



## Review Article

## Forensic gait analysis – Morphometric assessment from surveillance footage

Dilan Seckiner<sup>a</sup>, Xanthé Mallett<sup>b,1</sup>, Philip Maynard<sup>a,\*</sup>, Didier Meuwly<sup>c,d</sup>, Claude Roux<sup>a</sup><sup>a</sup> Centre for Forensic Science, University of Technology Sydney, 15 Broadway, Ultimo, New South Wales, 2007, Australia<sup>b</sup> School of Humanities and Social Science, University of Newcastle, Callaghan, New South Wales, 2308, Australia<sup>c</sup> Netherlands Forensic Institute, Laan van Ypenburg 6, The Hague, The Netherlands<sup>d</sup> University of Twente, Enschede, The Netherlands

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## ABSTRACT

Following the technological rise of surveillance cameras and their subsequent proliferation in public places, the use of information gathered by such means for investigative and evaluative purposes sparked a large interest in the forensic community and within policing scenarios. In particular, it is suggested that analysis of the body, especially the assessment of gait characteristics, can provide useful information to aid the investigation. This paper discusses the influences upon gait to mitigate some of the limitations of surveillance footage, including those due to the varying anatomical differences between individuals. Furthermore, the differences between various techniques applied to assess gait are discussed, including biometric gait recognition, forensic gait analysis, tracking technology, and marker technology. This review article discusses the limitations of the current methods for assessment of gait; exposing gaps within the literature in regard to various influences impacting upon the gait cycle. Furthermore, it suggests a 'morphometric' technique to enhance the available procedures to potentially facilitate the development of standardised protocols with supporting statistics and database. This in turn will provide meaningful information to forensic investigation, intelligence-gathering processes, and potentially as an additional method of forensic evaluation of evidence.

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## 1. Introduction

Surveillance is defined as 'the practice of monitoring, recording, watching and processing the particular conduct of events, locations and persons for the purpose of governing activity' by Wright et al., pg. 2 [1]. The importance of surveillance as an

\* Corresponding author.

E-mail address: [Philip.Maynard@uts.edu.au](mailto:Philip.Maynard@uts.edu.au) (P. Maynard).<sup>1</sup> Honorary Associate in Centre for Forensic Science, University of Technology Sydney.

investigative<sup>2</sup> and intelligence<sup>3</sup> -gathering tool cannot be over-estimated, and the number of cameras installed as part of this process is increasing [2]. The primary objective of installing surveillance cameras is to detect, track and extract information to discriminate between 'normal' and 'problematic' activities of persons (activity level inference), followed by feature assessment of people (source level inference) through the trace left on screen and on recorded footages.

As a result of increasing installation of surveillance cameras, the potential for increased analysis of surveillance footage has attracted more attention from researchers [2]. One such feature that makes gait analysis more desirable for analysis and separates it from other methods, is the potential for unobtrusive monitoring of one or several individuals and/or a situation from a distance (without the knowledge of the subject(s)), as well as the availability of some features even on lower quality recordings [2,3].

An important component of the assessment of gait involves the determination of the internal<sup>4</sup> and external<sup>5</sup> influences to an individual that may modify their gait. The process of targeting, isolating, and understanding these influences, followed by the observation of normal gait, attempts to distinguish which specific alterations affect gait the most. This review article follows on from Seckiner et al. [4] (Forensic Image Analysis – CCTV Distortion and Artefacts) with the purpose of addressing all these concerns, to discuss the research conducted within the gait analysis field, and to critically evaluate the limitations of the technique.

### 1.1. The gait cycle

Gait is defined as the synchronised oscillation sequence of body segments that form a locomotive pattern, specifically a single limb (i.e.) undergoing the gait cycle (stance and swing phases) [5–7]. The five stages within the stance phase includes [1]: initial contact [2], loading response [3], mid stance [4], terminal stance and [5] pre-swing [5–7]. The swing phase comprises three stages [1]: initial swing [2], mid swing and [3] terminal swing (*ibid*). The body is naturally symmetrical, but contains minor asymmetry, similar to the asymmetry of the face [8]. This is further expressed during gait through upper trunk movement and lower leg rotation, where the legs swing and rotate for advancement [9]. The minor asymmetry relates to intrinsic characteristics of healthy subjects, but major asymmetry is thought to be acquired characteristics consecutive with pathology or accidents. The existence of asymmetry therefore, is thought to enhance the observation of features from the body or gait.

