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Energy flow during Olympic weight lifting

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ABSTRACT

GARHAMMER, JOHN. Energy flow during Olympic weight lifting. *Med. Sci. Sports Exercise*, Vol. 14, No. 5, pp. 353-360, 1982. Data obtained from 16-mm film of world caliber Olympic weight lifters performing at major competitions were analyzed to study energy changes during body segment and barbell movements, energy transfer to the barbell, and energy transfer between segments during the lifting movements contested. Determination of barbell and body segment kinematics and use of rigid-link modeling and energy flow techniques permitted the calculation of segment energy content and energy transfer between segments. Energy generation within and transfer to and from segments were determined at 0.04-s intervals by comparing mechanical energy changes of a segment with energy transfer at the joints, calculated from the scalar product of net joint force with absolute joint velocity, and the product of net joint torque due to muscular activity with absolute segment angular velocity. The results provided a detailed understanding of the magnitude and temporal input of energy from dominant muscle groups during a lift. This information also provided a means of quantifying lifting technique. Comparison of segment energy changes determined by the two methods were satisfactory but could likely be improved by employing more sophisticated data smoothing methods. The procedures used in this study could easily be applied to weight training and rehabilitative exercises to help determine their efficacy in producing desired results or to ergonomic situations where a more detailed understanding of the demands made on the body during lifting tasks would be useful.

WEIGHT LIFTING, ENERGY FLOW, POWER OUTPUT, RIGID-LINK MODELING, BIOMECHANICS

During weight lifting energy must be generated by muscle contraction and transferred through the skeletal lever system to the barbell being lifted. This energy transfer can occur by forces acting through the joints themselves or via muscular torques generated around the joints. The purpose of this study was to utilize rigid-link modeling and energy flow techniques to analyze energy changes in body segment and barbell movements, energy transfer to the barbell, and energy transfer between body segments by each of the above mechanisms during execution of the competitive lifts. Analyses of this type were presented by Quanbury, Winter, and associates for gait using two- or three-segment link systems (7,8,9). The present analyses utilized a five-segment link system to provide information as to which dominant muscle groups make major energy contributions at any time during the lift.

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METHODS

Six snatch lifts (see Figure 1 of reference 5) and two clean lifts (see Figure 2 of reference 5) were analyzed from 16-mm films taken from a side view at 50 fps with a Photosonic, model 1P, camera at the 1975 U.S. Senior National Weightlifting Championships and 1978 World Weightlifting Championships. Subjects ranged from the 67.5-kg division to the 100-kg division (Table 1). Additional information relative to filming and digitizing procedures was published elsewhere (3,4).

Due to mid-sagittal symmetry, one side of each athlete was represented by a five-segment rigid-link model (3). The segments simulated the arm and hand (with the barbell in the hand), one side of the torso and head, thigh, shank, and foot, and were assumed to connect via frictionless hinge joints. The weight, center of mass, and moment of inertia of each segment were determined from the lifter's body weight and the anthropometric data as used by Dempster (1). Segment lengths were determined from the film of each lift analyzed, as were segment orientations, their center-of-mass positions, and bar positions. Smoothing and differentiation of linear and angular position data were accomplished by using a five-point moving arc technique (11).

The net forces and torques acting at each joint during a lift were determined by Newtonian rigid-body dynamics. Horizontal (H) and vertical (V) forces acting on the bar at the distal end of segment 1 (hand) were determined from the equations:

$$H = (Wb/g)\ Ax \qquad [1]$$

$$V = Wb + (Wb/g)\ Ay \qquad [2],$$

TABLE 1. Subjects and lifts analyzed by energy flow methods.

Subject	Body weight division (kg)	Meet	Lift	Barbell weight (N)
1	82.5	US75	Snatch	1396.5
2	75.0	US75	Snatch	1274.0
3	100.0	WC78	Snatch	1666.0
4	90.0	WC78	Snatch	1666.0
5	67.5	WC78	Snatch	1323.0
6	67.5	WC78	Clean	1764.0
7	75.0	WC78	Snatch	1519.0
8	75.0	WC78	Clean	1886.5

