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Review

The history of gait analysis before the advent of modern computers☆

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Abstract

Aristotle (384–322 BCE) can be attributed with the earliest recorded comments regarding the manner in which humans walk. It was not until the renaissance that further progress was made through the experiments and theorising of Giovanni Borelli (1608–1679). Although several scientists wrote about walking through the enlightenment period it was the brothers Willhelm (1804–1891) and Eduard (1806–1871) Weber, working in Leipzig who made the next major contribution based on very simple measurements. Both Jules Etienne Marey (1830–1904), working in France, and Eadweard Muybridge (1830–1904), working in America, made significant advances in measurement technology. These were developed further by Otto Fischer (1861–1917) in collaboration with Willhelm Braune (1831–1892). The major developments in the early twentieth century were in the development of force plates and the understanding of kinetics. The team headed by Verne Inman (1905–1980) and Howard Eberhart (1906–1993) made major advances in America shortly after the Second War. David Sutherland (1923–2006) and Jacquelin Perry pioneered clinical applications in America and Jurg Baumann (1926–2000) in Europe. It was not until the advent of modern computers that clinical gait analysis became widely available.

Keywords: Gait analysis; Kinematics; Kinetics; History

People have been thinking about how they walk since the earliest times. This article traces the history of this process from the time of Aristotle through to the dawn of the modern era of computerised analysis techniques. Through recounting this history it is possible to see how our present understanding of walking has developed as a series of steps each based on previous developments in the field and on the scientific and cultural environment in which the individual contributors were living. A particular aspect of the history of this field is how major developments have often been a consequence of collaborations of individuals with different expertise, particularly between those with expertise in the life sciences and those with expertise in the physical sciences. A list of major contributors to the field is given in Table 1.

Aristotle (384–322 BCE) made the first known written reference to the analysis of walking:

> If a man were to walk on the ground alongside a wall with a reed dipped in ink attached to his head the line traced by the reed would not be straight but zig-zag, because it goes lower when he bends and higher when he stands upright and raises himself. [1]

Unfortunately he lived in a society in which it was assumed that scientific truth could be determined simply by thinking about a problem. None of his propositions were ever tested by experiment. As a consequence, whilst this particular observation is true, almost all his other related conjectures are now known to be false.

It was not until the time of the renaissance in Europe that science and mathematics in Europe started to develop coherently. It was at this time that some of the concepts that

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Table 1
Time-line of major contributors to the history of gait analysis

Date	Name	Location	Contribution
384-322 BCE	Aristotle	Athens, Greece	Theories on the movement of humans and animals.
1501-1576	Girolamo Cardan	Milan & Pavia, Italy	Consideration of 3-d joint angles.
1564-1642	Galileo Galilei	Piza, Florence & Padua, Italy	The modern scientific method.
1596-1650	Rene Descartes	Leiden, The Netherlands	Cartesian co-ordinates. 1st test-book on physiology.
1608-1679	Giovanni Borelli	Pisa & Rome, Italy	Muscle and tendon biomechanics.
1642-1727	Isaac Newton	London, England	Newtonian mechanics.
1668-1738	Hermann Boerhaave	Leiden, The Netherlands	Application of Newtonian mechanics to human body.
1707-1783	Leonhard Euler	Basel, Switzerland & St Petersberg, Russia	Theory of 3-d joint angles.
1708-1777	Albrecht van Haller	France	Physiology of walking (ideas reviewed by Weber and Weber).
1734-1806	Paul Barthez	France	
1783-1855	Francoise Margendie	France	
1781-1840	Samuel Poisson	France	
1797-1856	Pierre Gerdy	France	
1804-1891	Willhelm Eduard Weber	Leipzig, Germany	Anatomy and mechanics of walking. *Mechanik der Gehwerkzeuge (1836).*
1806-1871	Eduard Friedrich Weber	Leipzig, Germany	
1795-1878	Ernst Heinrich Weber	Leipzig, Germany	Brother of and probable collaborator with Eduard and Willhelm.
1806-1875	Guillaume Duchenne	Boulogne, France	Founder of electrophysiology. Reported *Duchenne* gait pattern.
1844-1924	Freiderich Trendelenberg	Berlin & Leipzig, Germany	Orthopaedic surgeon. Reported *Trendelenburg* gait pattern.
1830-1904	Jules Etienne Marey	Paris, France	Physiologist. Force and pressure measurement. Chronophotography.
1849-1892	Gaston Carlet	Paris, France	Student of Marey. First essentially correct description of gait cycle.
1850-1918	Georges Demeny	Paris, France	Student of Marey. Pioneer of photographic method.
1830-1904	Edward Muybridge	Stanford then Pennsylvania, USA	Photography of movement.
1831-1892	Willhelm Braune	Leipzig, Germany	First 3-d gait analysis. *Der Gang des Menschen* (1895) [9]
1861-1917	Otto Fischer		
1896-1966	Nikolai Bernstein	Moscow, Russia	Development of theories of motor control.
1879-1935	Jules Amar	Paris, France	Pneumatic three-component force plate.
1893-1971	Wallace Fenn	Rochester, USA	Mechanical one-component force-plate
Unknown	Herbert Elftman	New York, USA	Mechanical three component force plate. Kinetics of walking
1905-1980	Verne Inman	Berkeley, USA	Founded biomechanics lab at University of California, Berkeley
1906-1993	Howard Eberhart	Berkeley, USA	
1925-1984	Pat Murray	Milwaukee, USA	Instrumented studies of normal walking in men and women
1918-	Jacquelin Perry	Downey, USA	Pioneer of clinical electromyography and observational gait analysis
1923-2006	David Sutherland	San Francisco then San Diego, USA	Digitisation of data from cine film. Development of walking in children
1926-2000	Jurg Baumann	Basel, Switzerland	Integration of cine photography with electromyography.

Entries in light type face refer to contributors to general scientific developments which have become important components of gait analysis but made no specific contribution to the field.

