The evolution of clinical gait analysis part III – kinetics and energy assessment

D.H. Sutherland*

Motion Analysis Lab., Children’s Hospital, 3020 Children’s Way, Mail Stop 5054, San Diego, CA 92123, USA

Abstract

Historically, clinical applications of measurements of force and energy followed electromyography and kinematics in temporal sequence. This sequence is mirrored by the order of topics included in this trilogy on the Evolution of Clinical Gait Analysis, with part I [Sutherland DH. The evolution of clinical gait analysis part I: kinesiological EMG. Gait Posture 2001;14:61–70.] devoted to Kinesiological EMG and part II [Sutherland DH. The evolution of clinical gait analysis part II – kinematics. Gait Posture 2002;16(2):159–179.] to Kinematics. This final review in the series will focus on kinetics as it relates to gait applications. Kinematic measurements give the movements of the body segments, which can be compared with normal controls to identify pathological gait patterns, but they do not deal with the forces controlling the movements. As a major goal of scientifically minded clinicians is to understand the biomechanical forces producing movements, the objective measurement of ground reaction forces is essential. The force plate (platform) is now an indispensable tool in a state-of-the-art motion analysis laboratory. Nonetheless, it is not a stand-alone instrument as both kinematic and EMG measurements are needed for maximum clinical implementation and interpretation of force plate measurements. The subject of energy assessment is also given mention, as there is a compelling interest in whether walking has been made easier with intervention. The goals of this manuscript are to provide a historical background, recognize some of the important contributors, and describe the current multiple uses of the force plate in gait analysis. The widespread use of force plates for postural analyses is an important and more recent application of this technology, but this review will be restricted to measurements of gait rather than balance activities.

Finally, this manuscript presents my personal perspective and discusses the developments and contributors that have shaped my thoughts and actions, and which I have found to be particularly noteworthy or intriguing. Just as in parts I and II, emphasis has been placed on the early development. All subtopics and important contributors, in this third and certainly most challenging of the review papers, have not been included. Some may find that my perceptions are incomplete. I accept responsibility for all deficiencies, as none were intended. Letters to selected contributors and their responses reveal how each contributor built on the work of others. The level of cooperation and sharing by these early investigators is extraordinary. Had they wished to withhold information about their own work, clinical gait analysis would have been severely delayed.

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1. Introduction

The force that the human subject applies to the ground or floor is equally matched by the reaction of the floor or ground. Even primitive man made deductions about the activities of animals or humans from their paw or footprints. Without any knowledge of Newton’s formulae for the effects of gravity and the third law of motion that states, “for every force applied there is an equal and opposite reaction” [3], they understood that bodies have mass (weight), and could deduce much about the identity of animals or humans from the shape, depth, alignment and spacing of the prints they produced.

The search for scientific methods of recording the magnitude of foot/heel contact began in the 19th century. Carlet, of France [4,5], and Ampar, his student, developed and utilized air reservoirs to measure the force applied to the heel and forefoot. Carlet started this work as a student of Marey, at his laboratory in Paris. A significant limitation of
this method was that it gave only one-dimensional information. Surprisingly, a subject with normal heel/toe contact produced a cursive “m” shaped curve with fair resemblance to the vertical force curve produced by a modern force plate (see Fig. 1). The pressures applied by the body through the foot to the ground are vector forces. The earliest investigators understood this, but they lacked the technology to separate the ground reaction into three dimensions. Fischer [6,7] of Germany deduced three-dimensional ground reaction forces from kinematic studies but did not measure them directly.

With another student, Georges Demeny, Marey went on to develop what would be considered as the first true force plate, which measured the vertical component of the ground reaction using a pneumatic mechanism similar to the one that Carlet had built into the shoe [8]. Jules Amar was a rehabilitation doctor working with amputees during and after the First World War in France. He developed the single component pneumatic force plate of Marey and Demeny to produce the world’s first three-component (pneumatic) force plate, which is called the “Trottoire Dynamique” [9]. Wallace Fenn, working in Rochester, was the first to develop a mechanical force plate. This was a one-component device measuring only the fore-aft forces. In an article in which he describes his device, he makes clear the debt he owed to Amar’s work [10]. Fenn was fundamentally interested in the consideration of the interchanges of kinetic and potential energy of the segments [11].

As a further development of Carlet’s work, Plato Schwartz contributed significantly with his work with a pressure sole, and a device to measure movements of the pelvis. He called the instrument a basograph and used it to demonstrate abnormal pelvic movements associated with specific limps [12]. In 1932, the same authors wrote about “The Pneumographic Method of Recording Gait” refining the original concepts of Marey [13], Carlet [4,5], and Ampar. A quotation from this article by Schwartz deserves mention, “Measurement is essential for the interpretation of normal and abnormal phenomena of the human body. Empiricism, fostered by trial and error, must continue to govern the therapy of abnormal function until measurement in some form improves the treatment of disabilities affecting the back and lower extremities” [14]. Fortunately, we now live in the era he envisioned. Many of his articles followed on foot function, both normal and abnormal using electrobasographic records of gait [15–20]. Dr. Schwartz, an astute clinician–scientist, represents the type of individual so essential as a team member in a clinical gait laboratory.

Elftman was an early pioneer in measuring the forces in more than one plane. With a device he described in a 1934 publication [21], vertical force and the dynamic pressure distribution during a step could be shown, but by Dr. Elftman’s own admission, quantification was lacking. In a 1938 publication in Science, a device capable of measuring the ground reaction in three planes was illustrated. An upper and a lower platform were suspended with calibrated springs that measured the ground reaction forces and separated them into components [22] (see Fig. 2). In a subsequent article, vertical force and shear forces in the sagittal plane are shown [23] (see Fig. 3). In this article Dr. Elftman discusses potential and kinetic energy, angular moments, and the influence of two-joint muscle action. His work, though hampered by a lack of technical sophistication, was highly creative and scientifically splendid.