US75 = 1975 U.S. National Championship
WC78 = 1978 World Championship

where Wb is the barbell weight, g is the acceleration of gravity, Ax is the horizontal, and Ay the vertical acceleration of the barbell. The values of H and V calculated from equations 1 and 2 were equal and opposite to the forces applied to the distal end of segment 1 and could be used to calculate the net horizontal (Rx) and vertical (Ry) force acting at the proximal end (shoulder) from the equations:

$$Rx = H + M1\ (A1x) \quad [3]$$

$$Ry = V + M1\ (g) + M1\ (A1y) \quad [4],$$

where M1 is the mass of segment 1, A1x the horizontal and A1y the vertical acceleration of its center of mass. These net force components included contact forces at the joint and the net muscle force applied at the joint. All forces acting on the segment could contribute to a turning effect. Summing torques about the center of mass of the segment resulted in an equation for the net torque generated about the proximal end (shoulder) due to muscle action:

$$T12 = I1\ (\alpha 1) + H\ (r1) \sin(\theta 1) - V\ (r1) \cos(\theta 1) + Rx\ (L1 - r1) \sin(\theta 1) - Ry\ (L1 - r1) \cos(\theta 1) \quad [5].$$

where I1 is the moment of inertia of segment 1, $\alpha 1$ its absolute angular acceleration, $\theta 1$ its orientation with respect to the right horizontal, L1 its length, and r1 locates the segment center of gravity.

The calculation procedure then continued sequentially through the remaining four links utilizing equations identical in form to equations 3 and 4. Equation 5 differs slightly for the second through fifth segment due to the addition of a torque term on the right side of the equation, which exists at the initial end of these segments. No such term appeared in equation 5 due to the modeling assumptions for hand-to-bar contact. Validation of this model was accomplished by filming identical lifting movements, performed by experienced lifters, in the laboratory on a Kistler force platform. The vertical force calculated for the distal end of segment five (foot) was found to be in agreement with the vertical force measured directly with the force plate although the magnitude was attenuated somewhat during periods of high acceleration (3).

Gravitational potential, linear kinetic, and rotational kinetic energy were calculated for each segment during the lifts at 0.04-s intervals from just prior to barbell "lift-off" until just after maximum bar velocity was achieved at the "top pull" position (see Figures 1d and 2d of reference 5). Calculation procedures of this type were previously described in detail by Quanbury et al. (7). Energy generation within and transfer to and from segments were determined by comparing measured segment mechanical energy changes with energy transfer at the joints calculated from the scalar product of net joint force with absolute joint velocity at 0.04-s intervals, at the shoulder for example,

$$\Delta E(\text{force}) = (\ Rx\ (Vx) + Ry\ (Vy)\ )\ 0.04 \quad [6]$$

and the product of net joint torque due to muscular activity with absolute segment angular velocity, at the shoulder for example,

$$\Delta E(\text{torque}) = T12\ (\omega 1)\ 0.04 \quad [7],$$

where Vx is the horizontal and Vy the vertical component of shoulder velocity, and $\omega 1$ is the absolute angular velocity of segment one (hand and arm). In general, a segment had energy exchange at each end due to both joint force and muscle torque action. The theory behind these computations was presented in detail for gait analyses by Quanbury et al. (7).

RESULTS AND DISCUSSION

Magnitude of segment energy changes

Calculation of body segment potential, linear, and rotational kinetic energies showed that potential energy increases during a lift were generally 4-6 times as great as the maximal level of linear kinetic energy for a given segment. Typical potential energy increases were 20–30 J for the arm, 80–150 J for the head and torso (one side), 10–25 J for the thigh, 2–4 J for the shank, and 0.1–0.3 J for the foot. Maximal linear kinetic energy values averaged about 5 J for the arm, 20 J for the head and torso, 4 J for the thigh, 0.7 J for the shank, and less than 0.1 J for the foot. Maximal rotational kinetic energies were 3–13 J for the head and torso. The only other segment to reach rotational values greater than 1 J was the arm, with average levels being less than 2 J. Potential energy increases of the barbell (one side) ranged from 500–630 J, while kinetic energy increases ranged from 80–170 J. The time course of total energy increase for the barbell (one side), head and torso (one side), thigh, and shank is shown for two snatch lifts in Figures 1 and 2.

The two clean lifts analyzed were made by athletes whose snatch lifts were also studied. The differences found between the snatch and clean lifts for a given lifter were small and attributable to the slower and less extensive movement during a clean lift (i.e., smaller values for potential, linear, and rotational kinetic energy of each segment during the clean lift). However, the barbell energies showed interesting differences. For both athletes the barbell's potential energy increased less during the snatch lift than clean lift, but its kinetic energy increased more for the snatch lift than for the clean lift. The total barbell energy for each subject was 3% lower in the snatch lift relative to the clean lift value. The higher body segment potential energies at the end of snatch pull, when kinetic energies are negligible, were almost exactly enough to balance the total barbell and body energy increase for the two lifts. Thus, the work done by either lifter during each lift was the same. It should be pointed out that the two subjects discussed above were world champions in their respective divisions at the 1978 World Weightlifting Championships, and both displayed excellent technique at that competition.

