PRELIMINARY EVALUATION OF THE VERTICAL ACCELERATION GAIT ANALYZER (VAGA)

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"Lift Power" is defined for a human being, when walking, as the product of the total vertical lift per step times his body weight divided by the time period for a single cycle (step). Typical units for Lift Power are Calories per Minute. J. E. Coates and F. Meade reported in 1965[1] that a linear correlation exists between energy consumption and Lift Power for a normal subject walking naturally on a treadmill. Direct energy Consumption measurements based on measurement of oxygen consumption are time-consuming and require substantial laboratory equipment. A simple-to-use instrument for rapidly measuring change (difference) in energy consumption based on Lift Power measurement of a patient "before" and "after" a treatment or alteration of a prosthesis could be very useful to the clinician who does not have an instrumented gait laboratory at his disposal. The central question, not answered as yet, is, "to what extent does Lift Power correlate with energy expenditure in various kinds of disability?"

The Rancho Vertical Acceleration Gait Analyzer (VAGA) measures vertical acceleration and through internal signal processing indicates Lift Power directly in Kilocalories per minute per pound of subject's weight. It requires only 10 steps of stabilized walking (about 5 seconds) for data input; thus, a number of data points required to produce a significant average value may be taken in a few moments. Digital indicators on the meter show Time Interval in seconds and the Integral of the Absolute Value of Acceleration. The Integral of the Absolute Value of acceleration divided by Time gives the Average of the Absolute Value of Vertical Acceleration. The instrument has been calibrated, as well, to read Lift Power in cal. per pound body weight per min. directly, while Lift may be calculated from the Average of the Absolute Value of Acceleration.

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A prototype VAGA has been developed (Figure 1). It is comprised of an Endevco accelerometer mounted on a small 3-legged platform that rests comfortably on the subject's head (held in place with a knitted ski-cap) and an electronic processing unit that is carried by the data-taker while walking behind the subject. In use, the data-taker following the subject starts the VAGA on heel strike and then stops it on heel strike 10 steps later. Two digital readouts hold data in the instrument until it is reset after being read.

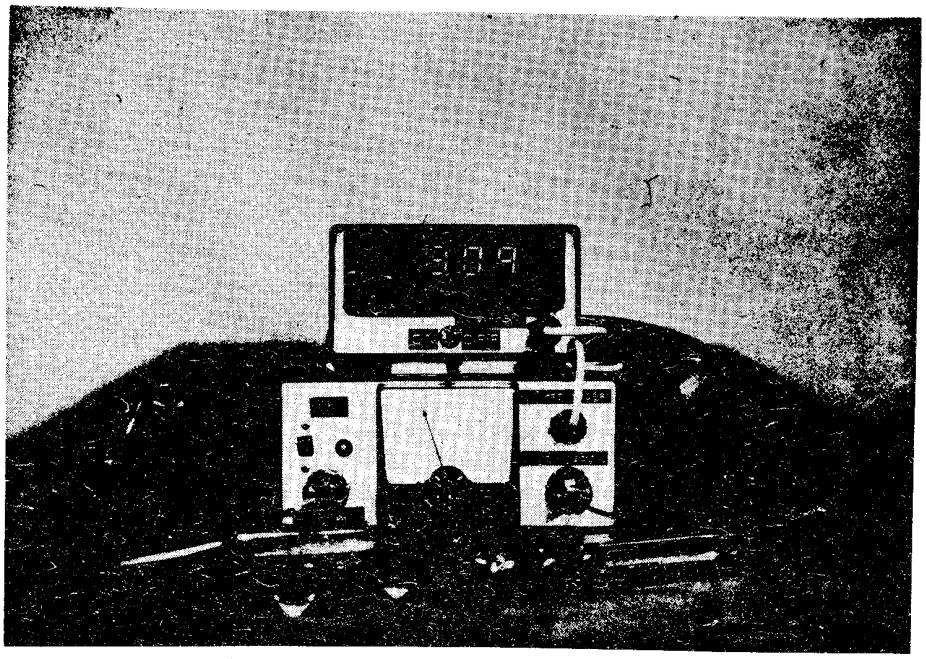

Figure 1. - Vertical Acceleration Gait Analyzer (VAGA) Accelerometer on 3-legged platform is shown at lower left. Electronic unit reads out elapsed time on upper left L.E.D. Indicator. Lift Power (for 10 steps) in cal. per min. per lb. body weight are indicated both on Analogue Meter and on Digital Display on top. Hand Control appears at lower right.

