Biomechanics of Sport

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1989

CRC Press, Inc.
Boca Raton, Florida

Chapter 5

WEIGHT LIFTING AND TRAINING

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I. INTRODUCTION

The term weight lifting has a variety of meanings to the general public. To many it relates to bodybuilding, to some it refers to competitive sport, and to others it is a form of exercise. In this chapter, the terms weight lifting and weight training will both refer to the use of free-weight equipment (barbells and dumbbells), weight machines, and other machines or devices that provide resistance to movement for the purpose of exercise and/or the enhancement of recreational and sport performance. Under this definition, bodybuilding is a special case of weight training where emphasis is placed on the development of muscular hypertrophy and definition, body symmetry, and the reduction of body fat. Competitive weightlifting is primarily encompassed by two distinct sports (1) powerlifting, which includes the squat, bench press and deadlift movements; and (2) weightlifting (correctly written as one word) which includes the overhead snatch and clean-and-jerk lifts which are contested in the Olympic Games. The clean-and-press was included in weightlifting for many years, but was eliminated from competition in 1972 due to difficulties in defining and judging proper execution technique.

The popularity of weight training in the U.S. and many other countries, is clearly evidenced by the extensive growth of the "Health Spa" industry and sales of resistive exercise equipment for home use. The increased popularity of, and participation in bodybuilding world-wide is also indicative of the level of interest in benefits derivable from weight training. The sport of weightlifting, though not very popular in the U.S., has enormous world-wide popularity with over 120 member nations in the International Weightlifting Federation. Powerlifting, though not nearly as popular world-wide, has grown rapidly in the U.S. in the past two decades with nearly 10,000 active competitors currently registered.

This chapter is not meant to be an exhaustive review of all literature available related to biomechanical considerations of weight lifting and weight training. Rather, it is an extensive review of much of the large variety of research and literature associated with weight lifting and weight training biomechanics that is available in the English language. An associated area of interest is the branch of occupational biomechanics that deals with work-related lifting tasks. Several sources of available literature on occupational lifting have been published.[1,2] This area is not included in this review, although some pertinent references and considerations are integrated into the discussion when particularly relevant. Likewise, the literature addressing the efficacy of use of different equipment and training programs for the improvement of strength and motor performance (e.g., athletic skills), and for rehabilitation, is not covered in any detail, although some discussion and associated references are given to emphasize statements and conclusions based on biomechancial considerations. For more information on this topic see Stone and O'Bryant[3] and Atha.[4]

The review begins with a discussion of types of equipment that can be used for weight training with regard to biomechanical properties, potential advantages and disadvantages, limitations, and manufacturer's claims. This is followed by an investigation of biomechanical information available on a number of common and popular weight-training exercises. Particular attention is given to variables such as speed and pattern of motion (techniques of exercise execution), load lifted, subject skill level, and the effects of changes in these variables on kinematics and kinetics. Since the three lifts contested in powerlifting are also very common weight training exercises, discussion pertaining to this sport is incorporated within the exercise section. Finally, the biomechanical literature on Olympic-style weightlifting is reviewed and connections to other forms of strength, power, and performance enhancement training are made.

II. RESISTANCE EXERCISE MACHINES

Machines used for weight training may not actually utilize weights of any kind. For example, air-compression cylinders, hydraulic mechanisms, springs, or elastic cables may provide resistance to movement. Of the vast variety of machines currently available for consumer use, however, those most commonly found in public exercise facilities are truly weight machines, that is, their use involves the lifting of weight-plates as part of a weight "stack". The brand name equipment of Universal® and Nautilus® are discussed first since they are widely known and used and are representative of weight machines in general. Isokinetic machines purported to control movement speed by providing "accommodating" resistance are then evaluated.

A. Universal® Machines

Universal® weight machines were commonly available in the 1960s and the company began to promote highly its advanced "Centurion®" design weight machines in the mid 1970s. Several lengthy brochures based on the work of Gideon Ariel were widely distributed explaining the reasoning behind their "dynamic variable resistance" (DVR) machine design.[5,6] A condensed version of this material appears in a recent Universal® equipment catalog,[7] and a summary of the equipments features and training philosophies has recently been published.[8] The major point these brochures made was that the overload imposed on muscles by standard free-weight equipment was submaximal through much of the range of motion for common exercises like the bench press and squat. By utilizing a moving (rolling) pivot at the attachment point of the bench press, leg press, and overhead press station weight stacks on Centurion® machines, the mechanical advantage of a trainee is decreased through the range of motion of the exercise due to changing lever-arm lengths. This requires an increasing effort force as each exercise movement progresses, and the design parameters supposedly result in the resistance felt by a trainee closely matching his or her natural force production capability curve. Independent laboratory evaluations[9] were provided as proof that resistance did increase considerably from the beginning to the end of the range of motion of the above-mentioned stations.

Unfortunately, the range of motion evaluated was much greater than could be executed by anyone other than the tallest of trainees. The DVR exercise stations were said to be designed to average specifications for leverage changes (details were not provided in the Universal® literature), but methods to adjust these devices in any meaningful way for the variety of user sizes, do not seem to exist. Additional DVR rolling-pivot exercise stations have been marketed since the mid 1970s and some stations now incorporate a variable-radius pulley wheel (cam) to alter the mechanical advantage of the trainee. One recent study[10] pointed out the disadvantage (limited movement range) of the DVR "squat" machine due to lack of adjustability to accommodate smaller-sized subjects.

Details of how free-weight bench presses and squats were performed (subject skill level, percent of one repetition maximum (1 RM), speed of execution) for analysis and comparison to DVR bench press- and leg-press "force" curves, were not given in the promotional brochures.[5,6] Theoretical arguments for DVR presented in these brochures, were confusing and denied the length-tension properties of muscle, ignored the existence of force-velocity constraints on muscle function, and confused basic terms such as velocity vs. acceleration and isokinetic vs. isotonic. Reasonable arguments, based on specificity of exercise, were presented in favor of strength-training exercises for performance enhancement that involve multiple joints and muscle groups and that are performed rapidly to involve accelerations as occur in sport activities. These latter arguments seemed to be directed toward competitive machine companies which emphasize slow, isolated joint exercises (see Nautilus® below) or whose equipment minimizes acceleration (see isokinetic machines below). This emphasis on acceleration and ballistic movement seemed contradictory, since DVR tends to minimize such factors due to increases in resistance through the range of exercise motion.

Experimental evidence that DVR does produce superior training results compared to free-weights, was also provided by Universal®.[11] Reported progress of both "experienced" subject groups in the bench press was unusually large, and had the study continued for 30 rather than 20 weeks some world records may have been approached. The superior progress of the DVR group was especially surprising since all testing was done on the free-weight barbell. Independent comparative studies of different weight-training equipment, as summarized by Stone and O'Bryant,[3] fail to support the superiority of any type of equipment over free-weights for the development of strength and power or for performance enhancement. Some additional comparisons of DVR and free-weight equipment are made in Section III.

Universal®, and weight machines in general, do possess other operational properties which can be advantageous. These include ease of resistance adjustment, reduced injury potential, and for some rehabilitation situations, joint and muscle group isolation and constrained-movement patterns. Starr[12] has pointed out additional positive factors about machines in a comparison with free-weights. Exercises which involve the movement of body segments toward each other, as with barbell curls or dumbbell chest flies, are known to require decreasing muscular effort toward the end of the movement range.[13] Machine designs utilizing pulleys and cams to "redirect" the pull of gravity on weights or which by other means increase the range of resistance experienced by a trainee during certain exercise movements, can certainly be considered advantageous in most situations. It should be pointed out that modified free-weight designs planned for marketing in the near future minimize this undesirable reduced-resistance property.[14] Not all free-weight exercises fall into this category, however; in fact, the most important ones do not as discussed in Section III.

B. Nautilus® Machines

Nautilus® machines also began to be promoted heavily in the 1970s. Their machine designs incorporate variable radius pulley wheels or "cams" which alter the mechanical advantage of the machines by changing the effective lever arm of the weight-stack during movement through the range of the exercise. As with the Universal® moving-pivot design, the cam shape supposedly matches the resistance to the user's maximal force-production capability curve.[15] Two independent evaluations of numerous Nautilus® machines, however, indicated that the required machine force curves do not match average human strength curves.[16,17]

The Nautilus® machine designs emphasize isolated joint exercises with the rotational axis of the active joint being in line with the rotational axis of the machine. Nautilus® training philosophy states that movements should be done slowly.[18] This philosophy appears to be related to their machine design, since inertial effects during rapid movements can cause a reduction in the resistance felt by the trainee. In order to justify the principles of slow, isolated joint strength training, Nautilus® supporters have published articles condemning the specificity of this exercise principle,[19] confusing well-established properties of fast- and slow-twitch muscle fibers,[20] and warning of greatly increased injury potential when overload exercise is done with rapid or explosive movements.[20] This latter point is not satisfactorily supported, since it is well known that bone and connective tissues exhibit viscoelastic properties which enable them to withstand greater maximum loads and absorb greater energy before failure when subjected to rapid vs. slow loading. Also unexplained, is why conditioning athletes with only slow exercise movements rather than a combination of fast and slow should better prepare them to withstand rapid muscle and joint loadings and impacts as frequently occur in most sport activities. No independent research is available to indicate any superiority of Nautilus® strength training over other methods, although some evidence indicates the opposite.[3] Of particular interest is a case study involving monozygotic twins where free-weight training produced better results than Nautilus®.[21]

C. Isokinetic Machines

The term, isokinetic, means constant movement, and is generally interpreted as constant movement per unit time or constant velocity movement. As with Nautilus® machines, many isokinetic machine exercises require that the axis of the joint being trained or tested be in line with the machine lever-arm axis. The lever-arm of this type of isokinetic machine is designed to move with constant rotational velocity so that a properly aligned body segment will also rotate with constant angular velocity. This does not mean that any of the involved muscles shorten with constant velocity as demonstrated mathematically by Hinson et al.[22]

Isokinetic exercise has been discussed and studied extensively since the 1960s.[23,24] Devices used to provide isokinetic movement for testing and exercise may involve different means of operation, such as those based on friction, hydraulic, or electromechanical mechanisms. The hydraulic isokinetic machines have the speed of movement controlled by a dial setting that adjusts the size of an orifice through which a fluid (usually light-weight oil) is forced as the machine lever-arm is turned by an externally applied force. Since the fluid is incompressible and flows through the orifice at a rate dependent on its radius, the machine lever-arm moves at a constant angular velocity provided the fluid pressure created by the externally applied force is above a minimal level. Applied-force variations merely alter the fluid pressure which is felt as resistance to movement by the subject. Thus, the machine is said to accommodate the subject's effort by providing more or less resistance while maintaining constant movement speed. For higher speed settings on these machines the subject's initial effort creates a large angular acceleration, since the weight of the lever-arm and fluid flowing through a larger orifice provides little resistance to movement. As rotational speed reaches that corresponding to the dial setting, resistance is suddenly experienced and an equilibrium is reached with constant movement speed occurring. Thus, in reality, exercise on this type (and other types) of accommodating resistance machine is not fully isokinetic. The actual sequence of events that often occurs, for example, is that muscle contraction tension developed in the body acts through its skeletal lever system to create an external force applied at some point on the machine's lever-arm. This applied force creates a torque about the machine's rotational axis, and as its lever-arm initially turns, little resistance is felt and a large angular acceleration occurs until the set rotational speed is reached. At this point, a transition from high acceleration plus low resistance movement, to zero acceleration plus accommodating resistance, is made during which velocity fluctuations occur while a steady-state fluid-flow through the orifice of the machine is established. The higher the speed setting on the machine the more extensive these undesirable effects will be.[25,26] Less than half the range of motion, for example, may be traversed at constant speed when the angular velocity is greater than 1.75 rad/sec (100°/sec).[26] These undesirable effects do not seem to occur or are very minimal at low applied-force levels and slow speeds as may typically occur in rehabilitation situations.[24]

Some studies indicate greater electromyography (EMG) activity from involved muscles when working "isokinetically" at slow speeds compared to fast speeds of movement.[27] This may be partially due to the lack of resistance early in the movement at fast speed settings as discussed above. Others[4] indicate greater EMG activity from involved muscles when similar exercise exertions are made using isokinetic vs. free-weight ("isotonic"., see discussion of this erroneous term below) and isometric equipment. The first case may be the result of neuromuscular effort required to balance and control multidimensional free-weight movement tendencies, while the second case may involve neural inhibition as proposed by Perrine and Edgerton[28] to explain the force decrement in muscle tension capabilities observed at very slow and zero movement velocities.[24] Some studies comparing strength gains in leg extension/flexion after weight machine vs. isokinetic training, have found greater gains from isokinetics.[29] In general, however, studies have not supported the superiority of isokinetic exercise over other methods of resistance training in producing strength and performance improvements. More details related to these considerations have previously been summarized by Stone and O'Bryant[3] and Atha.[4] Some comparisons of exercises performed with free-weights vs. isokinetic or with other equipment, will be presented in the next section.

Isokinetic machines have definitely added a new dimension to muscle training and testing. Despite the limitations pointed out above (which may be decreased by future improvements in equipment) the ability to accurately measure the torque created by muscle contraction through nearly a full range of motion at a variety of selectable speeds for segment rotation, is unquestionably of substantial value. For rehabilitation, patient records with this detail can help make exercise programs more specific and recovery more rapid. For research in muscle physiology and mechanics, the above parameters are very useful and permit easy calculation of other variables such as power (torque × angular velocity). For general training and sport enhancement, the applications are less clear, although use in teaching the concept of rapid explosive contraction for higher speed movement requirements may be very appropriate.

III. WEIGHT-TRAINING EXERCISES

The above section presented information on how a variety of strength-training machines operate and what their limitations are, relative to manufacturer claims and experimental evidence. A large percentage of people participating in weight training utilize free-weight equipment (barbells and/or dumbbells) for all or some of their exercises. The advantages of free-weight use over machine use are numerous, but one of the most significant is the need to balance the weight and one's body, and to control three-dimensional movement tendencies during the execution of exercises. These needs relate well to the requirements of daily work tasks and recreational and sport activities. O'Shea was one of the first individuals to recognize the undesirability of excessive "guided (resistance) apparatus" exercises and to warn of "hindered development of neuromuscular coordination and the antagonistic and assistance muscles."[30] These and many other considerations favorable to free-weight use have been discussed in detail elsewhere relative to general and sports conditioning[3,12,31,32] and rehabilitation.[33,34]

Above all else it must be emphasized that free-weight exercise is in no way isotonic (constant muscle tension) exercise. The load being lifted is constant, but the force applied to it is rarely constant since the lifting action involves movement and acceleration. Newton's second law of motion applied to a free-weight lift shows that the vertical lifting force (F) depends on the weight lifted (W) and its mass (M) and acceleration (A) according to the equation $F = W + MA$. Due to this fact, many free-weight exercises can be said to accommodate any muscle tension generated and the corresponding lifting force by accelerating at varying rates.[31] Even if the lifting force is briefly constant the muscle tension creating it varies due to leverage changes and the length-tension properties of muscle. Isotonic is a term that should rarely, if ever, be used in connection with weight training and muscle exercise. Isometric exercise is perhaps the only special case where the term isotonic can sometimes be appropriately used. Dynamic, can and should be substituted in almost all exercise literature for the term isotonic.

The following paragraphs discuss biomechanical information about several common weight-training exercises and in some cases contrast their performance on different types of equipment.