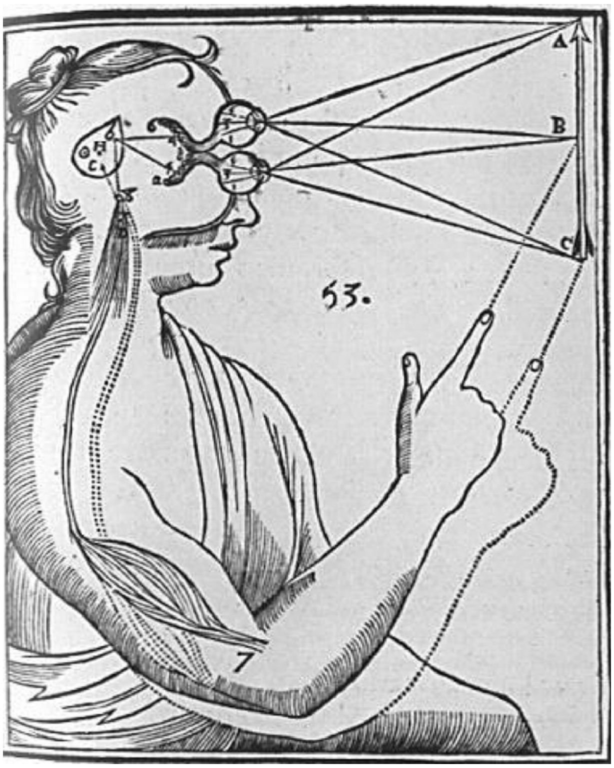

Fig. 1. Illustration from Descartes textbook of physiology De Homine (1662) [4].

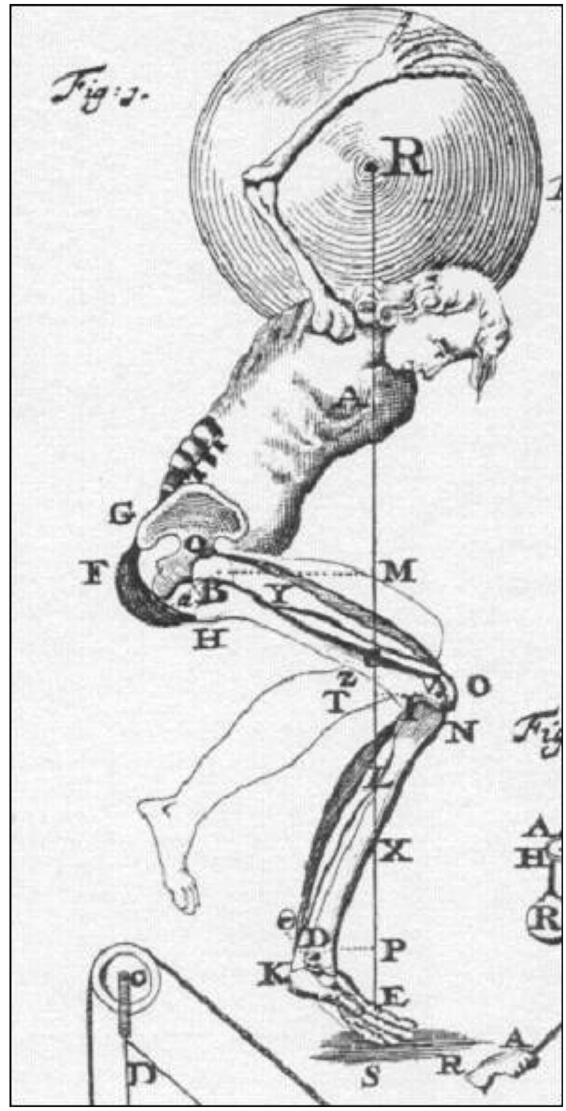

Fig. 2. Illustration from Table IV of Borelli's book On the Movement of Animals [5] showing his biomechanical analysis of a man bearing a load whilst standing on the toes of one foot (with kind permission of Springer Science and Business Media).

were later to form the mathematical basis of modern gait analysis were elucidated. Girolamo Cardan (1501–1576) was a professor of both mathematics and medicine in Milan and Pavia from about 1533 to 1552 [2]. As well as being the first European mathematician to use complex numbers (based on the square root of a negative number) and to study probability (he was a keen gambler), he also studied the properties of three-dimensional angles. Galileo Galilei (1564–1642) [3] contributed little directly to gait analysis but was perhaps the most significant physical scientist of this period in being the first person to marry deductive reasoning with experimental observation. Rene Descartes (1596–1650) first conceived of an orthogonal co-ordinate system for describing the position of objects in space. It is less well known that he also wrote the first modern textbook on physiology, De Homine [4]. This was ready for publication when Descartes heard of Galileo's trial and sentence to perpetual house arrest by the Pope in 1633. He withheld publication, which only happened posthumously in 1662. His advanced thinking is clearly demonstrated by one of the book's figures (reproduced here as Fig. 1) which clearly show closed loop motor control with the movement of the arm being controlled by muscular activity under the influence of nerves connected to the brain. Feedback is provided by the eyes.

It is no coincidence that it was one of Galileo's pupils, Giovanni Alfonso Borelli (1608–1679), who performed the first experiment in gait analysis [5]. He placed two poles an unspecified distance apart and tried to walk towards them keeping one pole in front of the other. He found that when doing this the near pole always appeared to move to the left and right with respect to the far pole. From this he correctly deduced that there must be medio-lateral movement of the head during walking. Borelli also studied the mechanics of muscles (see Fig. 2) and was the first to conclude that the forces within the tendons and muscles are considerably greater than the externally applied loads.

Borelli had great difficulty in getting his research published until he finally persuaded Queen Christina of Sweden to bear the costs. Unfortunately he was also the victim of the administrative inertia that even today typifies such schemes and had died by the time the money came through. The work was published posthumously in two parts

