an inverse dynamics approach was used to calculate peak internal mechanical power output for the hip, knee, and ankle joints along with the peak of the sum of all internal joint powers. All peak mechanical power outputs were expressed as relative peak power by either ratio (W/kg) or allometrically scaling to body-mass (W/kg$^{0.67}$). Correlation coefficients were used to compare power output measures. The greatest numbers of significant correlations between internal and external power outputs were observed at 85% of 1-RM, at this load hip and knee joint power outputs where correlated to external mechanical power output when calculated with the traditional work-energy method. In addition, the peak sum of all mechanical joint powers was correlated to mechanical power output when calculated with the impulse-momentum method at loads of 75% and 85% of 1-RM. Allometric scaling of power outputs yielded one more significant correlations than ratio scaled power outputs. These findings support the use of the work-energy method when making inferences about internal joint powers from external power outputs when loads equal to 85% of 1-RM are being lifted. In addition, the impulse-momentum method may be used to make inferences about the sum of all internal joint powers from external power outputs when loads between 75% and 85% of 1-RM are being lifted.

KEYWORDS: biomechanics, clean, barbell, velocity, ground reaction force

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INTRODUCTION

Resistance training programs that incorporate weightlifting exercises, or derivatives of these exercises, lead to a greater improvement in dynamic athletic performance than other training modalities (16). To maximize these adaptations it is generally purported that lifting loads that optimize mechanical power output is most effective in improving dynamic athletic performance (17). With respect to the program design process, it is therefore extremely important to know the loads at which mechanical power is maximized when an improvement in dynamic athletic performance is the primary goal of such a training program.

Several investigations have studied mechanical power output during weightlifting exercise (2, 7, 10, 11, 13). Most of these investigations focus primarily on the effects of manipulating load and the subsequent effects on maximal external mechanical power output, which is derived from either barbell kinematic data, ground reaction force data, or a combination of both (2, 10, 11). External mechanical power output therefore provides information on how much power is being produced at the level of either the barbell or the lifter-barbell system. These studies show that the production of peak mechanical power output is maximized at sub-maximal loads (2, 10, 11). While, these data provide important information about power production at the level of the barbell or lifter-barbell system, they do not however provide insight about power production of the individual joints used during weightlifting exercise.

Due to the specificity principle of resistance training, knowledge of mechanical power production at the joint level would provide important information for resistance program design. Few investigations, however, have studied the mechanical power output of individual joints (4, 13). These investigations provide evidence for load-dependent changes in joint mechanical power output. Specifically, it appears that similar to data from studies that have investigated external mechanical power output, internal mechanical power output is also maximized at sub-maximal loads (4, 13). Unfortunately, the equipment needed to acquire the data necessary to calculate internal joint powers (i.e., force plate and motion capture system) is expensive and the processing and reduction of such data, once obtained, is cumbersome and labor-intensive. From a pragmatic standpoint, it would be much easier if researchers or coaches could simply use easily acquired external mechanical power outputs to make inferences about joint mechanical power outputs. To this end, it is necessary to determine whether external and internal (i.e., joint) mechanical power output are correlated. The purpose of this study was therefore to examine correlations between common measures of external mechanical power output and internal mechanical joint power output across a range of sub-maximal loads during a commonly used weightlifting exercise, the clean.

METHODS

Experimental Approach to the Problem

To examine correlations between external and internal power outputs during a weightlifting exercise over a range of submaximal loads, subjects performed three sets of the clean at 65, 75, and 85% of their 1-Repetition maximum (RM). External and internal power values were then calculated and scaled to lifter's body mass with two different methods. The external power values were calculated with four commonly used methods. Internal power outputs for the three major lower extremity joints along with the peak sum of joint powers were calculated with a traditional biomechanical method. Correlations between external power outputs from the four calculation methods and internal power output measures were then investigated to determine the best method for estimating internal joint power outputs from external power outputs.