It was not until the work of Cunningham and Brown that force plate development took on the features that lend themselves to clinical use [24]. Their plate or platform divided the ground reaction forces into four components. This was achieved with strain gage technology, but the strain gages at that time were quite sensitive to temperature changes. The construction of the platform was complex and constant calibration was necessary. Computer processing of the raw data was not yet available. More technical development would be required before a commercially available plate, suitable for clinical use, would appear. Reduction in the complexity of the platforms, and improvements in the accuracy and reliability of the sensing instruments, came through the efforts of scientists in several locations: San Francisco, California; Boston, Massachusetts; Philadelphia, Pennsylvania; Glasgow, Scotland; Winterthur, Switzerland.

![Fig. 1. Carlet “m” shaped curve produced by subject with normal heel/toe contact utilizing air reservoirs, closely resembles the vertical force curve produced by a modern force plate today.](image1)

![Fig. 2. In 1938, a device capable of measuring the ground reaction in three planes was illustrated.](image2)
In the mid-1960’s, I requested development of a clinically useful, accurate and reliable force plate for the Shriners Hospital San Francisco Gait Laboratory. The challenge was given to John Hagy, an employee at Lockheed, Santa Cruz, California, who joined our research effort as a volunteer in 1965. His initial accomplishment was to design and implement a system to measure kinematics, using cinefilm and the Vanguard Motion Analyzer. A full description of this work is contained in part II [2]. With this success we turned our attention to the need for measuring the floor reaction forces. There were no commercially available force plates at that time. John Hagy used his considerable talent at eliciting help from within the Lockheed Missiles and Space Corporation. John Hawthorn, Supervisor of the Instrument Test Division, Santa Cruz, became an enthusiastic volunteer participant. I gave him a copy of the Cunningham and Brown article [24], and he remarked about the complexity and bulk of their instrument. John Hawthorn took a 2-week vacation from his employer and, during that time, experimented with the use of piezo-electric force transducers. At the end of his vacation, he showed up at our Shriners Gait Laboratory with a force plate under his arm. The force plate performed beautifully, but required the addition of charge amplifiers to maintain the signals. John Hawthorne, John Hagy, Cecil Keller, and Len Musil were the chief architects of the plate, which was completed and installed in April 1971, and issued a U.S. Patent on July 15, 1975 (see Fig. 4). The first plate was installed, tested, and put into clinical use in the Shriners San

![Fig. 3. Vertical and shear forces in the sagittal plane are illustrated.](image)

**Fig. 3.** Vertical and shear forces in the sagittal plane are illustrated.

**Fig. 4.** John Hagy designed “A Dynamic Force Plate” in 1971, which was issued a U.S. Patent on July 15, 1975.

**A DYNAMIC FORCE PLATE**

FOR PRECISE MEASUREMENT OF FOOT-FLOOR REACTIONS DURING GAIT, STANCE EVALUATION, OR OTHER MOTION STUDIES

**FEATURES:**
- Welded Tubular Steel Frame
- 24-In. Square Transparent Plate
- Shock-Resistant Piezoelectric Quartz Load Cells
- Wide Load Range - 0.02 lb. to 500 lb. (static with ±2% Accuracy)
- High Output Signal - ±10V
- Wide frequency Response - near DC to 500 Hz
- One-time Calibration

![Dynamic Force Plate Image]
Francisco Gait Laboratory. The second force plate was provided to my new gait laboratory at San Diego Children’s Hospital, the third was constructed for Dr. Edmund Chao at the Mayo Clinic, Rochester, Minnesota, and a fourth plate was constructed for Dr. Sheldon Simon at Boston Children’s Hospital. These plates performed well, but commercial production of piezo-electric plates by The Kistler Corporation, Winterthur, Switzerland, put an end to further construction of the Shriners model. The first Kistler piezo-electric plate, which of course later became standard gait lab equipment, was installed for Dr. S.M. Perren at the Laboratory fur Experimentelle Chirurgie in Davos, Switzerland, in 1969.

Prof. J.P. Paul, of the Bioengineering Unit Wolfson Centre, University Strathclyde, Glasgow, Scotland based his Ph.D., which was granted in 1967, on the measurements obtained with the force plate he built, and his key publication at that time, “Forces transmitted by joints in the human body” [25]. I have heard, but have been unsuccessful in documenting details of, his strain gauge force plate, patterned somewhat after that of Cunningham and Brown, which apparently was reliable and used for many years in clinical research. Two duplicate force plates were constructed and installed at the Limb Fitting Centre in Dundee in 1968 under the supervision of David Condie. Paul’s use of strain gauges in the construction of pylon transducers, to measure forces within artificial limb prostheses, was based on earlier work by Bressler and Frankel at Berkeley. He contributed a number of articles regarding the use of motion analysis to study the gait of lower limb amputees [26]. His pioneer efforts in kinematics have already been discussed in part II.

The efforts in Boston began under the direction of Dr. Sheldon Simon. In part I. I mentioned Dr. Simon’s Cave Traveling Fellowship that included a stay in San Francisco, and for a time at the San Francisco Shriner’s Gait Lab, then under the medical directorship of Roger Mann [1]. Upon his return to Boston, Dr. Simon established a gait laboratory on the sixth floor of Boston Children’s Hospital in the Physical Therapy Department. John Hagy and his colleagues constructed a second piezo-electric force plate for Dr. Simon, but conditions on the PT floor were such that vibration (not handled well by the piezo-electric plate) was a tremendous problem. The space under the floor was not large enough to place the cameras in a position to illuminate the footprints through the transparent plate, necessitating the use of raised computer flooring. In addition to these problems, Dr. Simon wanted two plates and his budget restricted him to the price of a single plate from Hagy and colleagues. Dr. Simon was acquainted with Walt Synutis, Associate Professor of Electrical Engineering at M.I.T. and inventor of a new improved strain gage. Dr. Simon persuaded Mr. Synutis to design a new force plate utilizing strain gauges, and two of these plates were installed when the laboratory opened in September 1974. Using simultaneously recorded force plate readings, they were able to output a “butterfly pattern of normal walking, before Cappozzo did it.” (Personal communication from Dr. Simon) part II contains information about Dr. Simon and his contributions following his move to Ohio State University in 1986 [2], and further mention will come in this manuscript under the heading of gait data interpretation.

