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A Straight-Line Graph for Leg-Length Discrepancies

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From the Shriners Hospitals for Crippled Children, Montreal

ABSTRACT: A graphic method is presented that facilitates the recording and interpretation of data in cases of leg-length discrepancy. It provides a mechanism for predicting future growth that automatically takes into account the child's growth percentile and the degree of growth inhibition in the short leg. It can be used to predict the effects of corrective surgical procedures and to choose a surgical timetable. A series of cases of epiphyseodesis is presented, showing the straight-line graph method to be significantly more accurate than the so-called growth-remaining method, particularly in cases of growth inhibition.

The first surgical techniques for lengthening and shortening the femur and tibia as treatment for leg-length discrepancies in children were described by Codivilla, Abbott and Saunders, and Rizolli. Their procedures have the advantages of adjusting accurately for the discrepancies and requiring neither a knowledge of the child's past growth nor a prediction of future growth to achieve the desired result. When Phemister introduced a technique for epiphyseodesis, the desired result depended on predictions of the child's growth and the rate of increase of the discrepancy. Although epiphyseodesis has less morbidity than procedures involving lengthening and shortening of the femur or tibia, at first its accuracy was poor because objective data regarding patterns of growth were scarce.

In 1942, Gill and Abbott suggested that growth be related to skeletal age, and in 1948 Anderson and Green published important data concerning the leg lengths of boys and girls. Their data were obtained by longitudinal studies of a group of children and they related the lengths of the femora and tibiae to skeletal age as defined by the Greulich-Pyle atlas^{4,5,13}. Shortly afterward, they produced a graph showing the "growth remaining in the distal end of the normal femur and in the proximal end of the normal tibia at consecutive skeletal age levels", and this graph has been an accurate and widely used clinical tool⁴.

There are several techniques for roentgenographic measurement of the bones of the lower extremity, the method of orthoroentgenography described by Green and associates in 1946 and Bell and Thompson's modification, the scanogram, being the most accurate methods. The latter technique involves a separate exposure of each hip, knee, and ankle, made with a radiopaque scale fixed beneath the lower extremity and with the patient immobile. All six joints appear on one roentgenogram, 35.6 by 43.0 centimeters in size. This was the technique of roentgenography used in the present study.

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At the present time the clinical results of epiphyseodesis may be compromised by any uncertainty or inaccuracy in predicting the growth of the long bones. The straight-line graph method described here is an attempt to provide a useful method of recording data and to remove some of the uncertainties and inaccuracies in prediction as performed by previous techniques.

The Method in Principle

Two new concepts distinguish this graphic method from the traditional one. The first is that the growth of the legs can be represented by straight lines by a suitable manipulation of the scale of the abscissa. The second is that a nomogram relating leg length to skeletal age provides a correction factor for the growth percentile that is easily applied to these growth lines.

With regard to the first concept, it should be emphasized that this is purely a mathematical principle and is not concerned with the nature of the data involved, nor does it involve an approximation of the data or a selection of an ideal case. In the straight-line graph method, the length of the long lower extremity is represented by a straight line because the method of plotting points defines it so. This procedure has several interesting and pertinent consequences:

1. The growth of the short leg is also represented by a straight line, which lies below that of the long leg and may have a different slope.
2. The leg-length discrepancy is represented by the vertical distance between the two lines.
3. The percentage inhibition of growth of the short leg is represented by the difference in slope of the two growth lines, designating the slope of the normal leg as 100 per cent.
4. The growth line of a lower extremity that has undergone surgical lengthening thereafter approximates a straight line of the same slope but is displaced upward on the graph by an amount equal to the lengthening achieved.
5. The length of a lower extremity that has undergone epiphyseodesis will thereafter approximate a straight line of decreased slope where the decrease in slope (if normal is defined as 100 per cent) exactly equals the percentage contribution that the fused growth plate would otherwise have made to the total growth of the extremity. Because the contributions of the proximal tibial and distal femoral epiphyseal plates are approximately 28 per cent and 37 per cent, respectively, of the total growth of the leg^{4,9}, one can predict the amount of inhibition to be introduced by epiphyseodesis. The growth line of the leg operated on in tibial, femoral, or combined epiphyseodesis will thereafter have a slope of 72 per cent, 63 per cent, or

35 per cent, respectively. This new growth line will be parallel to one of the three reference lines drawn on the graph with those specific slopes.