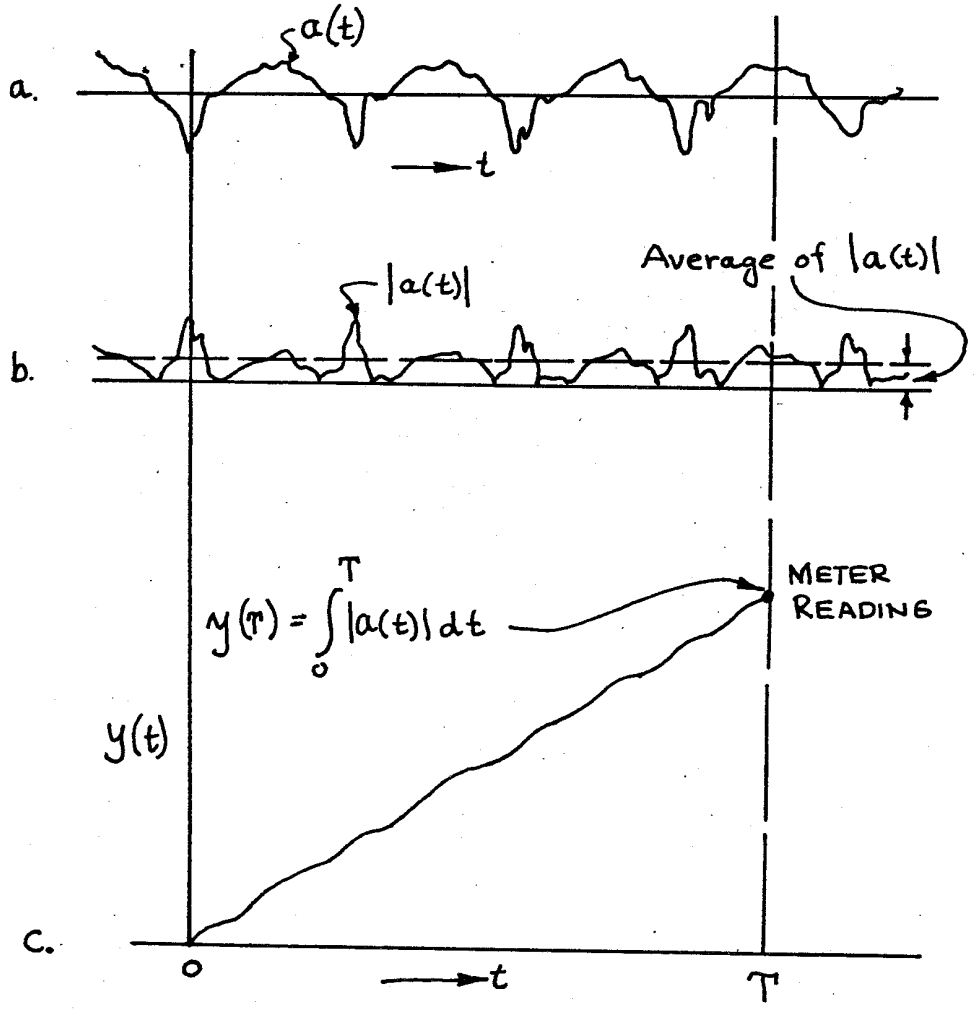

Figure 2. - a. Vertical Acceleration Record, b. Rectified Vertical Acceleration Shown, c. Time Integral of Rectified Acceleration from t = 0 to t = T.

Note: $|a(t)|_{ave.} = \frac{\text{Meter Reading}}{T} \times \text{Scale Factor}$

Principle of Operation:

The VAGA amplifies the acceleration signal obtained from an accelerometer that is held on the subject's head while walking. This signal is then rectified to produce the absolute value of acceleration continuously until the operator presses the "stop" button, usually on heel contact after 10 steps (5 strides). Output meters (digital) indicate integration time (T) for 10 steps and a number (in volts) which represents the integral of the absolute value of acceleration. The meter reading when divided by the time for 10 steps and multiplied by a constant gives the average value of absolute acceleration. The meter reading may furthermore be interpreted directly in Lift Power units. See Figure 2.