Subjects

Nine male subjects were recruited to participate in this study (mean±SD height: 1.85±0.09 m; mass: 106.0±13.2 kg). All subjects participated in resistance training programs that involved weightlifting exercises. In addition, a national USA Weightlifting coach deemed the technical level of all subjects to be representative of US collegiate weightlifters (Absolute 1-RM clean: 126.4±22.9 kg; Relative 1-RM clean: 1.19±0.11 kg/kg). All subjects were tested in an 'off'-week during a pre-season training phase. The study was approved by the University's Institutional Review Board and all subjects provided written informed consent before the beginning of any data collection.

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Data Collection

Subjects were allowed to engage in a brief warm-up routine, which included light calisthenics and several sets of sub-maximal (≤50% of 1-RM) clean lifts. After the warm-up, subjects performed a standardized work-out for the clean exercise that consisted of 2-3 repetitions at 65%, 75%, and 85% of 1-RM with 2-3 minutes of rest between each set. The 1-RM was self-reported and was based on the most recent testing session in the last training cycle. Subjects were instructed to perform the clean as they would in weightlifting competition. Kinematic and kinetic data were acquired during all sets. Kinematic data were recorded with 6-camera infra-red motion capture system (VICON 460, ViconMX, Los Angeles, CA, USA). Three-dimensional position data were recorded from reflective markers that were attached to bony landmarks of the participants (14). In addition to the markers attached to each subject, one reflective marker was also attached to each end of the barbell, and a single strip of reflective tape was attached longitudinally around the center of the barbell. Kinematic data were collected at 250 Hz. Kinetic data were recorded at 1250 Hz from two force plates (Kistler model 9281A, Kistler Instrument Corp, Amherst, NY, USA) that were built into an 8'x8' weightlifting platform. Before each of lift, subjects were asked to make sure that each foot was on a single force plate.

Calculation of internal mechanical joint power. A fourth-order low-pass Butterworth filter was used to filter all kinematic data at 6 Hz and all kinetic data at 25 Hz. The filtered kinematic data were used to calculate joint angles based on Euler angle rotation sequences (20). Joint angle data were then numerically differentiated with the central difference method to calculate instantaneous joint angular velocities. While kinetic data were initially collected at 1,250 Hz, they were subsequently down-sampled to 250 Hz to mesh with kinematic data. Kinematic and kinetic data were then combined with anthropometric measurements in a standard inverse dynamics approach to calculate net internal joint moments (20). Each joint moment was then multiplied with the instantaneous joint velocity to calculate internal mechanical power for the hip, knee, and ankle joint. All three joint powers were also added to calculate the summed total of joint power output (5). Custom-written MATLAB programs (MatLab, The Mathworks, Inc, Natick, MA, USA) were used for all calculations.

Calculation of external mechanical power. To calculate measures of external mechanical power, several additional processing steps were taken. The ground reaction force vectors from each of the force plates were algebraically summed into a single ground reaction force vector. Instantaneous vertical barbell velocities and accelerations were calculated from markers attached to the barbell; barbell velocity was calculated from the position data and the barbell acceleration was calculated from the barbell velocity data. In both cases, the central difference method was used. In turn, numerical integration with the trapezoidal rule was used to calculate barbell-lifter system velocity and position from the vertical ground reaction force data after dividing by the total mass of the barbell-lifter system.

Kinematic and kinetic data in the vertical direction were used to calculate mechanical power output based on four commonly used methods (6, 10, 11, 18). The first (BAR) and second (V&A) methods used solely on kinematic data, the third (GRF) used solely kinetic data, and the fourth (COM) used a combination of kinetic and kinematic data. The first method (BAR) used a work-energy approach to calculate external mechanical power output (6, 7). This method sums the total amount of potential and kinetic energy up to the point of maximum vertical barbell velocity and divides this sum by the time taken to reach this point. The second method (V&A) calculates mechanical power as the instantaneous product between the net force applied to the barbell (i.e., barbell mass x vertical barbell acceleration) and vertical barbell velocity (10). As mentioned above, the third method used a slightly different approach in that it relies solely on kinetic data and impulse-momentum equations to calculate power output (10, 11). Specifically, this method calculates mechanical power as the product between the vertical velocity of the barbell-lifter system and the vertical component of the ground reaction force vector. Lastly, the fourth mechanical power calculation method used a combination of kinematic and kinetic data in that it calculated mechanical power as the product between vertical barbell velocity and the vertical component of the ground reaction force vector (18, 19).

