European Review for Medical and Pharmacological Sciences 2023; 27: 3-12

Gait analysis advancements: rehabilitation value and new perspectives from forensic application

M. MANGONE[1], E. MARINELLI[2], G. SANTILLI[3], N. FINANORE[1], F. AGOSTINI[1], V. SANTILLI[1], A. BERNETTI[1], M. PAOLONI[1], S. ZAAMI[1]

[1]Department of Anatomical, Histological, Forensic, and Orthopedic Sciences, Sapienza University of Rome, Rome, Italy
[2]Department of Medico-Surgical Sciences and Biotechnologies, Sapienza University of Rome, Latina, Italy
[3]Unit of Physical Medicine and Rehabilitation, Sant'Andrea Hospital, Sapienza University of Rome, Rome, Italy

Abstract. – The clinical and rehabilitation value of gait analysis is remarkable and indisputable and poised to grow as technological advancements unfold. This article aims to shed light on the advances in how gait is assessed, enabling those who have suffered an injury impairing their motor skills to be diagnosed more accurately and efficiently as well as to compare the hallmarks of rehabilitative and forensic gait analysis. The authors have conducted an analysis of relevant papers (published between 1967 and 2020) from a medicolegal perspective, cited in PubMed, MEDLINE, Cochrane Library, EMBASE, and available recommendations for the legal application of such techniques. Moreover, considering the use of gait analysis as a forensic tool, this study broadens the scope of research by including search engines, legal databases, and court filings (DeJure, Lexis Nexis, Justia) between 2000 and 2022. The instrumental assessment of movement (Gait Analysis) has come to constitute an essential analytical tool for the biomedical sector to objectively and accurately assess human movement and posture. The article is also aimed at elaborating differences and similarities between clinical and forensic gait analysis. When it comes to the forensic applicability of gait analysis and its evidentiary value, however, there is a pressing need for a review of its scientific basis. Therefore, it is necessary to conduct a thorough evaluation of its use in legal practice, as stressed in scientific literature and surveys. It is of utmost importance to highlight the procedural and assessment standards currently applied to forensic gait analysis, to evaluate its strengths and weaknesses, and to achieve standardized guidelines based on broad scientific consensus.

Key Words:
Gait analysis, DAVIS protocol, Rehabilitation, Criminal Justice, Evidentiary value.

Introduction

The instrumental assessment of movement (Gait Analysis) is currently an essential analytical tool for the biomedical sector, in order to produce objective and precise evaluations of human movement and posture[1]. The biomechanical instrumental characterization of the various components of the movement (i.e., space-time, kinematics, kinetics, and surface electromyography, sEMG), as well as their variations with respect to a normal situation, are highly relevant in the clinical and research field for the diagnosis of particular conditions including one of the systems involved (neurological, musculoskeletal)[2], as well as for the prognosis and therapeutic approach, as well as for their follow-up[3]. Biomechanical research must include a multidisciplinary approach enabling movement analysis, in order to determine the different components that generate it in order to provide a clinically relevant interpretation[4-6]. A biomechanical analysis must be able to: describe the movement, regardless of the forces that cause it, in terms of displacement, speed and linear and angular acceleration (kinematics); study the forces which generate and oppose the movement itself (kinetics); characterize the activation of the final muscle effector that generates the movement (surface electromyography)[7]. In addi-

Corresponding Author: Marco Paoloni, MD; e-mail: marco.paoloni@uniroma1.it

tion, it should be emphasized that the use of these systems in the clinical setting is currently very oriented towards evaluating the follow-up of various types of patients who exhibit gait or movement changes[8] (e.g., neurodegenerative diseases[9]). Given the characteristics of the previously defined measurement system, other areas beyond rehabilitation could also benefit from an objective measurement of human movement. Among such areas, the forensic one could use the quantitative information that defines a pathological pattern deriving from traumas of various nature, and therefore be useful to clarify and quantify the damage and identify individuals in criminal investigations.