Roy Wirta, M.Sc., is another pioneer in force plate construction and analysis. Prior to the introduction of commercially available force plates, Mr. Wirta designed and constructed two plates for use in Moss Rehabilitation Center, Philadelphia, Pennsylvania. He also helped with the first calculations of mechanical work in an amputee study in the San Diego lab. We were using a single force plate at that time, so he added a right foot strike and a left foot strike from separate gait cycles together, and commented that ideally two or three force plates were needed to compute forces within a single trial [27–30].

In a personal communication he states:

“As to details of the force plates, there were two side by side. Each was 60 inches long by 12 inches wide. Three forces were sensed: vertical, longitudinal shear and lateral shear, each with strain gauges mounted on thin aluminum strips. The long plates allowed us to record several gait cycles with one pass from test subjects who were mostly stroke patients. We could isolate the needed weight bearing events, and not require them to do many repetitions, to get enough information to evaluate the various ankle-foot braces in the studies. We worked closely with Case Western Reserve in Cleveland, specifically with Vic Frankel, MD to hone in on the design details of the plates. The major impact of the studies was identification of the merits of the molded ankle foot orthosis. Accordingly, orthotists began making these at that time, and they have become the most popular orthoses for stroke patients” (Personal communication from Roy Wirta.)

Though he has retired, Roy Wirta remains active professionally. He is a highly valued volunteer consultant at Children’s Hospital, San Diego, for the Motion Analysis Laboratory and the Orthopedic Biomechanics Research Laboratory [31,32].

Another outcome of the work at Moss Rehabilitation center was the development of a system to superimpose the vertical ground reaction force vector and the sagittal film image of the subject throughout the stance phase of a gait cycle [33]. A summary of the technical process is as follows: the center of pressure is determined, and the voltages representing the vertical force and shear forces provide the necessary information to the force vector display circuitry. The force vector display is generated by application of sine waves having amplitudes proportional to the vertical and horizontal force components. The outputs of this circuitry are channeled to the vertical and horizontal inputs of an oscilloscope. An optical scanner is used to deflect the beam from a low power laser source onto a projection screen. The sagittal image of the subject on the screen, with the force
vector superimposed, is recorded on cinefilm or videotape, so that it can be viewed dynamically. The authors, Cook et al., acknowledge that this technique has been used and published earlier in conjunction with the persistent image display by Cappozzo et al. [34], by Boccadi et al. [35], and Pedotti [36]. This visual tool has served very well in teaching the biomechanics of gait.

Concurrently, Tait and Rose, in their work at Oswestry, UK, in displaying the force vector, had developed a technique to superimpose the ground reaction vector on a standard video recording. They used this technique very effectively, particularly in examining the effect of orthoses on walking over a considerable period of time [37].

2. Commercial companies to the rescue

Although a number of the custom force plates mentioned did yeoman service and were valuable in clinical and research studies there were obstacles in the path of all new laboratories seeking to include force analysis. On-site engineering talent was optimal for construction, operation, and service of the custom plate or plates. Inordinate amounts of time could be consumed in this process, interfering with quality time for the preparation of research proposals, training of technical assistants and for quality assurance. In case of mechanical breakdown there was not a company, with available parts and helpful advice, ready to assist. Perhaps the only exception for this grim scene in the post-Cunningham and Brown period was the Shriners plate but rapid expansion of production and service were not planned. Consequently, the entry of The Kistler Corporation, with a commercially available model, was enthusiastically welcomed. This corporate decision by an established and respected Swiss company gave a signal to other corporations that a new market was opening. The proof of this statement is confirmed by the development of Advanced Mechanical Technology, Inc. (AMTI) force plates with improved strain gage technology, by the entry of Bertec into the commercial scene and by the imposing list of commercial companies now producing force plates. A very large number of motion analysis laboratories are now using ground reaction measuring instruments in routine clinical and research studies (see Appendix A).

3. Applications of force measurement technology

Now, you say, we have these reliable and readily available plates, with excellent support, but how have patients benefited from use of these plates in clinical studies? We will work our way into that later in this manuscript, but first, there are important scientific contributions to describe. A steady evolution of applications followed force plate introduction. Early on, force platforms were used primarily to measure 3D ground reaction forces. This was very important, for without this information the contributions of gravity and energy cannot be appreciated. Utilizing force vectors derived from the ground reaction forces, the external forces tending to move joints can be studied. The commercially developed force plates do this well. Although early investigators using this powerful tool were well aware of the need for determination of individual joint moments of force (then generally described as torques) the limitations in computer development made hard work of the necessary mathematical computations. Without moment calculations, the estimation of net external and internal joint forces in stance phase is impossible; thus, raw force measurements, even though normalized for body weight and -height, do not give sufficient quantitative data at the inter-segment level.

Prof. David Winter deserves much credit for his scientific insights and popularization of the routine clinical use of moments and powers. He explains the evolution of his thinking on this subject in a letter dated 29 March 1996.

“...In terms of my interests in kinetics (moments, power and energy) my inspiration came from early papers by Bresler and Frankel (Trans. ASME, 1950) who presented the first correct way to calculate moments using inverse dynamics. The power approach was an even earlier paper by Elftman (Am. J. Physiol., 1939) where he presented analyzed data (all done by hand from film) showing the flow of energy across joints ‘passive power’ and the generation and absorption of energy by the muscles. His mathematical equations were not too clear but after half a dozen times through the data we finally saw his approach and his tremendous insight. Our first paper on power flows was published in 1975 and included a tribute to Elftman’s work. Entitled “Instantaneous power and power flow in body segments during walking,” J. Human Movement Studies, 1:59–67, 1975. It was authored by A.O. Quanbury, D.A. Winter and G.D. Reimer.”

In a review paper on “The Locomotion Laboratory as a Clinical Assessment System” [38], Winter emphasized the necessity of a multidisciplinary laboratory team and observed that too many efforts up to that time were limited to presenting kinetic data without directly linking the abnormalities to biomechanical explanations. Without correct interpretation and linkage, the voluminous information will not lead to improved treatment strategies for patients. Winter’s productivity in applying the utilization of moments and powers is evident in subsequent publications [39–45]. He uses the convention of internal moments throughout his writings, assuming the necessity of net forces resisting the measured external forces. The convention of internal moments is most frequently used in commercial gait software but controversy exists with some of the oldest laboratories (including San Diego’s) preferring the convention of external moments. So far there is very little give in the position of the two camps. This controversy should be resolved, as it confuses both new trainees in clinical motion analysis and experienced individuals accustomed to inter-
interpreting moment curves displayed in a different manner. The convention of external moments is the author’s choice, as it requires fewer assumptions about internal moments.