Segment energy changes related to lifting technique

Body segment and barbell energy changes also provided

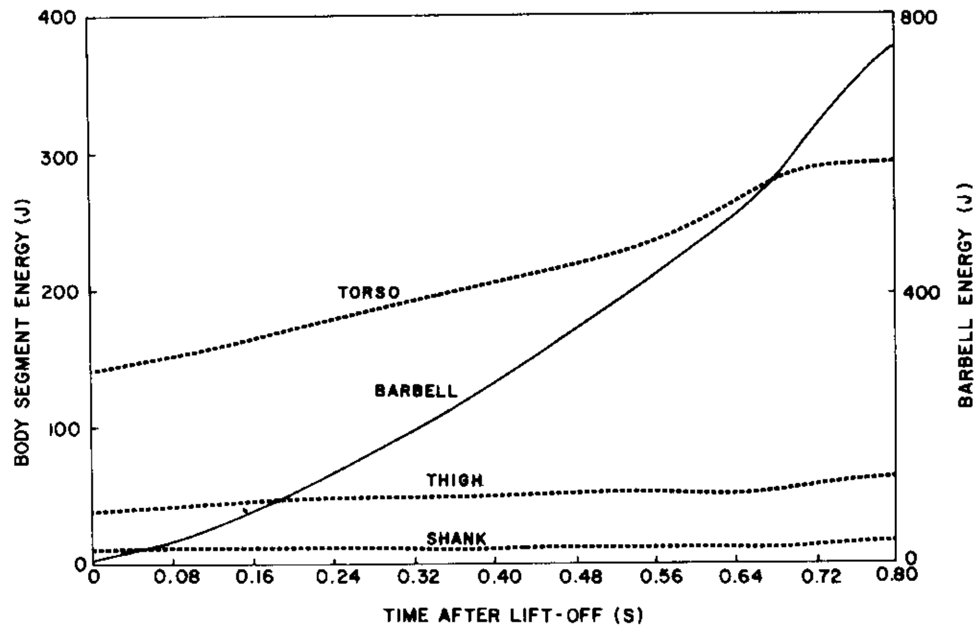

Figure 1—Total energy of the barbell and selected body segments for the snatch lift of subject 1.

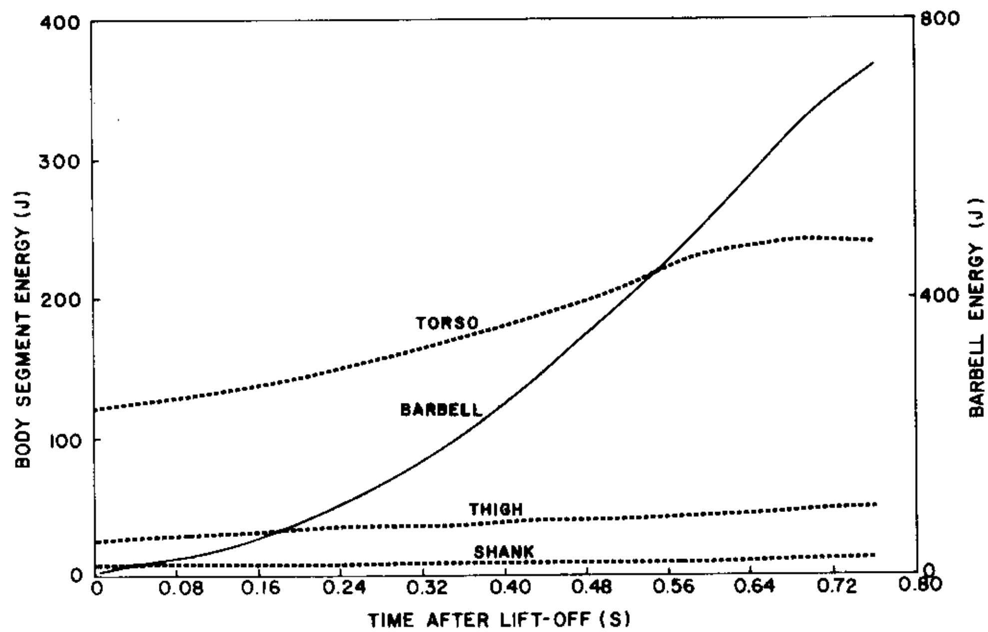

Figure 2—Total energy of the barbell and selected body segments for the snatch lift of subject 2.