With regard to the second concept, Anderson and associates⁴ implied that the child's growth in height should be taken into account when the calculation is made as to the predicted results of epiphyseodesis, but provided no method for applying a correction factor. Although they stated that "an extremely tall individual . . . might be expected to get a somewhat greater than average correction", they did not elaborate on how to apply a correction factor. In the straight-line graph method, a nomogram is used to accomplish this. Skeletal-age data are plotted with reference to sloping lines whose positions are based on the growth data of Anderson and associates⁵. The inaccuracies of single estimates of skeletal age are circumvented by making use of all longitudinal data plotted on the nomogram to predict the length of the child's normal lower extremity at maturity. This gives a representation of the percentile in which a child's growth plot belongs, and allows placement on the graph of a vertical line representing the cessation of growth. This line serves as a guide, not only to predict the child's final discrepancy, but also to estimate the final result of the surgery aimed at correction.

The straight-line graph method thus provides a means of assessing clearly and accurately the pattern of past growth of the legs and allows one to predict the pattern and end-point of future growth. The principle in using the graph to determine the surgical schedule is to manipulate the growth lines on the graph, either by displacing the growth line of the short leg upward for a leg-lengthening procedure or by decreasing the slope of the growth line of the long leg for an epiphyseodesis, in such a way that the two growth lines will converge at the cessation of growth (Fig. 2).

Assessment of Accuracy

In order to assess the accuracy of this method, records of the Shriners Hospitals for Crippled Children in Montreal, Quebec, Canada, and of the Alfred I. duPont Institute in Wilmington, Delaware, were reviewed. Of over 150 patients treated by epiphyseodesis, in fifty-seven the final discrepancies at maturity were documented by scanogram. Of these, I rejected nine for whom no skeletal-age roentgenograms were available; thirteen who had either no skeletal-age roentgenograms or no scanograms within two months prior to surgery; three in whom landmarks had been obliterated by arthrodesis or amputation; and two who had angular deformities so severe that the scanograms were not reliable. Thirty patients were left who had adequate documentation for inclusion in this series. Some of the causes of their discrepancies were: congenital anomaly, eleven cases; poliomyelitis, ten cases; and benign tumors, four cases. These thirty patients were subdivided into a group of twenty-three who had been followed for long enough preoperatively to determine their

growth inhibitions and a group of seven whose only preoperative scanograms were made just prior to surgery. All scanograms and skeletal-age roentgenograms were read by me to ensure that consistent criteria for landmarks and technique were used. Using only the preoperative data, the final discrepancy at maturity was predicted both by the straight-line graph and by the so-called growth-remaining method of Anderson and Green³. The discrepancies predicted by the two methods were then compared with the actual measured discrepancy at maturity to find the error in each method.

When applied to the twenty-three children with sufficient preoperative documentation to determine their growth inhibitions, the straight-line graph showed a mean error of 0.6 centimeter compared with 0.9 centimeter for the growth-remaining method. The difference is statistically significant at the $p < 0.05$ level using the unpaired Student *t* test. The maximum error occurred in the case of a boy with a discrepancy that was the result of poliomyelitis. His growth inhibition was 15 per cent in the short lower extremity. The error was 1.3 centimeters for the straight-line graph method and 3.1 centimeters for the growth-remaining method.

In order to assess how well the straight-line graph takes growth inhibition into account, the two methods were applied to eight children whose growth inhibitions were greater than 5 per cent. In this group, the straight-line graph showed a mean error of 0.6 centimeter and the growth-remaining method showed a mean error of 1.2 centimeters, the difference also being statistically significant at the $p < 0.05$ level.

Using the straight-line graph as a predictive tool for children with only one preoperative assessment is equivalent to making the assumption, perhaps incorrectly, that there is no continuing inhibition of growth. This assumption will nullify an important advantage of the method. Therefore, when both methods were applied to the seven children whose growth inhibitions were unknown and to the group of fifteen with growth inhibitions of less than 5 per cent, the difference in accuracy of the straight-line graph versus the growth-remaining method did not prove to be statistically significant. Although the straight-line graph method appeared to show improved accuracy when applied to the entire series of thirty children, with a mean error of 0.6 centimeter compared with 0.9 centimeter for the growth-remaining method, this difference also was not statistically significant.

In summary, the straight-line graph proved to be as accurate as the growth-remaining method generally, and more accurate in cases with high growth inhibition.

