Review Article

A historical review of gait analysis

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ABSTRACT

منذ وقت طويل ،يوجد لدى الأخصائيين في ميدان الرعاية الصحية اهتماماً كبيراً في تقييم مشية الإنسان، ولكن إلى وقت قريب فقط أصبح بإمكانهم استخدام الأجهزة لتحليل المشية بشكل روتيني في العيادة من أجل تشخيص حالة المريض مما يرشد إلى اختيار الطرق المناسبة لمعالجة الأمراض العصبية وأمراض الجهاز الحركي المعقدة. لقد تطورت أنظمة تحليل الحركة عبر مراحل عديدة بدءاً من أجهزة بسيطة نسبياً إلى معدات دقيقة ومتعددة الأشكال والاستعمالات ومتطورة جداً .وتتوفر في الأسواق حالياً أنواعاً عديدة من أنظمة تحليل الحركة بالحاسب الآلي من أجل قياس مشية الشخص، وتختلف هذه الأنظمة من ناحية التصميم والأداء .إن الغاية من هذا الموضوع هو تقديم خلاصة موجزة عن تاريخ التقدم والتطورات السريعة التي شهدتها تقنية تحليل المشية بواسطة الأجهزة خلال العقود الثلاثة الماضية . علاوةً على ذلك، نأمل بأن هذا الموضوع سوف يقدم للممارسين السريريين والباحثين فكرة عامة عن أنواع أجهزة القياس المختلفة المتوفرة حالياً من أجل تحليل المشية وكذلك لمساعدتهم على اختيار نظام تحليل الحركة بناءً على معرفة مسبقة بمعلومات عن الجهاز الذي يناسب احتياجاتهم السريرية إلى أفضل مستوى ممكن.

Healthcare professionals have long been concerned with the assessment of human gait, but only recently were they able to utilize instrumental gait analysis in routine clinical practice for diagnosis, and to guide the selection of treatment methods for complex musculo-skeletal and neurological disorders. The development of motion analysis systems has progressed through several stages from simple to more sophisticated, versatile, multimodal, and accurate equipment. Several computerized motion analysis systems are now commercially available for the measurement of human gait. These vary in their design and performance. The purpose of this review is to summarize briefly the history and advances in the technology of instrumental gait analysis, especially during the past 3 decades. Further, it is hoped that this review will give clinical practitioners and researchers a general insight into the variety of measurement systems that are currently available for gait analysis and enable them to make an informed choice of the motion analysis system that best suits their clinical needs.

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Clinicians' ability to study human gait was limited mainly to naked eye observation until recently. This was due to lack of effective scientific and objective methods of measurement. Consequently, the application of instrumental gait analysis in clinical practice was slow to develop. However, good progress was made in the last quarter of the twentieth century as a result of the advances in computer technology, video cameras, and improved electromyographic equipment. Since then instrumental motion analysis has contributed significantly to the understanding of gait abnormalities in orthopedic and neurological conditions.[1,2] The development of instrumental gait analysis systems can broadly be viewed as several distinct, but inter-related, stages starting with the study of the mechanics of human locomotion.

The early studies of human locomotion. The early studies of human locomotion started in the 17th century and were based on the Newtonian principles of mechanics. Borelli, a 17th century scientist, was credited with earliest descriptions of the distinct phases of the gait cycle and the muscle action during walking.[3] He was also the first to measure the body's centre of gravity, and to describe how the body balance is maintained in walking through the 'forward displacement of the centre of gravity beyond the supporting area'.[4] The influence of Borelli's ideas was most evident in the works of Wilhelm and Eduard Weber in the first half of the 19th century. A new milestone in the history of gait analysis was the development, by Wilhelm and Eduard Weber, of methods for the quantitative measurement of locomotion using observations of the stance and swing phases of the gait cycle. In 1836, these scientists postulated the pendulum theory of locomotion, which considered the swing phase as a purely passive movement and constructed images of the body structure during walking.[5] This stimulated the development of the photographic methods of motion analysis.