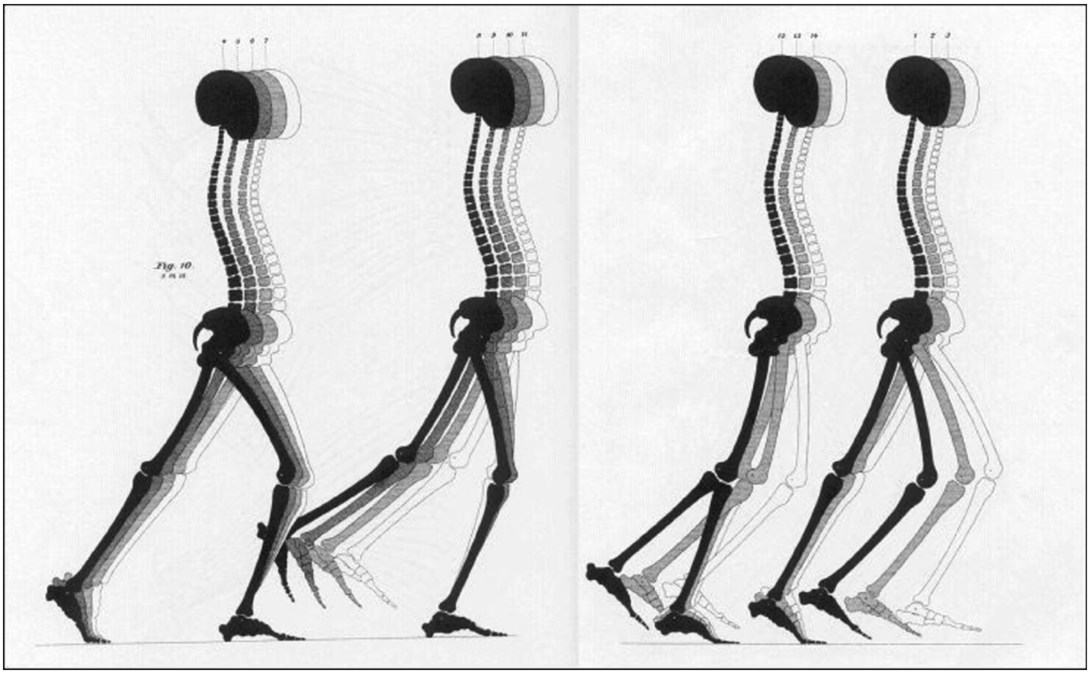

Fig. 3. The alignment of the trunk and lower limbs at 14 instants during the gait cycle (Plate XIII, Weber and Weber [8] (with kind permission of Springer Science and Business Media)).

by his colleagues. These parts were not brought together in their present form until 1734 with a comment by the great mathematician Johannes Bernoulli.

Despite his advances, Borelli did make elementary mistakes in the physical laws governing forces. He can hardly be blamed for this as they were only formulated properly by Isaac Newton (1642–1727) in *Philosophiæ Naturalis Principia Mathematica* [6] 9 years after his (Borelli's) death. Newton did not apply his ideas to the human body, he concentrated on heavenly bodies. Perhaps the strongest advocate of Newtonian mechanics applied to human movement was Hermann Boerhaave (1668–1738) working in Leiden in what is now The Netherlands [7].

Through the later part of the 18th and early part of the 19th century a series of great French physiologists (Albrecht von Haller (1708–1777), Paul Barthez (1734–1806), Francoise Magendie (1783–1855), Samuel Poisson (1781–1840) and Pierre Nicolas Gerdy (1797–1856)) made occasional observations on walking (reviewed by Weber and Weber [8]). Although all made original contributions there was little progress towards a modern understanding of human walking for two reasons. First there was no experimental work to corroborate their theories. Second the authors tended to have a knowledge either of mechanics or of physiology, but not both. Those with a physical background tended to assume that gravity was the primary motor in walking, those trained in physiology assumed that only muscular activity could produce movement.

The next major contribution was made by a team who addressed both of these problems. Willhelm Eduard Weber (1804–1891) was Professor of Physics at Göttingen (and later at Leipzig) and is still remembered in the eponymous SI unit of magnetic flux. Two of his brothers, Ernst Heinrich (1795–1878) and Eduard Friedrich Willhelm (1806–1871) both attained chairs in physiology at the University of Leipzig. The brothers worked closely on a number of publications and in 1836 Eduard and Willhelm published Mechanik der Gehwerkzeuge (Mechanics of the Human Walking Apparatus) [8]. For this they did considerable experimental work using only a stop watch, measuring tape and a telescope. The conclusions they drew directly from experimental evidence such as how step length and cadence change with walking speed are essentially reliable.

They also attempted to work out the position of the limbs at 14 different instants in the gait cycle and were the first to develop illustrations showing that attitude of the limb segments at these different instants (Fig. 3). These however were based primarily on conjecture and are far from reliable as commented upon by Braune and Fischer in 1895:

> . . . the conclusions drawn by the two authors from their direct measurements are very reliable. However, they also took the liberty of drawing conclusions which did not result directly from their measurements . . . these conclusions are, of course, much less reliable [9].

One such incorrect conclusion was that the knee is in a considerable degree of flexion at the end of swing. This was a consequence of an assumption that the swing phase movement is purely passive being driven by the action of gravity on the leg. This was correctly refuted by the French physician Guillaume Duchenne (1806–1875) who observed that patients with flaccid paralysis of the hip flexors cannot initiate swing properly and have to circumduct as a compensation. He argued that if initiation of swing is

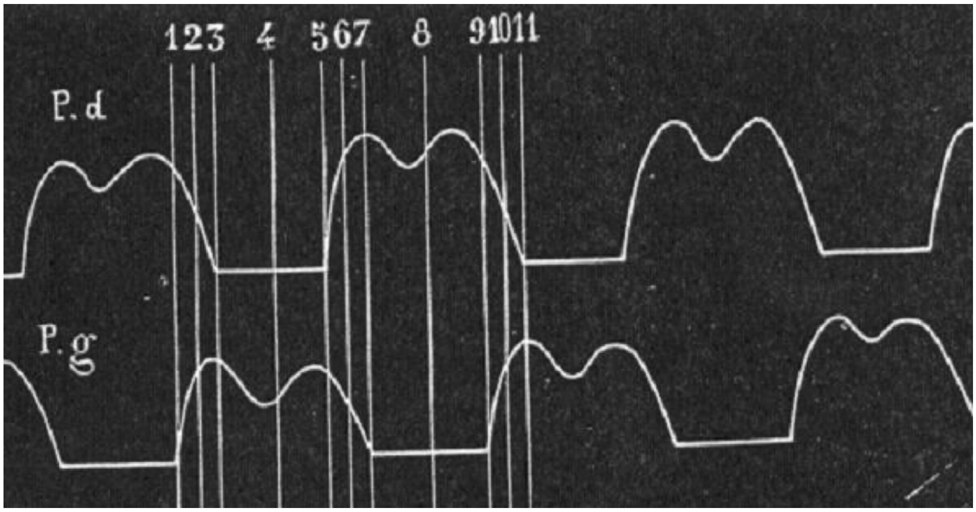

Fig. 4. The characteristic shape of the vertical component of the ground reaction force as first recorded by Carlet [13].

passive then it should not be influenced by such a condition [10]. This is a clear example of sound observation of gait and clinical reasoning identifying an error arising from too much faith in theoretical analysis.

Duchenne was the founder of electrophysiology and a student of human movement. In continental Europe his name is associated with the pattern of gait in which the pelvis is raised on the side of the swing limb and there is increased abduction at the stance side hip as a compensation for the absence of functional hip abductors. This is the opposite of Trendelenberg gait reported by the German surgeon Freiderich Trendelenberg[1] (1844–1924) in 1895 [11] in which the pelvis drops on the swing side and there is increased adduction during stance as a compensation for weak, but still functional, abductors.