Discussion

Certain assumptions that are implicit in this method and in the traditional methods for prediction of future growth merit discussion. It is well recognized that skeletal age is more appropriate than chronological age as a baseline for the study of growth. However, as a baseline it

is not perfect, and it may be that there are other indices of maturation that correlate more closely with growth than does skeletal age as defined by the method of Greulich and Pyle.

A roentgenographic method that defines landmarks in the pelvis was described by Acheson, but this has not been correlated with leg-length data. Therefore, its appropriateness to studies of growth cannot be assessed. Currently, the available reports on correlations between leg lengths and skeletal ages merely show the averages and not the curves in individual cases. The curves of individual children from these studies would have to be analyzed in order to assess their variations from the average and to normalize the curves with respect to the growth spurt.

On the straight-line graph, the growth line of the long lower extremity is straight by definition, and the assumption is made that the growth line of the short lower extrem-

ity also is straight when plotted on the same graph. This assumption is obviously false in cases of recent poliomyelitis, in which the growth rate is known to be variable, but it would appear that the inhibitions of growth in congenitally short legs¹⁶ and in paralyzed legs several years after an acute attack of poliomyelitis^{15,18} do in fact remain virtually constant. This assumption was supported by a linear regression analysis performed on those cases in this series followed for longer than one year. The lengths of the long and short lower extremities were found to be linearly related, with a correlation coefficient greater than 0.995 in every case.

Another assumption has been made: namely, that the individual child remains in the same percentile as regards growth with respect to skeletal age. This assumption is open to question even for normal children, but the inaccuracy of individual skeletal-age estimates makes it difficult