Mechanical power output was calculated from each method for each rep and set from each individual. The peak calculated mechanical power output for each measure was identified and used for subsequent analysis. Two methods were further used to calculate relative power: 1) each power output value was divided by the subject's body mass (ratio scaled: W/kg), and 2) each power output value was divided by the subject's body mass after being raised by to an exponential power (allometrically scaled: W/kg$^{0.67}$). Pilot testing showed that kinematic (i.e., peak vertical barbell velocity) and kinetic (i.e., peak vertical ground reaction force) variables had high reliability (inter-class correlation coefficients > .90).

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Statistical Analysis

Descriptive data are reported as Mean±SD. Simple linear regression analyses were used to test for correlations between power output measures. The criterion for statistical significance was set at an alpha-level of 0.05. All statistical analyses were performed in SPSS 19.0 (IBM Corporation, Somers, NY, USA).

RESULTS

Descriptive statistics for ratio and allometrically scaled relative peak internal and external power outputs at each load are presented in Table 1 and 2. Ratio scaled internal and external power outputs time-series data for one lift at 85% of 1RM are presented in Figure 1 and 2. Allometrically scaled power outputs are not shown, as they followed a similar pattern.

Insert Table 1 about here

Insert Table 2 about here

Insert Figure 1 about here

Insert Figure 2 about here

There were several significant correlations between the ratio scaled external and internal power outputs. At 65% of 1-RM, only one significant correlation was found (GRF and ANKLE: r = 0.820, p = .024). At 75% of 1-RM there were two significant correlations (GRF and HIP: r = 0.841, p = .036; GRF and SUM: r = 0.851, p = .015). At 85% of 1-RM, there were three significant correlations (BAR and HIP: r = 0.816, p = .048; BAR and KNEE: r = 0.787, p = .036; GRF and SUM: r = 0.807, p = .028).

There were several significant correlations between the allometrically scaled external and internal power outputs. In general, all ratio scaled correlations were still significant when data where allometrically scaled. Specifically, at 65% of 1-RM, only one significant correlation was found (GRF and ANKLE: r = 0.841, p = .018). At 75% of 1-RM there were two significant correlations (GRF and HIP: r = 0.875, p = .023; GRF and SUM: r = 0.880, p = .009). At 85% of 1-RM, there were three significant correlations (BAR and HIP: r = 0.865, p = .026; BAR and KNEE: r = 0.822, p = .023; GRF and SUM: r = 0.832, p = .020). The allometrically scaled power output data, however, yielded one additional significant correlations. At 75% of 1-RM, COM and KNEE were significantly correlated (r = 0.763, p = .046).

DISCUSSION

The purpose of this study was to examine correlations between common measures of external mechanical power output and internal mechanical joint power output across a range of sub-maximal loads during the clean. At 85% of 1-RM, hip and knee joint power outputs where correlated to external mechanical power output when calculated with the traditional work-energy method (6, 7). In addition, the peak sum of all mechanical joint powers was correlated to mechanical power output at 75% and 85% of 1-RM when the impulse-momentum method was used (10, 11).