Gait Analysis for Rehabilitation Purposes

Gait analysis is usually performed using a Motion Analysis Lab consisting of infrared cameras (8 infrared HD digital cameras with acquisition frequency of 100 fps); such cameras capture the trajectories of the markers, thus allowing the calculation of angular variations of each joint. The analytical process relies on two force platforms that record the 3 components of the reaction force to the ground, the coordinates of the Pressure Center (CoP) and the torque; such data combined with the kinematic data make it possible to calculate the moments and powers articular. An EMG Wireless System has been used, relying on at least 8 wireless probes with an acquisition frequency of 1000 Hz. Such probes are miniaturized and wireless, and do not alter the patient's natural movements. The electromyographic signal is synchronized with the kinematics and kinetics and allows to evaluate not only the activation of the muscle, but also the precise instant in which it occurs during the movement. Video recording relies on 2 high-definition cameras and real time visualization of the patient's movements, taken simultaneously from different points of view and synchronous with the other signals. In addition, the process requires a data-station that receives, integrates, synchronizes, and re-elaborates all the signals coming from the connected devices and software applications dedicated to gait analysis and to the evaluation of the movements of the body districts. The protocol used for gait analysis is the DAVIS protocol, which allows for the analysis of the human path from a kinematic and dynamic point of view and at the same time, for the evaluation of the electrical activity of the muscles involved in the movement. The protocol requires the positioning on the body of the subject of 22 spherical markers, of which 4 mounted on a rigid bar: 3 on the trunk, 3 on the pelvis, 3 on each thigh, 3 on each leg and 2 on each foot. This protocol is used to perform assessments concerning the movement of the lower limbs, pelvis and trunk[10,11]. Gait analysis is centered around measurement procedures grounded in measurable standards, which are introduced, analyzed, and interpreted, from which conclusions about the subject (health, age, size, weight, speed, etc.) can be drawn. The fundamental phases and methodologies of the gait analysis process have been detailed in Table I.

Forensic Gait Analysis on the Rise as a Contributing Identification Factor and Differences with Clinical Gait Analysis

Forensic gait analysis is the assessment, comparison and of analysis gait-related features and traits to be used in criminal inquiries. Essentially, forensic gait analysis may be defined as a contributing factor to the identification process rather than an identification method itself. It should be in fact noted that the individualization of certain human gait has not yet been fully substantiated scientifically; hence gait may not be ascribed to a given individual with absolute certainty. Therefore, forensic gait analysis may be a valuable tool and significantly contribute to the accurate comparison of criminals recorded while walking, running on surveillance closed circuit television (CCTV), or committing a crime, such as a robbery, burglary, assault, murder, and so on. There may also be civil cases where the way somebody walks may be relevant to the proceedings. Clearly, clinical gait analysis differs from forensic gait analysis as the data gathered through the former are planned, and the whole process is conducted under idealized conditions (e.g., lighting and camera positioning), with a cooperative subject (often partially undressed to remove the masking effect of clothing) and performing a standardized task (walking in a particular direction, in an open environment at a particular pace). Patients often have specific impairments which result in a gait pattern which is substantially different from the range of variation expected in the general population. Even though a direct comparison is not straightforward, this generally means that the forensic gait analyst has potentially greater,

Table I. Essential aspects constituting the gait-analysis process.

	Objectives	Fundamental features and measurement modalities
Temporal/spatial	It entails the calculation of speed, the length of the rhythm, pitch	Stopwatch and marks on the ground; Walking on a pressure mat; Range laser sensors scanning a plane a few centimeters above the floor; Inertial sensors and software to interpret 3D; Gyroscopes and 3D accelerometric data[10].
Kinematics	Chronophotography is the most fundamental method for recording movement. Strobe lighting at known frequency has been used in the past to aid in the analysis of gait on single photographic images. Video recordings from single or multiple cameras can also be used to gauge joint angles and speed variations. Such a method has been developed along with analysis software tools, which can significantly streamline the analysis process and allow for three dimensional measurements[2, 3].	Passive marker systems, generally relying on reflective balls or other reflective markers can accurately measure movements via multiple cameras (typically five to twelve) utilizing high-powered strobes (typically red, near infrared or infrared) with matching filters to record the reflection from body markers. Markers need to be placed on selected locations, bony landmarks, according to biomechanical models, in order to track feet, legs, pelvis, and trunk motions. The angle and time delay between the original and reflected signal are thus recorded and analysed, leading to the triangulation of the marker in space. Three dimensional trajectories from these markers are then outlined and ascribed identification labels. Joint angles from the relative marker positions of the labeled trajectories are then identified via computer model. Active marker systems are somewhat similar to the passive markers but have an advantage arising from individual markers working at predefined frequencies, which makes them identifiable. Hence, no post-processing of marker locations is required, though the systems tend to be less tolerant for out-of-view markers than the passive systems. Inertial systems based on MEMS inertial sensors, biomechanical models, and sensor fusion algorithms do not rely on cameras. These full-body or partial body systems can be used indoors and outdoors regardless of lighting conditions [7-10].
Markerless gait capture	Markerless gait capture systems utilize one or more color cameras or 2.5D depth sensors (i.e. Kinect) to directly calculate the body joint positions from a sequence of images; Such a system allows for non-invasive human gait analysis in a natural setting without the need for any attached marker; Thus, the applicability of human gait measurement and analysis techniques can be simplified by considerably reducing preparation time, and achieve accurate motion assessment in all kinds of applications.	The video-based motion capture with monocular camera or multiple camera studio is currently the most widespread markerless system; Nowadays, the depth sensor-based gait analysis for clinical applications appears to be increasingly widespread; Since depth sensors can measure the depth information and provide a 2.5D depth image, they have effectively simplified the task of foreground/background subtraction and significantly reduced pose ambiguities in monocular human pose estimation[2, 3, 7-10].
Pressure measurement	Systems relying on pressure measurement are effective at gauging and measuring gait by providing insights into pressure distribution, contact area, center of force movement and symmetry between sides and additional information, mostly according to: Force; Timing; Spatial parameters.	Different methods for assessing pressure are available, like a pressure measurement mat or walkway (longer in length to capture more foot strikes), as well as in-shoe pressure measurement systems (where sensors are placed inside the shoe); Many pressure measurement systems integrate with additional types of analysis systems, like motion capture, EMG or force plates to provide a comprehensive gait analysis. Kinetics, i.e. the study of the forces involved in the production of movements, and the study of patterns of muscle activity during gait (dynamic electromyography) are also key elements of the gait analytical process[8-10].