insights relative to the lifting technique used. The double-knee bend (DKB) technique was previously discussed and illustrated (2,5). All but one of the lifts analyzed were classified as having been performed by this method. The "non-conforming" lift was performed with a "frog leg" style where hip extension was of primary importance (see reference 3 for a more complete discussion of both techniques). One consistent finding for lifters using the DKB was that thigh and shank energy decreased slightly after the bar passed knee height and subsequently increased to maximum about the time that bar velocity reached maximum. The decrease in thigh and shank energy occurred about 0.6 s into the lift (Figure 1; the graph scale makes this decrease seem small, but the absolute percent decrease was distinct). The rebending of the knees and downward and forward movement of the hips after the bar passed knee level and prior to the start of the "second pull," when using the DKB technique, was responsible for the decrease (see Figures 1 b-c and 2 b-c of reference 5). A steady increase in thigh and shank energies occurred with the "frog leg" technique (Figure 2).

Torso (trunk and head) linear and rotational kinetic energy changes during a lift also characterized different lifting techniques. Details of the torso kinetic energy changes for the same athlete whose segment energy values were given in Figure 1 are shown in Figure 3. Linear kinetic energy increased for the first 0.3 s, decreased for about 0.2 s, and then sharply increased until 0.06 s prior

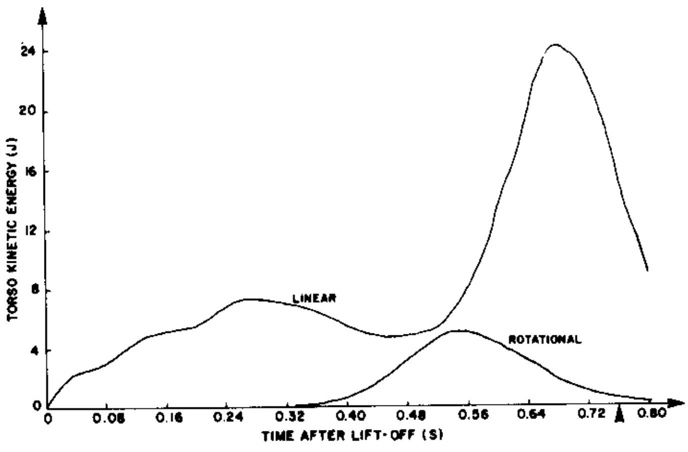

Figure 3—Torso kinetic energy components during the snatch lift of subject 1. (Arrowhead on the time scale indicates the point of maximum vertical bar velocity.)

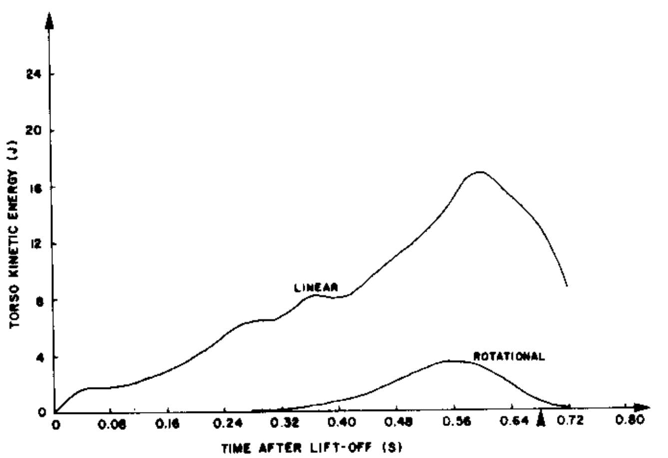

Figure 4—Torso kinetic energy components during the snatch lift of subject 2. (Arrowhead on the time scale indicates the point of maximum vertical bar velocity.)

to maximum vertical bar velocity (marked by an arrowhead on the time scale). During the "drop-off" period the rotational energy began to increase and then decreased as linear kinetic energy began its sharp rise. These observations can be explained in relation to the DKB. As the knees began to rebend and the hips moved downward and forward, the torso's vertical velocity was reduced. During this same period the torso began to rotate toward a more vertical orientation, resulting in increased rotational energy. As the torso approached a vertical position, its rotation slowed and the lifter began his "jump" with the weight (see Figure 1c of reference 5), which resulted in a sharp linear kinetic energy increase of the torso due to increased vertical velocity. The torso's potential energy increased almost linearly during the lift. Due to its much greater magnitude, relative to the kinetic energies, the general trend of total torso energy was also linear. However, as can be seen in Figure 1, the sharp increase in torso linear kinetic energy prior to maximum vertical bar velocity caused a noticeable increase in the slope of the total torso energy curve during the same period (0.60–0.68 s into the lift). The other six subjects using the DKB showed very similar torso energy curves.