The next major work on human movement was that of Jules Etienne Marey (1830–1904) in Paris (which has been comprehensively described by Braun [12]). He started training as a doctor, but was so fascinated with the physiology he was required to study that it became the focus of his life. Since the time of Newton there had been a fierce debate as to whether the human body was subject to the same laws as the rest of nature. Marey was convinced that it was. He was also convinced that by making careful and appropriate measurements that the way in which these laws operated could be deduced. In this sense he was the first modern gait analyst although his work was not limited to movement. In 1860 he recorded the first sphygmograph and in 1863 the first cardiogram.

His early work on gait was all done in collaboration with his student Gaston Carlet (1849–1892). Carlet developed a shoe with three pressure transducers built into the sole and recorded the forces exerted by the foot on the floor. He was the first to record the double bump of the ground reaction (Fig. 4). Various other experimental techniques were used and Carlet's thesis, published in 1872, concludes with a succinct description of the normal human gait cycle which is essentially accurate [13].

The next advances in the study of movement concern horses rather than humans. It is important to remember that, at the time, the horse was the primary means of transportation (other than walking). Thoroughbred horses conferred the same status as prestige automobiles do today and there was considerable interest in how they moved. In particular there was a persistent debate about whether or not there is an instant during the trot when all four hooves are off

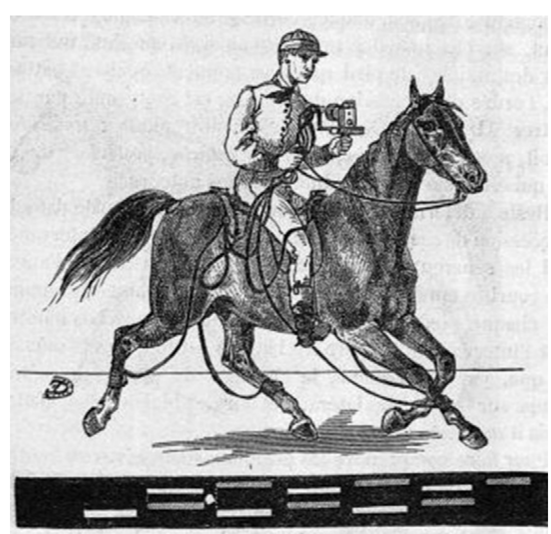

Fig. 5. Foot contact pattern of the horse during a trot. Marey's synoptical bar notations and drawing by Emile Dulhousset. White lines represent the right front and rear hooves and the shaded lines the left ones. 1872 Animal Mechanism [14].

[1] In *Trendelenberg* gait the pelvis is dropped and hence *ad*duction is increased during stance as a consequence of functional but weak abductors. In a *reverse Trendelenberg* or *Duchenne* gait the pelvis is raised and hence *ab*duction is increased as a consequence of the absence of functional abductors.

the ground. Marey adapted the devices for measuring pressure in the human shoe to detecting pressure in the equine cannon bone (in the distal portion of a horse's leg, equivalent to one of the human metatarsal or metacarpal bones). The recording instrument was held by the rider for a walk or trot but strapped to his back for the canter or gallop.

The results, which are plotted as a bar chart at the foot of Fig. 5, were conclusive. There is clearly a short period when none of the hooves are in contact with the ground. Marey had proved the issue beyond doubt and several artists used his notation to draw pictures of moving horses more accurately than ever before.

Beyond doubt for Europeans that is, but in America the debate still raged. One of the chief protagonists was Leland Stanford, builder of the Central Pacific Railroad, who had invested a large part of his wealth in developing the greatest racing stable on the West Coast at which he prided himself in acquiring and utilising the latest scientific research. He believed that there was an instant during the trot and gallop when no hooves were in contact with the ground and got caught up in a furious row with the wealthy sporting community on the East Coast who did not believe this. The whole argument was inflamed by the press. It is alleged that Stanford took on a wager for $ 25,000 on the issue but this is unlikely as he never even gambled on his own horses. He decided that the way to prove his point was to obtain a photograph of the horse at the instant of no contact. (The history of Stanford and Muybridge's collaboration and Muybridge's later work is well summarised by Taft [14].)

To do this he enlisted the help of Eadweard Muybridge (1830–1904), at that time the leading landscape photographer in America. Muybridge was an interesting character and consummate showman who had changed his name from Edward Muggeridge because he thought it sounded better. Stanford and Muybridge were aware of Marey's work and determined not only to take a single picture of the required instant of the horses trot but a series of images of the whole trot. After 5 years work the investment paid off and proof (to the acceptability of the American public) was available. The pictures were published in *Scientific American* on 19th October 1878 [15] and in the French journal *La Nature* later that year immediately stimulating the interest of Marey who started up a correspondence with Muybridge. Muybridge went on to invent the zoopraxiscope to project his images for public display and started on a series of lucrative lecture tours. He and Marey met in Paris in 1881.

Whilst Marey was inspired by Muybridge he also recognised that Muybridge's technique had limitations. Muybridge used a battery of cameras triggered in succession. This meant that each photograph was taken from a slightly different angle and this prevented useful scientific measurements being used. Marey therefore developed a shutter which enabled several different images to be captured on the same photographic plate (the chronophotograph).

At about this stage Marey started to work with another student, Georges Demeny (1850–1918). A limitation of the chronophotograph was that the images overlapped and measurements were still difficult. Demeny and Marey thus experimented with different types of markers. The technique resulted in exquisite images from which it is clearly possible to make meaningful measurements (see Fig. 6).

Marey went on to refine this technique in different ways and used it to study pathological walking, he was, after all, a doctor by profession. The work was continued well into the 20th century by the Ducroquet family [16] (father Charles and sons Robert, Jean and Pierre) and later by Michael Sussez (all surgeons). Marey started to experiment with moving the glass plate behind the shutter to separate out the images and, when photographic film was invented, started also to use this. In effect he produced the world's first cine camera. He was a scientist however, interested in making measurements not movies, and the Lumière brothers working elsewhere in France are generally credited with the invention of cinema [17].