Average of the absolute value of acceleration is given by:

$$\frac{\text{Meter Reading (in volts)}}{\text{T (sec.)}} \times 0.2 = |a|_{ave} \text{ in g} \qquad (1)$$

(0.2 is the inherent calibration constant of the instrument; i.e., 5V = 1g)

Based on a sine wave of amplitude which has the same $|a|_{ave}$ as that measured, Lift (L) (double amplitude) is given by:

$$L = \frac{|a|_{ave.} \, T_s^2}{4\pi} \text{ [inches]} \qquad (2)$$

where:

$|a|_{ave.}$ = average of absolute value of acceleration in in./sec.^{2}

(note: $|a|_{ave.}$ [in./sec.^{2}] = 386 $|a|_{ave.}$ [g])

T_s = step time = $\frac{\text{Time for 10 steps (T)}}{10}$

Lift Power (LP) is given by:

$$LP = \frac{\text{Lift} \times \text{Weight}}{T_s} = \frac{|a|_{ave.} \times T_s \times W \times 60}{4\pi} \left[\frac{\text{lb-in.}}{\text{min.}}\right] \qquad (3)$$

or $$LP = \frac{\text{Meter Reading [volts]}}{T} \times \frac{0.2 \times 386 \times 60 \times T \times W}{4\pi \times 10} \left[\frac{\text{lb-in.}}{\text{min.}}\right] \qquad (4)$$

or LP per lb. body weight = 36.9 Meter Reading [in/min.] (5)

Now, since 1 cal = 37.027 in-lb:

$$\text{LP per lb. body weight} = \frac{36.9}{37.0} \times \text{Meter Reading} = 1.0 \text{ Meter Reading } \left[\frac{\text{cal.}}{\text{lb-min.}}\right] \quad (6)$$

Thus, for a 10-step test the Lift Power may be obtained by simply multiplying the Meter Reading (in volts) by the subject's body weight. Result will be in calories per min.

Test of VAGA as Vertical Amplitude Indicator:

The VAGA integrates the absolute value of vertical acceleration to produce the average of this absolute value. Equation (2) for Lift assumes that the double amplitude of a sine wave with the same average of its absolute value as that measured by the VAGA will closely approximate the true Lift. An independent experiment was performed to test this assumption.

A camera with a telephoto lens was modified to superimpose a calibrated reticle on the film. An infra-red filter was placed in front of the lens. A device with two bright lamps -- one steady and the second pulsed at 1/2-sec. intervals--was constructed to be worn by the subject on his head when walking. The telephoto lens placed the camera 30 ft. from the subject to reduce parallex errors. Figure 3 shows a typical "Lift Record" obtained in daylight on an outside walkway.

Figure 4 shows the correlation between Lift as measured by the VAGA and the actual Lift as photographed for 9 different subjects. Correlation was acceptable.

Correlation Between Lift Power Indicated by the VAGA and Energy Consumption

To date, eight subjects have been studied to evaluate the VAGA as an energy consumption indicator. VO_2 consumption was measured by collecting expired air in a modified Douglas bag system while the subject walked around a level outdoor track 60.5 meters perimeter for a period of time sufficient to reach a steady state and then to collect a two-minute sample of expired air. The Pathokinesiology Service computerized analysis system provided a printout of VO_2 consumption in Liters per min., as well as a number of other physiological and gait parameters. Since it was desired to compare our data to that reported by Coates and Meade[1], we used their factor of 4.875 to multiply VO_2 consumption by , to obtain energy cost (consumption) in Kilo calories per minute.

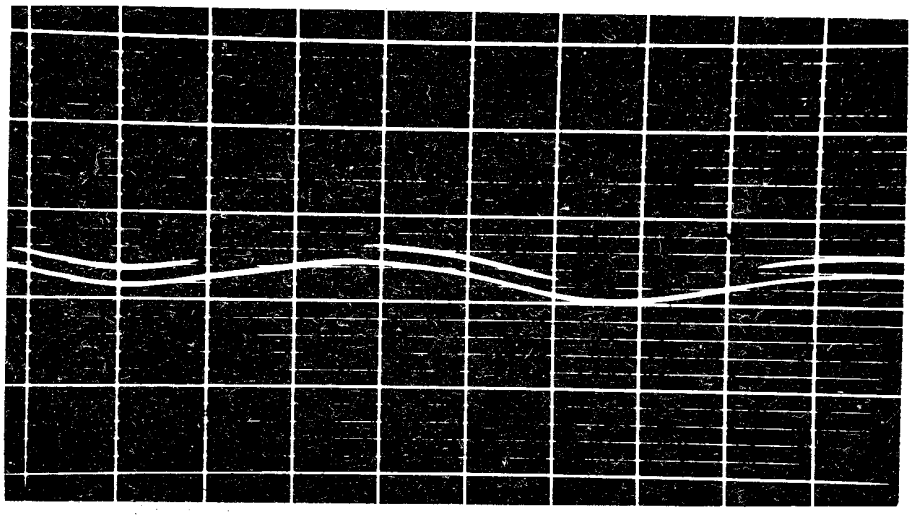

Figure 3. - Typical Lift Record. Two Lamps, 1 steady and the other pulsed at 1/2 sec. intervals, are attached to subject's head. A reticle, designed to calibrate at 5 inches between heavy lines is projected on Infra-Red film during a 2-sec. exposure while subject walks through camera field. Lift, velocity and step length can be measured directly.