Dr. Gage was influenced by the writings of Dr. Winter about moments and powers and work was started at the Newington Laboratory on this subject in 1987, according to Dr. Gage. Roy Davis, Ph.D., Associate Professor, Department of Engineering and Computer Science, Trinity College, Hartford, Connecticut was a Visiting Biomechanics Researcher at the Gait Analysis Laboratory, Newington Children’s Hospital, Newington, Connecticut. This brought about the enthusiastic collaboration of the two on the subject of moments and powers. Dr. Gage writes:

“The clinical moments and powers work started in 1987 when I was on sabbatical in England. I had obtained a copy of David Winter’s first monograph in which he discussed moments and powers, and I started to think that it would be very useful to have these in our clinical software. Consequently, when I returned from my sabbatical I asked to have one of the engineering students assigned to the project. At that time, Roy Davis was an Associate Professor at the University of Hartford, and he was supervising our engineering program. Consequently, Roy ended up supervising the engineer on the project. The engineering student’s name was Jim Corless. That project would have been completed probably in the spring of 1988, but it was not in a form that could be used. From that point Sylvia Ounpuu and Roy Davis and I worked together to hone the software down to its present form, and that work was eventually published in the enclosed article in The Journal of Pediatric Orthopaedics in 1991 [46]. Roy Davis was obviously the principal author of the software, and I just basically supplied critique.”

Further information on Roy Davis, and his involvement with the Newington Gait Laboratory, comes from his personal correspondence:

“My association with the lab began in 1983, soon after my arrival in Connecticut. I was awarded a Young Investigator’s Grant from the National Science Foundation that dealt with the Stump/Socket Force Distribution in the Lower Extremity Prosthetic Limb. It was an opportunity to get to know Dr. Gage and Scott Tashman in the Gait Lab and a number of the prosthetists and orthotists that worked at Newington. This research project provided the impetus for me to learn more about the biomechanics of human locomotion and capabilities of the gait lab. This provided the basis and introductory experience that I needed prior to my more formal involvement with the hospital and lab, beginning in 1987.”

“When I arrived in Connecticut in 1983, I inherited a graduate student in need of a faculty advisor named James J. Corless. Jim was very close to completing a master’s thesis entitled ‘Moments of force developed in the human hip, knee, and ankle joints during level walking’. He graduated in 1983 and moved on. His work was never published.’’

“I developed the kinetics software for the lab in 1987. I set aside Jim’s previous work and started ‘from scratch’. It was easier to start fresh.”

Dr. Davis is greatly in demand for his exceptional skills in communicating the science and clinical applications of gait analysis. He is both a leader and a consummate team player. It would require pages to outline the honors that have been awarded to him. He was the founding President of the North American Society of Gait and Clinical Movement Analysis, 1995–1996. Some of his notable publications involve the topics cerebral palsy [47–51], myelomeningocele [49,52], orthotics [53,54], normal pediatric gait [46], and geriatrics [55]. As an addition to our understanding of moments and powers he proposed the clinical use of joint stiffness measurements [56]. Engineers have long been acquainted with measurements of resistance to applied torque defined as the slope of applied force plotted as a function of displacement. Dr. Davis took this established engineering concept and applied it in the clinical arena. He proposed the idea that dynamic measurements of joint moment and angular displacement during walking could be useful in providing a quantitative measurement of net joint stiffness. In this important article he describes normal ankle values and gives examples of the result of surgical intervention. Once again, it is important to note, that concurrent work was being performed by Murali Kadaba in New York, resulting in the well known, and extensively utilized, Helen Hayes Software [57].

An example of the importance of kinetic measurements at the joint level is that the majority of interventions carried out by orthopaedic surgeons are to lengthen or transfer contracted muscles. Moment and power calculations combine kinematic and force data to tell us whether the net forces resisting applied moments are yielding (eccentric muscle action) or producing movement in the opposite direction (concentric muscle action). Furthermore, they put numbers to the information so that comparisons can be made. It is hard to argue against the need for obtaining more data about how muscles are functioning before and after surgery, orthotic application, Baclofen pump insertion, physical therapy, or selective dorsal rhizotomy. There are limitations and some pitfalls in the interpretation of joint moments and powers; these will be discussed later in this manuscript.

4. Mechanical work

Can the global output of successive foot floor contact force measurements be used to determine mechanical work? Cavagna and Margaria thought so, and used two custom force plates to measure vertical and forward velocity of the center of mass of the human body in walking and running.
Two platforms were inserted on a wooden track. One platform was sensitive to the vertical and the other to the forward component of the force impressed by the foot on the ground [58]. In a personal communication I posed several questions to Dr. Cavagna. In response he wrote:

“I am MD and I became involved in this type of human ergonomics when I was student in the lab of Professor Margaria who was interested in Sport Medicine. I remember that Margaria, Saibene and I arrived to the idea to use the force plate in order to measure the work necessary to move the center of mass of the whole body (external work) mainly thanks to the fundamental work of Wallace Fenn (1930) who used a force plate to measure the mechanical work necessary to account for the velocity changes of the center of mass during running.”

“My brother Carlo constructed the first computer program to measure work directly from the force on the ground, and Prof. Taylor did a lot of work in making the manuscript understandable. More recently Prof. Norman Heglund improved considerably the force plate design and extended it for use in the anomalies of locomotion.”

“Clinical application was tentatively suggested in the paper “Ergometric evaluation of pathological gait”. [59] “I think this system is now used in clinics and I know that my colleagues at the University of Louvain are working in this direction.”