The athlete using the "frog leg" style showed distinctly different torso kinetic energy curves (Figure 4). His linear kinetic energy increased in an almost linear manner until 0.08 s before maximum vertical bar velocity and then began to decrease. Rotational energy began to increase at about 0.32 s. The rate and extent of increase was less than that seen in Figure 3. A larger value was expected for rotational torso energy with the "frog leg" style because of the importance of hip extension. However, with this style, hip extension was a major contributor to barbell acceleration (see Figure 5 of reference 3) and, thus, there was a large resisting force minimizing torso angular acceleration and maximum rotational velocity. With the DKB there was an "unweighting" phase during the period of maximal torso rotation (2), which reduced the resisting force and permitted a greater angular acceleration. The torso's potential energy for this subject was also found to increase almost linearly and, combined with the steadily increasing linear kinetic energy, resulted in a fairly steady increase in total torso energy during the lift (Figure 2). The increased slope prior to maximum vertical bar velocity, previously noted for total torso energy with the DKB style, was not seen.

A 90-kg athlete reached the highest level of torso rotational energy (13.4 J). This was due in part to his body weight (only one subject was heavier) and the fact that he was the tallest subject studied; however, his lifting technique was probably also a factor. He pulled the bar vigorously from "lift-off" to knee height, resulting in a larger than usual vertical bar acceleration and, ultimately, vertical bar velocity at the start of the rebending of the knees. In order to maintain this high velocity, the shift of the torso toward the vertical had to occur very rapidly so that the "upper pull" could begin and carry the bar to maximum velocity without an undesirable period of barbell deceleration. This fast initial pull version of the DKB technique was used successfully by several members of the Bulgarian Team at the 1978 World Championships and seemed to be characteristic of their lifting technique philosophy. Most lifters would not find this method to their advantage because a fast first-pull usually results in the hips rising faster than the shoulders so that the torso rotates in the opposite direction to that needed prior to the second pull. This, in turn, makes the transition into the second pull slower and more difficult, with a high probability of bar deceleration.

The potential energy of the barbell increased steadily during all lifts studied. However, the kinetic energy for subjects using the DKB technique leveled off or decreased slightly as the bar passed the knee height and the lifter shifted into position for the second pull. Enoka (2) has argued that this is acceptable because of subsequent benefits due to improved mechanical advantages and "re-employment" of the knee extensors over their optimum range for force production. The athlete using the "frog leg" style had a continuously increasing barbell kinetic energy and the rate of total barbell energy increase rose gradually during the lift. The rate of total barbell energy increase for athletes using the DKB diminished during the shift prior to the second pull and subsequently increased sharply during the second pull.

Arm and foot energy changes were very similar for all lifts studied. The measured values supported the concept of using the arms primarily as cables to transfer energy from the leg and hip muscles to the barbell. The feet remained flat on the floor during most of the lift but the heels rose at the end of the second pull (see Figures 1d and 2d of reference 5). This heel lift resulted in slight increases in the energy components of the foot.

Energy transfer between segments

Detailed study of energy generation and transfer provided additional information that distinguished the two lifting styles previously discussed. It also supported the accepted theory that knee and hip musculature are of primary importance in the Olympic lifting movements. Typical results are shown in Figure 5 for three positions during a snatch lift of the 100-kg division winner. Position A represents the situation 0.16 s after lift-off, with the energy changes that occurred during the previous 0.04 s interval. Note that the energy changes of a given segment do not balance exactly with the energy flow into or out of the segment. This was due to measurement errors, assumptions made in the rigid-link model used to determine joint forces and torques, and the data-smoothing and differentiation method. In the torso, for example, 61 J energy entered through the hip joint while 21 J left via the shoulder joint, 31 J left via hip musculature, and 3 J left via shoulder musculature. This should result in a net gain of 6 J, but 5 J were found by calculating the change in potential, linear, and rotational kinetic energies. Energy input to the thigh was 64 J (44 + 18 + 2), while output was 61 J at the hip. The net energy gain measured was 2 J rather than 3 J as indicated above. Larger energy balance discrepancies were found for the shank and arm (7 and 8 J, respectively). Measurement of total barbell energy showed an increase of 26 J while energy flow calculations indicated a gain of 29 J. It can be seen that at this stage of the lift large amounts of energy developed in the knee and hip regions and flowed through the torso and arm to the barbell. Ankle plantar flexors contributed most of the energy to the shank (10 J) that flowed through the knee joint (18 J) as the leg straightened. The outflow of energy at the hip due to muscle absorption (−31 J) at this position was due to the hips rising faster than the shoulders causing an angular velocity opposite to the direction of the net muscular torque.