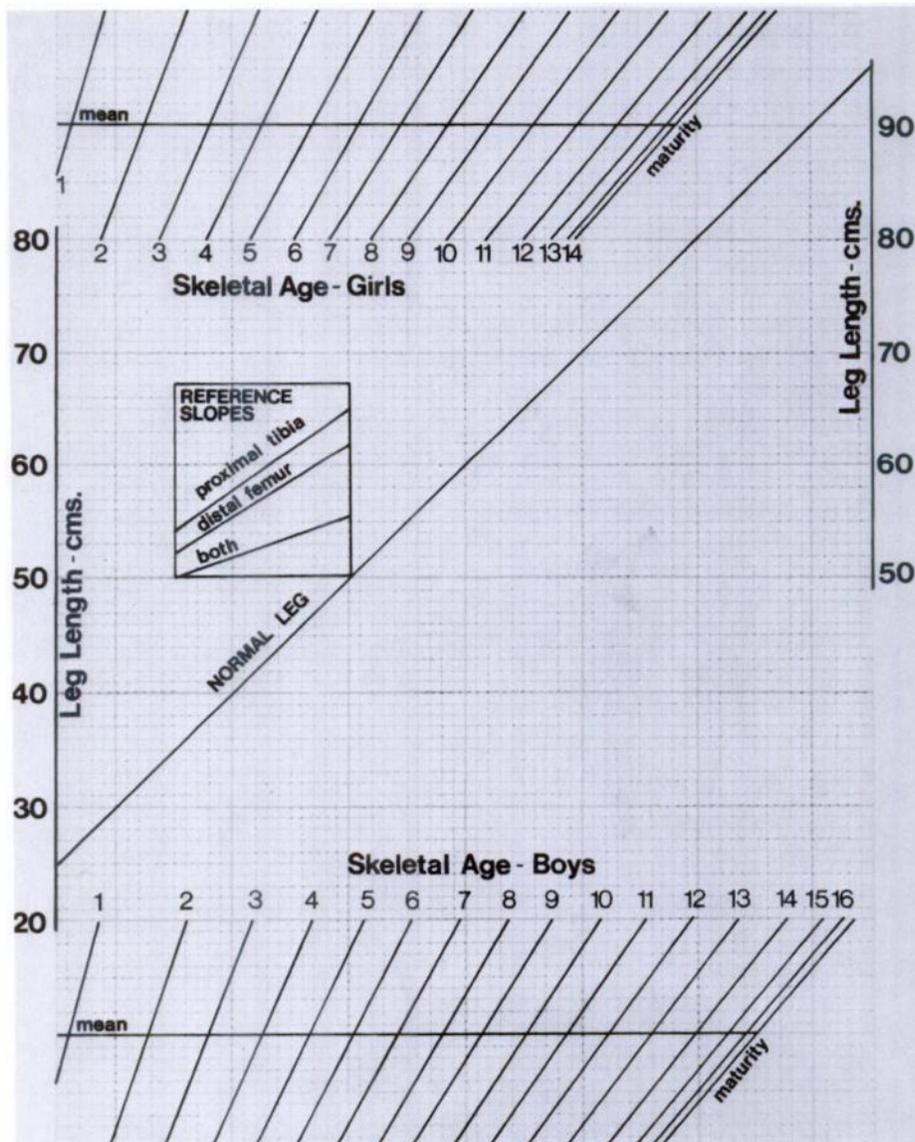


FIG. 1

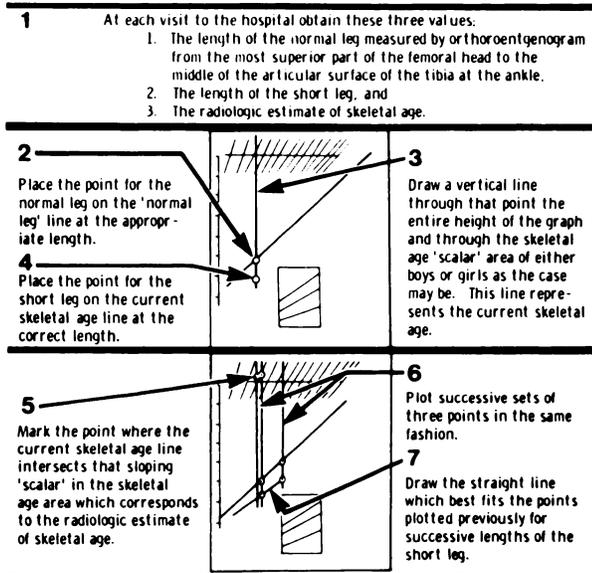
The straight-line graph. (Graphs in a form suitable for clinical use can be obtained from the author.)

to test. Neither the straight-line graph nor traditional methods provide an accurate quantitative means of accounting for such factors as varying nutrition and levels of

activity, which may influence the rate of leg growth from year to year.

The skeletal-age nomogram is based on the assump-

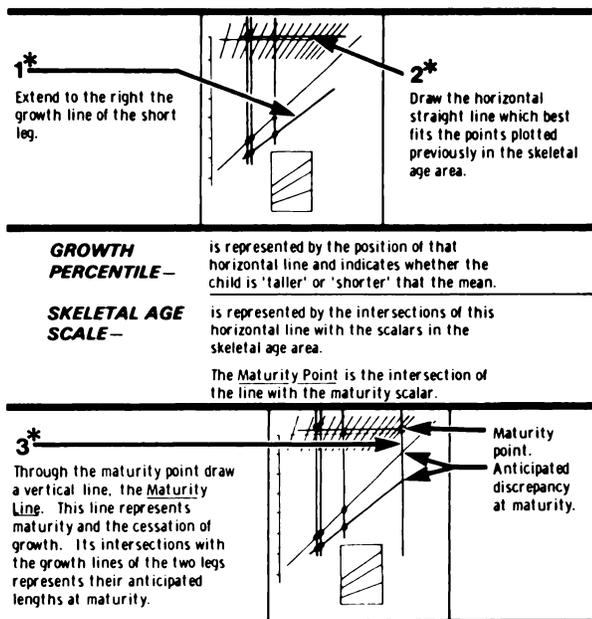
A THE DEPICTION OF PAST GROWTH



DISCREPANCY — is represented by the vertical distance between the two growth lines.

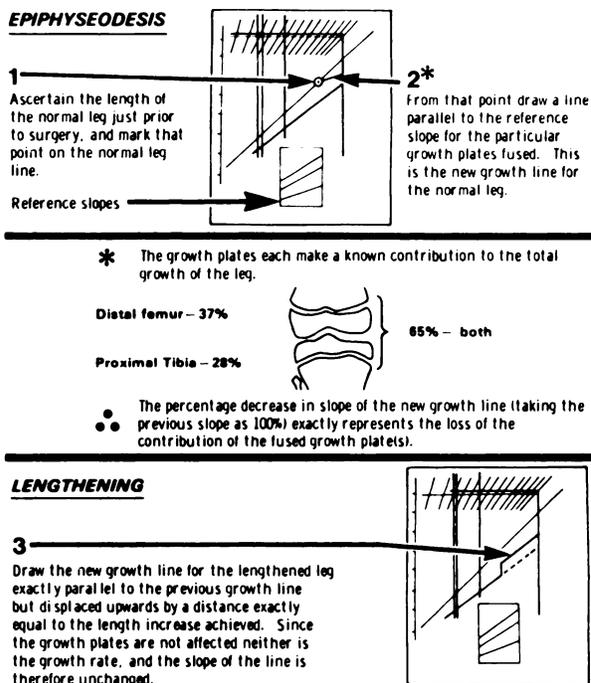
INHIBITION — is represented by the difference in slope between the two growth lines, taking the slope of the normal leg as 100%.