The study of gait kinematics with photographic methods. The study of gait kinematics, namely, the measurement of the range of motion at limb joints during ambulation, provides valuable diagnostic clinical information about the subject's gait. The observations of the Weber brothers evolved into a method of measuring the kinematics of movement from serial pictorial images, and the construction of "stick diagrams." This method was known as chronophotography and was first adopted by Marey in Paris (1885) and Edward Muybridge in California in 1902 who demonstrated the sequence of motion of a horse running at normal speed by using several stationary cameras. Although chronophotography was an effective method of studying human gait, it was time-consuming. This limitation of chronophotography stimulated the search for other methods of motion analysis.[6]

Three-dimensional motion analysis. A break through in the evolution of instrumental gait analysis was effected in the 1890s, by the work of Braune and Fischer (an anatomist and mathematician) who introduced a method of three-dimensional (3-D) analysis of human movement. Light-emitting markers were used with trigonometric measurement to produce pictures with a frequency of 26 images per second. Braune and Fischer were able to study the angular displacements of the lower limb joints using this technique.[4]

The study of gait kinetics. While kinematics study the degree and pattern of displacement of limb segments during walking, kinetics measure the force that act on these segments during locomotion. Kinetic analysis allows the measurement of hip, knee, and ankle joint moments and powers.[7,8] The early attempts to study gait kinetics were successful in measuring the energy and the resultant forces acting at the hip, knee, and ankle joints provided by the muscles during walking, but not the actual muscle and ligament loads.[9,10]

The contribution of Verne Inman and his team. Research into human gait advanced significantly during the 1940s and 1950s. Pioneering work by Verne Inman and his team at the College of Engineering and the Medical School of the University of California drew attention to the importance of exploiting the sciences of engineering, orthopedics and anatomy in gait analysis.[11] This approach enabled the study of the displacements and rotations of limbs in space, velocities, and accelerations, external forces acting on the limbs, energy expenditure during walking and of recording the myo-electrical activity of muscles during movement (with dynamic electromyography). Soon after, the use of force plates for the measurement of gait kinetics,[12] accelerometers to measure limb accelerations,[13-16] single channel electromyography,[17] and later, multi-channel electromyography[18] were introduced. Subsequently, the use of these, and other measurement equipment, was integrated into one system, such as the automated kinematic measurements with video camera and dedicated computer interface and direct extraction of coordinates of imaged markers from video signal.

Goniometry was introduced in clinical practice in the 1970s. Measurement of the sagittal, coronal, and transverse rotations about the hip and knee joints became possible with a 3 plane, exoskeletal, electro-goniometric method.[19] Subsequently, Kettelkamp et al[20] used an electrogoniometer to measure the range of motion in normal and pathological knee joints in clinical practice. However, the limitations of this method, which includes errors due to the geometrical offset of the goniometer with respect to the joint center, and due to the mobility of the soft tissues to which the goniometer is strapped, reduced its utility in everyday practice. In 1974, Perry[21] introduced the use of foot switches and a four-bar linkage goniometer.

The early automated motion analysis systems. In 1972 the Vanguard Motion analyzer was introduced.[18] It consisted of cameras that operated at 50 frames/second in order to freeze the motion of the subject for the analysis portion of the study. The advantages of this method were that no apparatus was attached to the subject, and multiple measurements could be made in the same session. Electromyographic activity may be superimposed on the motion picture film for simultaneous recording, and the recording from both legs can be made simultaneously. However, this system was cumbersome and the data analysis was time-consuming. A further refinement of this system was a 6-channel electromyography (EMG) with telemetry and a high-speed cine camera that recorded at the same speed as the moving patient, providing more reliable measurements. A further improvement of the 2-D system were the use of television cameras to track the movements of markers attached to the limb of the study subject and a video tape recorder to record motion data with computer-assisted calculation of the values of the joint angles to produce a simple description of the locomotion system during walking. The main advantage of this system is that the patient is not required either to wear power packs, or to be hard-wired, thus allowing the free movement of the subject.[22]