At 85% of 1RM, internal joint powers at the hip and knee were significantly correlated with external peak power output calculated with the traditional work-energy method (6, 7). This method has been used extensively in the evaluation of weightlifting performance (i.e., power imparted to the barbell), but has not been used much outside this area. Nonetheless, the correlation between this method and the knee and ankle joint power at 85% of 1RM indicates that knee and ankle joint power output is partially related to barbell mechanical power output at high loads. The results from the current study therefore support the use of this method as a predictor of individual joint powers at sufficiently high sub-maximal loads. The lack of any significant correlations between individual internal joint powers and external mechanical power outputs at 75% of 1RM may point to a possible threshold effect in that loads of at least 85% of 1RM are needed before internal and external mechanical power outputs reach agreement. This agrees, in part, with the general tenet that competitive lifting technique and biomechanical parameters stabilize at loads in excess of 80% of 1RM (15). In contrast to the other methods of external power calculation, the work-energy method only calculates mechanical power applied to the barbell and thus captures only the ability to perform work or impart power

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to an external object. The power output calculated from this method therefore excludes power produced by the lifter-barbell system or the lifter alone. For the same reason, however, this method may be especially suitable to evaluate mechanical power during weightlifting exercise in populations that have to manipulate external objects, such as throwers, American football linemen, and obviously weightlifters.

The analysis also identified significant correlations between the peak sum of internal joint powers and peak external power output calculated with the impulse-momentum method. This method has been frequently used in the literature to study load-power relations across a variety of tasks (10-12). Since this method uses ground reaction force and velocity data of the lifter-barbell system as calculation input, the mechanical power output calculated from this method reflects the mechanics of the entire system. Similarly, the peak sum of internal joint powers reflects the total power generated by the three major lower extremity joints (5). The correlation between these internal and external power outputs may therefore not be surprising since they capture power production of the entire lower extremity and the entire lifter-barbell system. Interestingly the correlations between these power output measures were significant at 75% and 85% of 1-RM, which would indicate that these correlations are robust over a greater range of loads.

Apart from discussing the strengths and significance of the correlations between measures of mechanical power output, it is perhaps prudent to briefly consider the technical pitfalls associated with some of the methods. Previous research advocates that a combination of kinetic and kinematic data should be utilized to obtain the most valid estimate of mechanical power during dynamic movements (1, 10). For external measures of mechanical power output, only one method in the current study used both kinematic and kinetic data (i.e., input data included barbell velocity and ground reaction force). The joint power output data, however, also uses kinematic and kinetic data input, but at the joint level. The general concern is that excessive data manipulation (e.g., multiple differentiation) may proliferate signal noise, which may adversely affect results (20). As for external power calculation methods, double differentiation is used in the V&A method. In contrast, the work-energy method uses only kinematic data and relies on a single differentiation to obtain barbell velocity. It should be pointed out, however, that the inverse dynamics approach used to calculate internal joint powers also involves calculation of segmental accelerations through double differentiation. It could be argued though that the greater number of positional input data points (i.e., four markers used to calculate the position of the shank or thigh) used to calculate joint kinematics compared to the smaller number of positional input data points for the calculation of barbell mechanics (i.e., a single marker) renders the joint kinematic output data as a more robust data set that may attenuate deleterious effects of excessive processing.

The results from this study provide novel information about mechanical power output during weightlifting exercise. A brief qualitative visual inspection of the graphs that depict relative power output, however, suggests that there may also be temporal differences between the timing of peak internal and external power outputs. For example, most external power output measures along with knee and ankle internal joint powers peak towards the end of the clean, during the powerful second pull and triple extension that has been observed during weightlifting exercise (3, 8, 9, 13). Conversely, internal hip joint powers appear to peak much earlier during the clean. Examining the timing and temporal structure of internal and external power outputs may thus provide additional and perhaps more relevant information. The use of time-series analyses, such as cross-correlation, may be particularly helpful in this endeavor. Such studies may provide information that can be used to better guide exercise prescription guidelines when the development of maximal power output is a major training goal.

PRACTICAL APPLICATIONS

The results from this study provided novel information about the correlations between different measures of external mechanical power output and internal mechanical joint power output across a range of sub-maximal loads during a weightlifting exercise. The results support the use of the traditional work-energy method to make inferences about internal joint powers during the clean. These inferences, however, should be limited to the hip and knee joint and restricted to sufficiently high loads (~85% of 1-RM) at which lifting technique stabilizes. In addition, the impulse-momentum method may be used to make inferences about the total sum of all mechanical joint power outputs at 75% and 85% of 1-RM.