A. The Squat

The squat exercise, sometimes called the deep knee bend, has a long history of controversy as briefly reviewed by Rasch and Allman,[35] who point out that published criticism of the lift appeared as early as 1946. Klein's papers[36] are probably the most quoted and debated of those warning of possible dangers associated with squatting. Todd[37] recently provided a detailed history of the use of this lift and insights into the "Klein" controversy. The potential problem debated was that full squats may cause stretching of medial and lateral ligaments at the knee joint, resulting in decreased stability of the knee. It is important to note that the above-quoted literature indicates that only "full" squats (fullest possible range of motion/

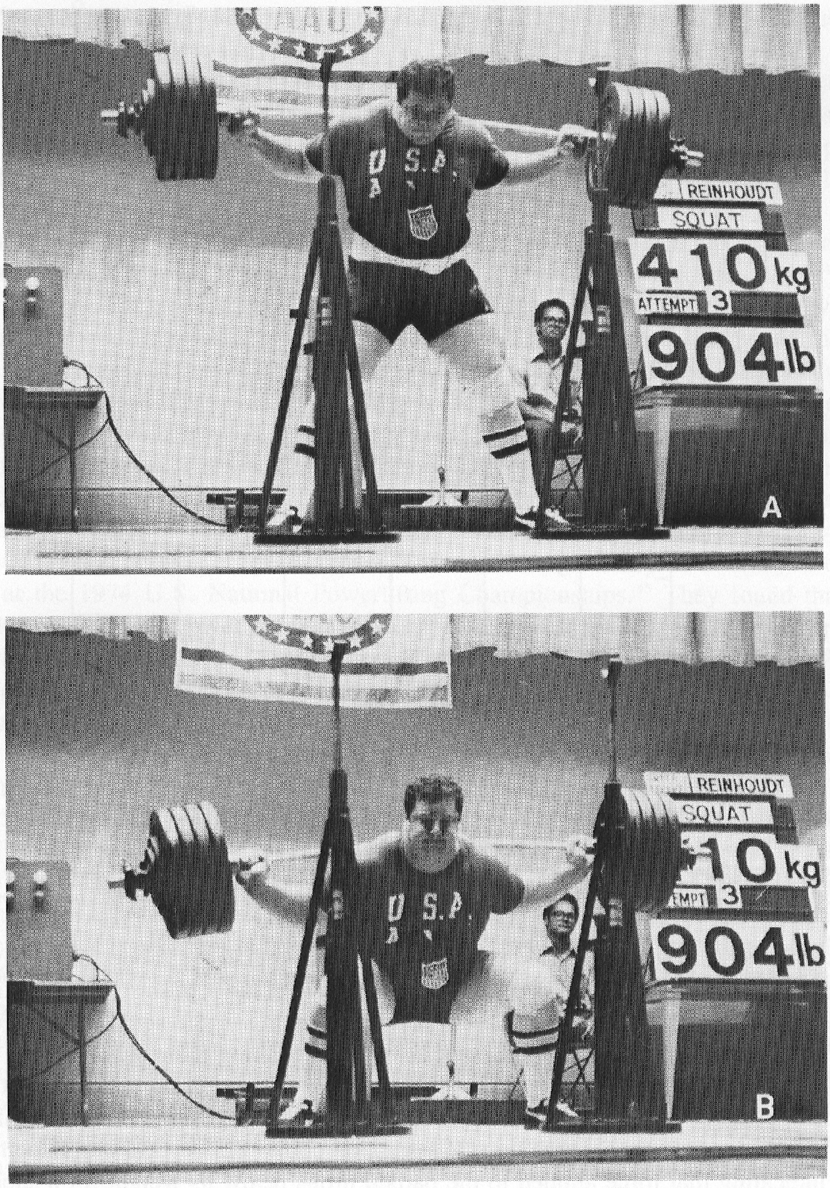

FIGURE 1. The squat exercise as performed in competition. (A) The start and finish position. (B) The bottom or minimum low position (thighs parallel) accepted during the squat exercise in competition. (Photo by B. Klemens.)

maximum knee flexion) were criticized and even Klein himself recommended half squats, which were defined as knee bends to the point of the thighs being parallel to the floor or slightly below (cf. Figure 1). The vast majority of competitive and exercise squats done today are to this depth, as is commonly recommended.[38-40] A recently published ''roundtable' discussion[40] involving noted researchers and strength and conditioning coaches clearly shows the support for, and perceived importance of, incorporating squatting exercises into strength-training programs.

Considerable biomechanical research on the squat has been published in the past decade. McLaughlin and co-workers[41] have determined the squat kinematics of competitive pow-

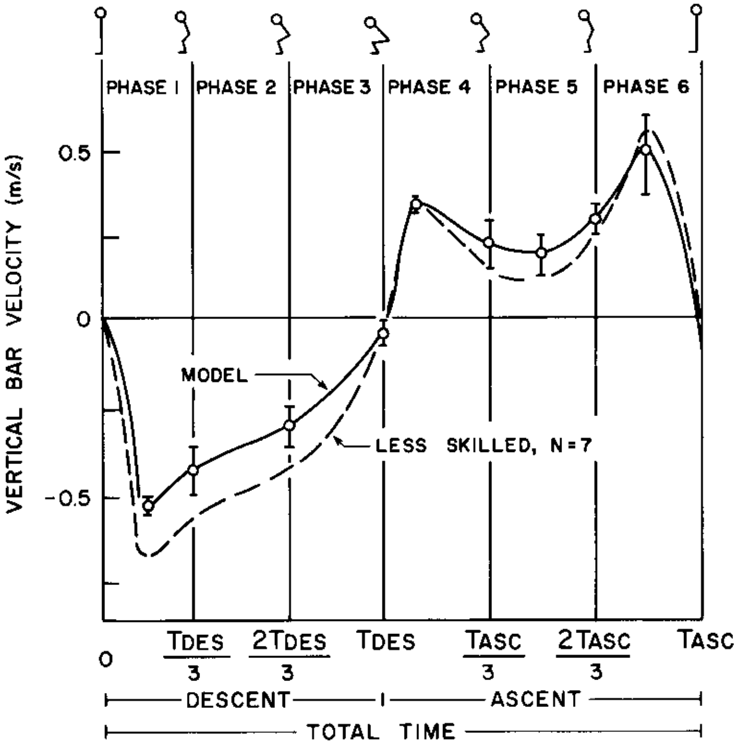

FIGURE 2. "Model" velocity profile during the squat as performed in competition by elite powerlifters (N = 17) as compared to less-skilled (but still national caliber) powerlifters. TDES is average descent time, TASC is average ascent time, and TOTAL TIME is approximately 4 sec. *Note:* Other research indicates that novices exhibit greater velocity extremes and fluctuations during execution of the squat exercise than shown here. (From McLaughlin, T. M., Dillman, C. J., and Lardner, T. J., *Med. Sci. Sports,* 9, 128, 1977. With permission.)

erlifters from a variety of bodyweight divisions and formulated a model of highly skilled performance based on the pattern of vertical barbell velocity. Contrasting two skill levels showed that the higher skill group (based on world ranking in the squat) (1) descended at a lower rate, and thus approached the lowest (bottom) position more slowly, with less of a "bounce" effect; (2) maintained a more vertical torso position during the entire lift; and (3) maintained a higher vertical bar velocity through the "sticking point" region. This region was characterized by a first minimum (the "sticking point") in vertical bar velocity during ascent, indicating that force applied to the barbell drops below its weight for a short period of time. It was noted that this first minimum of ascent velocity occurred at approximately a 30° thigh angle above the horizontal for all subjects despite a variety of torso and shank angles (cf. Figure 2). Research is needed to investigate the multisegment leverages and single and dual joint muscle interactions that are responsible for this observation.

The average magnitude of both the maximum vertical ascent and descent velocity in the above model was approximately 0.5 m/sec. with the ascent maximum value occurring after the "sticking point". Less-skilled subjects had a slightly greater magnitude for both values. A similar kinematic investigation by Malone[42] involving subjects of considerably lower overall skill level than those analyzed to develop the McLaughlin model, showed much less consistency between and among the two skill-level groups formed. The main similar finding in both studies was the double peak in average ascent bar-velocity curves. In the Malone study, maximum ascent velocity for both groups also occurred after the "sticking point", but was found to average approximately 0.7 m/sec. 40% above that of the McLaughlin model. Other comparisons between these two studies are of questionable value due to the large differences in subject skill levels.

More extensive work has been done involving kinetic as opposed to kinematic analyses of the squat. Plagenhoef[43] used a static three-segment rigid link model to show how segment orientation can affect the dominant muscle torques required for equilibrium at the hip, knee, and ankle joints. Evaluation of one position with excessive forward torso lean resulted in a net flexor torque at the knee, opposite to that expected.

Dynamic three-segment rigid link models have been used to evaluate hip, knee, and ankle forces and torques that are generated while squatting with heavy overloads. Ariel[44] found that the shearing force component at the knee and the net (extensor) knee torque were less for an experienced lifter using 2900 N than for a less-experienced lifter using a lighter weight. A "bounce" action at the lowest position in the squat of this latter subject resulted in a sharp increase in these parameters. Maximum knee torque values for typical subjects were listed at approximately 245 N·m. It was pointed out that forward knee movement during the squat was associated with the development of large shearing forces which could increase injury potential, and that one subject was able to reduce undesirable force components during the squat training period (presumably due to improved lifting technique).

McLaughlin and co-workers performed a similar three-segment dynamic analysis on competitors at the 1974 U.S. National Powerlifting Championships.[45] They found that some highly skilled lifters had lower maximal (extensor) torques at the hip joint than lesser-skilled lifters who were of lighter bodyweight and were squatting with a lighter barbell. This was attributed to greater forward torso lean and the resulting longer lever-arm of the barbell relative to the hip in the less - skilled group. The highly skilled lifters also exhibited larger extensor knee torques than the less skilled, possibly indicating greater reliance on thigh extensor rather than hip extensor musculature. The maximum hip and knee torques calculated were 705 and 500 N·m, respectively. Many peak knee torques were in the range of 100 to 300 N·m which agrees with typical values found by Ariel[44] as stated above. Also in agreement with Ariel was the finding that peak knee torques typically occurred at the lowest position (maximal knee flexion) of the squat. McLaughlin noted, however, that knee torque decreased during early ascent and was relatively low at the "sticking point" position introduced in his previously discussed kinematics paper.[41] Hip torques were generally near maximum at this point.

The above findings can be related to anatomical considerations. Greater forward torso lean requires greater hip extensor torque for equilibrium. The hamstring muscle group would likely contribute to creating this torque and in so doing would generate a flexor torque at the knee, thus reducing the effect of the knee extensors (quadriceps). Rigid-link modeling equations provide "net" force- and torque values at the link joints, so less extensor or even flexor dominance at the knee would be expected and was found for subjects with greater torso lean. Plagenhoef,[43] as discussed previously, showed that excessive forward torso lean results in the calculation of a flexor-dominant torque at the knee for a static squat position. McLaughlin[45] showed that acceleration factors during the heavy squats analyzed were small and that their elimination reduced dynamically calculated joint forces and torques by only approximately 10%. Thus, Plagenhoef's static calculations do provide insights applicable to at least heavy (slow) squats. The above consideration of the dual hamstring effect may indicate that forward torso lean does not necessarily reduce quadriceps activity, but may somewhat negate its effect by producing an opposing flexion torque. It should also be noted that larger magnitude hip extensor torques relative to knee extensor torques do not indicate that hip extensors play a more important role or are more involved than knee extensors in the execution of the lift. Any given net knee extensor torque value could represent maximal tension capability of the associated muscles acting through a given lever arm. A larger hip extensor torque at the same instant could result from submaximal tension of the associated muscles (whose maximal tension may be much greater than that of the knee extensors) acting through a more favorable leverage system. The effect of antagonistic muscle torques in the calculation of net joint torques, must be remembered.

A detailed model of the leg and primary muscles active during squatting movements has been developed by Dahlkvist and co-workers.[46] The model was individualized for six subjects, half of whom performed "fast" squats, while the other half performed "slow" and "fast" ascents from the deep-squat position. No load was used other than bodyweight and details of body segment angles and timing during the squat movements, were not given. However, the model, coupled with EMG data (which was used to determine if a given muscle should be considered a tension producer at any given instant in the activity), did result in estimates of various muscle tensions and joint-force components. Maximal and average quadricep and hamstring muscle forces were found to be greater during "fast" movements compared to slow, but the opposite was generally found for the gastrocnemius. Quadricep muscle tensions ranged from 3.6 to 8.6 times bodyweight depending on the subject and type of squat movement. Corresponding hamstring and gastrocnemius ranges were 0.8 to 2.46 and 0.7 to 1.8, respectively. Average joint-forces normal to the tibial surface ranged from 4.7 to 5.6 times bodyweight, while tangential values were 2.9 to 3.5. Joint-torques, and parameters needed to calculate them, were not given, so that such values from the previously discussed papers could not be compared. It is interesting to note that no reference was made in the paper by Dahlkvist et al. to any published work analyzing the squat as performed for exercise or in competition even though a number were available years in advance of its publication. The detailed model and methods used could provide considerably greater insight into the demands placed on body components (e.g., bones, ligaments, and muscles) if applied to such squats, and may illuminate factors related to the "sticking point" phenomenon. Hopefully, someone will soon accept this challenge.

Cappozzo et al.[47] have determined spinal compressive loads at the L3-L4 joint for two male and two female athletes while performing half squats with a barbell loaded in the range of 0.8 to 1.6 times bodyweight. Methods used are similar to those commonly found in analyses of occupational lifting tasks.[1,2] Fourier analysis of vertical ground-reaction forces and barbell and body segment vertical accelerations, showed that 95% of the signal power fell below 8 Hz. Such information is valuable in determining sampling and cut-off frequencies for data acquisition and smoothing. L3-L4 compressive forces were found to be 6 to 10 times bodyweight and modeled erector spinal forces were found to range from 30 to 50% of published maximal isometric levels for workers. Peak forces occurred at or very near the point of maximum knee flexion (approximately 80°). The spinal compressive forces were increased with forward torso lean and with faster squat-execution times. A shim was placed under the heels of the subjects during the squats, probably to aid in balance. One trial without the shim resulted in the subject leaning further forward. This indicates the importance of joint flexibility in maintaining a more upright torso position and reducing spinal compression and shear forces. Though not discussed, data presented indicated a shift of balance toward the heels during early descent and a shift toward the toes later in descent and during early ascent. The heel shim may have influenced this balance pattern. Balance on the feet during squats with heavy overload has not been, but should be, thoroughly investigated.

The muscle forces required to perform any given weight-training exercise have always been assumed to increase as the weight lifted increased. Hay et al.[48] examined this assumption using dynamic rigid-link modeling techniques with the squat exercise. They found that hip, knee, and ankle torques were linear functions of external load only if the kinematics of the squat were held constant. In practice, when subjects performed squats with increasing loads, the actual torque curves differed from the theoretical curves due to variation in movement kinematics. These differences were generally not large in magnitude, and a similar effect should be expected in the corresponding muscle tensions. Thus, to gain a proportional increase in the tension demands placed on each muscle involved in a multijoint exercise, consistent technique is required.

An extension of the above research included use of a Universal® DVR squat machine.[10] A larger difference in experimental vs. theoretical knee-joint-torque curves was found as load increased on the machine than when using a barbell.[48] A major cause of the torque changes was cited as being an increased torso lean as the machine load increased. This factor has been discussed above as a cause of increased hip/torso extensor muscle tension and spinal compression. Another possible cause (not discussed by the authors) is the fact that machine squats fix the position of both the feet and the shoulders and force the body segments to shift between them during the squat. This movement constraint may result in undesirable and variable segment movement patterns, since the body cannot easily shift balance.[50] Since the squat machine shoulder pads are in a fixed position relative to the ground a subject may unknowingly place his or her feet at slightly different locations under the apparatus for different trials, adding variability to the loading and likely causing movement pattern variability. This problem does not occur with a barbell where balance on the feet can be freely and consistently adjusted to the most comfortable and advantageous leverage position. Also, the DVR machine increases resistance through the range of motion and the pattern of increase may depend on the number and location of plates being lifted as well as subject size. Thus, although the authors suggest that certain types of machines may reduce variability in exercise kinematics, the squat machine seems to have increased torso inclination variability as a function of load more so than occurs with a barbell. (See also the discussion in Reference 50.)

The effects of speed of squat execution on joint-torques, were also investigated.[10] DVR machine and barbell squats were performed with 1-, 2-, and 3-sec ascents, but consistent 2-sec descents. The trend was toward higher joint-torques for faster ascents, as also noted in other studies.[46,47] Since the force-velocity property of skeletal muscle dictates that maximum tension production capability decreases with increasing speed of contraction, the faster squats are likely to require a higher percentage of maximal tension and provide a greater training stimulus. Caution must be exercized, however, since faster squats not only require greater muscle tension, but also increase the likelihood of incorrect technique and injury potential. Speed variation should only be considered for the ascent phase of the squat, never for the descent which should always be done in a slow and controlled manner. It has been shown that squats performed in competition[45] and at reasonable speeds[10] have such low accelerations that these accelerations can be ignored for all or most of the range of motion in dynamic calculations, with the effect being only approximately a 10% reduction in force- and torque values. True "speed" squats, such as jump squats, can (and should only) be done with relatively light weights.