B THE PREDICTION OF FUTURE GROWTH

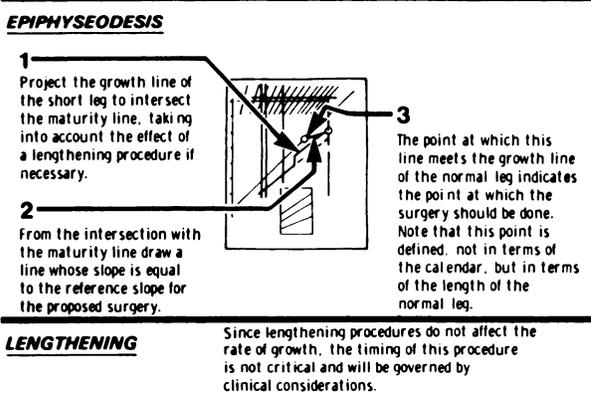


* In keeping a child's graph up to date it is recommended that these lines be drawn in pencil. The addition of further data makes this method more accurate and may require slight changes in the positions of these lines.

C THE EFFECT OF SURGERY



D THE TIMING OF SURGERY



E POST-SURGICAL FOLLOW-UP

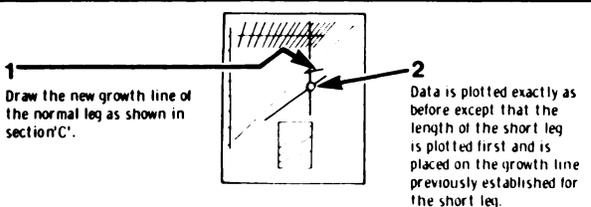


FIG. 2

tion that the lengths of the lower extremities of all children of a certain skeletal age are the same proportion of the leg lengths of those individuals when they reach adulthood, regardless of their growth percentiles or chronological ages. It is unlikely that this assumption is true for children of different races or with markedly different familial habitus. Bailey and Pinneau^{6,7} correlated height with skeletal age and stated that on the one hand, there is a high correlation between skeletal age and the proportion of adult height achieved; but that on the other hand, chronologically older children achieve a slightly greater proportion of their adult height than younger children with the same skeletal age. In view of this observation, I studied the possibility that the mean of the chronological and skeletal ages might correlate better with the length of the lower extremity than the skeletal age alone. This entire series^{6,7} was studied, but the mean value did not correlate any better than the skeletal age alone. There do not appear to be satisfactory data available describing the patterns of growth of children of other than the white race, and the surgeon must recognize this as a possible source of error in applying the straight-line graph or the growth-remaining method.

Following surgical lengthening, the projection of the growth line as a line of unchanged slope ignores the possibility that a surgical procedure on the diaphysis might stimulate or retard the rate of growth of the epiphyseal plates of the bone operated on. There does not appear to be any way of confidently predicting whether or not such an effect will occur.

Some epiphyseal plates appear to continue growing for a limited period of time after epiphyseodesis. In some cases up to five millimeters will be added to the bone before the fusion is complete. How often this occurs is difficult to assess, because the amount in question is very close to the standard error of the measuring technique. It would seem reasonable that this effect would be minimized if the Phemister or White and Stubbins type of epiphyseodesis was accompanied routinely by a curetting of the growth plate to the greatest extent possible.

Conclusions

This method has several significant advantages over traditional methods, both with respect to the collection and recording of data and with respect to its interpretation and use in predicting correction. For each assessment only three data points are plotted: the lengths of the two lower extremities and the skeletal age. No other readings have to be made from the roentgenograms and the actual discrepancies do not have to be calculated. Errors that could occur in making decisions based on single estimates of skeletal age are minimized by making use of all longitudinal data. Maintaining the graph continuously as part of the child's permanent record and adding new data points to it as the child is followed enables reviewers to see clearly and accurately the pattern of the child's past growth without mathematical calculations. Errors in reading the scanogram may be recognized as soon as they are plotted due to the fact that they do not fit the previously established pattern of growth.