### 1.2. Development of gait assessment

Gait patterns have been studied for centuries, but the first forensic application of biometrics for identification purposes was in 1883, when Bertillon measured the face and body of many offenders in an attempt to improve the individualisation process through the accurate record of physical characteristics [10]. While measurements of gait were not conducted on offenders, it was the beginning of a technique that aimed to achieve identification and is still applied within modern methods. A study by Stevenage et al.,

almost two decades ago, established the possibility of distinguishing between various gait patterns (i.e. scissoring gait), thus a degree of recognition of people by gait, by viewing gait from video footage [11].

The most common biometric applications for the purpose of identification focus on DNA, fingerprint, face, voice, hand signatures, gait, and iris [2]. For gait specifically, each person's manner of walking is said to show some degree of distinctness (*ibid*). Gait analysis is being continually developed through advances in the fields of physical medicine, psychology, and biomechanics [3]. Although studies in gait are developing continuously, in the forensic context, empirical substantiation from the evaluation is necessary – especially gait analysis from CCTV footage.

CCTV footages are often of poor quality [4], particularly when the position of the camera, and camera settings are intended for determining the activity of persons by monitoring a large, public area. Additionally, camera resolution/quality are designed to continuously record its surroundings while footage accommodates a set storage space. Upon analysis, a POI (person of interest) is rarely observed to remain still, but rather seen to be in motion whilst committing a crime or fleeing from the scene of the crime. Therefore, the gait analysis is often important for assessing any patterns or behavioral traits.

### 1.3. Impacts upon gait

To allow a holistic approach in gait analysis, influences that impact upon the manner in which a person walks need to be considered during analysis. This evaluation can be divided into two categories: [1] intrinsic features and [2] acquired features. Physical influences relate to the features that are within the biology of the POI, whereas external influences refer to environment or other influences that are introduced to the body to cause a change, for example alcohol consumption. Table 1 highlights the various physical influences that may change the gait of a person, while Table 2 lists and describes the external influences.

## 2. Forensic use

Biometric recognition is defined as a set of human-based and automated methods used for the recognition of people [54,55], which includes measuring and statistically analysing distinctive physical and behavioural traits [54,55]. Forensic biometrics are included within several forensic processes, such as: forensic investigation, forensic intelligence [56], forensic evaluation, and in some instances, forensic identification and forensic identity verification [54,55]. The method of forensic biometrics involves the extraction and comparison of distinctive features of a pair of specimens (mainly a reference and a trace specimen) to determine their similarities and differences and, ultimately, assess the strength of this evidence for the inference of identity of source. The holistic treatment of this information across the three dimensions mentioned above (i.e. investigation, intelligence, and evaluation) fits the transversal model described in Morelato et al. [57] and Baechler et al. [58].

Gait assessment is currently thought to be mainly human based and computer assisted; where gait assessment is not restricted to only biometrics. Subtle differences exist between the current comparison techniques, but the automated process does not differ from one another where comparison applies. The assessment of gait based on memory recall is also known as 'recognition', where the observer recollects the manner in which a person walked through previous perception [59]. There is no comparative technique in memory recall (aside from comparing the memory of past encoded in the brain and present stimulus observed), but

<sup>2</sup> For the purpose of this article, the definition is as follows - forensic investigation: produce lists of candidates from the comparison of a trace material to a database of references

<sup>3</sup> For the purpose of this article, the definition is as follows - Forensic intelligence: produce links between cases from the comparison of traces

<sup>4</sup> Physical influences relate to the pathology or physiology detected within the body.

<sup>5</sup> External influences are not influences that occur from the body, but rather from objects (i.e. footwear) or environmental impacts (i.e. ground surfaces).

**Table 1**

List of possible intrinsic features altering gait. The following table details the potential features that may alter gait that could affect gait behaviours.