still unsolved, and unregulated challenges to address than does clinical gait analysis; consequently, it should not be assumed that results from clinical gait analysis can necessarily be acquired and used for forensic purposes[12]. Reliance on forensic gate analysis still has a rather mixed international record. For more than 15 years, forensic gait analysis has been used to collect evidence in criminal cases in the United Kingdom and for over 10 years in Denmark. On the other hand, in the Netherlands, gait analysis has only rarely been performed in the past 20 years, although two recent criminal cases renewed interest in the topic in the country. Forensic gait analysis is an often-overlooked piece of visual evidence in America, despite its relatively widespread use in the UK. In addition to helping to compare a perpetrator caught on CCTV video to a suspect, forensic gait analysis may even show that the same individual was involved in two or more criminal acts in different locations and/or at different times. Tying (or untying) an unknown culprit caught on video to more than one criminal act may be useful in helping to solve different cases or link them together. Nowadays, the widespread use of video cameras all over the world for the surveillance of businesses and properties very often results in criminals being recorded on video while walking or running from the crime scene, or in the criminal act itself. Obviously, using forensic gait analysis or gait comparison entails the presence of a suspect. Investigators should be aware that the criminal captured on CCTV may have visited the crime scene earlier in the day or in the days prior to the criminal act; earlier footage may in fact reveal the suspect. Should a person of interest be identified in earlier video footage, the gait of the person of interest and the criminal can be analyzed and compared. In the United States the way in which a person walks has been the subject of courtroom testimony since 1908. In a case occurred in Texas, USA, a robbery victim testified that even though the perpetrator was not recognizable, the victim knew him by his voice and "his walk"[13]. Nowadays, analysts and experts worldwide tend to rely on a stepwise approach to analyzing how a perpetrator walks (forensic gait analysis) and then transpose and compare such an approach to the suspect walking characteristics. The process starts with forensic analysts evaluating the video footage with the criminal and suspect walking in order to determine whether the surveillance footage is usable to perform a forensic gait analysis. Then, forensic gait analysis and comparison of the way a criminal walk (or moves or runs) on video (CCTV) may be used to help rule in or out suspects, and investigators could greatly benefit from obtaining surveillance video of suspects[14]. Should investigators make an arrest based at least in part on how the suspect walks, an expert analysis of the suspect's gait may be valuable in terms of helping the courts reach a conclusion that the criminal caught in the surveillance video and the suspect walk with similar gait features (if that is indeed the case). Defendant attorneys may therefore choose to have their client's gait analyzed by an expert in cases where they believe that it differs from that of the perpetrator caught on tape. The admissibility of evidence obtained through gait analysis has recently come under criticism in Canada. The main concerns highlighted by Edmond and Cunliffe[14] are mostly centered around the validity, reliability, and evidentiary value of forensic gait analysis. Moreover, the relative inability of courts to properly assess the expertise of expert witnesses, and hence the value of their conclusions, also presents a substantial setback. Still, it is worth specifying that the authors have drawn their conclusions based on only two cases[15]. The investigative value of gait recognition for the purpose of forensic analysis stems from the fact that gait can be detected and recorded from a distance, even by low-resolution cameras, unlike other biometric traits, which require far greater proximity and clarity[16]. Furthermore, an undisputed advantage of relying on gait recognition is its non-invasive nature, which does not necessarily need the individual to be cooperative with the acquisition process. Hence, by virtue of such features, gait analysis is particularly well-suited whenever direct contact with the perpetrator is not available. In addition, since the purpose of any reliable biometric system is to be as thorough as possible in order to reduce the possibility of any adulteration or forgery the acquisition and analysis of gait-related features based on human motion, is the only likely identification methodology that can be relied upon when covert surveillance is required. Thus, gait analysis is arguably far better-suited to forensic investigations than other biometric-based traits linked to the presence at a crime scene, which can be concealed or disguised with relative ease; the gait pattern is in fact not concealable, as perpetrators have to walk or run from the scene. From the standpoint of recognition, gait analysis has more computational complexities than other biometric standards, because it requires a sequence of images from video footage instead of just one for analysis[17] (a single frame may be enough for facial recognition). However, since the gait cycle (from a

Table II. Relevant elements likely to shape gait peculiarities.