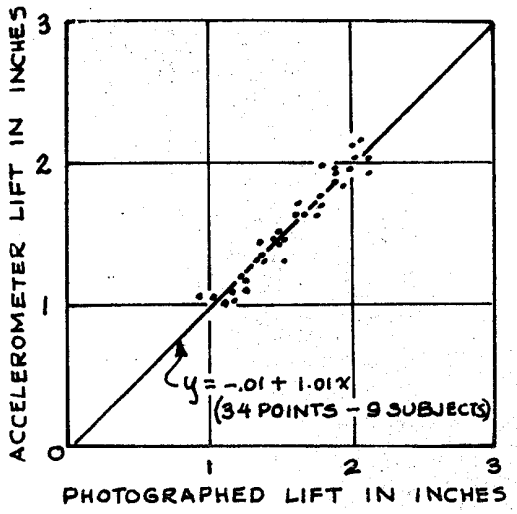

Figure 4. - Lift as determined by the VAGA compared with Lift determined from simultaneous photographs of subjects walking at various velocities.

Figure 5 shows the relationship between Energy Consumption and Lift Power as indicated by the VAGA for subjects walking at various velocities (including rest). Data points above 1.2 K cal./min. Lift Power were obtained at maximum walking velocity.

It is interesting to observe that for walking velocities through "free" (up to 1.2 K cal/min. of Lift Power on Figure 5) a straight line correlation seems reasonable. This line is close (but with slightly greater slope) to that first published by Coates and Meade. The difference may be attributable to the fact that their subjects walked on a treadmill while ours walked outside on a large walkway. However, the maximum velocity points (above 1.2 K cal/min.) show a higher slope; i.e., increasing energy consumption versus Lift Power. It is reasonable to conjecture that subjects require additional energy for muscular activity beyond that required to lift their centers of gravity when walking at forced fast velocities.

Average Acceleration versus Velocity and Cadence

Figure 6 shows the average of the absolute vertical acceleration for the 8 subjects as a function of velocity, and Figure 7 shows average acceleration as a function of cadence (steps per min.). Average acceleration versus velocity may be closely fit by a power function with exponent 1.6 as shown, while average acceleration versus cadence is better approximated with a cubic function.

Discussion

The VAGA instrument may be used to indicate Lift Power directly and by a single calculation, it gives the average of the absolute value of vertical acceleration. Step time is also given directly so that cadence is easily calculated. Velocity must be measured independently (if timed over 10 steps) but can be determined if the instrument is started and stopped over a measured walkway.

The correlation between energy consumption and Lift Power for normal subjects is reasonably good at normal walking speeds. It remains to be determined if this correlation holds for patients. While this study has concentrated on the use of the instrument as an absolute instrument, its value is expected to be found in use as a relative value or change

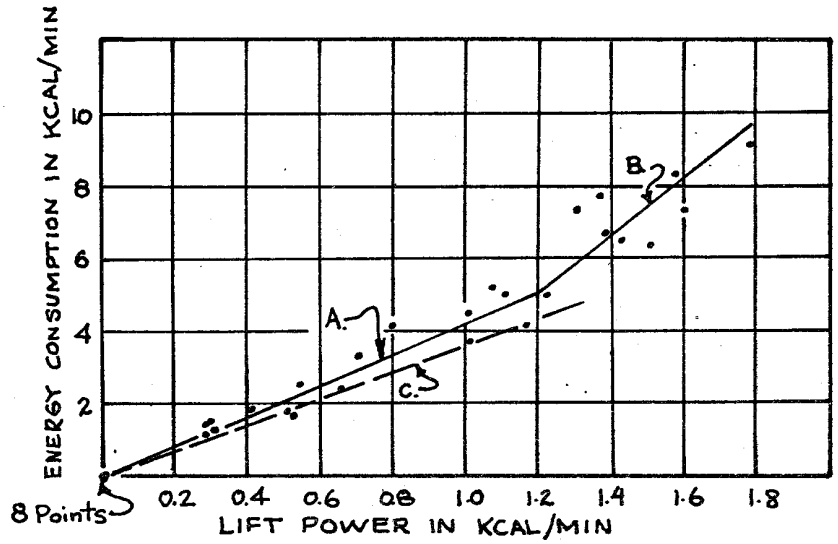

Figure 5. - Energy Consumption based on VO_2 consumed versus Lift Power as measured by the VAGA for 8 subjects walking at various velocities. (Resting VO_2 was subtracted from all values for each subject; thus, rest value for each subject is zero.)