Marey never showed any interest in three-dimensional measurements. Otto Fischer (1861–1917, Fig. 7b) was a German mathematician who was the first to conduct a three-

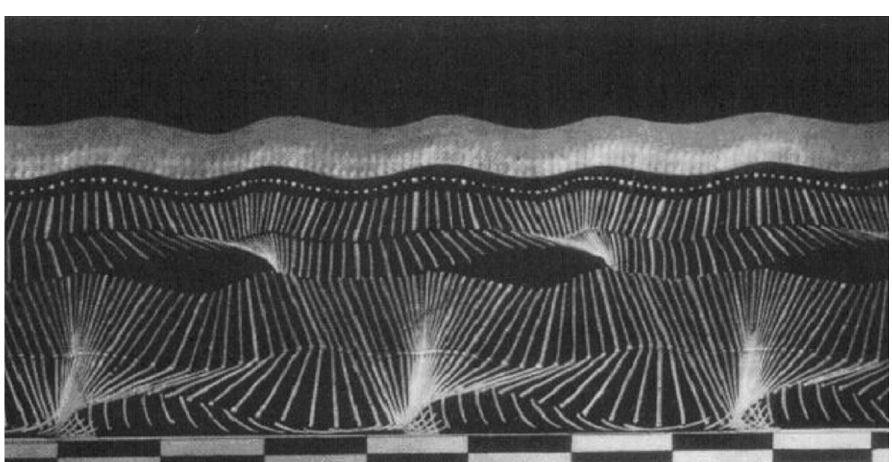

Fig. 6. Joinville soldier walking, 1883. College de France.

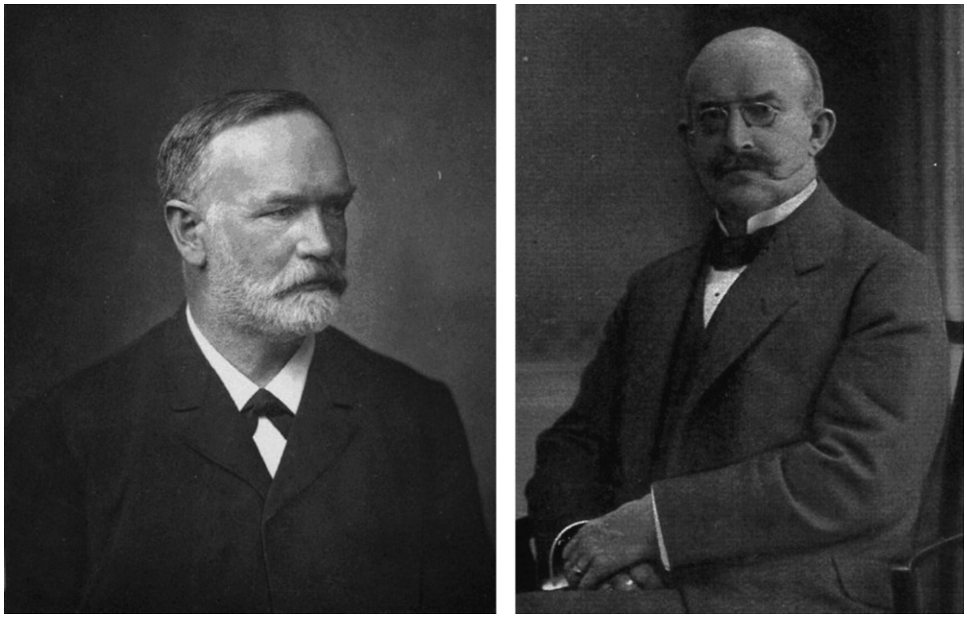

Fig. 7. Wilhelm Braune and Otto Fischer (photographs courtesy of Leipzig University Archives).

dimensional gait analysis. His name will always be associated with Willhelm Braune (1831–1892, Fig. 7a), a Professor of Anatomy with whom he had worked previously in measuring the inertial parameters of the human body [18]. Braune actually died early on during this subsequent work but, even so, it is still often reported as collaborative [9].

They used continuous exposures with the subject walking in the dark with Geissler tubes strapped to his body (see Fig. 8). A tuning fork was used to make and break the electrical circuit thus ensuring accurate timing of the flashes of light. To provide electrical isolation thick rubber strapping was used.

''Perhaps we were over-concerned with regard to insulation and could have saved ourselves a great deal of time because it took us between 6 and 8 hours to dress the experimental subject. However, we thought that the subject would walk more naturally if he knew the electric current, of which so many people are afraid, would not come in contact with his body.''

Experiments were carried out at night since there was no way of darkening the whole room. From the many series taken on different nights three were selected for further analysis from one particular night, 24th July 1891. Two were of normal walking, and one of walking with

''army regulation knapsack, three full cartridge pouches and an 88 rifle in the 'shoulder arms' position . . . The helmet had to be discarded because it would have required removal of the head tube.''

Critical to this process was the accurate determination of camera position. The mesh frame that the subject appears to be wearing in Fig. 8 is actually a calibration object superimposed on the camera from a separate exposure. Significant processing of the data was envisaged so particular care was taken in making the initial measurements from the images. This was accomplished with equipment manufactured in Leipzig capable of measuring a point on the 18 cm $\times$ 24 cm photographic plate to an accuracy of 0.001 mm.

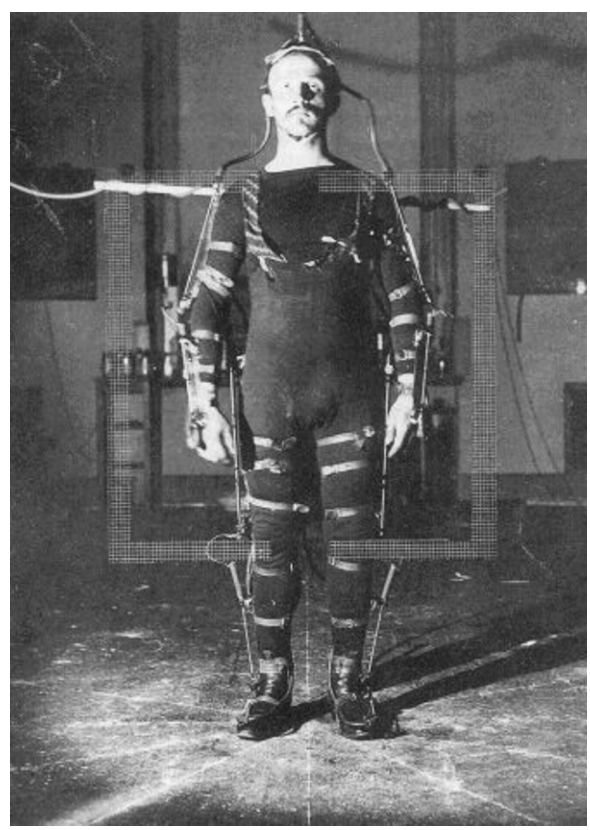

Fig. 8. Braune and Fischer's subject wearing the experimental suit [9] (with kind permission of Springer Science and Business Media).