A final topic covered by the same group of researchers involved the concept of joint-shear at the knee during squatting.[49,50] After defining several methods that could be used to calculate joint-shear, it was shown that shear-force components vary during the squat, are maximal at the lowest position of the squat (thighs near parallel), and are larger when the squat is performed fast (1 sec/phase) vs. slow (2 sec/phase).[49] Similar results were found when DVR machine squats were compared to barbell squats.[50] However, greater force levels were found with the machine due to the fact that the resistances used (percentages of 4 RM) were larger on the machine. This was probably related to the fact that no balance was required to use the machine,[10] range of motion was generally smaller on the machine due to lack of adjustability for different sized subjects,[10] and the DVR machine increases resistance through the range of motion. The greater force levels found with machine squats could produce a greater muscular training effect as well as increase injury risk.[50] However, with the free barbell, squat balance and neuromuscular coordination, can be better developed.

In an unpublished study involving only one subject, Malone[51] made several interesting comparisons. He found that fatigue did affect the kinematics of the first two as opposed to the last two repetitions of an eight-repetition set of squats with 90% of 1 RM. Velocities were generally less, particularly in the "sticking point" region, for the later repetitions. Initial acceleration during the ascent was similar in each case and a hypothesis was postulated that elastic energy provided a major contribution to contractile tension during this phase of the lift. Kinematics of the seventh repetition of the training set were later compared to those of a 1-RM squat performed in competition, and no differences were found. Finally, the 1-RM kinematics were compared to those of an isolated squat ascent (barbell lifted from supports) with maximum possible weight. The large initial ascent velocity and acceleration that existed during the 1-RM squat were not found for the isolated ascent and only a very small velocity decrease took place in the "sticking point" region for the latter movement compared to the former. These observations were taken as support for the hypothesis that elastic energy recovery is an important factor in the initial ascent from the low-squat position. Leverage factors were credited with being more important toward the end of the ascent. Malone's reasoning in the above comparison seems to follow that given in studies of vertical jumps with and without counter movement.[52] It is certainly plausible that elastic energy does play an important part in squatting due to the eccentric contractions and muscle stretch that occur during descent and its termination, and the rapid concentric contraction immediately following that permits ascent.[53]

Based on the above research, several summarizing statements are appropriate:

1. There is no objective scientific evidence that the squat exercise to the "thighs parallel" position will damage the knee joint. The possible harmful effects of the full squat on the knee joint are controversial. Any "bouncing" action to help initiate ascent from the full squat position will subject the knee joint to much higher mechanical stress.
2. Squats should be performed with a slow, controlled rate of descent to the "thighs parallel" position followed by an immediate initiation of the ascent if stored elastic energy is to be recovered and aid in the ascent.
3. The torso should remain as close to vertical as possible, relative to the anthropometry and flexibility of the trainee, during the entire lift.
4. The movement of the knees forward during descent should be minimized; maximal forward movement should place the knees no more than slightly in front of the toes.
5. Every effort should be made to maintain stable form (pattern of motion) during every repetition in order to load the muscles in a consistent manner.

NOTE: The depth of a squat is frequently judged in a subjective manner. Such judgements cause controversy in competitive situations and may have important consequences in rehabilitation. With the ever-decreasing price of computers and the increasing availability of electro-optical devices to monitor movement in real time, such subjectivity can, should, and hopefully soon will be eliminated. A hard-wired forerunner of potential future wireless squat depth monitors has already been developed.[54]

B. The Bench Press

The bench press is perhaps the most widely used weight-training exercise in the world (cf. Figure 3). It is the second of the competitive powerlifts and is described in varying detail in almost all weight-training books[3,12,30,39] and in specific articles.[55] Yet, until the last few years, little or no biomechanical analyses of this lift had been published, as evident in a review article written in 1979 by Hatfield and McLaughlin.[56] Part of the reason for this is likely to be the need for three-dimensional considerations and the complex interrelated nature of shoulder and shoulder-girdle movements that occur in the bench press. This fact has also limited modeling of the "shoulder complex" in occupational biomechanics.[57]

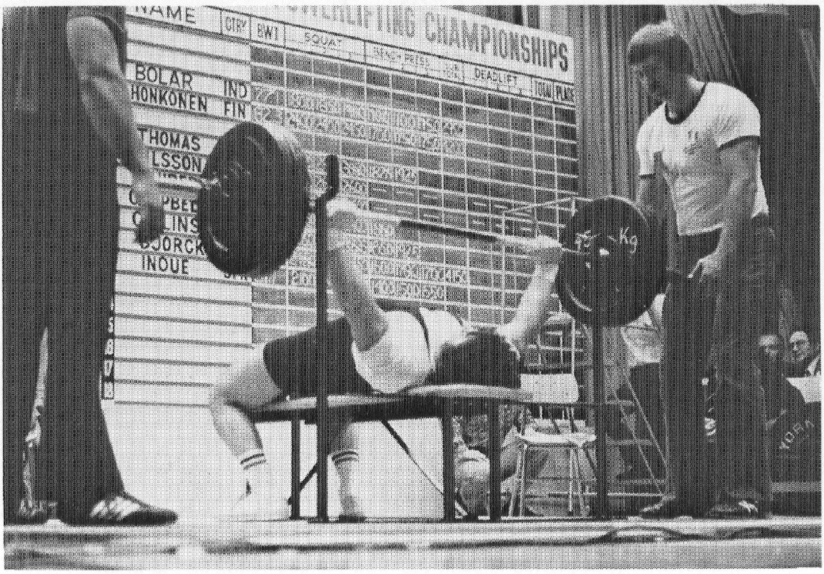

FIGURE 3. The bench press exercise as performed in competition. Shown is the start and finish position. The barbell is lowered to the chest and then raised to the finish position. (Photo by B. Klemens.)

Madsen and McLaughlin[58] have provided some groundwork for future study of the bench press in a paper largely describing and contrasting two-dimensional kinematics of the lift as performed by elite competitive lifters and novice lifters. An extension of this paper provided data for elite heavyweight powerlifters,[59] and McLaughlin has expanded discussion of this research and suggested possible applications in book form.[60] Key differences found between elite and novice groups included a slower rate of lowering the barbell, a movement pattern which kept the bar closer to the shoulder (sagittal plane view), and a more consistent level of force application to the bar for the elite lifters. Some longitudinal data indicate that elite lifters modify technique over time toward the above characteristics.[60] The elite group also followed different bar paths when raising vs. lowering the bar, while the novices followed very similar paths (cf. Figures 4 and 5). Graphs of upward bar velocity showed a minimum between two peaks for almost all subjects, but this minimum was more pronounced for the novices, very similar to what was found for upward velocity in competitive squats[41,45] (Figure 6). Thus, this mimimum velocity point was again labeled the ''sticking point''. The argument presented previously for elastic-energy recovery being associated with the existence of the sticking region during ascent from a squat,[51] should not apply for the bench press, since the rules of competition require a complete stop at the chest prior to raising the bar (also see McLaughlin[60]. This period of static hold should eliminate or severely reduce elastic-energy recovery.[53] An alternative cause of initial upward-thrust enhancement could, however, be associated with a voluntarily generated intraabdominal/intrathoracic pressure surge and/or recoil of the rib cage due to appropriate muscle contractions.

Differences found between novices and heavy bodyweight elite (HB E) lifters were generally the same as those found relative to lighter bodyweight elite (LB E) lifters. One exception was that HB E lifters generated nearly twice the shoulder joint torque (force on bar × sagittal plane lever-arm) as LB E lifters, although they only handled approximately 30% more weight. The LB E lifters generated approximately the same shoulder-joint torque as novices even though they handled 79% more weight. Body size corrections predicted less than 50% increases in torque for the HB E vs. LB E subjects. Some possible reasons for this discrepancy were presented based on handgrip spacing, bar path geometry, and bar

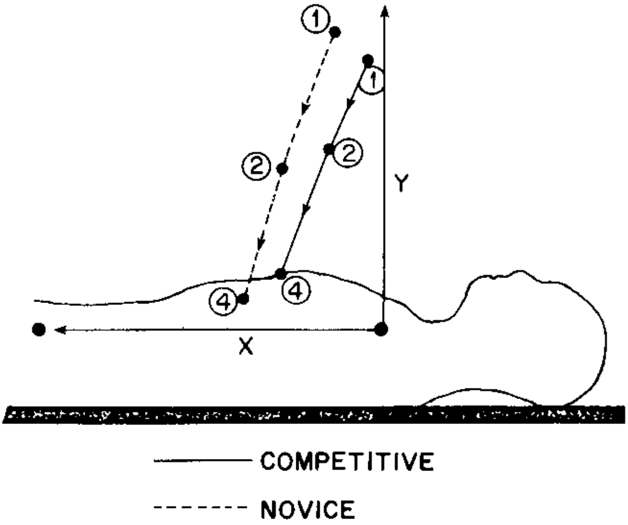

FIGURE 4. Comparison of paths followed while lowering the bar in the bench press. (1) start, (2) maximum velocity of descent, (4) chest contact. Also see Figure 6. (From Madsen, N. and McLaughlin, T., *Med. Sci. Sports Exercise*, 16, 376, 1984. With permission.)

acceleration differences. Three-dimensional analyses are clearly needed to gain more insight relative to these types of questions.

In a comparison of free-weight and isokinetic bench presses Lander et al.[26] also found that a sticking point (region) existed. In their protocol, subjects were not required to stop the free bar at the chest so that elastic energy utilization was likely. The mean force-time curves for both types of bench presses were very similar, except at the beginning and end of the movement when the isokinetic device provided no resistance (cf. Figure 7). Areas under the curves, which are related to work done, appeared very nearly equal. The isokinetic device used did not provide constant velocity of rotation through the entire range of motion and the isokinetic range decreased as speed increased. The authors felt that both types of equipment accommodated maximal lifting efforts, the isokinetic device via resistance changes, and the free-weights via acceleration changes. The differences found were attributed to a lack of eccentric loading and baseline force with isokinetic equipment and the need for balancing forces with the free barbell. Ability in the free-bar bench press was shown to be related to the ratio of first to second force peak in the isokinetic bench press. Better free-weight bench pressers had lower ratios (0.81), as they did for the same force-peak ratios determined with the free bar (1.25). Other factors subjectively related to ability in the bench press included handgrip spacing, and arm-forearm and arm-torso angles. Mean maximal-force values for the six subjects whose best bench presses ranged from 1333 to 1822 N (1.27 to 2.16 times bodyweight) were approximately 2000 N for the free bar and 1900 N for the isokinetic device. These values compare reasonably with those for HB E, LB E, and novice lifters whose values were 2621, 2004, and 1349 N for mean lifts of 2349, 1814, and 995 N (1.92, 2.36, and 1.32 times bodyweight), respectively.[59]

Minimal data from three-dimensional (3-D) analyses of the bench press have been found. Two published abstracts[61,62] and short sections in McLaughlin's book[60] report the use of EMG with 3-D analyses to study the effects of variables such as handgrip spacing and load. One study[62] indicated that peak shoulder torques were higher for wide grips (97 N·m) than for narrower grips (70 N·m) and were higher when lifts were performed at higher speeds of movement. Load values were not given in the abstract so it was not possible to speculate

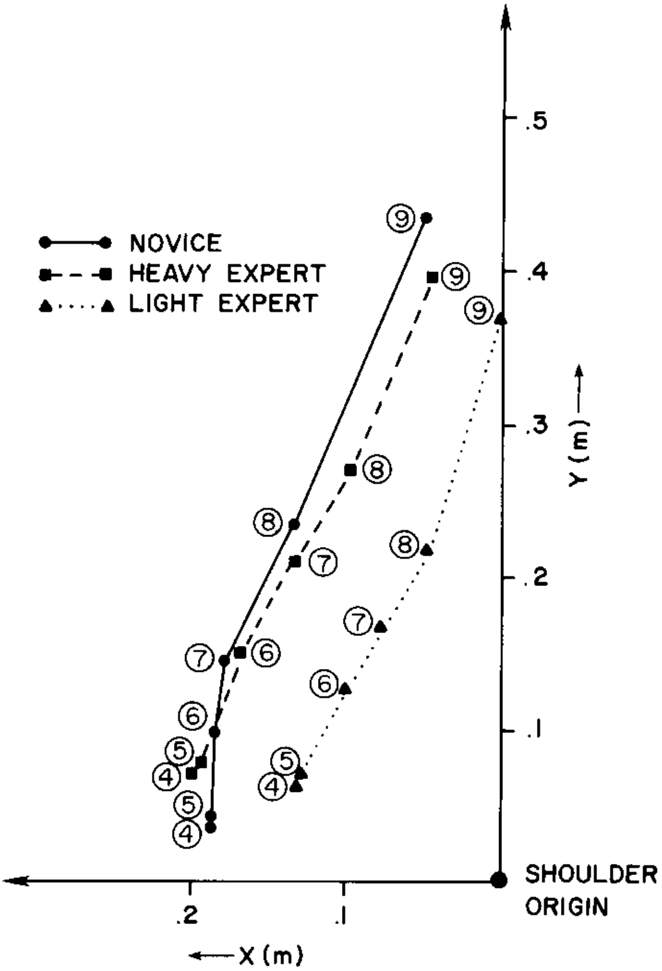

FIGURE 5. Comparison of paths followed while raising the bar in the bench press. (4) chest position, (5) maximum upward acceleration, (6) maximum upward velocity, (7) minimum upward acceleration, (8) minimum upward velocity, (9) finish. (From McLaughlin, T. M. and Madsen, N. H., *Natl. Strength Cond. Assoc. J.*, 6, 44, 1984. With permission.)

on why these values were so much lower than those estimated with 2-D analyses of novice (255 N·m), LB E (261 N·m), and HB E (501 N·m) lifters.[58,59]

C. The Deadlift

The deadlift is the third of three lifts contested in power lifting and it, or one of its several variations, is commonly used in exercise programs (cf. Figure 8). Despite its frequent use, it has received almost no attention from biomechanists. Various lifting postures which have some relationship to the deadlift as performed for exercise and in competition, have been studied relative to occupational applications,[1,2,63] but will not be discussed here. Techniques for performance of the deadlift are presented in most books on weight training,[3,12,30,39] and have been covered in specific articles.[64]

The only pertinent data found were recently published by Brown and Abani.[65] They analyzed teenage powerlifters from film taken during a competition, and compared kinematic and kinetic parameters between "skilled" and "unskilled" subjects who represented almost all bodyweight classes, and successfully deadlifted between 140 and 272 kg. The unskilled