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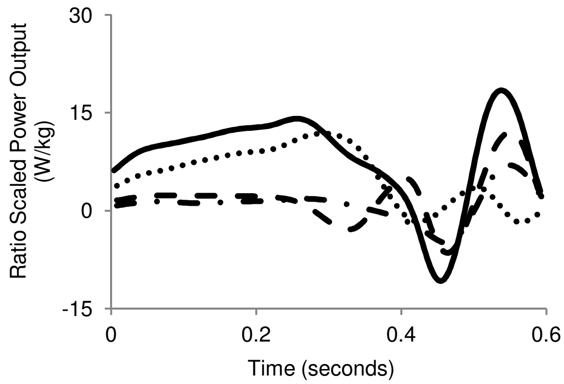
FIGURE LEGEND

FIGURE 1: Internal ratio scaled power outputs (W/kg) time-series data for one representative individual lift at 85% of 1RM (Hip joint power = dotted line, knee joint power = dashed line, ankle joint power = dash-dot line, summed joint power = solid line).

FIGURE 2: External ratio scaled power outputs (W/kg) time-series data for one representative individual lift at 85% of 1RM (BAR power = solid line, V&A power = dotted line, GRF power = dash line, COM power = dash-dot line).


30
15
0
-15
Ratio Scaled Power Output (W/kg)
0
0.2
0.4
0.6
Time (seconds)

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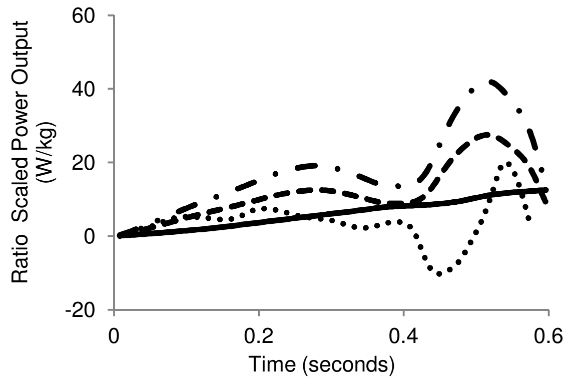

TABLE 1: Mean±SD peak external power output values for the four different calculation methods (BAR, V&A, GRF, COM) at 65%, 75%, and 85% of 1-RM when ratio scaled (W/kg) and allometrically scaled (W/kg$^{0.67}$).

	Peak External Power Output							
	Ratio scaled				Allometrically scaled			
Load	BAR	V&A	GRF	COM	BAR	V&A	GRF	COM
65	13.8±7.2	13.2±7.2	32.3±11.4	53.0±13.8	49.8±11.3	64.6±11.3	157.0±58.1	249.1±65.4
75	14.3±4.2	15.4±9.0	33.7±13.5	53.8±11.0	65.5±21.8	70.1±21.8	167.9±66.4	256.6±58.9
85	14.9±4.2	17.0±13.7	30.1±12.2	52.8±10.1	64.2±18.8	66.8±31.2	152.0±53.9	254.9±49.9

TABLE 2: Mean±SD peak internal power output values for the three lower extremity joints and the summed power (HIP, KNEE, ANKLE, SUM) at 65%, 75%, and 85% of 1-RM when ratio scaled (W/kg) and allometrically scaled (W/kg$^{0.67}$).

	Peak Internal Power Output							
	Ratio scaled				Allometrically scaled			
Load	HIP	KNEE	ANKLE	SUM	HIP	KNEE	ANKLE	SUM
65	7.9±2.7	7.0±2.9	6.0±2.5	16.4±4.4	37.0±13.1	33.0±14.3	28.0±12.6	168.6±42.2
75	8.8±3.4	7.9±3.3	6.4±2.3	15.8±5.3	37.0±12.9	36.8±16.4	30.1±11.4	162.0±50.9
85	8.5±1.8	6.4±3.3	7.8±2.7	18.4±5.2	38.9±9.6	30.1±16.3	36.4±13.4	189.2±52.7