Figure 5B shows the situation for the same lift 0.4 s after lift-off. This was at the start of the rebending of the knees. Energy balance was very good for all segments, but energy flow to the bar was 7 J greater than the calculated value (53 vs 46 J). An important observation was that energy flow through the knee and hip joints (1 and 14 J, respectively) toward the bar decreased greatly relative to position A. For the next few positions these energy flows became negative and then increased rapidly during the second pull. This reversal in energy flow direction during the shift prior to the second pull was found for all lifts performed using the DKB technique. The range of minimum values at the hip was −4 to −24 J and at the knee was −1 to −15 J. The subject using the "frog leg" style did not at any time during the lift have a negative energy flow at the hip (+6 J was minimum) and only had one

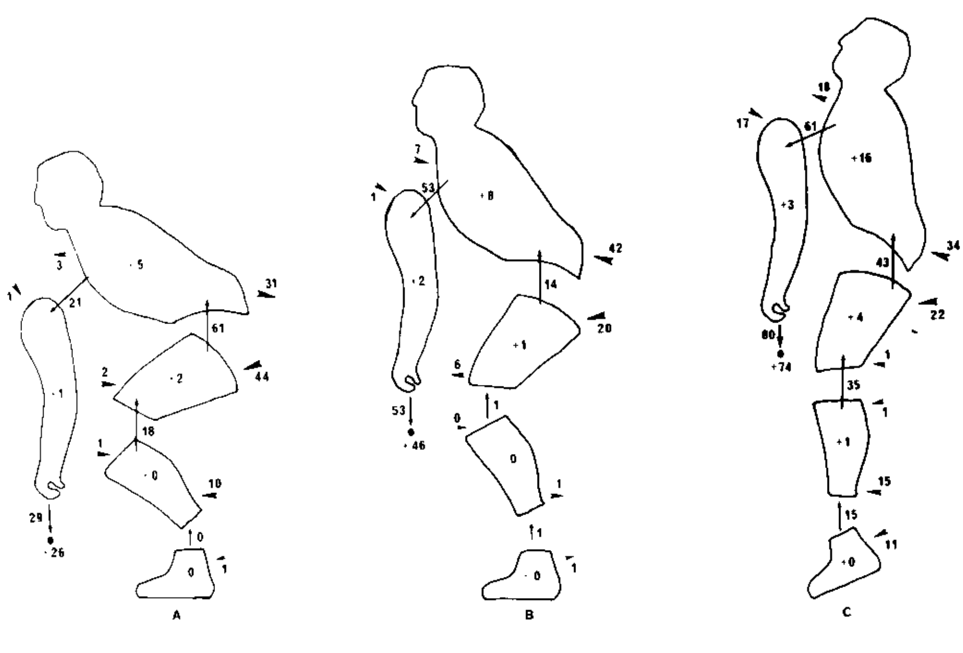

Figure 5—Energy flow at three positions during the snatch lift of subject 3. A=just after lift-off, B=starting to rebend the knees, and C=near the top-pull position.

negative energy flow value (−0.7 J) at the knee. The energy flow reversal for DKB lifts was caused by the reversal in movement direction of the knee and hip prior to the second pull (see Figures 1b-c and 2b-c of reference 5). Thus, energy flow analysis was another method that distinguished between lifting techniques and also provided a measure of the extent to which a given athlete utilizes the DKB style, i.e., magnitude of negative energy flow at the hip and knee.

Figure 5C shows the energy transfer 0.65 s after lift-off, which was just prior to the top-pull position (Figure 1d of reference 5). Again large amounts of energy developed in the knee and hip regions and flowed through the torso and arm to the barbell. At this position, however, a large amount of energy (15 J) also flowed across the ankle joint due to plantar flexion. Energy balance for the segments was not as good as seen for earlier positions during the lift (e.g., errors of 11 J for the thigh and 18 J for the torso). These larger errors were probably related to the smoothing and differentiation method used. This position occurred during a period of rapid changes in acceleration when smoothing tends to reduce the magnitude of the calculated joint forces and torques. This problem is discussed more fully below. The energy balance discrepancies pointed out above were representative of those found for all lifts analyzed.

Note the large amount of energy flowing into (half) the barbell at this position (80 J). The mechanical energy change was 74 J. This value corresponds to a power input of 1850 W (74 J/0.04 s) to half the barbell, or 3700 W total. The maximum power input was reached 0.04 s later and was about 4700 W. This did not include work done in elevating the body's center of mass. A conservative estimate of this additional work raised the peak power output of the athlete to 5700 W. The average power output for the entire second pull of this lift (0.14 s) was previously reported as 5243 W (4). The estimated peak value of 5700 W (0.04 s) corresponds to 60.4 W/kg of body mass for the athlete involved and is one of the highest human power outputs ever reported.