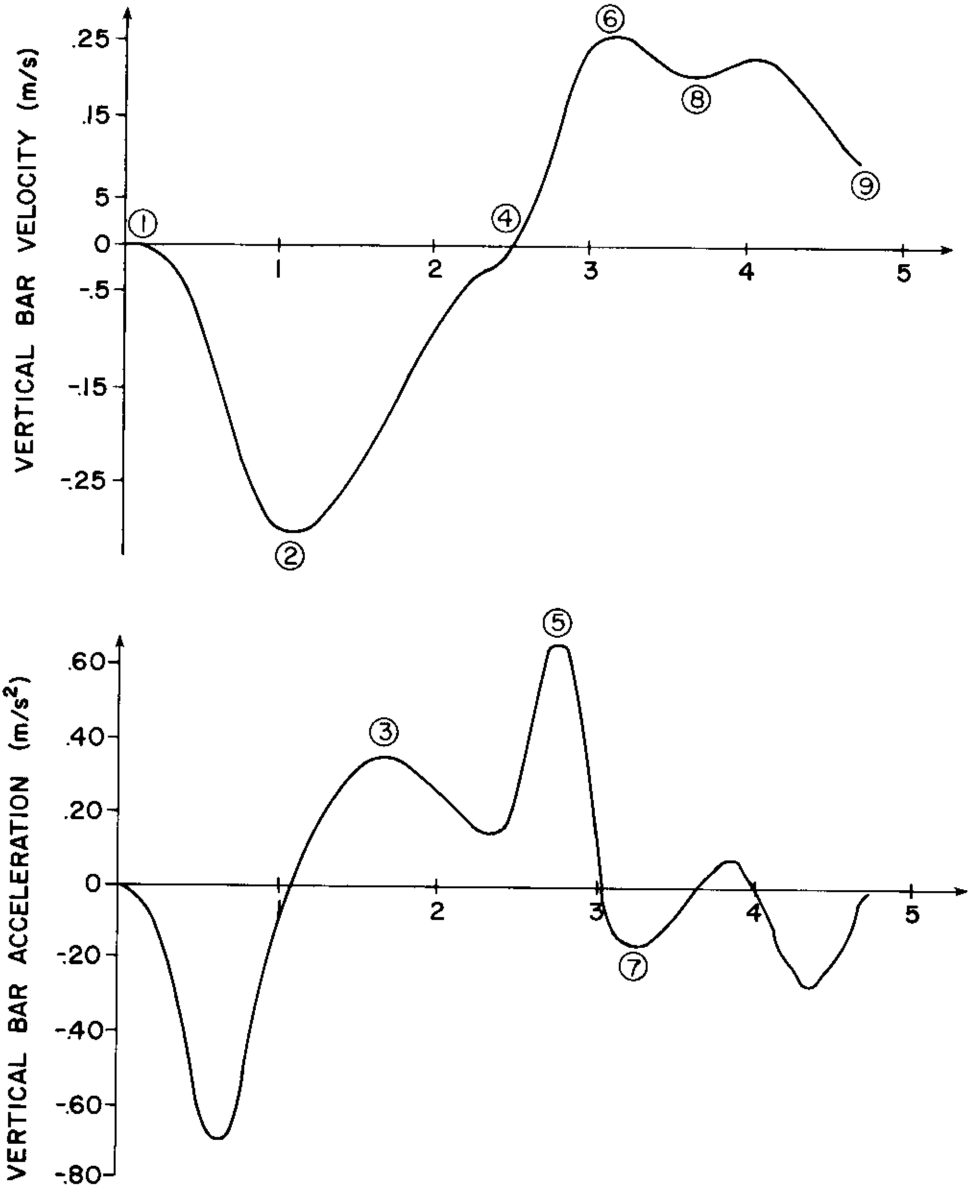

FIGURE 6. Typical bar velocity and acceleration patterns for the bench press performed by a competitive lifter. Numbered points defined in Figures 4 and 5. Madsen, N. and McLaughlin, T., *Med. Sci. Sports Exercise*, 16, 376, 1984. With permission.)

group had a greater range of motion for the thigh and shank and more forward torso lean during the lift. None of the skilled lifters generated a vertical bar acceleration greater than 0.41 m/sec during a lift, while several unskilled lifters had values more than twice as great. Typical durations from lift-off until completion of a lift were approximately 2 sec. Torques required at the hip, knee, and ankle were greatest at the start of the lift and were larger for the skilled lifters (means of 436, 44, and 190 N·m, respectively). Inertial effects were small in comparison to barbell mass and its lever-arm distance to the joints for torque calculations of both groups. The results of this study indicate that skilled deadlifters maintain a more upright posture during the lift, keep the bar as close to the body as possible so as to minimize

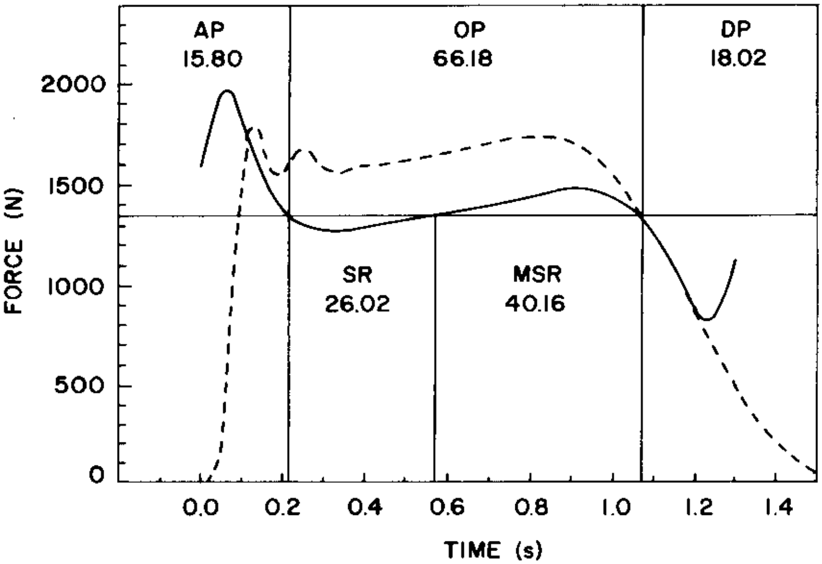

FIGURE 7. Mean applied force vs. time patterns for free weight (solid line ——, heavy weight condition) and "isokinetic" (dashed line - - slow speed condition) bench presses. Marked phases (AP, acceleration; OP, oscillation; DP, deceleration) and regions (SR, sticking, MSR, max strength) are percentages of the duration of the free-weight activity. (From Lander, J. E., Bates, B. T., Sawhill, J. A., and Hamill, J., *Med. Sci. Sports Exercise*, 17, 344, 1985. With permission.)

lever-arm distances, and apply a more consistant vertical force to the bar so as to minimize acceleration and inertial forces. These characteristics are similar to those noted previously for skilled squatters.[41,45]

D. Power Output

The mechanical power output produced by the body during execution of the above three weightlifting exercises, which are contested in the sport of powerlifting, has been calculated. Values are presented in Table 1 along with typical values for the two Olympic lifts. Power output is lowest for the bench press and greatest for the snatch and the clean. This is to be expected since the bench press involves the smallest muscle mass, while the Olympic lifts involve essentially the whole body and must be executed rapidly (also see Section IV). Another interesting consideration is the order of world-record weights lifted by heavy bodyweight athletes in these five lifts (essentially identical trends also exist for lighter bodyweight athletes). Using approximate values, the order is squat (1000 lb, 4450 N), deadlift (900 lb, 4050 N), bench press (700 lb, 3150 N), clean (600 lb, 2700 N), and snatch (465 lb, 2092 N). Excluding the bench press, the trend is higher power output for lower load lifted. Time of force application during the actual lifting phase of these movements also shows a trend with the Olympic lifts requiring 0.6 to 0.9 sec[66,67] and the power lifts approximately 2 sec.[45,58,59,65] Since the range of motion is greatest in the former and least in the latter lifts, it is evident from the definition of power (force × displacement/time) why the power output order is as listed in Table 1. Also note that vertical accelerations commonly occurring in the snatch and clean exceed 6 and 5 m/sec^2, respectively,[68,69] and result from applied forces far in excess of the static load value (F = W + MA, as discussed previously). On the contrary, accelerations measured for the competitive power lifts are near 1 m/sec^2 or less,[45,58,59,65] resulting in minimal inertial effects. With the exception of the bench press, the above lifts can be considered to involve the major muscle groups and segments (shank, thigh, and torso) of the body. The force-velocity relationship has been well supported for

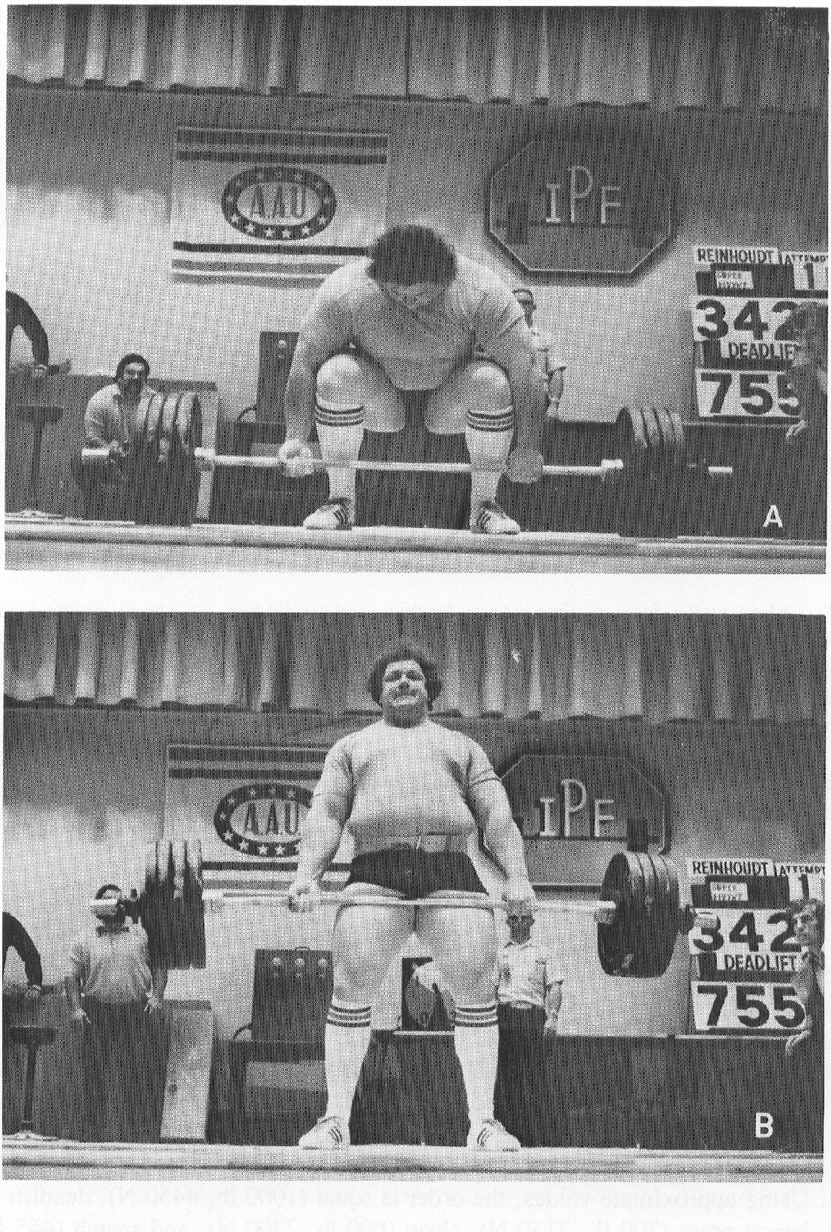

FIGURE 8. The deadlift exercise as performed in competition. (A) Just prior to the start of "lift-off", (B) finish of the deadlift (Photo by B. Klemens.)

in vivo single-joint human-muscle function,[28] and data supporting the extension of such a relationship for multijoint activities, are also available.[70-73] The above observations tend to lend further support to such a relationship.

Since power output capability is an important factor in most athletic performances, the above data provide some insights useful in developing a power vs. strength training program. The so-called "power lifts" actually are more strength dependent than the Olympic lifts, which are highly power dependent. Also, data provided in Table 1 and elsewhere[73-75] clearly indicate that power generated increases as an athlete executes any of the above lifts with less than a 1-RM load. Bench-press data [74] show an increase from 100 to 60% of a 2-RM load with a large jump between 85 and 80%. Data for the other four lifts cover smaller load

Table 1
POWER OUTPUT DURING EXECUTION OF SELECTED LIFTS

Lift	Subject	Power (W)	Ref.
Bench Press	Novice (60%—2 RM)	481	74
	Novice (85%—2 RM)	366	74
	Novice (100%—2 RM)	247	74
	Light novice	243	58
	Light elite	267	58
	Heavy elite	415	59
Deadlift	(Similar to squat values)		75
Squat	Heavy elite (93%)	1259	75
	Heavy elite	900	75
Snatch	Light elite (95%)	2821	73
	Light elite	2675	73
Clean	Heavy elite (92%)	3877	73
	Heavy elite	3413	73

Note: All values are for 1 RM unless listed otherwise. Values are for a specific elite athlete for each lift except bench presses which are group averages. All values, except bench presses, include horizontal work and work performed to elevate the body's CG.

ranges as occur in competitions when athletes are ''peaked'' for maximal performance and are allowed only three attempts at each lift.[73,75] Ueya and Ueya[76] have presented data showing a decrease in power output in the clean-and-jerk after substantial load decreases from maximum. Danoff [77] has shown peak power production to occur at submaximal loads during maximal efforts at elbow flexion. Current data are insufficient to determine the best percentage of 1 RM to train with in any given lift for any specific goal, but since variation in training stimuli is valuable,[3,39,78] it would seem reasonable to emphasize lifts in 70 to 90% of the 1-RM range for a balance of strength and power development. Higher intensities are highly stressful to the body and result in lower power output, while lower intensities will reduce the overload and stimulus for strength gains.

E. Assistance Exercises

The squat, deadlift, snatch, and clean lifts discussed above can be called primary or ''core'' exercises, since their execution requires a very large percentage of the body's muscle mass to be active. The bench press, behind-neck press, bent-over-row, and leg press are common weight-training exercises which involve several, but fewer, muscle groups and joints in movement patterns that relate well (kinesiologically) to many everyday activities. Still other overload exercises isolate muscles and single joints and can be called assistance exercises, since they generally contribute to specialized needs, such as forearm strength for a tennis player or rehabilitation of an injury. As examples of this type of exercise, arm curls, leg extensions and curls, and sit-ups, will be discussed.

1. Arm Curls

Arm curls are extremely popular among male trainees due to the enhanced size and shape of flexor muscles in the upper arm that results from their use. Hay et al.[13] have biomechanically analyzed two common methods of arm curls performed with the upper arms resting on an inclined support (''preacher bench''). A barbell and a Universal® DVR (see Section II. A) curl machine were the equipment used for three speed and three load conditions. Details of the equations of motion used in the analyses were provided. The loads used (40, 60, and 80% of 4 RM) were found to affect the magnitudes of elbow torque required during the curls, but not the shape of the torque curves. Differences in physical size of the three subjects also had little effect on the shape of the torque curves (values given below are for the middle-sized subject, 1.83 m tall, 841 N bodyweight).

Movement speed (1-, 2-, or 3-sec concentric and 2-sec eccentric phases) and equipment type, had considerable effect on the elbow-torque curves. Barbell curls required an elbow-extensor torque in the region of maximal elbow flexion (60 to 120 N·m) and required the greatest flexor torque (100 to 140 N·m) in the region of maximal elbow extension. The fastest speed of execution required greater torques at the extremes of movement range, but similar torques compared with slow and medium speeds in the mid-range of motion. DVR machine curls resulted in an almost constant elbow-flexor torque (80 N·m) for slow and medium execution speeds, but oscillating values (0 to 100 N·m) for the fast speed. Extensor torque did not develop with the DVR machine. Since skeletal muscle can produce lower maximal forces at higher contraction rates, it was argued that the fast curling speed provided greater overload (absolute and relative to maximal capability). This is true, but injury potential is also increased with speed, especially at the extremes of motion when elbow-torque values were greatest. This is especially true with ''preacher bench'' curls since the upper arms are in a fixed position. A standing barbell curl may be safer for fast curling speeds since the torso and upper arms can move to absorb kinetic energy at the extremes of motion. Such ''body swing'', however, is often used to initiate the curl motion and thus reduces flexor muscle range of involvement.