“The main advantage of using the force platform is not the determination of the external work, but to study the mechanical energy changes of the center of mass at each instant during the step cycle. This allowed the description of the two basic mechanisms of locomotion: the pendular mechanism of walking, with a large exchange between potential and kinetic energy of the center of mass of the body, and the elastic, bouncing mechanism of running where the two energy changes are in phase. This also helped to understand human locomotion at different gravity values, and the optimal speed in walking. The energy expenditure is a consequence of the total external work done (external + internal). The schema of the force plates we originally used (which were not side by side, but in a row) is described in the paper “Force platforms as ergometers”. [60]

There is controversy about the methods of measuring mechanical work and about their correlation with total energy expenditures. In general the opposition to the Cavagna method relates to a belief, based on theoretical grounds, that combining the moments from each individual body segment would better represent mechanical work and secondarily that the correlation between oxygen cost and mechanical work is not high enough to accept mechanical work as an index of energy consumption. The second objection has particular clinical importance, as clinicians need to know how much effort is required for walking and what changes occur with treatment. If mechanical work measurements can give an appropriate representation of energy cost their use will be attractive. Obviously, data from force plate recordings is easier to obtain than O2 measurements.

David Winter is a proponent of link segment analysis for the calculation of mechanical work. He criticizes the Cavagna method because of his perception of its major assumption: the body’s center of gravity represents the sum of all segment energies. Winter believes that reciprocal movements do not show up as a change in the body’s center of gravity, or as a change in the force plate curves. Also, rotational kinetic energies, especially of the lower limbs, remain undetected.

Other objections to use of the Cavagna method of calculating mechanical work of moving the common center of mass from force plate data alone have come from McDowell [61], who stated that there was a low correlation of mechanical work calculated in this manner with VO2 cost. Technically, his estimates of mechanical work come from a kinematic determination of the center of mass movement, rather than from force plate measurements. This was based on the work of Eames et al. [62], which had established a correlation between the two. Zatsiorsky argued that internal work was not properly, accounted for in this method [63,64], and in the words of Aleshinsky:

“Although the system energy can be represented as a sum of the external and internal energies, a similar representation of the external and internal work is not correct: Total mechanical energy expenditure is not equal to the sum of the external and internal work.” [65] Most of the authors who criticize the Cavagna methodology say that the method was not validated.

By contrast Burdett et al. [66] studying five normal adult subjects found that mechanical work measured by three techniques: (a) the Cavagna method from force data alone, (b) multi-segment energy calculations of kinetic and potential energy exchanges from kinematic data alone, and (c) multiple joint moment calculations all gave good correlations with oxygen consumption (mls) but not with O2 cost (ml/m). Burdett et al state that total mechanical work; whether it is determined by force plate analysis alone, by multiple segment energies or by multiple joint moments, clearly is not the same as total energy consumption. Nevertheless, it has the ability to pinpoint high points in mechanical work expenditure at specific points in the gait cycle. We can summarize their paper as saying that mechanical work is not the same as energy consumption, but it is still very useful considering the equipment readily available in most clinical gait laboratories today.

5. More about external work

Three models of calculating external work were compared with oxygen cost measurements in 26 subjects
with myelomeningocele [61]. The models employed were (1) vertical excursion of the center of mass, (2) external work done by the center of mass, and (3) a full body model allowing energy transfers between segments within limbs. Although all three models showed significant difference between S1 and L4/L5 level involvement, there was not a significant correlation with oxygen cost in models 2 and 3, and only a mild correlation with model 1. This study tends to illustrate the ongoing search for the most effective model for relating external work to, the currently accepted gold standard, oxygen cost. Other references on this subject include Frost et al. [67] and Unnithan et al. [68]. Eames [62] compared estimates of the total body center of mass in three-dimensions in normal and pathological gaits and found that the center of pelvis measured from an anatomical point or points on the pelvis had a greater excursion than the center of mass (CM) as determined from ground reaction forces or a whole body kinematic model. His conclusion was that “for accurate determination of the position of the CM in a clinical setting a full body kinematic analysis is required” [62]. Donelan et al. [69] hypothesized that the positive and negative work must be calculated individually for each lower extremity to determine the true mechanical work exerted on moving the center of mass; 97% of the double support positive work is performed by the trailing leg while the leading leg performs greater than 94% of the double support negative work. The combined limbs measures of positive and negative external work were approximately 33% less than those calculated using the individual limbs method. Comparisons such as those used in these references will continue for sometime, hopefully in conjunction with oxygen cost and physiologic cost index comparisons.

Where does this controversy leave clinicians? It certainly has been argued that mechanical work calculations under-represent total energy expenditures. However, clinicians also wonder if oxygen consumption and oxygen cost may inflate energy cost calculations by their inherent sensitivity to anxiety, or physiological state of the subject, such as pulmonary or cardiac status. Perhaps mechanical work will play an increasingly well-defined role in objective outcome comparisons of treatment protocols and individual treatment outcomes, supplying different but still useful information. Orthopaedic surgery addresses biomechanical problems; thus, measurement of changes in mechanical work is an important element for follow-up studies after surgical intervention. Mechanical work is not subject to physiologic variables and therefore is more robust in making pre- and post-treatment comparisons. More research must be carried out to compare mechanical work, and oxygen consumption and cost, on the same subjects. It will be very important in all such research to compare the variability in the measures as an important indicator of the validity of the clinical test. It is time to leave this subject and move into the historical evolution of oxygen consumption and oxygen cost.

6. Oxygen consumption and oxygen cost

Sustained interest has been shown in the metabolic energy costs of human walking and other activities. To this day, oxygen consumption and oxygen cost measurements remain as the gold standard against which other methods of energy measurements are compared. Early references are found in German and English literature, but in keeping with the general format of this manuscript, which begins with the work of Inman et al., Henry J. Ralston, Ph.D., 1906–1993, and his contributions, will begin the story.

Henry J. Ralston PhD
1906-1993

Ralston was a lean and intense scientist, one of the many talented academics in the Inman-led research team on human walking. Dr. Ralston easily gained my respect and the respect of other orthopaedic residents who were privileged to hear him lecture. He talked in scientific terms, but explained them fully, proved his points by experimental studies, and made us realize that real progress in orthopaedics would come from scientific investigations. We were encouraged by his example, to dream about experimental studies to address clinical questions. It was fascinating to us to hear that, left to our own devices, most of us will adopt a walking speed that conserves the most energy. To carry out his experiments, an octagonal shaped track, 24.4 m in length, was used along with a large frictionless revolving boom, which carried the leads from the patient to the recording apparatus.
in an adjacent room. The volume of expired air was measured and fractions of the same were analyzed with the respirometer developed at the Max Planck institute in Germany. An assistant carried the meter and, after a period for stabilization, the subject was walked at varying speeds. The results of normal subjects walking at different speeds, and a similar study of one hemiplegic subject, are to be found in the writings of Bard and Ralston [70,71]. Both ‘too slow’ and ‘too rapid’ walking increase the energy costs of walking. This concept has survived a great deal of experimental testing, and is responsible for the current use of “free speed walking” as the ideal format for comparison of individuals before and after treatment. It is always simple to add some increased speeds, which will reveal further information. For example, patients with cerebral palsy can increase their speed of walking, but ordinarily this requires some increase in cadence with less ability than normal subjects to increase the stride length.