Points were measured on the images from each of the cameras on the respective side of the subject and a full three-dimensional reconstruction of the true position of the point calculated. Calculations were done with the help of a machine and were all then checked for errors. The time taken for this was not recorded but a special acknowledgement is given to a Dr. Höckner who actually did the work. The point on the head was seen by both pairs of cameras and thus served as a check on the data. Agreement between the two completely independent systems was of the order of 1 mm in all three dimensions.

Once the point co-ordinates had been calculated then the joint centres were calculated. It was not possible to pick up the internal or external rotation of the limbs so it was assumed that the elbow, wrist, knee and ankle joint centres were medial to the joint markers by half the measured joint width. A slightly more complex technique could be used for the hips and shoulders as measurements from both sides could be used to determine the rotations of trunk and pelvis in the transverse plane.

The results were then plotted out by hand (Fig. 9). This looks similar to the photographic plate of Marey's (Fig. 6) but is more accurate in that all effects of parallax have been compensated for by the three-dimensional analysis. Fischer did not stop there however. He went on to calculate the trajectory of the centre of mass of each of the body segments and of the whole body (see Fig. 9). Using a full inverse dynamics approach he was thus able to calculate the joint moments for the lower limb joints during the swing phase of gait.

The work of Braune and Fischer was modified and repeated by Bernstein (1896–1966) in Moscow in the 1930s on a greater range of subjects including older people and children. Rather surprisingly he suggested medio-lateral movements were unimportant and that smoothing the data caused loss of important information. (Bernstein's publications have been catalogued by Jansons who also gives a useful summary of his contribution to movement analysis [19].)

Whereas Braune and Fischer's work remained the definitive work on kinematics for several decades, the development of force plates to enable kinetic measurements continued. Marey and Carlet had developed a pneumatic system to measure in-shoe pressures [20]. Demeny and Marey used much the same technology to devise a pneumatic force plate [21] that they used in conjunction with the chronophotograph to start investigating the energetics of gait.

Demeny's force plate only measured the vertical component however and it was clear that in order to fully understand walking a knowledge of all three components of the ground reaction was required. Jules Amar (1879–1935) working in France during and after the first world war was the first to develop a three-component force plate [22]. This had a mechanical mechanism compressing rubber bulbs and pneumatic transmission of the signals similar to Demeny's approach (see Fig. 10). Amar's work is notable in that his work was driven by a clinical need rather than scientific curiosity. Amar was, amongst other things, a rehabilitation specialist looking to measure rehabilitation of those injured during the war [23].

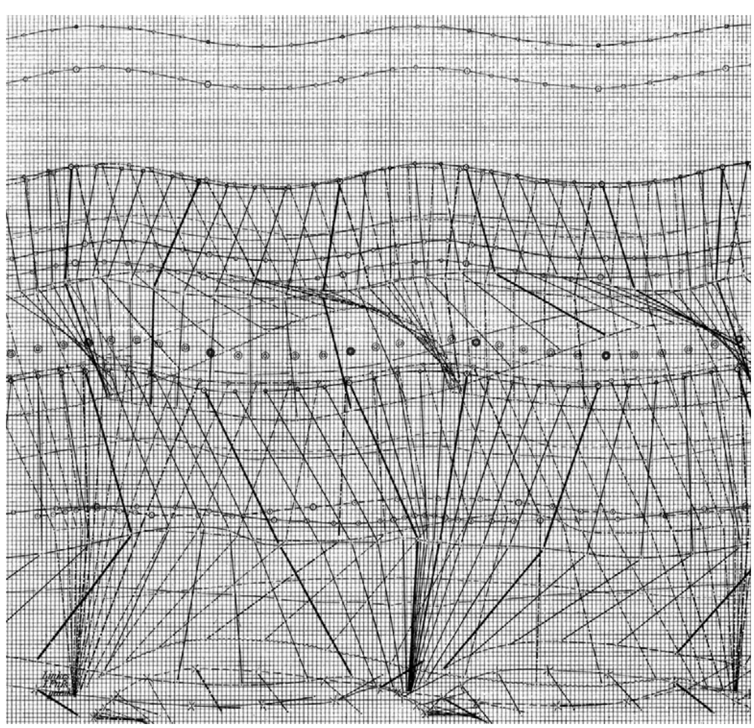

Fig. 9. Braune and Fischer's true two-dimensional measurements of human walking [9] (with kind permission of Springer Science and Business Media).

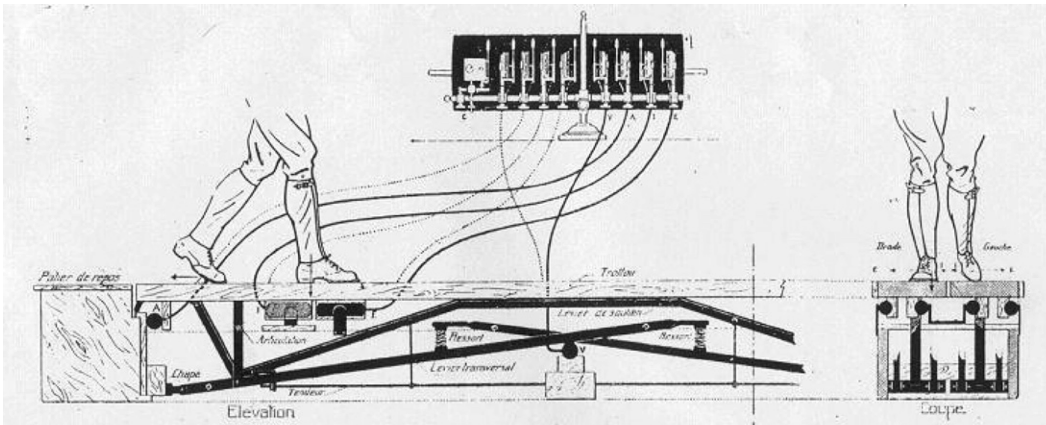

Fig. 10. Amar's "Trottoire Dynamographique" [20].