Comparison of the two types of equipment at any given speed was difficult and no definitive choice of one over the other could be made. The barbell required greater torque in the region near full extension, while the DVR machine maintained a flexor torque in the region of full flexion when the barbell created the need for an extensor torque. As stated in Section I.A, a modified free-weight design may soon be marketed which minimizes the shift toward elbow extensor torque in the range of full flexion during a barbell curl.[14]

2. *Leg Extensions and Curls*

Leg extensions and curls can be performed with a variety of equipment. These exercises work the knee extensors (quadriceps) and flexors (hamstrings) respectively. Probably the oldest equipment used for these exercises is some form of weighted boot attached to the foot or ankle region. Leg extension and curl machines are now more popular, with the original design being a flat bench with a padded lever arm rotating from one end. Free-weight plates are attached to the lever which is forced to rotate by muscular exertion of the trainee who has his or her knee joint(s) aligned with the lever axis and, applies force to the pad in the ankle region. Countless design modifications now exist, such as leg curl bench surfaces equipped with an inclined and declined section to tilt the pelvis posteriorly and provide the hamstrings with a mechanically more advantageous angle of pull. Some newer machine designs, such as compressed air cylinder and isokinetically controlled machines, permit leg extensions and leg curls to be executed continuously from the same seated position. An important property of the ''free-weight'' leg extension machines is that they provide almost no resistance at the start of movement, since gravity pulls straight downward on the weight plates which hang directly below the lever-arm pivot. As movement occurs, the lever-arm of the weights relative to the pivot increases and so does the joint-torque required to continue the movement. This pattern of increasing overload may be desirable in some rehabilitation situations. However, such a pattern does not exercise the involved muscles efficiently through much of the range of motion. To reduce this inefficiency, cables and pullies were added by many machine companies so that the resistance was more evenly distributed through the range of motion. A design common to several popular brands of machines provides the greatest resistance at the start of motion and a slowly decreasing resistance as the movement continues. These different loading properties based on machine design can be very important relative to the stresses placed on the muscles and joint structures and the specific strengthening effects obtained. It should be noted that basic mechanical equilibrium considerations show that a large shearing-force component is required at the knee toward completion of a leg extension on these machines. Such considerations are often discussed in books on therapeutic exercise.[79]

3. Abdominal Exercises

Sit-ups and other common exercises used to strengthen the abdominal muscles have been studied in considerable detail. Rasch and Burke[80] have summarized the findings of several EMG studies performed in the 1950s. The first part of the sit-up exercise (spinal flexion) is called a trunk curl and it activates the upper rectus abdominis and to a lesser extent the obliques. If resistance is held in the shoulder area the greatest increase in activity occurs in the obliques and lower rectus. The following phase of the sit-up is a flexion of the hips and involves the abdominals only isometrically. Hip flexor muscle activity increases if the feet are held down, while abdominal activity increases if they are not. It is recommended to keep the knees and hips flexed (hook lying position) when performing sit-ups as opposed to extended (long-lying supine position). This position results in an improvement in the mechanical advantage of hip flexor muscles and a decrease in their length, both of which can reduce the tension generated. This is desirable, since excessive pull of the rectus femoris and the illiacus may tilt the pelvis anteriorly causing accentuated lumbar curvature, which may add to a spinal hyperextension effect (psoas paradox) resulting from the direct pull of the psoas major. These undesirable effects may be minimized by strong abdominals which can resist the anterior tilting of the pelvis. Unfortunately, many people with weak abdominal musculature perform full sit-ups to strengthen this muscle group, but soon develop low back pain. Thus, it is reasonable to suggest bent-knee trunk curls as a productive means of strengthening the abdominal muscles without the risk of aggravating the lowerback complex. Similar concerns exist about other common abdominal exercises, such as leg raises, which are primarily hip flexion exercises. Any torso-twisting motion that is added to a trunk curl or sit-up exercise will increase the activity of the internal and external oblique muscles.

The above recommendations are supported by a recent study of four types of sit-up exercises.[81] All resulted in a ''hollowing'' under the lumbar spine at the start of movement due to forward (anterior) pelvic tilt. The trunk-curl movement resulted in the greatest abdominal muscle activity during the initial 40 to 50° of torso flexion. From the above information it is strongly suggested that a conscious effort be made at the start of sit-up exercises to keep the abdominal wall flat by contraction of all four abdominal muscles, which will minimize forward pelvic tilt and lumbar hollowing (hyperextension). The importance of intra-abdominal pressure (IAP) to lumbar support during lifting and its relationship to abdominal muscle strength and activity, has been supported in many studies.[82,83] IAP effects must be incorporated into future weight-training exercise models.

IV. OLYMPIC-STYLE WEIGHTLIFTING

The biomechanical literature available on Olympic-style weightlifting is much more extensive than that on other lifting exercises. Three papers written from 1979 to 1980[73,84,85] contain reviews of considerable detail on weightlifting biomechanics (note that publication of Garhammer and Hatfield[84] was delayed 5 years and that it contains numerous typographical errors, since an opportunity for proofreading was unfortunately not provided). An additional, but shorter review was written in 1983.[86] Rather than repeating this information it will be

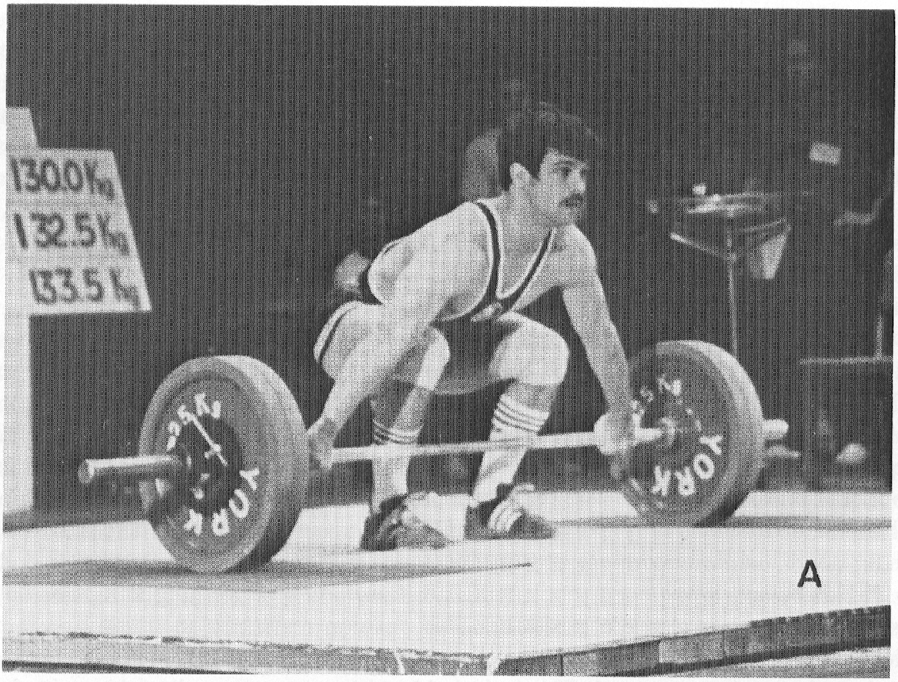

FIGURE 9. The snatch lift as performed in competition. (A) Start position just prior to "lift-off" or start of the first pull; (B) mid-way through first pull; (C) end of first pull; (D) end of shift, transition or "scoop" phase; (E) top pull position (end of second pull or jump phase); (F) catch or receiving position; and (G) finish. (Photo by B. Klemens. From *Weightlifting USA*. With permission.)

summarized within the current review, which will emphasize other and more recent work, a synthesis of available knowledge in the field, and recommendations for future work.

The two movements now contested in weightlifting are the snatch and the clean-and-jerk lifts (cf. Figures 9 and 10). The snatch requires a barbell to be lifted from the floor to straight arm's length overhead in one continuous motion and is sometimes referred to as the single movement lift. The clean-and-jerk is a double-movement lift where the barbell is first lifted from the floor to the shoulders in one continuous motion and then jerked to straight arm's length overhead using primarily leg and hip thrust. These lifts are done very rapidly with less than 1 sec being used for the propulsion phase of any of the movements. Due to the explosive strength (muscular power) required to perform these lifts they are often used in training by athletes in other sports involving "explosive" actions such as throwing (shot put and hammer) and jumping (volleyball and high jump). Subdivisions of the complete lifts (e.g., high pulls and push jerks) are often described in more detailed weight-training books,[3,39] and are also sometimes used in general strength-training due to the large muscle mass employed and the speed factor.

A. Data on Elite Lifters

An obvious first biomechanics question concerns the kinematics of these lifts as performed by world-champion athletes. Extensive data of this type are available from several sources. The Soviet Union has the largest population of competitive weightlifters and it is not uncommon for eight or nine of the top ten lifters in the world in a given bodyweight division to be from the U.S.S.R. Dr. Yessis has translated countless reports written by Russian weightlifting authorities on analyses of top athletes' training methods and lifting techniques. Many of these contain detailed information about the kinematics (and some kinetics) of one or more lifts performed by specific world champions.[87-97]

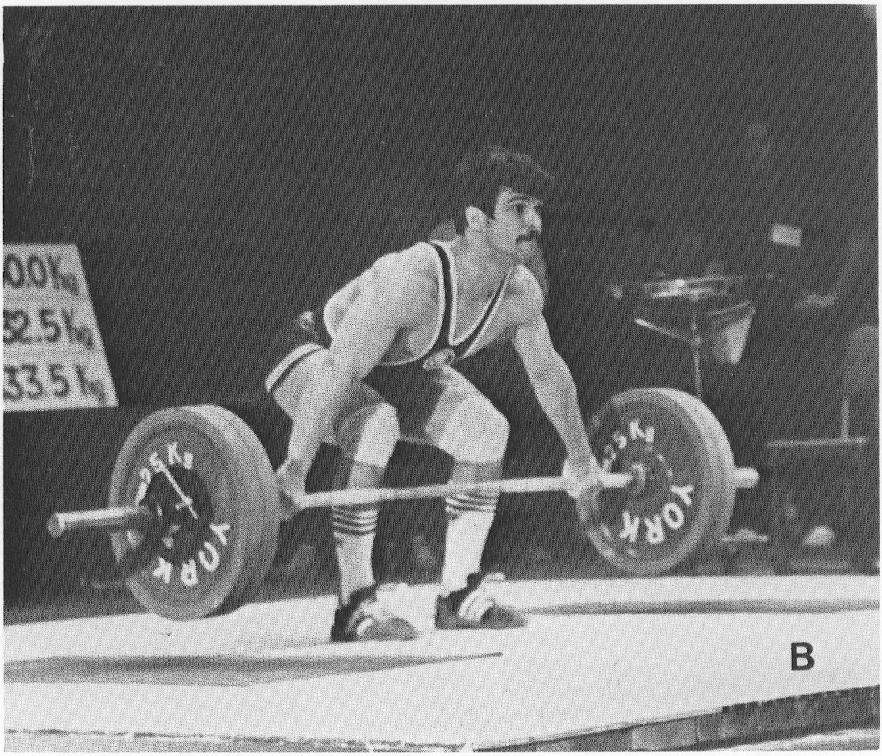

FIGURE 9B.

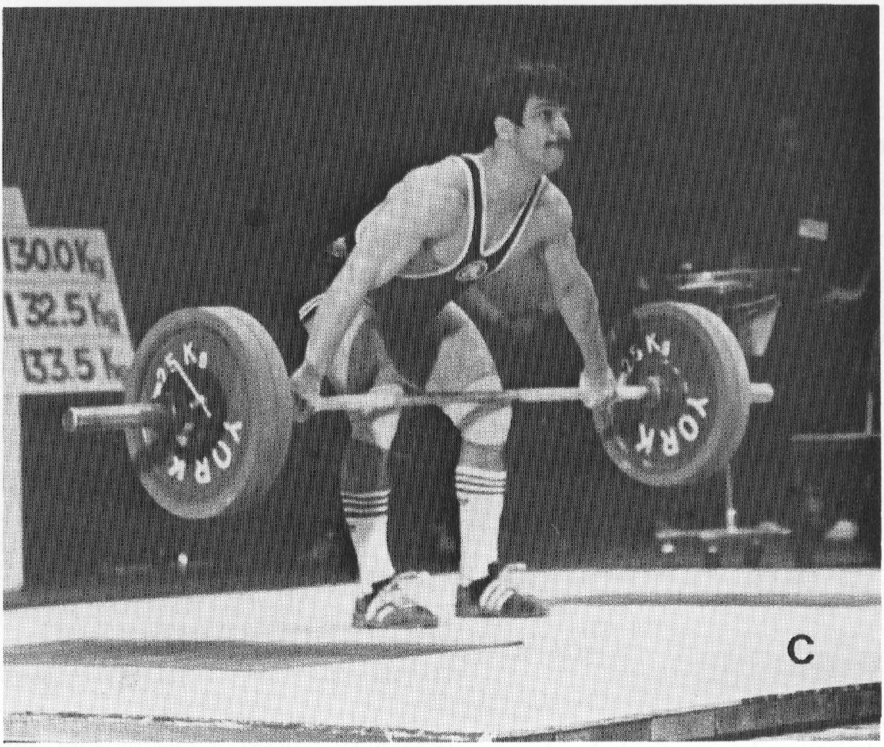

FIGURE 9C.

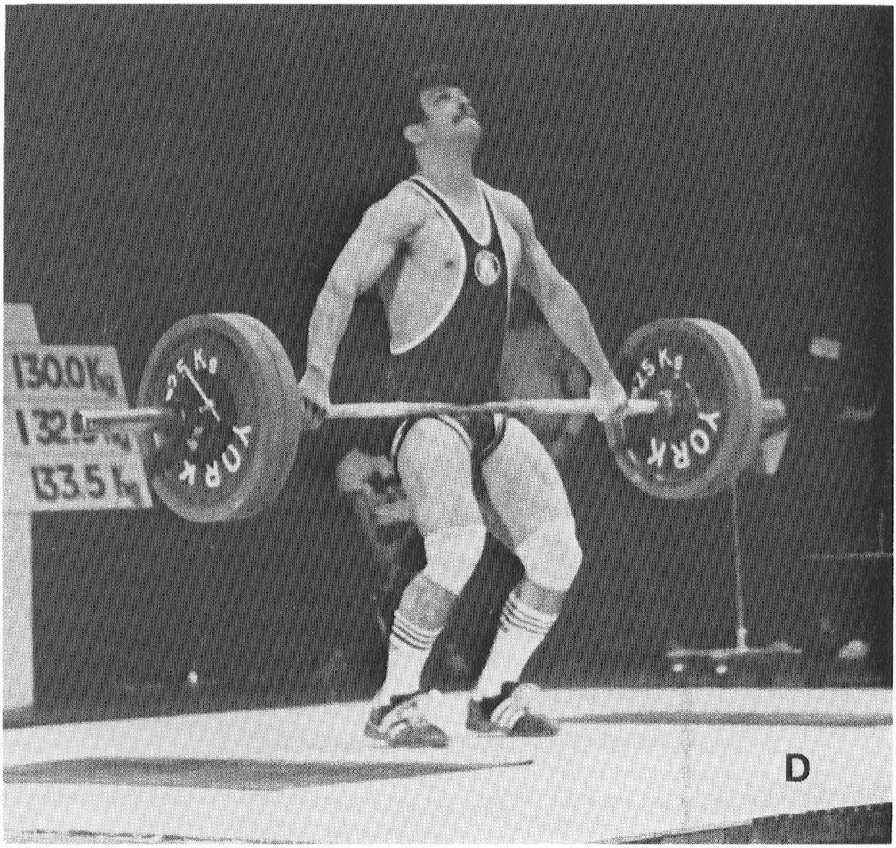

FIGURE 9D.

Recent articles,[87,88] for example, contain the following information on world-record holder U. Zakharevich: height and foot length; sequential photos, and stick-figure representations of key positions during the execution of a world-record snatch (192.5 kg), including joint angles and torso inclination; detailed figures and data tables describing horizontal and vertical bar position (trajectory), and velocity during the third attempt at a world-record lift, a lighter first attempt lift (188 kg), and a missed second attempt at the world record, and durations to a hundredth of a second for all key phases of the lift from prior to lift-off until bar fixation overhead. Discussion includes a comparison of these parameters for the above three lifts.

An additional source of such information is a published collection of approximately 30 individual analyses of world-champion lifters performed by the Soviet experts Roman and Shakirzyanov.[98] *U.S.S.R. Weightlifting Yearbooks,* which generally contain biomechanical data as well as detailed training and technique information, have also been translated and are readily available.[99] Translations from Russian on biomechanical considerations of other specific lifting topics, have been published.[100-105]

Individual authors from other countries have also analyzed world champions and world-record lifts.[67,73,106-113] The parameters studied by these researchers varied, but included bar trajectory,[67,73,106,108,111,113] bar velocity, [67,73,106,108-112] joint- and body-segment angles, [73,107,112] and work/power output.[67,73,106,108-111]

B. Bar-Trajectory Data

Bar-trajectory data, particularly when coupled with bar-velocity data, are very informative about an athlete's technique in the snatch and clean movements. Detailed discussion of a

FIGURE 9E.

variety of observed trajectory patterns and a recommended optimal ("rational") pattern, has been given by Vorobyev.[114,115] The optimal pattern consists of initial bar movement after lift-off being toward the lifter (4 to 6 cm) followed by movement away from the lifter, crossing a vertical-reference line passing through the position of the bar prior to lift-off. Movement is then essentially straight upward (during the mid- and final part of the second pull; see below) until the bar hooks back toward the lifter (again crossing the vertical-reference line) and descends as the athlete rapidly moves under the barbell to catch it (see Figure 11).[96,97] Numerous world-record lifts have been found to follow this "rational" pattern (e.g., a clean by Rusev[111] and a snatch by Blagoev,[108] both representing Bulgaria), but many others have not.[87,88] This latter lift followed the most common deviation from the "rational" pattern. The trajectory of Figure 11 is tilted to the right so that the bar-path never crosses the vertical-reference line, and is caught farther back from the initial horizontal position than with the optimal pattern. Such a pattern is most likely caused by premature movement of the shoulders to a position behind the bar during the second pull.[114,115] Although some discussion has been published concerning the effects of relative segment lengths (arm, torso, thigh and shank) on lifting technique[115] much more work is needed, particularly employing mathematical optimization methods.