The introduction of the 3-D motion analysis systems. The mid 1970s heralded the introduction of the 3-D techniques of motion analysis. The first version of the 3-D system was constructed by adding a sonic digitizer to 3 high-speed movie cameras with a Vanguard motion analyzer to make a 3-D coordinate system. However, the data still had to be digitized manually. The development of microchip computer technology enabled further advances in motion analysis. The current systems are now capable of producing a computerized visual image of body movement, which could be displayed graphically on the PC screen in less than a minute. In addition, the introduction of small, lightweight markers, either active small infrared light emitting diodes (LEDs) or passive infrared reflective spheres, and EMG telemetry facilitated the easy acquisition of a large number of gait data.

Camera-based 3-D motion analysis systems. The first of these, the automatic motion measurement system (SELSPOT), was developed in 1976. It was based on the use of a television video camera and computer. The system utilizes from 1-16 cameras, a set of segment LED markers placed over anatomical landmarks, and a data transfer system to a controlling computer. The particular advantage of this system is that since the active markers are pulsed sequentially, the identity (namely, the anatomical location) of each marker is known by the controlling computer. Its main disadvantage is that the patient has either to wear power packs or be hard-wired to a computer in order to receive the necessary power for marker illumination. This disadvantage was overcome in the VICON system. The VICON motion analysis system (Oxford Metrics Limited) is an opto-electronic motion measurement system, which uses 5 television cameras placed around a 10 m walkway. The markers used are passive retro-reflective infrared on each camera, and the operator initially identified each marker. The system is capable of tracking up to 30 markers simultaneously. A major advantage of this system is that the patient does not need to wear a battery pack or be hardwired to a computer,[23] and the patient's movements can also be recorded on video. Despite these advantages, VICON has the 2 following limitations, firstly the system uses passive markers, and this affects the resolution (accuracy) of the acquired data, secondly, it needs to be recalibrated for every test, due to the camera sensors being sensitive to the movement of the camera, room temperature, and humidity. This is time-consuming. These limitations were overcome in the design of the Cartesian Optoelectronic Dynamic Anthropometer.

The Cartesian Optoelectronic Dynamic Anthropometer (CODA). The CODA motion analysis system uses 3 mirror scanners, rather than television, to capture the 3-D coordinates of limb position. The detection system consists of compound cylindrical lenses in 3 electronic cameras. It is 'pre-calibrated' and does not require adjustments before each use. The latest version of this system, CODA mpx30, differs from the old versions in several important ways: it is all solid state with no moving parts, it is much smaller and lighter, and therefore portable, the markers are active LEDs, not passive corner cube prisms. This allows the use of many more markers with completely secure automatic identification, markers can be placed as close together as desired (this is not possible with passive markers such as those used in video based systems), the system uses a scanner unit, not rotating mirrors, sampling rates up to 800 Hz are possible, the software is more extensive and is Windows based, CODA mpx30 has a resolution (accuracy), which is at least 5 times better than other systems that are based on video cameras such as VICON, and it also has a greater dynamic range, which means that fine details can be seen, even in large scale movements, with much greater resolution than with other motion analysis systems.

Other motion analysis systems. In addition to VICON and CODA mpx30, there are several other motion analysis systems. These systems use either active infrared LEDs or passive markers. Systems that use active infrared LEDs markers include those used with the Selspot (Selcon System, Ltd., Southfield, MI) and Optotrack systems (National Digital, Inc., Ontario, Canada). Passive reflective markers are used with MacReflex (Sweden), Kinemetrix (Medical Research Ltd., Wortley Moor Road, Leeds, United Kingdom), Expert Vision and Orthotrak (Motion analysis corporation, Santa Rosa, CA), Peak Performance (Peak Performance Technologies Inc., Englewood, CO), Primas (Netherlands), Qualisys Inc (USA), Qualisys AB (Sweden), Elite (Bioengineering Technology and systems, Milan, Italy) and Ariel Dynamics (Life Systems Inc. La Jolla, CA).

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