Evaluation of the accuracy of energy flow calculations

It was previously noted that energy balance for individual body segments was sometimes good and other times poor. In an effort to evaluate energy balance over the entire pull and thus gain additional insight relative to the accuracy of the methods used, the measured total torso and thigh energies were compared to total torso and thigh energies found by adding net energy gain or loss for the segment due to energy flow. Figures 6 and 7 show these comparisons for the snatch lift of a 90-kg lifter and the clean lift of a 67.5-kg lifter. For both lifts the torso energies were in agreement during the first half of the lift but drifted apart during the second half. Total energy calculated by adding net energy flow into or out of the torso dropped well below the measured mechanical energy (presumably accurate) in both cases. Total thigh energy values via energy flow first dropped well below and then rose well above the mechanical energy value for the snatch lift (Figure 6). The two thigh energy values for the clean lift (Figure 7) remain in agreement throughout the lift. The disagreement was most likely caused by excessive smoothing during periods of rapid acceleration change, such as during and after the second knee bend. It has previously been shown (3) that the rigid-link model used to calculate joint forces and torques during lifting attenuates joint force values. The same effect should be present in torque values since these quantities were derived by using second derivatives of linear or angular position data. Energy flow was calculated by using the above two quantities coupled with absolute joint velocities or segment angular velocities. The early energy and "power flow" studies of gait by Quanbury et al. (7) and Winter et al. (9) also showed balance errors. A direct comparison of errors was difficult since both of the above papers presented data in terms of rate of segment energy change ("power flow") rather than absolute segment energy changes. Quanbury et al. (7) theoretically showed that the rate of energy change of any segment was equal to the rate of energy flow to or from the segment due to net joint forces and net muscular torques at the joints, which indicated that absolute energy balance should exist for any small time interval during movement. Quanbury et al. (7) presented data which indicated a maximal discrepancy of about 11 W between the two calculation methods when total "power flow" to the shank was about 90 W (12%). A discrepancy of about 6 W was seen when total "power flow" was about 15 W (40%). Both of these errors occurred during periods of rapid change in "power flow" to the shank. Winter et al. (9) presented an example where "power flow" to the thigh was calculated to be 5 W, while the rate of change in thigh energy was determined to be −3 W. The 8 W difference was attributed to measurement error and the fact that the thigh energy curve changed slope rapidly at the time in question. The torso energy values shown in Figures 6 and 7 drift apart slowly, indicating that for any 0.04-s time interval the absolute energy change discrepancies were generally small. In the gait studies referred to above, the "power flow" differences of each interval were discussed. No cumulative discrepancies were presented as was done for Figures 6 and 7. A later paper by Robertson and Winter (8) compared rate of energy flow ("power") delivered to the thigh, shank, and foot during walking as determined by energy flow methods with that obtained by differentiating segment mechanical energy content relative to time. Agreement between the two methods was very good except for the foot "during weight acceptance and late push-off." Again, these were periods of high acceleration for the segment in question. Thigh energy agreement in this study for the two calculation methods used was good for the clean lift