C. Film Analysis and Computer Modeling

The biomechanical techniques most commonly used to study weightlifting are film analysis, EMG, and force-plate measurement. In addition to many of the studies cited above

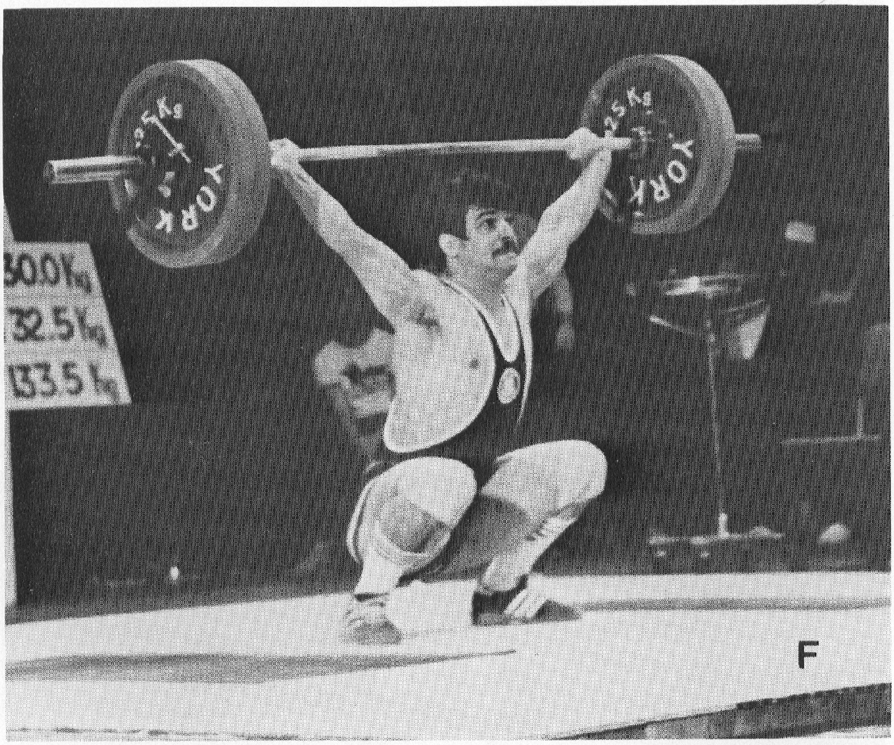

FIGURE 9F.

which employed film-analysis methods, many others have been published which include varying levels of detail and sophistication and subject skill level. Some of these involved comparisons of subjects representing different skill levels and are discussed in Section IV.G. Others simply noted technique characteristics and discussed them relative to mechanical principles and coaching standards.[116-119] Still others utilized rigid-link modeling methods and input data from film analysis to estimate joint-forces and torques. One study[120,121] showed that torque patterns at the knee and hip were distinct for two different lifting styles — the "double knee bend" (DKB, see below) and a style emphasizing hip extension ("frog-leg pull"). By comparing these torque patterns with the corresponding bar-acceleration patterns, it was evident that the former style depended mainly on knee extension to accelerate the barbell during the second pull.

A slight modification of the above modeling technique permitted estimation of the tension in the patellar ligament at rupture during a jerk attempt by a highly skilled lifter. The value was 17.5 times the athlete's bodyweight.[122] In the analysis of Dahlkvist[46] one subject (No. 3) was very similar in size to this injured athlete and was found to have a patellar ligament tension of approximately 3 times bodyweight at 90° of knee flexion (position of injury occurrence) and a maximum of approximately 6 times bodyweight at maximum knee flexion (50°) during a fast squat descent with no load.

The DKB style involves a rebending of the knees after the barbell has been lifted from the floor to just above knee level (first pull). During this second knee bend, the torso rotates to a more vertical position for the final knee extension (second pull), which leads to the top-pull (full extension) position just before the lifter moves under the bar to catch it (cf. Figures 9 and 12). Enoka[123-126] has analyzed the DKB and shown that it permits re-employment of the powerful knee-extensor muscles through their strongest range of motion. Elastic-energy storage and stretch-reflex facilitation of the final knee extension, may also

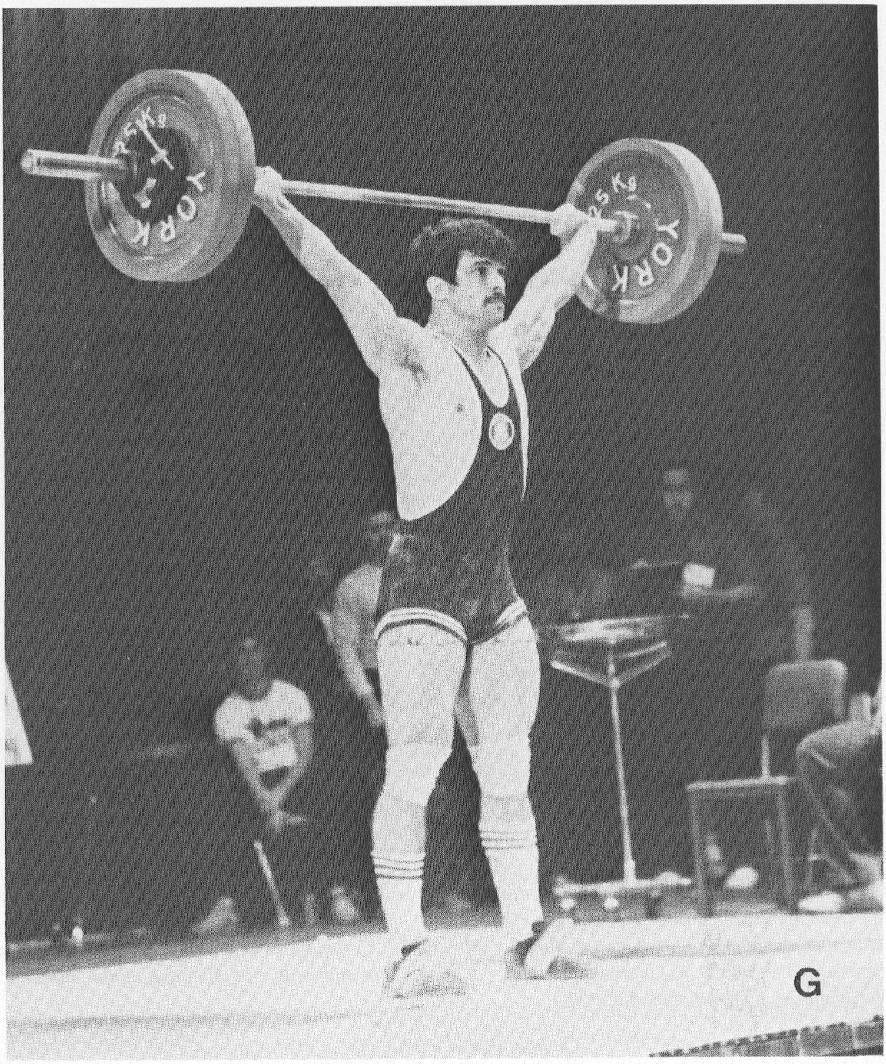

FIGURE 9G.

be very important aspects of the DKB technique. Modeling of the torso, which included consideration of IAP effects, provided evidence that the DKB greatly reduced stress on the lumbar spine.[123,124]

Hall[127] has used rigid-link modeling methods to estimate the net forces and torques acting at the base of the lumbar spine during clean-and-jerk exercises performed at three load and speed conditions. The subjects were not highly skilled due to the low loads lifted (40, 60, 80% of 1 RM, which was less than bodyweight) and IAP effects were not considered. Results, however, were consistent with those found for similar conditions with lifts previously discussed; mechanical stress on the lumbar spine increased with load, speed of movement, and forward torso lean.

D. EMG Studies

Cerquiglini and co-workers[128] used both EMG and phonomyography to study selected muscle activity in weightlifters. Spectral analysis of both signals showed differences between novice and experienced lifters. After a period of training, amplitude and higher frequency

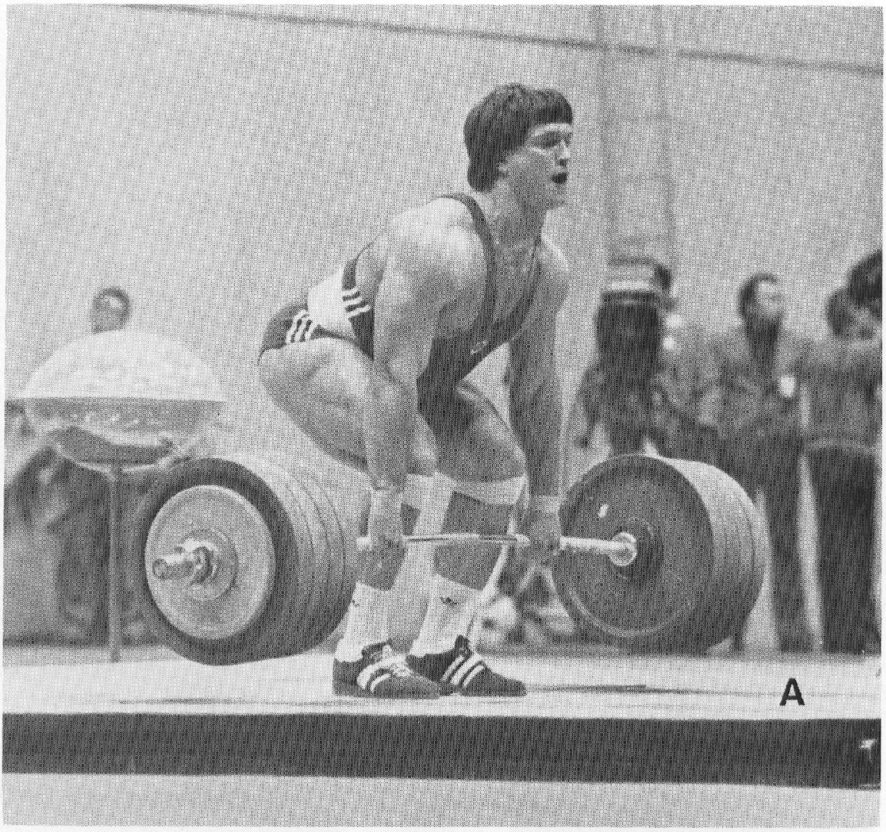

FIGURE 10. The clean-and-jerk lift as performed in competition. (A) Middle of the first pull after ''lift-off''; (B) end of first pull; (C) end of shift, transition or ''scoop'' phase — start of second pull; (D) catch or receiving position for the clean; (E) preparation position for the jerk; (F) lowest point of the dip prior to the upward thrust to jerk the barbell overhead; (G) catch or receiving position for the split jerk; and (H) finish. Photo by B. Klemens. From *Weightlifting USA*. With permission.)

content increased for the former group. This may have been related to enhanced recruitment of fast-twitch motor units, but it was not discussed by the authors. They did, however, suggest that the acoustic signals could be used for ''feedback'' to aid the lifter in learning proper technique.

Lehr and Poppen[129] used EMG to compare one skilled lifter with two less-skilled lifters during execution of the squat and power cleans. Clear differences were found between the two types of cleans as well as between skill levels. A similar study[130] involved 17 subjects of varying ability lifting 60, 80, and 95% of 1 RM in the clean-and-jerk. Differences in muscle activation patterns were again found relative to load and skill levels. In both of these studies, EMG patterns were clearly related to the major phases of the lifting movements performed.

Cameron[85] analyzed the clean pull via synchronized EMG and cinematography. Segment kinematics and electrical activity of four muscles were determined for groups of highly skilled and less-skilled subjects while cleaning 85% of 1 RM. The former group was found to follow a movement sequence that resulted in greater extension of the body (higher center of gravity [CG] position at top pull) and superior leverage for the hip and lumbrosacral joints relative to the latter group. They also exhibited different electrical-activity patterns in selected muscles and lower overall EMG activity despite lifting heavier weights. Thus, the highly skilled group seemed to be more efficient in using their muscle activity and leverages.

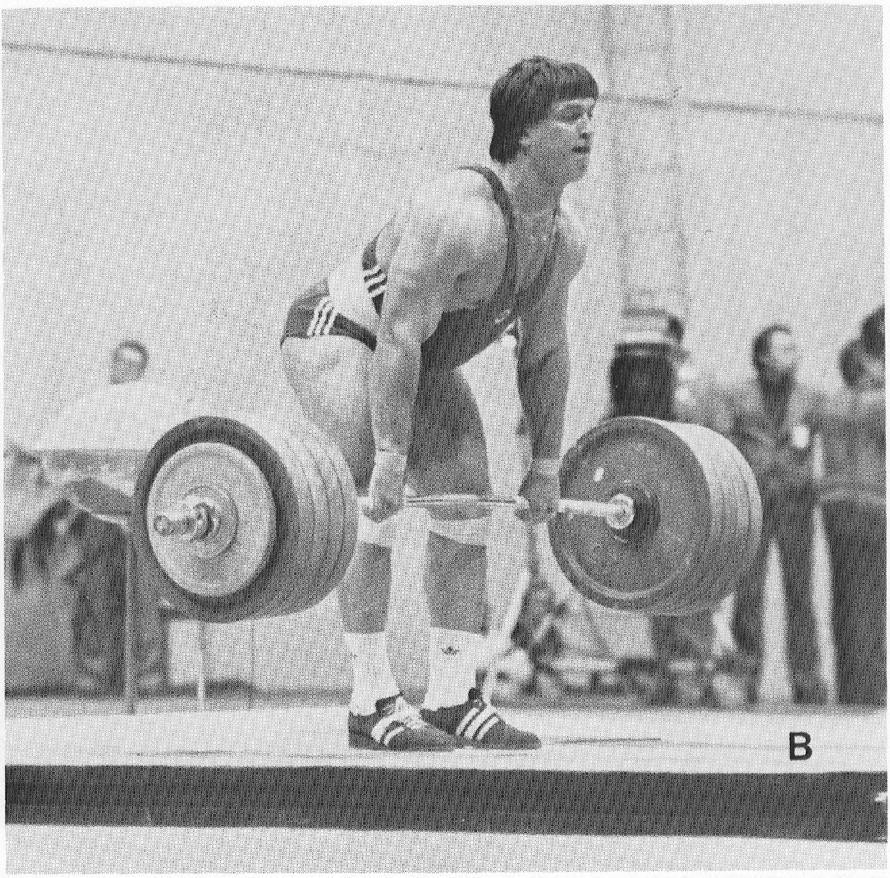

FIGURE 10B.

An interesting hypothesis was made by the author that differences in the movement sequence/pattern betweeen the two groups may have been due to differences in the percentage of bodyweight being lifted. The CG trajectories of the body alone were different, but not those of the combined body-barbell system. Movement sequence/pattern differences may have been a manifestation of attempts by both groups to be more efficient in raising the combined CG of the system. This could be a very enlightening area of study, and Nelson and Burdett[110] have provided some pertinent isolated and combined CG movement data across bodyweight divisions, but did not compare skill levels nor address the above hypothesis.