Most relevant factors liable to influence one's gait	Gait-influencing dynamics
Footwear	It can bring about gait pattern variability, increased hip movement, longer or shorter stride length; fatigue, impacting the gait cycle and pace via energy depletion of energy[24];
Sex	It can be identified through gait patterns[23, 24];
Speed	It is well-known how gait patterns reflect fluctuations between normal walking patterns and running patterns[23-25];
Illness/pathological conditions	Health-related factors constitute rather common elements influencing gait characteristics, as in cases of neurodegenerative diseases, e.g. Parkinsonian gait[26], Huntington's disease-linked choreiform gait, rheumatoid diseases, festinant gait, shuffling gait, scissors gait[27, 28];
Age	It can majorly affect gait patterns, considering how walking largely depends on muscular strength variations, in turn affected as people grow older[28].

recognition perspective) is made up of mostly repetitive stages[18], the process of recognition results somewhat simplified[19]. A standardized gait pattern for normal walking people was attained in 1964, through medical investigations conducted by Murray[20], and ultimately focused on gait patterns for pathologically abnormal patients. Such experimental studies were carried out on sixty people, between 20 and 65 years of age. Each individual was instructed to walk for a repeated number of trials. For the collection of gait data, special sets of markers were attached on every subject. Murray[20] concluded that gait in humans is made up of 24 distinct components, making the gait pattern unique for every person if all gait movements are taken into account. Reportedly, the motion patterns related to the pelvic and thorax regions presented a high degree of variability among different individuals. Furthermore, Murray[20] pointed out that the ankle rotation, pelvic motion, and spatial displacements of the trunk embed the subject individuality due to their consistency at different trials. In 1977, a seminal study was published[21], which substantiated the possibility of identifying people by gait through the observation and analysis of mobile lights installed on the joints' positions. Although, there are a great deal of studies centered around gait in the literature for medical use, with a few referring to the identifiable and distinguishable nature of gait patterns, none of them is closely related to the automated use of gait for recognizing individuals through biometrics. The gait measurements and results introduced by Murray[20] will be greatly beneficial to the development of systems based on automated gait biometric. However, the extraction of gait characteristics patterns has proven complex using computer vision methods. An automated vision-based system for human identification *via* individual gaits is conceived to focus on and extrapolate gait characteristics and peculiarities with no need to resort to markers or specific sensors for the gathering of evidential matter. To that end, an ordinary video camera linked to a special vision-based software is all that is needed. Markerless motion capture systems are suited for applications where the placement of sensors or markers on the individual is not feasible, such as in forensic investigations. Typically, the gait biometric system is constituted by two main components: 1) a hardware platform for data acquisition (this can be a single CCTV camera or distributed network of cameras); 2) a software platform for data processing and recognition. The architecture of the software side for gait biometric system has three fundamental pillars: 1) detection and tracking of the subject, 2) feature extraction and 3) classification stage[22]. The admissibility of evidence obtained from gait analysis is still controversial; this issue was raised in the United Kingdom over ten years ago and is still being addressed.

Forensic Gait Analysis in Court: Valuable Tool with a Few Caveats

Gait analysis with its investigative potential has already led to noteworthy results in cases where positive identification was not an option based on conventional indicators. In a recent case handled by the Metropolitan Police of London, there

Table III. Gait analysis-related criminal cases.