There has been a divergence on the method of measuring oxygen costs and oxygen consumption, treadmill versus level walking. The level walking enthusiasts are convinced that this is the ideal way because it is more natural. There are none of the changes brought about by the treadmill, and furthermore there are a large number of patients with disabilities who cannot walk on a treadmill. Nonetheless, they can do over-ground walking. Sports medicine evaluations have more often been done on a treadmill. This method allows all of the monitoring equipment to be kept in one place, but treadmill walking alters gait and necessitates the use of different control values. If over-ground studies are to be done, telemetry is desirable. A revolution has occurred in the oxygen cost/oxygen consumption measuring equipment.

An example is the current Cosmed system, developed by Cosmed S.r.l. headquartered in Rome, Italy, that is entirely portable and does not require either a cart or an assistant to carry the equipment. It is self-contained on the subject. A comparison of the Cosmed K2 system of children with cerebral palsy walking on a treadmill with a non-portable breath-by-breath system and over-ground walking using the Cosmed K-2 did not show appreciable differences in energy cost [72]. There has been an evolution in this area, which needs to be developed, with the appropriate references. However, I will not attempt to tackle that endeavor within the constructs of this manuscript.

Dr. Ralston advised against using net energy, which is obtained by subtracting resting energy from the total energy produced during steady state in a prescribed activity such as free- or controlled-speed walking. Many investigators, though not all, have followed his recommendation. My comment is that, if one wishes to determine the exact difference between resting state and a proscribed activity, net energy is relevant. If the need is to determine the advisability of encouraging an activity for an individual exhibiting excessive energy demand, the gross energy costs are uppermost in importance. For clinical follow-up to determine the ease of walking after surgical, orthotic, prosthetic or physical therapy intervention, net information is highly relevant. By subtracting the resting energy requirements for this individual the variables that may change over time such as altered cardiac or pulmonary function, meals, and/or mental tension, allows concentration on whether the intervention made walking easier. There can be little argument with the common practice of collecting and reporting both gross and net energy levels. An excellent summary of Dr. Ralston’s work, as well as an “In Memoriam” tribute, is found in Chapter 8, second edition of “Human Walking” [73].

The historical trail of the “Energetics of Walking” moved to Rancho Los Amigos Hospital and Rehabilitation Center. Robert L. Waters, MD has been the prime investigator there. He earned his medical degree at the University of Chicago. His orthopaedic residency was served at The University of California San Francisco. During his residency he completed a fellowship at the Biomechanics Laboratory, where Dr. Ralston, Dr. Inman and the other creative scientists associated with Dr. Inman’s research team were his mentors. He served a fellowship at Rancho Los Amigos, later joined the staff and invested himself heavily in research. A letter written in response to a number of questions I posed to Dr. Waters is very illuminating, and direct quotations may be found in Appendix B. The laboratory methods for measuring energy in the Pathokinesiology Laboratory at Rancho Los Amigos Hospital are well described in Chapter 21, Energy Expenditure, by Robert L. Waters, in “Gait Analysis – Normal and Pathological Function”, by Perry [74]. The method of gait analysis used is a modification of the Douglas Bag technique: “The system is harnessed to the subject’s shoulders. A multi-ported valve enables multiple collected gas samples in non-porous polypropylene bags while the patient walks around a circular 60.5 meter outdoor track. The subject breathes through a well-fitted mouthpiece and wears a nose clip to prevent air leakage. The directional flow of inspired and expired air is controlled by two large diameter, one-way ‘J’ valves mounted over each shoulder.” (To enable continuous gas analysis while subjects walked around a track, Corcoran [75] developed a velocity-controlled motor driven mobile cart carrying the gas measurement apparatus.)

Dr. Robert Waters currently holds the position of Chief Medical Officer at Rancho Los Amigos National Rehabilitation Center, which he joined in 1971, Clinical Professor of Orthopaedics at the University of Southern California, Project Director of the Regional Spinal Cord Injury Care System of Southern California, and Co-Director of the Rehabilitation Research and Training Center on Aging With a Spinal Cord Injury.
Another important contributor in the field of energy studies is Jessica Rose, PT, Ph.D. [48,73,76–79]. Dr. Rose has deep roots at U.C. Davis (undergraduate studies), Stanford School of Physical Therapy, and the Motion Analysis Laboratory, Packard Children’s Hospital at Stanford, where she currently holds the position of Director. Her personal communication shows the network of influences in her career and her current thinking about the role of heart rate measurements. Quotations from her personal communication may be found in Appendix C.

At this point, we stop to consider some of the clinical contributions that have come from energy measurements, in addition to those mentioned by Drs. Waters and Rose, such as examples utilizing these assessments in studies of myelomeningocele and cerebral palsy patients as follows.

6.1. Myelodysplasia/myelomeningocele

Independently ambulatory myelodysplasia patients with S1 level involvement demonstrate lower oxygen cost than patients with L4 and L5 level involvement [61]. The oxygen cost of walking is significantly better for children with myelodysplasia L4, L5 and sacral level lesions when using ankle-foot orthoses, then when walking barefoot [80].