Connan and co-workers[131] performed a complex analysis of the snatch lift using video, film, EMG (eight muscles), and force-plate records. Three skill-level groups were used and loads lifted ranged from 50 to 95% of 1 RM. Pull height and maximal first-pull velocity decreased with increasing load for all subjects. Variations in EMG patterns decreased for all skill levels as load increased. It was suggested that training resulted in learned muscular patterns needed to lift heavy loads which are not readily adapted to lighter loads. If this is correct it would indicate that excessive training with too light a load could be detrimental to maximal performance. The authors also stated that variations in barbell kinematics and ground-reaction forces resulted more from load changes than from body segment movement/pattern alterations. This could relate to Cameron's hypothesis discussed above. Some additional EMG data are available in other references[143,146] and are discussed in Sections IV.F and IV.G.

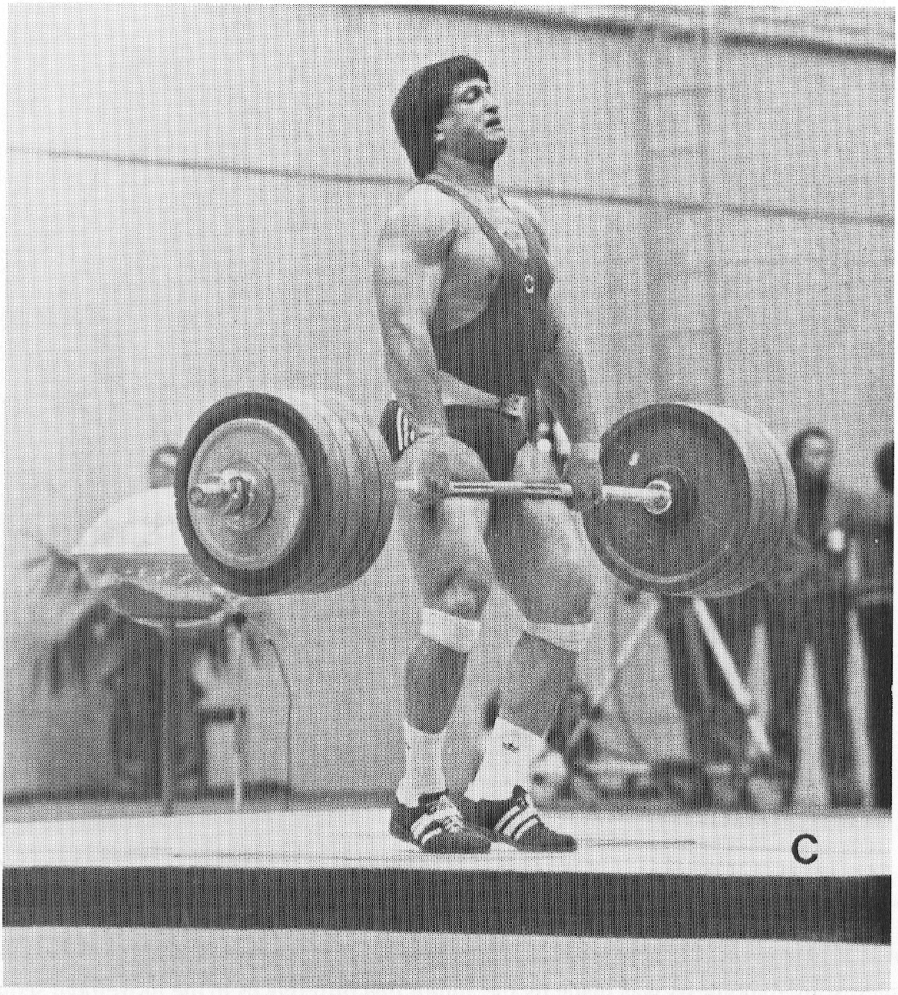

FIGURE 10C.

E. Force-Plate Studies

Payne et al.[132] obtained force-plate data for a number of athletic activities in 1968. These included a power clean-and-press, snatch, and clean-and-jerk for a single experienced lifter. One of the more interesting findings, though not discussed by the authors, was the existence of two vertical ground-reaction force peaks separated by an ''unweighting'' period during a snatch and power clean pull. This is what is seen with a DKB pull — a technique not commonly taught until the 1970s. Enoka[123-125] has documented and discussed vertical ground-reaction force during the DKB in detail (see also Figure 12).

Garhammer[133] utilized force-plate measurements to study the movement of the center of pressure (CP) on one foot during snatch lifts. For most subjects CP was found to move rapidly from the ball-of-foot/mid-foot area to the heel and back toward the toes during the transition from the first to the second pull. This CP movement was related to use of the DKB pulling method and seemed to be quantitatively related to the extent of horizontal bar movement during the pull. One subject who had difficulty in completing his lifts had a straighter bar trajectory and little movement of the CP from the ball of his foot. Data presented in other studies using a force plate show that extensive anterior-posterior CP shifts take place during snatch and clean pulls,[76,134] but the authors do not discuss this parameter.

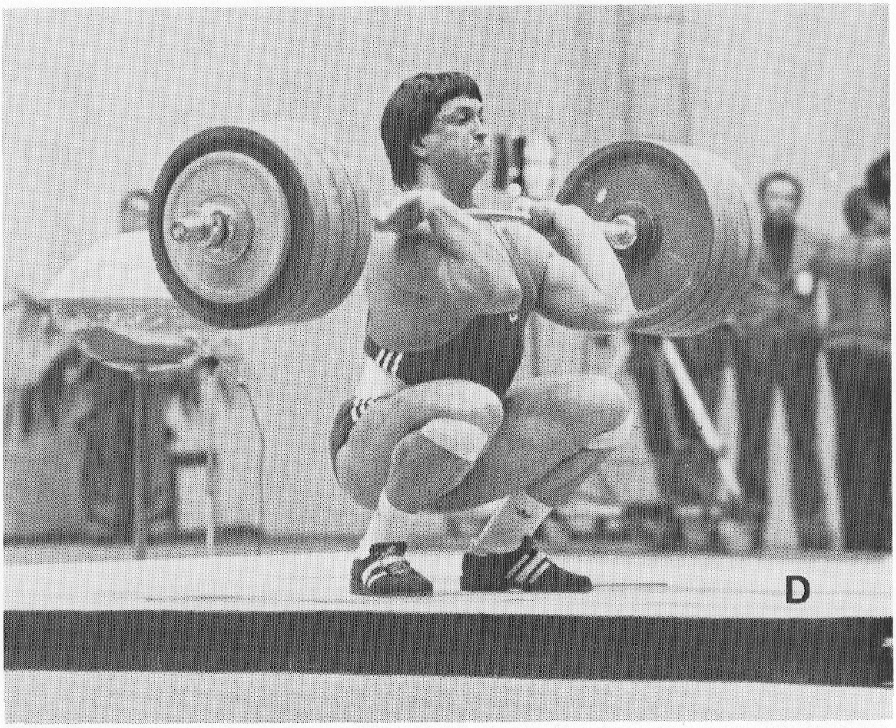

FIGURE 10D.

In an effort to gain more insight into the possible connection between bar trajectory and CP movement, Garhammer carried out additional force-plate work with highly skilled subjects from various bodyweight divisions performing both snatches and cleans.[135,136] Lifts were done with both feet on the plate, and minimal lateral CP movement indicated symmetrical force application.[108] Extensive anterior-posterior CP movement was again found with the pattern being similar to that previously noted.[133] Posterior CP movement during the first pull correlated to movement of the bar toward the lifter both temporally and in magnitude. Anterior CP movement during the transition to, and early part of, the second pull preceded forward bar movement and had some relationship to its magnitude. CP movement pattern consistency was excellent for a given athlete in a given type of lift. It was suggested that coaches consider teaching pulling techique in terms of interrelated horizontal barbell and anterior-posterior CP movement.

Vertical jumps have an ''unweighting'' phase (countermovement) and thrust phase.[52] This is also true of DKB pulls.[123] The ground-reaction force patterns for these activities have been compared temporally and in magnitude.[137] Similarities were noted, particularly when one subject performed both activities. The maximal force generated was found to decrease as the percentage of maximal effort increased. However, longer force durations at submaximal levels resulted in larger impulses for greater efforts. The use of DKB pulls was recommended for jump training due to the kinetic and temporal similarities found. Similarities of the leg and hip action as used in the DKB pull to leg and hip action in a number of other sport activities, have been pointed out by Miller.[138]

F. Work, Energy, and Power Output

As noted in Section III.D the competitive Olympic lifts are performed rapidly and require a large power output. The power output during a single clean was reported in 1958 as approximately 1940 W (2 hp).[139] The next consideration of work-related parameters in

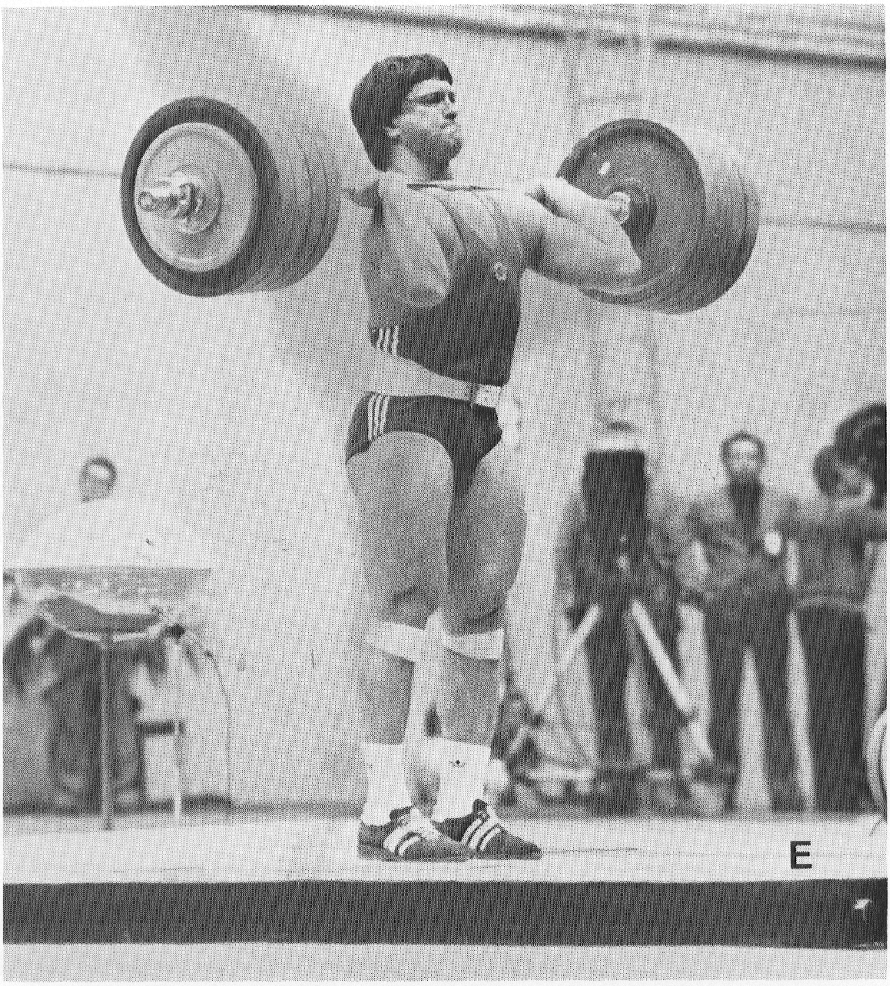

FIGURE 10E.

weightlifting appears to be by Ranta,[140] who developed an objective evaluation scale based on the work-energy principle to compare lifters of different bodyweights. Soon thereafter, Nelson and Burdett[110] published time-, displacement-, work-, and power values obtained from film of world-class lifters performing at an international meet. Power values ranged from approximately 1400 W in the lightest weight class to nearly 3000 W in the heaviest. Their most interesting finding was that average power output in the snatch-and-clean pull was very similar for a given athlete. This observation was supported and extended to other groups of movements by later research.[66,67] The high-skill level and inclusion of work done in lifting the body's CG resulted in these higher values relative to the 1940-W value cited above.

Garhammer[141] modified and extended Ranta's application of work-energy concepts to weightlifting and used the resulting methodology to make precise power-output calculations for five different lifting movements.[66,67] Values obtained were much higher than previously determined and reached approximately 4000 W for complete pulls by heavier lifters and approximately 6000 W for second pulls and jerk thrusts. This calculation technique has been applied to many groups of lifters with similar results.[73,106,108,109,111] When referenced to body weight, power values generally fell in the range of 31 to 37 W/kg for complete pulls by

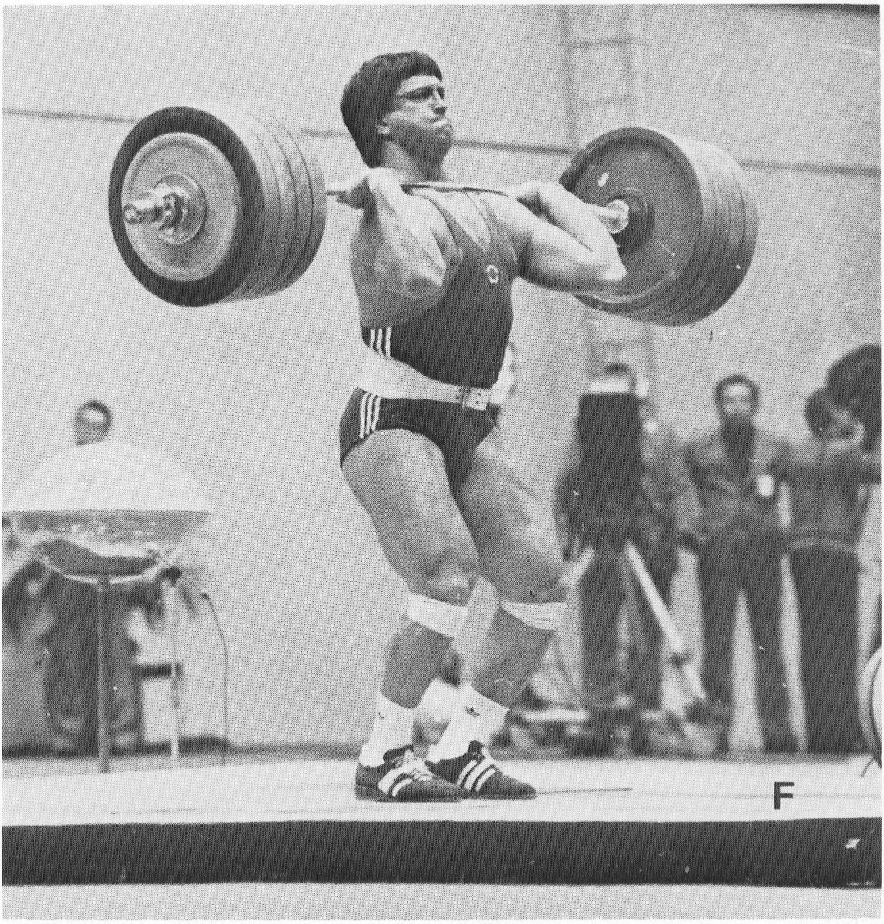

FIGURE 10F.

elite lifters. Second pull- and jerk-thrust values were in the range of 45 to 60 W/kg. These magnitudes are near maximal theoretical values for humans.[73]

Previous discussion (Section III.D) pointed out that power output increases as the load lifted decreases from the 1-RM value. Other studies, though not actually calculating power, have provided data that are indicative of this inverse relationship. Campbell et al.[142] found that maximum bar height and velocity decreased as the load for power cleans increased from 40 to 80% of 1 RM (also see Conan et al.[131] discussed in Section IV.D). Hakkinen et al.[143] found that for both Finnish national level and district-level lifters increasing loads in the snatch-and-clean resulted in lower peak ground-reaction forces (GRF) (in agreement with Garhammer and Gregor[137]), lower barbell velocities, and lower maximal barbell heights.

One paper has analyzed the development pattern of energy in body segments and its transfer between segments and to the barbell during snatch and clean lifts performed by elite athletes.[144] The results provided insights relative to the time-course of dominant muscle group action at the joints and the magnitude and temporal characteristics of energy flow. The method used showed potential as a means of quantifying lifting technique and evaluating rehabilitation exercises and lifting tasks in industry.