Defendant, Case Specifics, Location/Court of Law	Outcome
John Saunders (2000), The Old Bailey Central Criminal Court, London, UK. Consultant Podiatrist Haydn Kelly was able to identify jewellery thief John Saunders as the person who had attempted a robbery, from earlier police surveillance footage.	Although Saunders was wearing two pairs of pants, gloves and a face mask, Kelly ultimately concluded that roughly five per cent or less of the British population had gait-related mechanics similar to the suspects. The evidentiary value of that conclusion made it possible to convict the perpetrator, a career criminal who had committed a string of robberies across Surrey[30].
Mijailo Mijailovic (2004), Supreme Court of Sweden. The case involved the assassination of Swedish Minister for Foreign Affairs Anna Lindh, who was stabbed to death at the NK department store in Stockholm, on 10th September 2003.	Facial comparison, as well as gait and body measurements, were gauged and evaluated between the accused and a person of interest (obtained from surveillance footage) – and contributed to the conviction of the defendant[31, 32].
Undisclosed identity, Noerager, Denmark (2004): an incident involving a bank robbery which was handled by the Unit of Forensic Anthropology at the University of Copenhagen. As the police investigators noticed, the perpetrator exhibited a peculiar gait pattern, and turned to gait experts for consultations. The police were instructed to carry out a covert recording of the suspect walking pattern from the same angle as the surveillance recordings in order to draw a meaningful comparison.	The gait analysis eventually produced several matches between the perpetrator and the suspect as an outward rotated feed and inverted left ankle during the stance phase. Further posture analysis using photogrammetry highlighted similarities between the two recordings, including a restless stance and anterior head positioning. Some discrepancies were observed during the analysis, including a wider stance and slightly leaned forward trunk, with elevated shoulders. That was suspected to be due to the sense of high alertness and anxiety while committing a crime. Based on the analysis that was conducted, a statement was issued to the police regarding the identity, although such methods do not have the same degree of confidence and reliability as well-established methods such as fingerprints, facial recognition or DNA. The findings were subsequently presented in court and the suspect was convicted of robbery, with the court stressing the value of gait analysis as a forensic tool[33].
R v Otway (2011). The defendant appealed against his conviction for the murder of 25-year-old, who was shot dead in Wythenshawe, UK, in August 2006, objecting to the expert evidence. The evidence was from a podiatrist who studied CCTV footage; comparing CCTV of Mr O. at a garage and CCTV of Mr O. from the police station.	Evidence stemming from the defendant's gait analysis was compared to reference sequences. It was criticized by the defense, however, that there were no statistical database and no scientific basis of the method as support for its inclusion. The appeal filed on such grounds was ultimately rejected and gait analysis was declared admissible[34].
Mohammed Hashi (2014), London's Appeal Court. The defendant, who had been found guilty of murder, challenged his conviction.	The CCTV was not clear enough for facial recognition, so the prosecution had to rely on expert consultancy. The evidence thus produced found considerable similarities existed between the walking gait of the male caught on CCTV cameras and the police station footage showing the defendant. The Court of Appeal referred to gait analysis as a "developing science"; still, it approved of the evidence being allowed in the trial, as the jury (given there was also a contradictory defense expert report) was able to weigh all the issues[35,36].

was a number of assaults and robberies against women walking on a short pathway alongside an underground station in one of London suburbs[23]. The same crime had reportedly been perpetrated several times at the same location and with similar dynamics. The chief suspects were the same members of an organized criminal youth gang, aged 17 to 20. Various CCTV cameras covering the crime scene were operating at the time. Two of them were pointing towards the entrances of the subway, while two others recorded both views of the walking pass alongside the station. The police provided a set of videos in order to find further investigative elements through gait analysis. CCTV footage from all cameras for the crime scene at two different days was made available to the Image Processing Research group at the University of Southampton. The police provided another video of a suspect, a member of the gang being recorded while being held at the police custody. The video was recorded at a 2 frames per second rate and 720× 576 resolution. In a video dated 4th

April 2008, two gang members wore helmets to cover their faces while riding a motorcycle. A female passer-by came walking through the subway where they followed her from behind along the path. As soon as she entered the station, she had her purse snatched, with such violence that she fell and was dragged on the ground[24]. The assailants then took off on a motorcycle. In a different CCTV footage recorded the following day, the same crime was committed by similar looking perpetrators on a motorcycle. The police eventually succeeded in identifying the alleged culprits. Nonetheless, no facial recognition is usually possible in such instances, due to the low-resolution images and the fact that the perpetrators often conceal their faces. Such cases are rife, hence the need to further develop valuable innovative technologies such as gait biometric analysis. Overall, the proposed method for gait analysis from video sequences acquired from CCTV cameras relies on Instantaneous Posture Matching (IPM).

Medical and psychological studies[24-29] confirmed that the act of natural walking is carried out in uniquely different ways for each individual.

Furthermore, the multiple internal as well as external factors liable to affect gait characteristics cannot be overlooked. The very act of walking is frequently not a fully "conscious" behavior, but rather essentially spontaneous. Table II briefly maps out the chief relevant features which determine gait peculiarities.

Given the unique traits of each individual's gait, as well as contributing identifying factors, limbs position and walking patterns are recognizable in every phase of the movement; the kinematic properties of the human body can therefore be effectively used for identity matching between different videos.

Forensic gait analysis may even prove helpful in the assessment of height and gender, body weight, and in cases where a series of footprints or gait patterns are available for analysis, assessment as to the number of people involved through the analysis of step length[30].

Table III summarizes five noteworthy criminal cases where gait analysis played a role in establishing the facts and identifying (or excluding) the suspects as culprits[31-37].