Features	Description	References
Genetically defined features influencing the gait		
Sex	The sex of an individual, places them into the male and/or female category. For this article, the secondary sex characteristics will be considered. One such observed feature to distinguish between sexes, was seen in male subjects, who tend to increase their shoulder swing, whilst females increase the swing in their hips. Although studies have determined such correlations within sex, and separated features that belong to the two, deviations may arise and the features (shoulder or hip swing) may not strictly fall within the male or female groups – primarily as a result of differing skeletal features.	[12–16]
Ethnic background	Infants with different genetic ancestry have shown a different capacity to acquire walking ability. In average, children with an African ethnical background been observed to first walk at the age of 11 months; Caucasian children at 12 months and Asian children at 13 months. Further research is required within this particular subcategory to determine its effects on gait.	[17]
Epigenetic and phenotypically defined features influencing the gait		
Somatotypes (genetic) and body mass index (phenotypical)	Varying shapes and body sizes are thought to be contributing influences upon gait. To provide an example, the three fundamental physique types comprise of: [1] Mesomorphs – muscular and athletic [2], Endomorphs – rounded [3], Ectomorphs – tall and thin. Although the use of a body mass index (BMI) was considered, it was however, replaced in 2008 to somatotyping, primarily due to its limitations (provides value to determine fat content) of classifying the various body types from distribution of fat – which is possible through somatotyping.	[18–21]
Centre of gravity	The assumed point in the body that differs between the somatotypes and shifts during gait is also known as Centre of gravity (COG). To provide an example, endomorphs, have a low COG, while in ectomorphs it is positioned higher up.	[22]
Transient and permanent features	Transient features (relates to motion and physiology in this instance) are visible only upon certain actions for a partial amount of time, an example would be the changeover from stance to gait. Therefore, as soon as someone starts walking, transient features become visible. Permanent features (relate to anatomy and posture) differ as they remain unchangeable within the body i.e. position of the knee cap; which is expected to remain in the same position regardless of subject in stationary position or motion. Transient features also relate to temporary conditions, such as a pulled muscle or pregnancy, which is not permanent but rather alters gait for a period of time	[23,24]
Speed	As the speed of walking increases, so does the stride and cadence. Increase in speed is demonstrated visibly by arm swing, where arms were seen to swing faster and higher to accommodate quicker and longer steps taken by the legs. Another study showed lateral instability of the knee of a POI during increased speeds, with this feature not seen during walking. Hence, it is suggested that in a reconstruction scenario, police officers accompanying suspects, should adapt the speed of the POI captured on CCTV footage to aid the comparative analysis, thus increasing accuracy upon examination between POI and suspect.	[25–27]
Fatigue	Fatigued muscles, also known as the inability to keep an expected force output can be commonly seen by the affects upon foot stability, where supplementary eversion or inversion of the foot is present. Furthermore, upon comparison of fatigued and non-fatigued people, increased stride variability and instability when fatigued was observed.	[28,29]
Standardisation	The unperturbed manner of walking is referred to as 'Normal' gait, thought to offer some distinctiveness between people. If 'normal' mannerisms of walking (correlating with normal anatomical structure) are not fulfilled, then this is considered as 'Pathological gait' or 'Directed gait' i.e. marching. Further research in this area can be completed in tandem with existing research to assess normal activity (unforced), degraded activity (pathology, age), and forced activity (marching, disguise).	[30]
Directed	'Directed gait' is walking under specific instructions. One such example is marching, where it is observed to be a directed manner of synchronous walking in which pathological complications (i.e. the feet, lower limbs or pelvis) may arise as a consequence of 'directed' gait. Such pathological complications include stress fractures, blisters, sprains and strain.	[31,32]
Habitual nature, pathology or otherwise features influencing the gait		
Pathology and accidents	Pathology in relation to gait relates to one or many body deformities. Gait that is free of pathology requires a sufficiently operational locomotor system, absent of body deformities and/or pathological conditions, including accidents (amputation). Such pathological gait includes multiple sclerosis for instance	[33]
Age	Age relates to the lifespan of the particular person and how old they can be categorized into [1] a learning phase [2], a stable phase and [3] a decay phase. For instance, children were seen to have differing gait to adults, including gait parameters surrounding stride length, cadence and velocity (i.e. stride length were shorter in children as a result of height. The body deteriorates with age – or so it is commonly thought. The way that studies have shown that speech and handwriting affects age, so does gait. Some studies contrariwise observed that abnormalities within the elderly subjects were based on pathology rather than age progression.	[30,33–38]
Hand preference	Hand preference relates to the preferred use of one, or both hands more than the other, also referred to as the dominant hand(s). Anatomically, the body is mainly symmetric, but physiologically as a lot of activities are asymmetric, this asymmetry is thought to be mirrored in gait. The body contains some asymmetries in nature, for instance, the left shoulder of a left-handed person is generally lower when compared to their right shoulder. This is thought to result from the positioning of the body (in particular the torso) while using the dominant hand. A lowered shoulder does not always indicate the dominant hand, it does however provide a possible reason for the morphological feature observed.	[39–41]
Habitual mannerisms	Certain habits or 'mannerisms' may also alter the gait of an individual, whether they are behavioural/psychological and/or pathological/physiological. To provide an example, tics (i.e. Tourette's syndrome) are caused as a result of neurodevelopment disorders, arising from physiological circumstances.	[42,43]
Emotional mind state	As behavioral biometric trait, the gait modes is also a vector of expression of emotions. One study showed that depression and sadness influence gait at such a degree that walking speed, arm swing and head movements (vertically) were reduced, alongside a slumped posture and an increased lateral upper body sway. Furthermore, it was determined that while angry, gait contained longer stride length with increased heavy-footed step and happy gaits were detected to contain a faster pace.	[44,45]