Since this method does not require mathematical calculations, it eliminates possible errors in calculation and the need to decide which mathematical operations to perform. Perhaps its greatest advantage is that it not only demonstrates clearly the presence of growth inhibition, but automatically takes it into account when making decisions regarding the timing of surgery. Other commonly used methods have not provided a mechanism for dealing with growth inhibition, and the data I have presented concerning the comparative accuracy of the straight-line graph method and the Anderson and Green method³ would indicate that this is an important consideration. Although only small errors are derived from a child's being very tall or very short, this method takes growth percentile into account and can alert the surgeon to unusual patterns of growth.

NOTE: The author is grateful to Dr. G. Dean MacEwen for making available the records of the Alfred I. duPont Institute, Wilmington, Delaware, and to Ruth Milner of the Department of Epidemiology and Biostatistics, McMaster University, Hamilton, Ontario, Canada, for performing the statistical analysis.

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Human Patellar-Tendon Rupture

A KINETIC ANALYSIS*

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ABSTRACT: The first biomechanical analysis of a human patellar-tendon rupture during actual sports competition is reported. Cinematographic data for analysis were collected at a national weight-lifting championship. Dynamic equations to mathematically model the lifter were developed to compute time course and magnitudes of hip, knee, and ankle-joint moments of force and of tensile loading of the patellar tendon before and during tendon trauma. Results provided evidence that the range of maximum tensile stress of the tendon may be considerably greater during rapid dynamic loading conditions, as in many sports situations, than maximum tensile stress obtained during static test conditions.

Injuries to ligaments and tendons occur when those structures are subjected to rapidly applied loads of high magnitude¹⁸, but little is known about the magnitudes of loads or loading rates during actual injuries in humans. It generally is not feasible to obtain any useful data during the ordinary course of human activity, and it would be unconscionable to allow human subjects to approach maximum loading conditions experimentally. An unusual opportunity arose for us when we were collecting cinematographic data on weight-lifters for the analysis of joint forces and moments of force. We observed a human patellar-tendon failure during actual sports competition. The purpose of this study is to report the time course and magnitude of knee-joint moments of force and patellar-tendon tensile loading before and during the failure of that patellar tendon.

Methods

Cinematographic data were collected for all weight classes at the 1975 U.S.A. National Weightlifting Cham-

pionships. The subject of this study was a twenty-nine-year-old man who competed in the light heavyweight division. He then weighed 82.2 kilograms and was of world-class caliber. He had won the championship of his weight class just prior to the attempt in which his right patellar tendon ruptured. During subsequent surgical repair it was found that the patellar tendon was attenuated throughout its course. Portions of its mass had pulled out both from the distal pole of the patella and from the patellar-tendon insertion on the tibia.

The subject had no previous history of injury to the right knee.

A camera had been positioned ten meters to the right of the geometric center of the competition platform and perpendicular to the lifter's plane of motion. The platform was four meters square and the optical axis of the camera passed one meter above the center of the platform. The motor-driven camera was set at fifty frames per second.

Serial film images were projected onto a digitizer with a measurement rounding error of 127 micrometers. Digitized rectangular coordinates were available for the center of gravity of the lifted weight; for positions of the lifter's right hip, knee, ankle, and fifth metatarsophalangeal joint; and for the top of the lifter's head. These coordinates were transferred directly to digital cassette tapes and computer programs were written for subsequent analyses which included the calculation of center-of-gravity locations⁵ and segmental inclinations for each twenty-millisecond time interval in the analysis. A least-squares five-point moving arc technique was used when time derivatives of linear or angular position data were required^{22,24,25,36}.

Film-derived kinematic segmental linear and angular accelerations and mass parameter estimates⁵ were incorporated into the kinetic equations of motion for a mathematical model of the lifter. The lifter was modeled in two dimensions as a five-link rigid-body system with the assumption of symmetry about the cardinal sagittal plane. The five constituent links were: (1) a point mass at the center of gravity of the weight being lifted, which was

* Read in part at the Annual Meeting of the American College of Sports Medicine, Anaheim, California, May 1976.

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