When it comes to the forensic applicability of gait analysis and its evidentiary value, there is a pressing need for a review of its scientific basis through a comprehensive evaluation as to its use in legal practice, as shown by currently available scientific findings. A 2015 study conducted by Birch et al[38], leading forensic gait analyst and member of the UK-based Chartered Society of Forensic Sciences, which was published in the Science and Justice Journal, showed how experienced analysts were able to link suspects to the crime scene with a 71% degree of accuracy[15,39-41]. As a study of scientific literature suggests[12-47], various approaches have been used for assessing gait in the forensic setting. The computer vision approach is based on algorithms designed to achieve automated gait recognition from video footage. The algorithm system can identify and analyze gait features and draw comparisons between perpetrators and suspects; it is a highly automated process, with limited intervention by human operators, or none. In observer-based methods, on the other hand, human operators acting as gait analysts systematically observe, evaluate and rate the presence or absence of certain gait features and compare these between perpetrators and suspects. The latter approach has been used in several criminal cases[42], and the widespread use of CCTV has evolved alongside the potential of forensic scientific analysis (the UK has the highest number of cameras *per capita* in Europe). A 2016 paper published in the Journal of Forensic Sciences pointed out that gait patterns analysis from CCTV footage, coupled with photogrammetry, were relevant, albeit challenging, forensic tools[43]. In order to buttress that point, the authors tested the feasibility of 3D reconstructions for forensic gait analysis and found considerable interobserver variability in data interpretation. Relying on biometric evidence in criminal investigations and trials is certainly of utmost importance for its evidentiary value. Still, it is worth bearing in mind that the current state of biometrics-based forensics is still evolving, and not yet well-established. Forensic CCTV footage is a fundamental element to criminal investigations and law enforcement in the modern era.

Conclusions

There is no denying that the clinical and rehabilitation value of gait analysis is remarkable and poised to grow as technological advancements unfold. In fact, both the equipment and the methodology for gait analysis has substantially developed and evolved over recent years. The advances in how gait is assessed, as well as the innovative tools and techniques used to correct and restore normal gait, make it possible for those who have

suffered an injury which negatively affects their ability to move, walk or run to be diagnosed more accurately and efficiently. Once a diagnosis has been made, a therapeutic plan for gait-related issues can be outlined and specifically targeted to the affected limbs, for the ultimate purpose of restoring the patent's highest level of mobility and functioning in the shortest time possible. As for the forensic applications, since the turn of the century gait analysis has been acknowledged as having at least some degree of scientific value on various occasions in British Courts and elsewhere, based on the already mentioned 2015 Birch study[38]. Findings in that study seem to point to a significant degree of scientific validity, which may pave the way for a more large-scale use of gait analysis techniques in order to positively identify perpetrators through their peculiar gait features. Nonetheless, since most criminal legal statutes are based on systems of broad-ranging safeguards for defendants on trials, more research and progress are needed in order to fine-tune and standardize gait analysis techniques, so that the highest possible standards of scientific reliability can be achieved (i.e., a degree of probability close to certainty), as required in criminal trials. Most likely, standardized and widely acknowledged guidelines will be issued in the foreseeable future, so that forensic gait analysis will be an even more helpful investigative tool. Attempts in that direction have already been made; the recent publication of the forensic gait and DNA analysis primer for courts constitutes a valuable effort towards clarifying the most contentious aspects of evidence admissibility when it comes to gait analysis. It is also worth mentioning the 2019 Code of practice for forensic gait analysis, written by the Chartered Society of Forensic Sciences' Forensic Gait Analysis Working Group in collaboration with the College of Podiatry[44]. As a result of such documents published in past years, focus is therefore gradually being shifted towards evidence quality, validity of methodologies and their reliability and reproducibility. As a matter of fact, irrespective of how well-established and acknowledged a forensic science is in the legal realm, that status should not be construed as a sort of "mark of approval" for evidence produced by insufficiently supported methodologies, with scarce or no validation[33,45]. Conversely, neither should evidence types which are less commonly used in criminal trials be set aside or underestimated only on those grounds, but rather estimated, judged and applied on their merits and reliability[46,47]. Hence, harmonizing the way gait analysis is applied and assessed will likely go a long way towards providing law enforcement and courts with new, objective and dependable investigative tools.

Conflict of Interest

The Authors declare that they have no conflict of interests.

Data Availability

Data may be provided on reasonable request to the corresponding author.

Funding

Unit of Physical Medicine and Rehabilitation of the Sapienza University of Rome, Rome, Italy.

Ethical Approval

Not applicable.

References

1) Baker R, McGinley JL, Schwartz MH, Beynon S, Rozumalski A, Graham HK, et al. The gait profile score and movement analysis profile. Gait Posture 2009; 30: 265-269.
2) Lo Torto F, Kaciulyte J, Marcasciano M, Casella D, Bernetti A, Mangone M, Agostini F, Ciudad P, Fioramonti P, Ruggiero M, Ribuffo D, Carlesimo B. Peroneus Brevis flap in Achilles tendon reconstruction. Clinical, radiological and functional analysis. Foot Ankle Surg 2020; 26: 218-223.
3) Paolucci T, Bernetti A, Bai AV, Segatori L, Monti M, Maggi G, Ippolitoni G, Tinelli L, Santilli V, Paoloni M, Agostini F, Mangone M. The sequelae of mastectomy and quadrantectomy with respect to the reaching movement in breast cancer survivors: evidence for an integrated rehabilitation protocol during oncological care. Support Care Cancer 2021; 29: 899-908.
4) Damiani C, Mangone M, Paoloni M, Goffredo M, Franceschini M, Servidio M, Pournajaf S, Santilli V, Agostini F, Bernetti A. Trade-Offs with rehabilitation Effectiveness (REs) and Efficiency (REy) in a sample of Italian disabled persons in a in post-acuity rehabilitation unit. Ann Ig 2020; 32: 327-335.
5) Seccia R, Boresta M, Fusco F, Tronci E, Di Gemma E, Palagi L, Mangone M, Agostini F, Bernetti A, Santilli V, Damiani C, Goffredo M, Franceschini M. Data of patients undergoing rehabilitation programs. Data Brief 2020; 30: 105419.