A. Linear regression line for all points up to 1.2 K Cal/min. Lift Power.

B. Linear regression line for all points above 1.2 K Cal/min. Lift Power.

C. Linear regression line reported by Coates and Meade from subjects walking on treadmill.

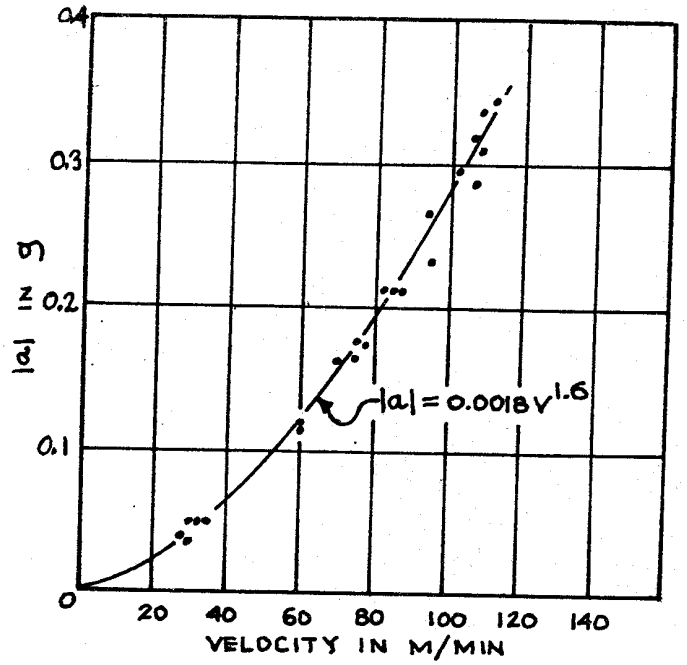

Figure 6. - Average of the Absolute Value of Vertical Acceleration versus Velocity for 8 subjects. Curve may be fitted by $|a| = 0.0018\ v^{1.6}$.

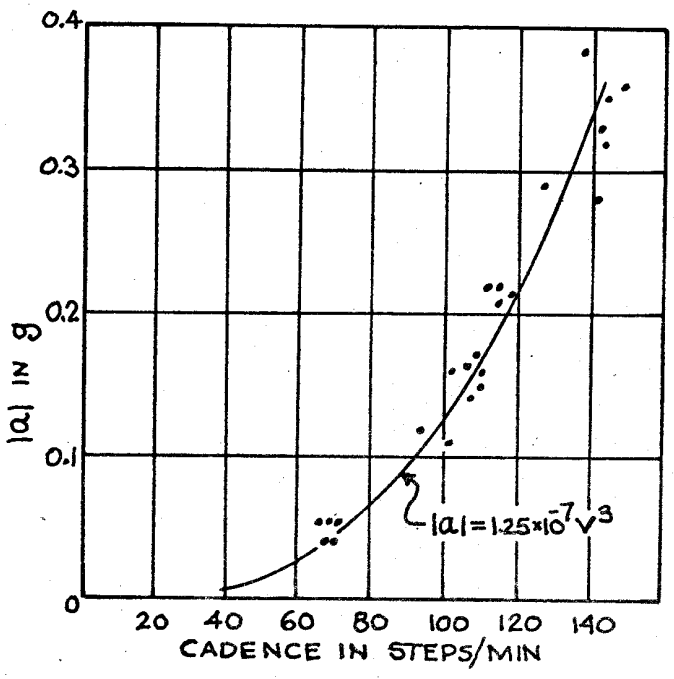

Figure 7. - Average of the Absolute Value of Vertical Acceleration versus Cadence (steps per minute) for 8 subjects. Curve may be fitted by $|a| = 1.25 \times 10^{-7} V^3$

indicator. For example, it is hypothesized that measurements made on an amputee for various prosthesis configurations will show the lowest Lift Power reading when the prosthesis is most efficient and comfortable.

Future studies will be directed at evaluating the VAGA as a clinical tool.

Reference:

1. Coates, J. E. and F. Meade: "The Energy Expenditure and Mechanical Energy Demand in Walking," Ergonomics, Academic Press, 1965.