Independent ambulators with high sacral myelomeningocele demonstrate oxygen cost and oxygen consumption values exceeding the normal level by more than one standard deviation. Of the kinematic measurements, pelvic obliquity demonstrated the strongest relation with oxygen cost [81]. Comparison of the rate of oxygen consumption and oxygen cost for lower lumbar myelomeningocele subjects reveals a higher oxygen cost for reciprocal walking than for a swing-through gait, leading the authors to conclude that swing-through gait proves to be the more efficient walking pattern in this group of patients [82]. A comparison of oxygen cost and velocity in children with myelomeningocele using hip-knee-ankle-foot orthoses (HKAFO) revealed similar oxygen costs as children with reciprocating gait orthoses (RGO), while achieving a faster velocity. With increasing age and upper extremity development many of the children progressed from RGOs to HKAFOs. The authors stated that wheelchair mobility should be offered when speed and an energy efficient method of community mobility are necessary [83].

6.2. Cerebral palsy

Use of hinged ankle-foot orthoses lowers the oxygen cost of walking in children with spastic cerebral palsy, but affects neither net heart rate (beats/min minus one), nor the respiratory exchange rate [84]. A study of children with spastic diplegic cerebral palsy comparing the use of anterior and posterior walkers indicates that the posterior walker has advantages in terms of upright positioning and energy conservation [85]. A retrospective review of temporal–spatial gait parameters of children with cerebral palsy walking bare-foot and with clinically prescribed ankle-foot orthoses showed a significant increase velocity, stride length, step length and single limb stance when the orthoses were used [86].

6.2.1. Present reality

Kinetic data and energy measurements are capstones to kinematic and EMG measurements. The necessary instruments are well developed and available to new users as well as experienced gait laboratory personnel. A multi-disciplinary team is optimal and even essential for maximum clinical applications. None of these strong tools can be used as a stand-alone system and in my opinion the term clinical gait analysis should be reserved for laboratories offering complete data gathering instruments and individuals capable of gathering good data and providing clinical interpretation. The rapid expansion of automated real time data capture greatly eases this task and allows more time for interpretation of the data. As a result of much hard work on the part of many and tremendous technical advancements, clinical gait analysis has emerged as an essential discipline to be used regularly before and after major treatment changes for children and adults with walking impairment. The basic components are EMG, kinematics, kinetics, and energy. The addition of dynamic foot pressure is highly desirable. Most of the laboratories in the United States offering clinical as well as research studies...
provide at least three of the listed components. How available are these services? The areas with the greatest concentrations are the West Coast where the movement began, the East Coast, and the Great Lakes Area. There is still limited access for many patients in a large area in the United States (see Fig. 5). However, laboratories continue to be established at major medical centers and in University complexes, even though financial hardships for medical institutions prevail. There are as many, or more, centers outside of the United States, where clinical gait analysis is performed. All of the equipment is commercially available, allowing for earlier utilization after suitable training. The greatest need at this time is for individuals capable of interpreting the data and making rational comments and recommendations. The residents and fellows completing their training will make up some of this deficit, but an introduction of the subject at the medical school level is needed.

6.2.2. Future

Multiple disciplines such as neurology, psychology, radiology, physiology, neurosurgery, ergonomics, sports medicine and pediatrics have entered the arena of clinical investigation using gait analysis tools. Observant readers will notice that even now movement analysis presentations, without objective movement data, seldom reach podium presentations in major meetings, even if they are presented with video, and are even less likely to be published. Claims of efficacy of treatment regimes must be tested and proven scientifically. Science, by its very nature, is progressive not regressive. Therefore, the science of motion analysis, although currently well established, will continue to advance as fresh insights are gained and new technologies become available. Treatment options, such as pharmaceutical, orthotic, surgical, or physical therapy regimes, will be better directed. The outcome of these interventions will be evaluated in a truly scientific manner. Who are the primary beneficiaries of this remarkable and ongoing evolution? Hopefully, our patients.

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Appendix A. A partial list of commercial force platform and energy consumption systems

Advanced Mechanical Technology, Inc. (AMTI)
176 Waltham St.
Watertown, MA 02472
Tel: (617) 9266700
Fax: (617) 9265045

Bertec Corporation
6185 Huntley Rd.
Suite B
Columbus, OH 43229
Tel: (877) 8848725
Fax: (614) 4305425

Cosmed S.r.l.
Via dei Piani de Monte Savello, 37
PO Box 3
Pavona di Albano – Rome, Italy
I-00040 – Italy
Tel: +39 (06) 9315492
Fax: +39 (06) 9314580

Kistler Instrument Corp.
75 John Glenn Dr.
Amherst, NY 14228-2171
Tel: (888) 5478537
Fax: (716) 6915226

Sensor Medics
Savi Ranch Parkway
Yorba Linda, CA 92687-4609
Tel: (800) 2312400
Fax: (714) 2838439

Vacumetrics, Inc.
4538 Westinghouse Street
Ventura, CA 93003
Tel: (805) 644-7461
Fax: (805) 654-8759
Appendix B. Quotes: Robert L. Waters, MD

“I selected UCSF for a residency because the program provided the opportunity to spend a year in the Biomechanics Lab. I received a grant from the Easter Seal Society to study the effects of spinal immobilization by different types of back braces on the EMG activity of trunk muscles and trunk motion. That is how I became interested in gait. I found the precise interplay between the vertical rise and fall of the trunk, and the backward and forward acceleration of the trunk to be fascinating.”

“After working in the Biomechanics Laboratory, I rotated to Children’s Hospital in San Francisco and was exposed to the gait lab at Shriners Hospital. Dr. Sutherland was one of the pioneers in the application of gait study in planning children’s surgery in cerebral palsy and other conditions. The pain staking methods to measure gait motion available at the time were arduous since many measurements and calculations from single frames of film were needed just to describe a single step. It seemed to me that a simple, global method of summing up the energetic penalties of abnormal limb movements in the gait cycle was needed. Since ultimately all limb motion results from muscle contraction and the metabolic energy expended by muscles directly correlates with O₂ consumption, I was convinced oxygen could provide important global information on the overall efficiency of gait to supplement specific data being collected related to stride analysis, joint motion analysis and dynamic EMG.”

“I later rotated to Rancho Los Amigos National Rehabilitation Center as a resident and had a chance to work in Dr. Jacquelin Perry’s Pathokinesiology Lab and pursue my desire to study energy consumption in disabled gait. Rancho’s different patient care programs had a large population of nearly every conceivable type of gait disorder.”