6) Zucchi B, Mangone M, Agostini F, Paoloni M, Petriello L, Bernetti A, Santilli V, Villani C. Movement Analysis with Inertial Measurement Unit Sensor After Surgical Treatment for Distal Radius Fractures. Biores Open Access 2020; 9: 151-161.
7) Paolucci T, Bernetti A, Bai AV, Capobianco SV, Bonifacino A, Maggi G, Ippolitoni G, Tinelli L, Santilli V, Agostini F, Paoloni M, Mangone M. The recovery of reaching movement in breast cancer survivors: two different rehabilitative protocols in comparison. Eur J Phys Rehabil Med 2021; 57: 137-147.
8) Paolucci T, Bernetti A, Paoloni M, Capobianco SV, Bai AV, Lai C, Pierro L, Rotundi M, Damiani C, Santilli V, Agostini F, Mangone M. Therapeutic Alliance in a Single Versus Group Rehabilitative Setting After Breast Cancer Surgery: Psychological Profile and Performance Rehabilitation. Biores Open Access 2019; 8: 101-110.
9) Alharbi N, Shosha E, Murad H, Alhomud I, Alshehri A, Almuhaizea M, Cupler E, Al-Hindi H, Monies D, Bohlega S. Clinical and genetic features of Calpainopathies in Saudi Arabia - a descriptive cross-sectional study. Eur Rev Med Pharmacol Sci 2021; 25: 4941-4952.
10) Paoloni M, Di Sante L, Dimaggio M, Bernetti A, Mangone M, Di Renzo S, Santilli V. Kinematic and kinetic modifications in walking pattern of hip osteoarthritis patients induced by intra-articular injections of hyaluronic acid. Clin Biomech (Bristol, Avon) 2012; 27: 661-665.
11) Santilli V, Mangone M, Paoloni M, Agostini F, Alviti F, Bernetti A. Comment on "Early Efficacy of Intra-Articular HYADD® 4 (Hymovis®) Injections for Symptomatic Knee Osteoarthritis". Joints 2018; 6: 131-132.
12) The Royal Society. Forensic gait analysis. A primer for courts. ISBN: 978-1-78252-302-4. Issued on November 2017. Available at: https://royalsociety.org/~/media/about-us/programmes/science-and-law/royal-society-forensic-gait-analysis-primer-for-courts.pdf.
13) Nirenberg M, Vernon W, Birch I. A review of the historical use and criticisms of gait analysis evidence. Sci Justice 2018; 58: 292-298.
14) Edmond G, Cunliffe E. Cinderella story? The social production of a forensic "science." J Crim Law Criminol 2017; 106: 219-275.
15) Cunliffe E, Edmond G. Gaitkeeping in Canada: Mis-Steps in assessing the reliability of expert testimony. Can B Rev 2013; 92: 327-368.
16) Van Mastrigt NM, Celie K, Mieremet AL, Ruifrok ACC, Geradts Z. Critical review of the use and scientific basis of forensic gait analysis. Forensic Sci Res 2018; 3: 183-193.
17) Takemura N, Makihara Y, Muramatsu D, Echigo T, Yagi Y. Multi-view large population gait dataset and its performance evaluation for cross-view gait recognition. IPSJ T Comput Vis Appl 2018; 10: 4.
18) Ngo TT, Makihara Y, Nagahara H, Mukaigawa Y, Yagi Y. The largest inertial sensor-based gait database and performance evaluation of gait-based personal authentication. Pattern Recog 2014; 47: 228-237.
19) Macoveciuc I, Rando CJ, Borrion H. Forensic Gait Analysis and Recognition: Standards of Evidence Admissibility. J Forensic Sci 2019; 64: 1294-1303.
20) Murray MP. Gait as a total pattern of movement. Am J Phys Med 1967; 46: 290-333.
21) Cutting JE, Kozlowski LT. Recognizing friends by their walk: Gait perception without familiarity cues. Bull Psychon Soc 1977; 9: 353-356.
22) Bouchrika I. Evidence Evaluation of Gait Biometrics for Forensic Investigation. In: Hassanien AE, Mostafa Fouad M, Manaf AA, Zamani M, Ahmad R, Kacprzyk J, editors. Multimedia Forensics and Security. Cham: Springer International Publishing 2017; 307-326.
23) Bouchrika I, Goffredo M, Carter J, Nixon M. On using gait in forensic biometrics. J Forensic Sci 2011; 56: 882-889.
24) Seckiner D, Mallett X, Maynard P, Meuwly D, Roux C. Forensic gait analysis - Morphometric assessment from surveillance footage. Forensic Sci Int 2019; 296: 57-66.
25) Larsen H, Budka M, Bennett MR. Technological innovation in the recovery and analysis of 3D forensic footwear evidence: Structure from motion (SfM) photogrammetry. Sci Justice 2021; 61: 356-368.
26) Nguyen D-P, Phan C-B, Koo S. Predicting body movements for person identification under different walking conditions. Forensic Sci Int 2018; 290: 303-309.
27) Ricciardi C, Amboni M, De Santis C, Improta G, Volpe G, Iuppariello L, et al. Using gait analysis' parameters to classify Parkinsonism: A data mining approach. Comput Methods Programs Biomed 2019; 180: 105033.
28) Yang SXM, Larsen PK, Alkjaer T, Lynnerup N, Simonsen EB. Influence of Velocity on Variability in Gait Kinematics: Implications for Recognition in Forensic Science. J Forensic Sci 2014; 59: 1242-1247.
29) di Biase L, Di Santo A, Caminiti ML, De Liso A, Shah SA, Ricci L, Di Lazzaro V. Gait Analysis in Parkinson's Disease: An Overview of the Most Accurate Markers for Diagnosis and Symptoms Monitoring. Sensors (Basel) 2020; 20: 3529.
30) Krishan K, Kanchan T, DiMaggio JA. Emergence of forensic podiatry—A novel sub-discipline of forensic sciences. Forensic Sci Int 2015; 255: 16-27.
31) Badiye A, Kapoor N, Kathane P, et al. Forensic Gait Analysis. [Updated 2020 May 15]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2020.
32) Hastings R. From grainy CCTV to a positive ID: Recognising the benefits of surveillance. The Independent. Issued on 1st January 2013. Available at: https://www.independent.co.uk/tech/from-grainy-cctv-to-a-positive-id-recognising-the-benefits-of-surveillance-8434644.html
33) Brickley M, Ferllini R, editors. Forensic anthropology: case studies from Europe. Springfield, Ill: Charles C Thomas, 2007.