His ideas were later developed by several workers in the United States. In 1930 Wallace Fenn an engineer in Rochester produced a purely mechanical force plate to measure the horizontal component only [24] and Elftman later made a full three-component mechanical force plate at Columbia in 1938 [25]. Elftman requires special mention as developing both the practice of measuring the ground reaction and the pressure distribution under the foot and the theoretical analysis of the forces, moment and energy changes in the leg during walking. He went on to become Professor of Anatomy in the College of Physicians and Surgeons at Columbia University, no small achievement for an engineer.

The next development in force plate technology was that of a full six-component force plate using strain gauges by engineers Cunningham and Brown at the University of California in the late forties [26]. Similar plates were soon manufactured in other institutions, an early European one was produced at Strathclyde University in Scotland. The first commercially available force plates specifically designed for Biomechanics were however piezo-electric plates. These were developed by Kistler in 1969, first for surgeon Dr. S.M. Perren, then at the Laboratorium für experimentelle Chirurgie in Davos (Switzerland). Commercial strain gauge platforms became available in the early 1970s. There has been little development in the basic principles of operation of either type of device since this time.

As the casualties of the First War drove Amar to develop his techniques in France, so those from the Second War drove the biggest advance in Gait analysis this Century in America. In 1945 the National Research Council set up the Committee on Prosthetic Devices and a team of about 40 scientists was assembled at the Biomechanics Lab at the University of California at Berkeley. Their work is well documented in the book *Human Limbs and their Substitutes* [27]. The team was headed by Verne T. Inman (1905–1980), Orthopaedic Surgeon and Howard D. Eberhart (1906–1993), Engineer. Eberhart, originally a structural engineer, had his foot crushed by a heavy lorry simulating the weight of a bomber aircraft during testing the construction of a runway at an airbase. Inman first met him as the surgeon who amputated the foot.

The group started with a study of normal locomotion using a variety of techniques. Both cine photography, which had of course developed significantly from Marey's time, and interrupted light photography were used. Perhaps the most notorious aspect of the work was their use of bone pins on volunteers (see Fig. 11). They were driven to this by the recognition that no other technique would be accurate enough to pick up the transverse rotations of the joints.

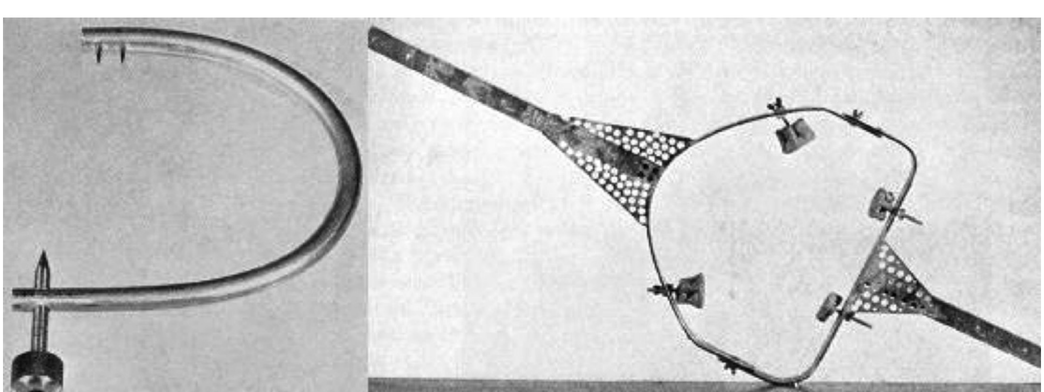

Fig. 11. Devices used at Berkeley to remove the effects of skin movement [25].

Rather surprisingly given this they were reluctant to use fine wire electrodes for EMG as these were perceived as too invasive!

The work of the Berkeley group was founded on the principal that an understanding of normal gait was a pre-requisite of a study of amputee gait. Their work was, as a consequence, applicable to many fields:

" . . . it is obvious that any improvement - either in surgical and physiotherapeutic procedures or in braces and prostheses - must rest upon an accurate knowledge of the functional characteristics of the normal locomotor system."

Another aspect of their expertise was the way in which they communicated their results. They developed methods for presenting data which are a model of clarity in explaining the complexity of gait with concepts which were accessible to all. Saunders, Inman and Eberhart's classic paper [28] and Inman, Ralston and Todd's Book, *Human Walking*, are the epitome of this [29]. Although this work has received some criticism recently, it laid a basis for the understanding of gait which allowed tremendous progress to be made.

However, to analyse one single stride 14,000 numerical calculations were performed by hand, 72 curves were plotted, 24 curves subjected to graphical differentiation. This work required approximately 500 man-hours at first but due to increased experience of the personnel the computations on the fourth subject were completed in "just" 250 man-hours. The final challenge in establishing gait analysis as a clinical tool was in reducing the processing time to sensible limits. The development of more and more powerful computers, of course, had the biggest impact on this but several other methods are also worthy of consideration.

The study of walking in 60 normal men conducted by Murray et al. in Milwaukee [30], Wisconsin was probably the most direct development of the techniques pioneered at Berkeley. Interrupted light photography was used in the sagittal and transverse planes on the same photographic plate by putting a large angled mirror over the walkway. The resulting images were similar to those of Braune and Fischer. Although the German's full three-dimensional reconstruction of marker positions was not attempted some key measures were corrected for parallax. Their analysis of age and height related variability in walking patterns in adults is still regarded as the definitive work on this subject. Following this Mary Pat Murray, who was a physical therapist, went on to study many aspects of pathological walking.

The development of clinical gait analysis was driven by two of surgeons who had studied under Inman; Jacquelin Perry (originally a physical therapist) and David Sutherland. Each went their separate ways but took what they had learnt with them. Perry went to Ranchos Los Amigos in Downey, California and Sutherland to San Francisco Shiner's (and later to San Diego). Electromyography, being an analogue signal, was much easier to capture and reproduce than three-dimensional movement data. It is probably primarily for this reason that, in the 1960s and 1970s, it took a pre-eminent role in clinical gait analysis.

Both Perry and Sutherland recognised that electromyography alone was not enough. Perry developed methodological approaches to observational gait analysis to complement it [31] as well as instrumented methods for measuring simple temporal-spatial parameters [32]. Sutherland continued to look for ways of obtaining three-dimensional information from cine film. In 1972 Sutherland and engineer John Hagy reported on a method for making measurements of five joint angles using semi-automated digitisation of movie file from three cameras [33]. The article stated that the test itself took around 20 min and that one investigator could reduce the data for all five joint angles in about 2 h.