“Although Dr. Perry permitted me to use her gait laboratory, I had no equipment. Fortunately, I was able to scrounge. I found out that plastic garbage bags could be made into a good Douglas Bag. Leg bags for urinary collection in spinal cord injury patients were impermeable to O₂ and CO₂ and proved excellent for storing air samples. I borrowed an O₂ and CO₂ analyzer and an old Tissot volumeter from the pulmonary laboratory. In later years, the engineers in the lab built more sophisticated energy measuring systems that enabled continuous telemetry of stride characteristics, respiratory rate and heart rate while subjects walked around a circular track unimpeded by connecting wires or cables. I did not follow Ralston’s protocols. He did not generally record heart rate or respiratory rate while walking so it was not possible to determine from his studies whether measurements were taken in “steady state” conditions. More importantly, Ralston and others, had generally studied gait on a treadmill or at a constant velocity. As a clinician, I knew that disabled patients often had a narrow range of reduced walking speeds and many had difficulty walking on a treadmill or a controlled velocity other than their comfortable walking speed (CWS). Testing under these conditions in patients who could not adapt would introduce experimental artifact. This was particularly true of patients with neurological disabilities. For these reasons, we set up our testing procedure so that data collection began after the patient reached steady state conditions at the patient’s CWS. I wanted our measurements to reflect as closely as possible normal walking conditions and introduce as little experimental artifact as possible.”

“Over the following years, we tested almost every type of gait disorder. More that 20 PT students helped. Every level of amputation in both the dysvascular and traumatic amputee populations was studied. We studied arthritis of both the knee and hip and the effect of total joint replacement. We studied stroke patients, cerebral palsy patients, myelomeningocele patients, patients with hip and knee fusions, patients with lower extremities immobilized by casts, crutch-walking, patients with spinal cord injury – and probably more that I have forgotten. We also studied wheeling and the effects of different types of floor surfaces.”

“We found that preservation of limb length was crucial in amputees. Amputees at increasingly higher amputation levels slowed their CWS to keep the rate of energy expenditure from rising above normal limits indicating the importance that surgeons perform amputation at the lowest possible level. We also found out that the gait of traumatic amputees was different than the older dysvascular amputees at the same levels of amputations. Heretofore, most gait studies of amputees mixed both dysvascular and traumatic patients together.”

“The spinal cord injury (SCI) studies were particularly illuminating. By comparing energy expenditure of swing-through gait to wheeling, we found out why most patients required to utilize this type of gait pattern ultimately discontinued walking for much less physiologically stressful wheeling. For those SCI patients who could walk using crutches, we found very elegant and strong relationships between the amount of paralysis in the lower limbs, the amount of axial load applied to the crutches and the rate of O₂ consumption and other parameters. In other words, these studies directly demonstrated how the arms directly substitute for lower extremity paralysis and how the amount of arm work increases the rate of physiologic effort and limits endurance.”

“Joint fusion studies were very interesting because we were able to demonstrate the importance of normal motion at each joint by measuring the effect of joint fusion on energy consumption. Loss of ankle motion resulted in the least energy penalty followed by the knee and then the hip.”

“Cerebral palsy was also interesting in that our studies demonstrated how with advancing age and weight gain, children tended to walk slower and at a greater energy cost. This led to the conclusion that one of the main reasons many
children stopped walking in their 20’s and 30’s was due to weight gain and declining maximal aerobic capacity.”

“Myelodysplastic children, due to their light total body weight, strong arms and relatively high maximal aerobic capacity, were able to functional ambulate even with much greater paralysis than adults with spinal cord injury. Many had a very functional swing-through gait and were able to meet this energy demand. However, as in cerebral palsy, with advancing years, we concluded this high rate of energy consumption became no longer tenable so that those children with severe lower limb paralysis generally became wheelchair users.”

“I do not believe it necessary to routinely perform energy consumption studies in all patients. As in any clinical measurement, there are specific indications for ordering a test. However, energy consumption provides important information anytime walking endurance or fatigue is of clinical concern. Energy consumption studies enable one to advise patients on the practical scope and range of walking activities. From an energy conservation perspective, this information helps the clinician recommend to the patient daily living walking activities in such a way as to keep energy demands within a reasonable limit. Energy consumption can provide information when walking is no longer practical and when wheelchair use is most highly correlated with oxygen consumption/kg while walking. We have assumed it would be better to subtract the resting rate, but I’m not sure if that has ever been determined.”

“We do routinely measure resting and walking heart rate and record the slow, comfortable and fast walking speeds and energy expenditure index (EEI). We do not call it the physiologic cost index (PCI) because Dr. Ralston insisted on being specific and pointed out that there is more to physiologic cost than energy expenditure, and that what was being estimated was energy expenditure, and thus, we still refer to it as EEI.”

“As the methods of direct measurement of energy expenditure improve and become less cumbersome and expensive, I do believe that heart rate monitoring will be less common and, given the choice, I would prefer to have oxygen consumption data. Unfortunately, my capital budget has not allowed this yet, but it is a goal!”

Appendix C. Quote: Jessica Rose, PT, Ph.D.

“I became interested in gait analysis as an undergraduate student at UC Davis while working with children with cerebral palsy as a volunteer at a Medical Therapy Unit in Sacramento. Dr. Warden Waring, a biomechanical engineering professor at Davis gave intriguing lectures on center of pressure movement during gait; thus, I became aware of the impact of gait deviations on center of pressure displacement and the energy cost of walking. Unfortunately, my sister had suffered a severe head injury after being hit by a drunk driver and was struggling to recover. She had and still does have difficulty walking and I became keenly aware of how fatiguing walking disorders can be and the importance of the energetics of walking.”

“While in physical therapy school at Stanford, my mentor, Dr. Ann Hallum (now at SF State, she used to direct the PT school there and now is a Dean) suggested that I contact Dr. Henry J. Ralston, a physiology professor at UCSF who was an expert on the energetics of walking. He became an important mentor and helped me to apply his expertise to cerebral palsy gait analysis.”

“It was at my own initiative to study heart rate while walking in children with cerebral palsy, it seemed to be a simple and inexpensive estimate of energy expenditure. The complications with heart rate are primarily related to resting heart rate, which as you know, decreases with age and increases with anxiety. A good study would be to determine if walking heart rate or walking heart rate – resting heart rate

References