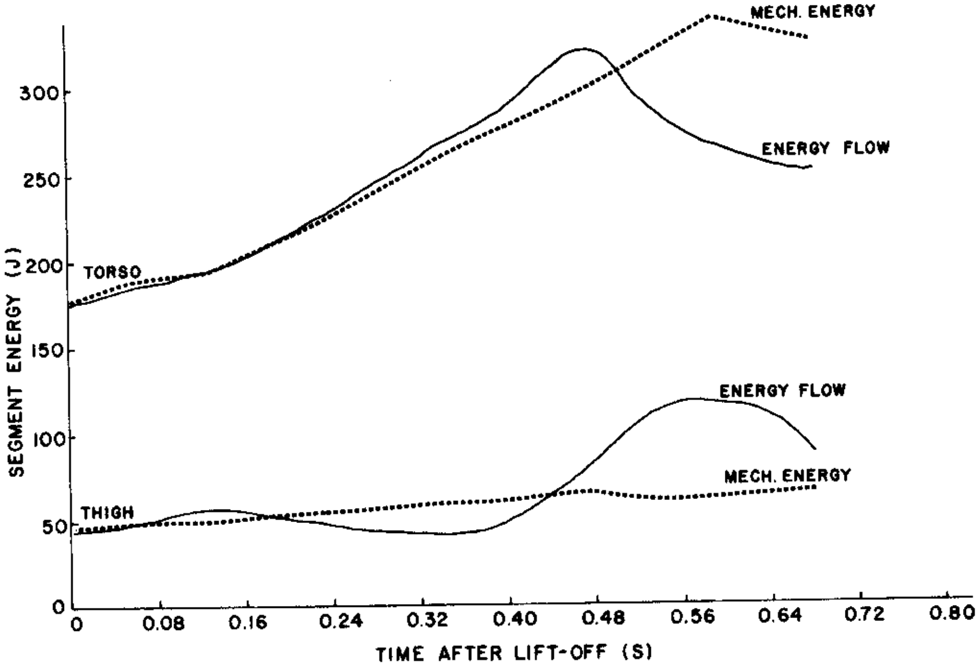

Figure 6—Comparison of two methods used to calculate total energy of selected body segments during the snatch lift of subject 4.

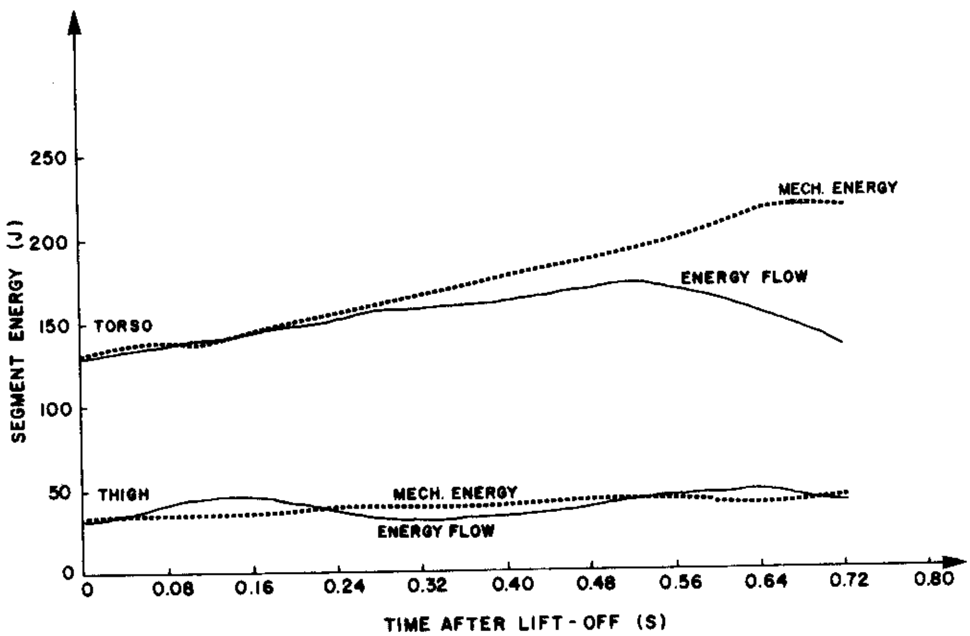

Figure 7—Comparison of two methods used to calculate total energy of selected body segments during the clean lift of subject 6.

(Figure 7) where velocities and accelerations were generally low relative to the snatch lift. Thigh energies in Figure 6 did not agree well. This was the earlier discussed snatch lift by the Bulgarian lifter, whose pulling technique resulted in larger than usual bar and body segment accelerations.

It was reasonable to conclude from the above discussion that the methods used here to study energy development and transfer during lifting provided qualitatively accurate information about the dominant muscle groups used and their temporal involvement. Other methods for smoothing and differentiating data, or higher sampling rates (0.025), should be used to increase quantitative accuracy. Winter et al. (10) have presented excellent results in gait analysis using digital filtering techniques. Quanbury et al. (7) have suggested using this method to calculate "energy flow" due to joint torques by subtracting inter-segment joint force contributions from total flow determined from the derivative of total segment energy values. This procedure would eliminate the need for many assumptions used in calculating net joint torques and the corresponding energy flow. Spline function techniques have also been shown to yield excellent results in the analysis of data from sport activities (12).

The information obtained through energy flow analyses also provided a means of quantifying lifting technique (also see reference 6). The procedures used in this study could easily be applied to weight training and rehabilitative exercises to help determine their efficacy in producing desired results or applied to ergonomic situations where a more detailed understanding of the demands made on specific regions of the body during lifting tasks would be useful.

Extensive details of the rigid-link model used in this study may be found in: Garhammer, J. "A dynamic rigid link model applied to the olympic snatch lift." M.Sc. Thesis, University of California at Los Angeles, 1976.

John Garhammer is a Fellow of the American College of Sports Medicine.

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