G. Comparative Studies

A number of investigators have compared lifters of different skill levels or have compared

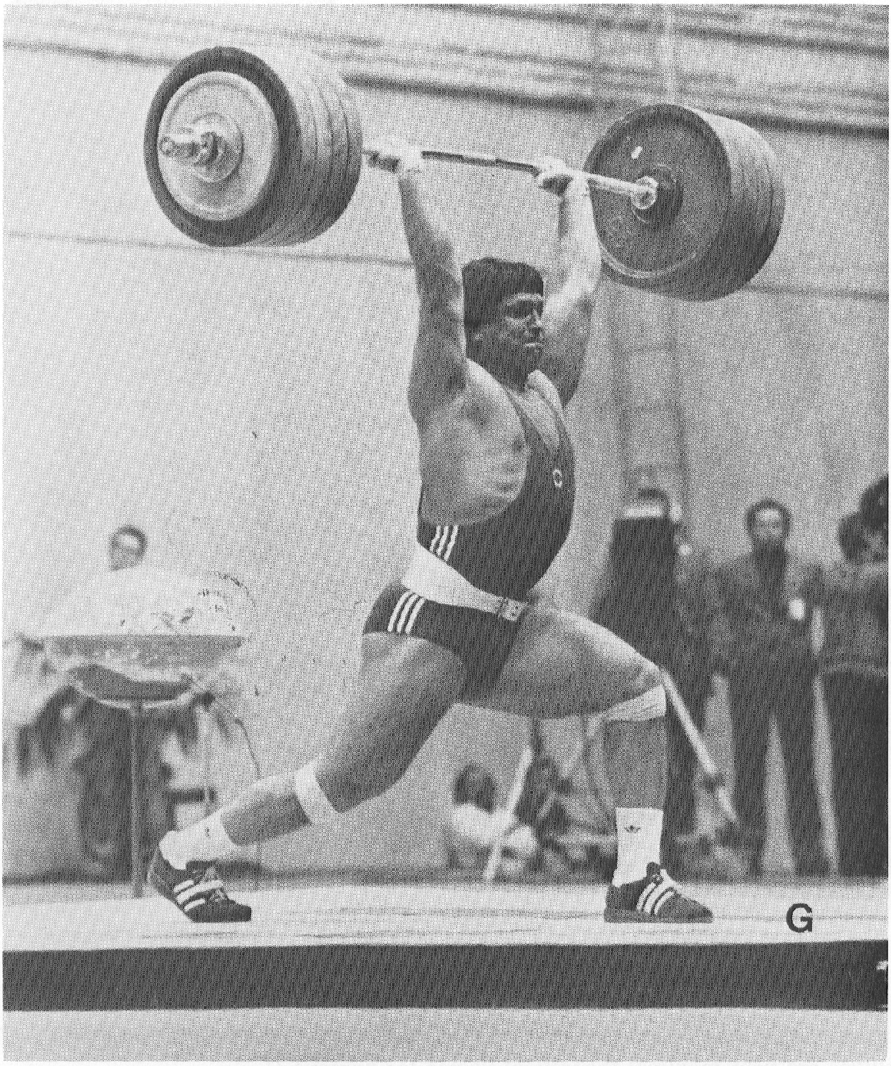

FIGURE 10G.

the kinematics of successful vs. unsuccessful lifts. Comparisons of the former type using EMG, were covered in Section IV. D.[85,129] Kinematics derived from film in various studies showed that some or all of the following characteristics were exhibited by the higher-skilled athletes during the snatch and/or clean[107, 111-113,145,146] (1) faster movement during one or more phases of the lifts (opposite of what was found for higher- vs. lower-skilled powerlifters, see Sections III.A to III.C); (2) greater body extension during the pull; and (3) lower peak bar height relative to body size. In addition, Kauhanen et al.[146] noted greater relative maximal GRFs during each major phase of a lift for the elite vs. district level athletes. They also found correlations between neuromuscular performance parameters (e.g., isometric force level generation times and CG rise in drop jumps) and lifting ability. A report comparing American champions with world champions,[111] showed that the latter group produced higher power outputs, and had greater consistency in power output for similar lifting movements and in the duration of the pull from "lift-off" until maximum bar velocity and bar height were attained.

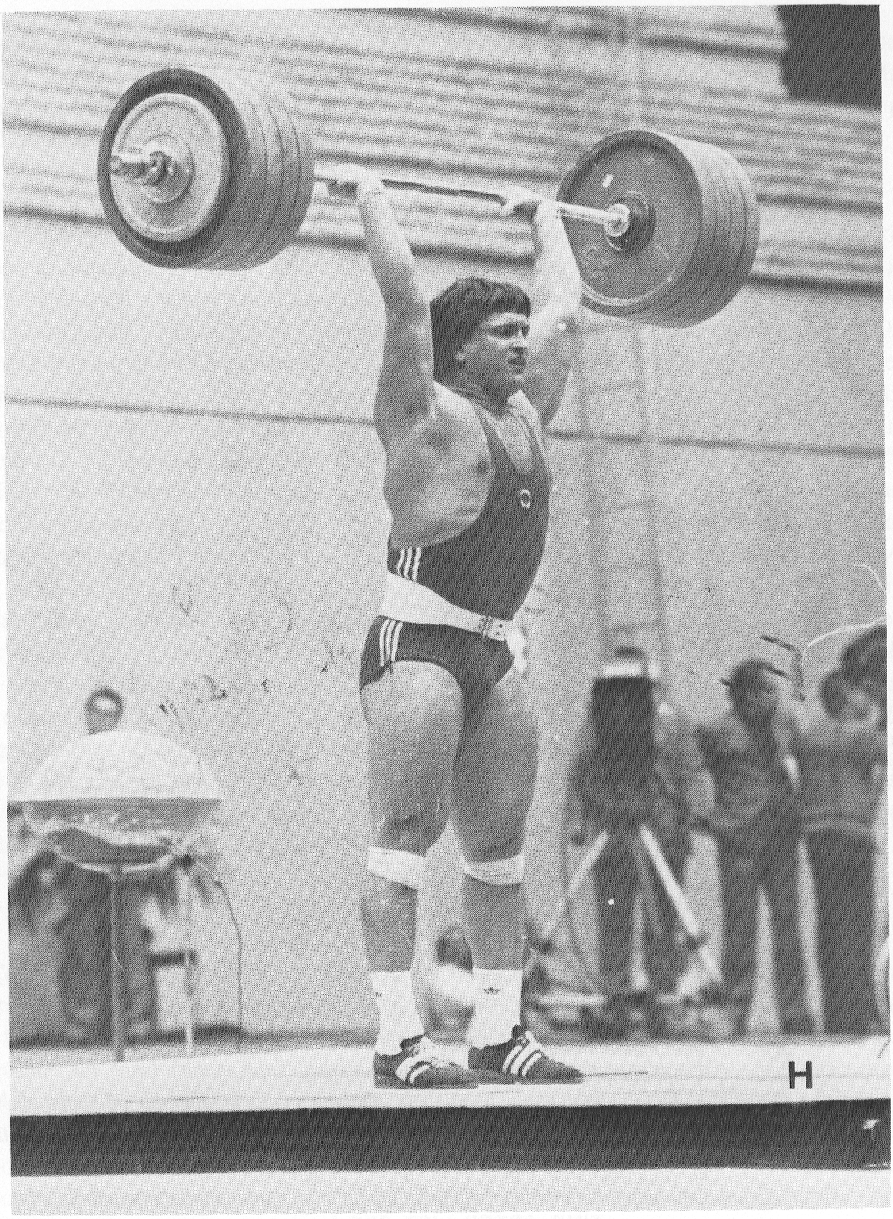

FIGURE 10H.

Grabe[147,148] used a numerical classification analysis method to compare kinematic variables associated with the jerk phase of the clean-and-jerk lift as performed by athletes of differing skill levels. Some reference values were obtained from translations of Russian literature on the jerk characteristics of world champions.[100] Some findings were in agreement with another recent investigation involving the jerk as performed by lifters of different skill levels.[146] Those more highly skilled had a shallower dip and shorter braking phase prior to the jerk thrust, and less horizontal barbell movement. Unsuccessful attempts often had excessive rather than insufficient height.

Successful vs. unsuccessful attempts in the snatch and/or clean were compared in several studies.[112,120,149] Differences between good and missed lifts with equal or slightly different

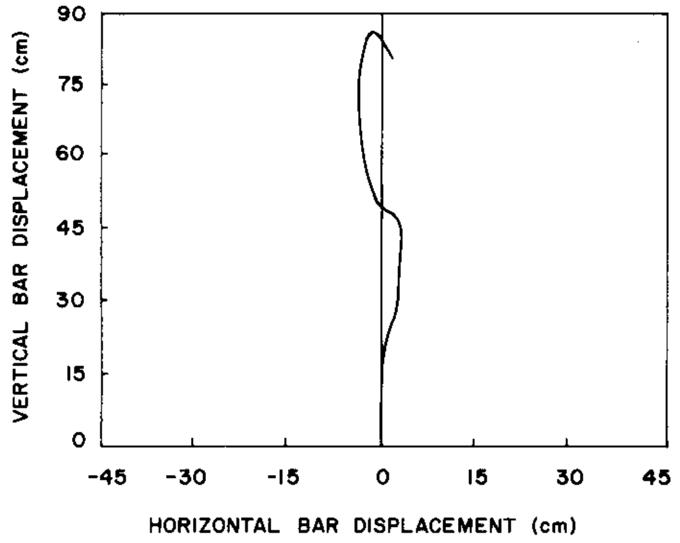

FIGURE 11. Bar trajectory for a 217.5 kg clean by a 1984 Olympic gold medalist. From Garhammer, J., *Intl. J. Sport Biomech.*, 1, 122, 1985. With permission.)

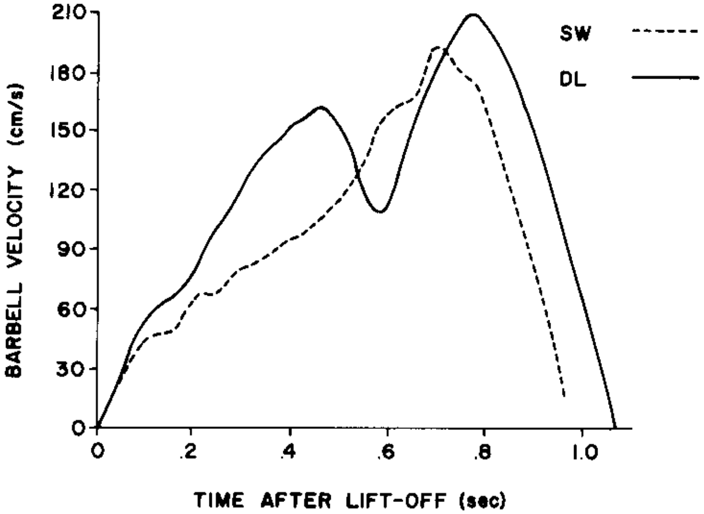

FIGURE 12. Bar velocity patterns for two snatch lifts at the 1984 Olympic Games (SW—120 kg, DL—172.5 kg). DL used the DKB pulling technique (note the double peak in velocity), while SW used a pulling style more dependent on hip extension — see text for discussion. (From Garhammer, J., *Intl. J. Sport Biomech.*, 1, 122, 1985. With permission.)

weights, were not consistent. Sometimes a missed lift, for example, had a higher maximum vertical velocity than a good lift. Results seem to suggest that timing and duration of the lifting phases may be equally or more important than kinetic variables such as maximum force applied.

A longitudinal comparison of highly skilled lifters has been made by filming them in competitions which occurred 2 years apart.[109] The parameters compared, included peak bar velocities, power outputs, and joint-torque patterns. This method seemed to be sensitive enough to distinguish between performances with regard to the amount of weight lifted. A higher digitizing frequency (50 vs. 25 Hz) would provide greater sensitivity and permit smaller changes in technique to be determined quantitatively.

H. Data Smoothing

Detailed general discussions of data-smoothing techniques have been published with example applications usually related to running and gait.[150] The studies reviewed in this manuscript used a variety of data-smoothing methods including spline functions (SF), digital filters (DF), and ''least squares'' moving arc (MA) curve fitting. One comparative evaluation of these three methods has been performed.[68] Results indicated excellent agreement between methods when the sampling frequency was 50 Hz. The optimal DF cut-off frequency was approximately 4 Hz for vertical movement and 5 Hz for horizontal movement during a snatch lift. Corresponding values for a clean were 5 and 6 Hz. Grabe and Widule[148] used a DF to smooth barbell- and joint-movement data for jerk lifts. They found these movements were best represented by a third-level harmonic (4 Hz). One analysis of squats[47] found 95% of the signal power for vertical GRFs and barbell- and joint accelerations to lie below 8 Hz. The subjects were not competitive powerlifters, and since they were using squats in sport training they may have moved slightly faster than competitive lifters would while using maximum loads. Optimal SF error estimates were approximately 2.7 mm for both lifts and movement directions.[68] This is in agreement with work by McLaughlin et al.[151] Garhammer has expressed concern about using a MA method with a sampling frequency of 25 Hz, and suggested that 50 Hz or a different smoothing technique could improve accuracy.[73,120,121,144] Due to the ease of use of the MA method, and the minimal differences found between the DF, SF, and MA at a 50-Hz sampling frequency[68], it seems an appropriate and advantageous choice for weightlifting analyses.

V. SUMMARY

Considerable information is obviously available on the biomechanics of weightlifting exercises. Several areas, however, clearly require more detailed analysis. Computer models for lifting movements must be improved. The use of 2-D dynamic rigid-link models to calculate net joint forces and torques, has been employed repeatedly. More detailed joint models must be used to supplement the results of rigid-link analyses[122] or to replace them.[46] Industrial lifting models have advanced more rapidly than exercise models. IAP, for example, is commonly considered in the former, but seldom in the latter. Enoka[123] has used it for lower-back-force calculations in a quasi-static model of the pull for cleans, while Cappozzo et al.[47] have argued that it is not needed for lower-back analysis during squats without providing quantitative data to support their conclusion. Observations such as the ''sticking point/region'' in the squat[41,45] may be explained if detailed models including dual joint muscles and skeletal geometries, such as in Dahlkvist et al.,[46] are extended to the torso with consideration of IAP.

Force-plate analyses must go beyond vertical GRF patterns. Anterior-posterior- and mediolateral forces as well as balance patterns must be evaluated and interpreted for many additional weightlifting exercises. Force-plate data must also be incorporated into more sophisticated computer models to improve or verify accuracy.

Three-dimensional analysis is needed for many lifting activities, some more than others. Again, occupational models seem to be ahead of exercise models.[2] The bench press appears to be the only lifting exercise where 3-D analysis has even begun.[60-62]

For competitive lifting and many other exercises, combined force-plate- and 3-D film analysis (with or without modeling) would be extremely enlightening. Even combined 2-D film and force-plate data are limited primarily to Olympic lifting studies performed in a laboratory setting (see Sections IV.C and IV.E). The International Olympic Committee and International Weightlifting Federation are taking steps to eliminate this gap in knowledge. One step involved major filming projects at the 1984 Olympic Games.[152] More recently, the 1985 World Weightlifting Championships were held with specially made Kistler force plates used as part of the competitive platform, and with synchronized 35-mm cameras used to record selected lifts. Detailed analyses of these data are planned.[153] Powerlifting needs to move in this direction after preliminary laboratory studies are done. General weight-training exercises should also undergo such detailed study if they are to be more fully understood in terms of stresses placed on the body.

Finally, biomechanists should evaluate new weight (resistance) machines that are placed on the consumer market. Manufacturers often refer to biomechanical principles to justify and support the value of their product. However, it is clear (see Section II.) that advertising claims and objective measures are not in agreement. If biomechanics is to be widely recognized and respected it must serve the common person as well as research interests. Many newer resistance devices add color and ''bells and whistles'' to exercise, but they may not, for example, accurately control or record movement speed and force level as claimed (to say nothing about providing improved training results). Such limitations must be made known both for fairness to the consumer, who may exercise on the device, and for scientific accuracy in research measurements made using the device. Many of the countless published research papers based on ''isokinetic'' muscle-function evaluation may now be criticized due to the discovery that movement speed is often not uniform through the range of motion.

ADDENDUM

Since this chapter was completed in early 1986, some of the most recent research in weight lifting biomechanics is not covered. One notable addition includes a 3-D film analysis synchronized with force-plate data made at the 1985 World Weightlifting Championships. (Baumann, W. et al., *Intl. J. Sport Biomech.*, 4(1), 68, 1988).

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