rather an example would be recognising someone the observer already knows (familiar human-based recognition). This term is not interchangeable with 'biometric gait recognition' or 'gait biometrics', where instead, gait is assessed through static and dynamic measurements, thus automated objectively [60].

Forensic gait analysis is not cognitively based, but rather involves the scientific application of [1] anthropometry (measurement) [2], morphology (features), and [3] superimposition (overlay) to objectively compare a person's gait distinctiveness

(i.e. a suspect) to that of a POI. To fully understand the differences between 'gait recognition' and 'forensic gait examination', developments and limitations within the current literature will be outlined.

While commonalities are present between gait recognition and forensic gait analysis, the conditions of camera recording differ significantly [6,26,61]. To provide an example, gait biometrics/recognition includes the "model-free" 2-D method (extracted from gait databases), and the "model-based" approach (extracting

**Table 2**

List of possible acquired features altering gait. The following table details the potential features that may alter gait that could affect gait behaviours.

Features	Description	References
Ensemble features influencing the gait		
Attire	Attire of the POI reveals or obstructs particulars of the body. Generally, the type of clothing worn, good fit and definition is achieved visually from the upper back and shoulders as a result from the force of gravity acting upon it. It is commonly seen for a POI to wear shapeless, baggy clothes whilst committing a crime to deter analysis. Although some features of the body may be obscured, the gait of that particular person and distinctive features of gait can be still observable.	[26,40]
Footwear	Footwear is available in various styles, shapes and sizes i.e. heels, sandals, sports shoes. Following the various short-term changes in gait that footwear has been seen to affect (i.e. flip-flops compared to well support sports shoes), the long-term alterations of gait caused are also questioned. Footwear has been seen to have long term alterations of gait, where high heels result in the instability of the foot (from fatigue) of muscles such as the gastrocnemius lateralis and peroneus longus.	[28]
Load carriage	Load carriage refers to the carrying weight on parts of the body, such as bags and personal items during the time of analysis. Studies have shown that upon carrying a bag, stride length and single support time (when on one limb) is decreased; while an increase of double support time (on two limbs) and frequency of stride were observed. Another study assessed the influence of a single-strap bag during gait and results showed a decrease of stride length (contralateral leg) while carrying a bag on the forearm and minimal variances were seen with a bag over shoulder.	[46,47]
Environmental features influencing the gait		
Environment and culture	The cultural and surrounding environmental influences upon gait are yet to be determined. No research has been acknowledged in this particular area, but it is thought that it would be one of the lengthiest; this would require isolated groups of varying cultures (i.e. subpopulations, indigenous), and environments (city, country, village) as well as consideration for temperature, altitude, type of ground and declivity which may impact on gait.	No reported research found on this topic
Angular momentum	Angular momentum is known as the rotational behaviour of the body, where stability and control during the gait cycle are provided by this mechanism. The effects of angular momentum on gait variability was observed through a study, where subjects walking on an incline showed greater forces applied to the ankle, knee and hip of the individuals with distinctly increased ankle motion observed.	[25,48,49]
Treadmill	The use of treadmills to analyse gait has been heavily scrutinised and challenged across many studies; whereby some favour the benefits of a controlled ground surface, speed and environment, whilst other studies indicate variations caused in gait due to treadmills. Displacements in anatomy, such as the ankle and the head were seen in one particular study, whereas, another study states that a subject walking on an 'ideal' treadmill has no difference to walking on ground.	[9,16]
Other features influencing the gait		
Music	Music is well known for its influential motivation for movement. Studies have been undertaken to determine the effects of music and the beat upon gait. On such study, observed subjects during gait, who listened to their own selected music containing metronomic rhythm, matched the tempo of the music, as well as increase their stride length, cadence and velocity. Another study however, assessed participants walking to music that did not contain metronomic rhythm and found that music did not significantly alter the gait dynamics.	[50,51]
Alcohol influence	The influences on gait caused by alcohol consumption, drugs of abuse and medicine have not been extensively explored due to ethical reasons. One study however, indicated that high levels of alcohol consumption, increased the stride length during gait; which was the only significant variation detected in their gait. Ingesting lower levels of alcohol caused fewer variances from the original gait patterns observed within the same individual. Studies into speech have indicated that speech is progressively altered as a result of alcohol – further studies into gait will improve the understanding of the effect of drugs and alcohol.	[52,53]