In Europe the most active work between the wars had been conducted by the surgeon Richard Scherb in Basel. Before the advent of reliable EMG he had actually pioneered a technique for identifying the phasic activity of different muscles during treadmill walking by palpation. Graphical output from this process still exists (Fig. 12). In 1960 surgeon Willy Teillard founded the Gait Laboratory at the Children's Hospital also in Basel. In 1963 most of the group moved to Geneva. Jurg Baumann, another surgeon, took over the running of the Basel Laboratory in 1964 bringing

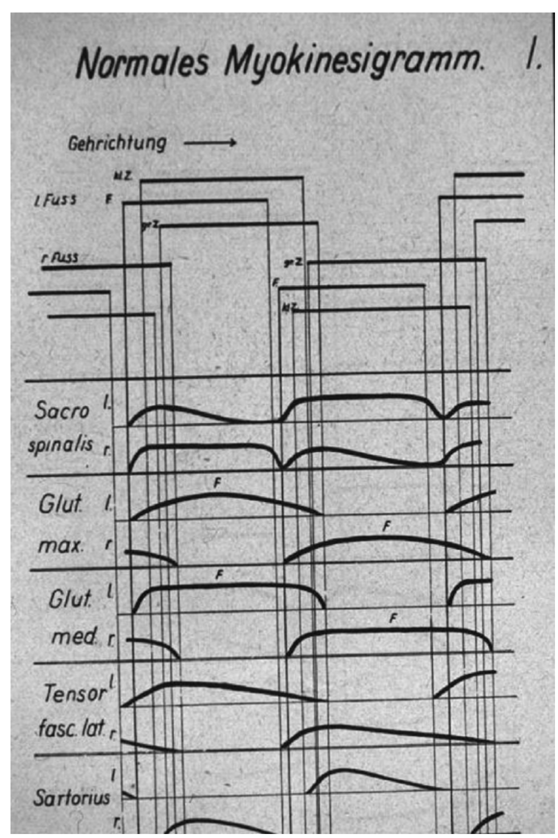

Fig. 12. Richard Scherb's recordings of muscle activity through the gait cycle based on palpation of tendons during treadmill walking (1927) (illustration form the personal collection of the late Jurg Baumann).

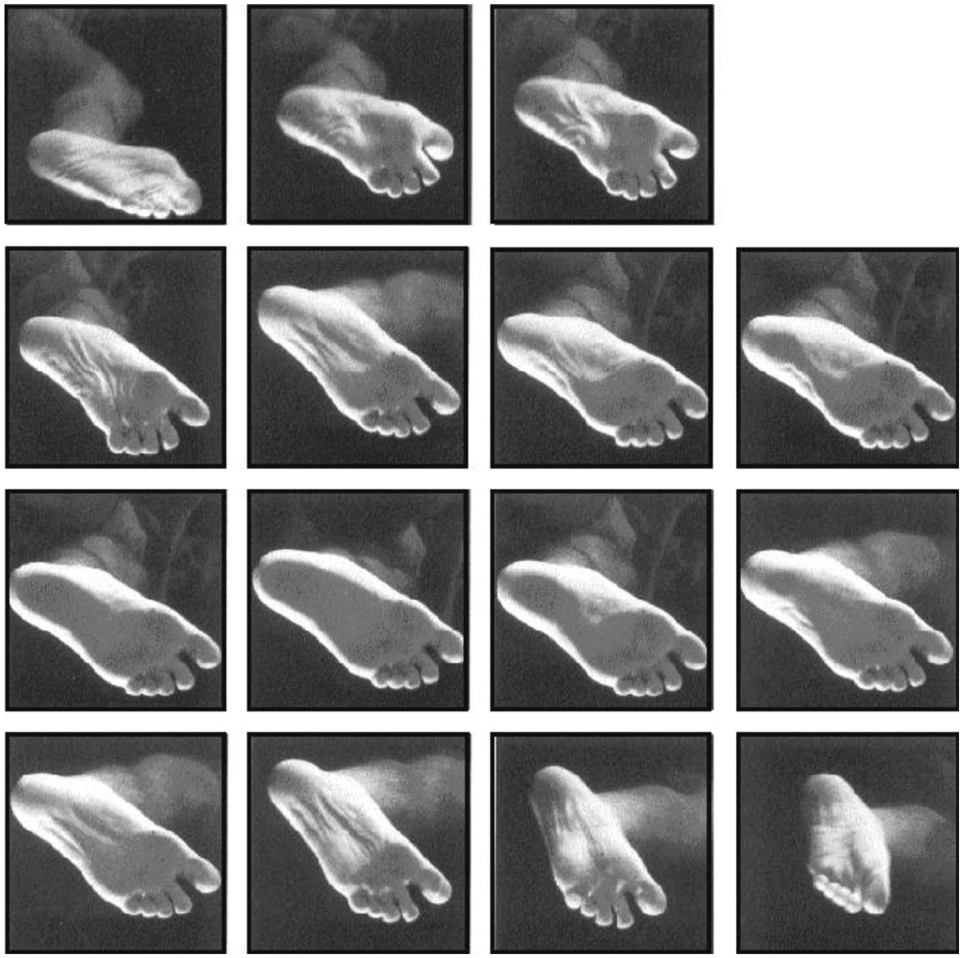

Fig. 13. Photographs of plantar surface of foot taken through a transparent force plate (illustration form the personal collection of the late Jurg Baumann).

with him the experience of 2 year's fellowships with David Sutherland and Sheldon Simon. He continue the work on EMG but worked to incorporate the time synchronised still images from movie film with this [34,35]. As cameras improved so did Baumann's output. The series of pictures illustrating the movement of the foot during stance phase, including images from underneath a transparent foot plate are, to this day, some of the most informative recordings we have of foot movements during gait (Fig. 13).

Perhaps the final development in gait analysis in the pre-computer era was the use of electrogoniometers to measure movement at specific joints. Engineer Larry Lamoreux fixed goniometers to a metal exoskeletal frame to measure three-dimensional joint kinematics at the hip and one-dimensional angles at the knee and ankle [36]. It was similar work using goniometers to measure three-dimensional knee movement that led another engineer Ed Chao to lay the foundations for the modern use of three-dimensional joint angles [37].

Even by the end of the 1970s however instrumented gait analysis had not really moved away form being a research tool only possible on a limited number of subjects. Equipment was generally cumbersome and time-consuming to use. Perhaps most importantly, the amount of time required to process data and the limited options for output, prevented that data being presented in a format that was clinically meaningful. Luckily this was the dawn of the computer era with allowing for faster and faster processing of data and more and more options for output. The development of modern gait analysis was just waiting to happen—but that is another story.

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