34) Birch I, Nirenberg M. Forensic Gait Analysis: Principles and Practice. 1st ed. CRC Press, 2020.

35) Kelly HD, editor. Forensic gait analysis. Boca Ranton, FL: CRC Press, 2020.

36) Larsen PK, Simonsen EB, Lynnerup N. Gait Analysis in Forensic Medicine. J Forensic Sci 2008; 53: 1149-1153.

37) Lynnerup N, Vedel J. Person Identification by Gait Analysis and Photogrammetry. J Forensic Sci 2005; 50: 1-7.

38) Birch I, Vernon W, Walker J, Young M. Terminology and forensic gait analysis. Sci Justice 2015; 55: 279-284.

39) Birch I, Birch M, Asgeirsdottir N. The identification of individuals by observational gait analysis using closed circuit television footage: Comparing the ability and confidence of experienced and non-experienced analysts. Sci Justice 2020; 60: 79-85.

40) Vernon W. The development and practice of forensic podiatry. J Clin Forensic Med 2006; 13: 284-287.

41) Birch I, Birch M, Asgeirsdottir N. The identification of individuals by observational gait analysis using closed circuit television footage: Comparing the ability and confidence of experienced and non-experienced analysts. Sci Justice 2020; 60: 79-85.

42) DiMaggio JA, Vernon DW. Forensic gait analysis. In: DiMaggio JA, Vernon DW. Forensic Podiatry: Principles and Methods. 2nd edition. Boca Raton: CRC Press, 2017; 153-180.

43) Sandau M, Heimbürger RV, Jensen KE, Moeslund TB, Aanaes H, Alkjaer T, Simonsen EB. Reliable Gait Recognition Using 3D Reconstructions and Random Forests - An Anthropometric Approach. J Forensic Sci 2016; 61: 637-648.

44) Code of practice for forensic gait analysis. Published on behalf of the Chartered Society of Forensic Sciences and the College of Podiatry by: The Forensic Science Regulator. Crown Copyright 2019. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/918878/137_Forensic_Gait_Analysis_Issue_2.pdf (Accessed on 4th November 2022).

45) van Asten AC. On the added value of forensic science and grand innovation challenges for the forensic community. Sci Justice 2014; 54: 170-179.

46) Kloosterman A, Mapes A, Geradts Z, van Eijk E, Koper C, van den Berg J, Verheij S, van der Steen M, van Asten A. The interface between forensic science and technology: how technology could cause a paradigm shift in the role of forensic institutes in the criminal justice system. Philos Trans R Soc Lond B Biol Sci 2015; 370: 20140264.

47) Badiye A, Kathane P, Krishan K. Forensic Gait Analysis. 2021 Nov 14. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing 2022; PMID: 32491616.