features directly from a subject) [26]. The 2-D model-free approach uses a representation (such as a silhouette) on a single camera and analyses the distinctions of gait patterns [6,62]. The 'model-based' approach extracts variables (features) from the human body whilst in motion and aims to match the features to corresponding model components [6]. In this way, the gait of a POI can be assessed from a distance. This differs significantly from facial analysis, where a POI is required to be closer to the camera (otherwise, a longer focal lens is required) – in other words, gait features are more available in forensic trace material than facial features [6,61]. The following section will highlight the differences between human based approaches and computer based-human assisted approaches in gait analysis.

### 2.1. Forensic gait examination: human based

The combination of photographic comparison and forensic image analysis results in forensic gait examination [63]. Initially, photographic comparison was primarily used for frontal facial assessment from images, however, more recently its application for body assessment has been demonstrated. The concurrent application of photo comparison and forensic imagery results in a technique known as forensic gait examination.

#### 2.1.1. Photo comparison

Analysis of gait was established to be useful for comparison of a POI and suspect as demonstrated through *Murdoch v The Queen, 2007 HCATrans 321* [64]. Measurements are a component within anthropometry; defined as the quantification of measurements,

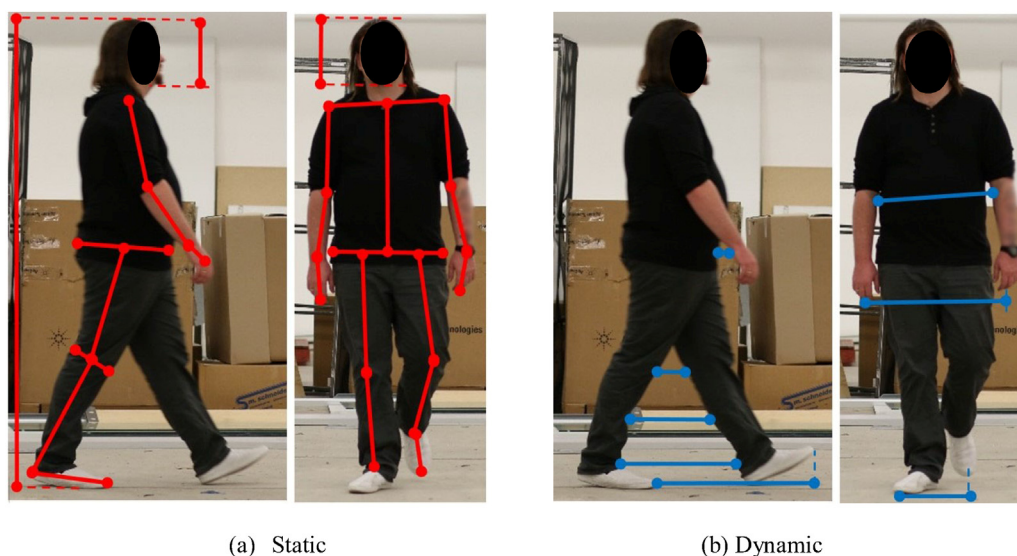
proportions, angles, dimensions, and anthropometric landmarks of the face and body (Fig. 1) [65]. Thus, photo-anthropometry is the specific technique applied in forensic gait examination, which allows comparison of POI captured on CCTV to reference images (suspect or victim) [65]. Set landmarks are then measured to ultimately attain proportional indices or produce ratio [65].

Morphology includes the qualitative analysis (feature by feature) of the shape, form and size, of the face and body (Fig. 2) [66,67]. The amalgamation of anthropometric measurements with morphological classifications are defined as 'morphometric analysis' forming two of the three key components within photographic comparison [65].

The third and final component of the photographic comparison technique is superimposition, which involves the overlay of features, enabling analysis of image comparison between POI and suspect, thus resulting in a visual representation (Fig. 3) [65]. Once again, superimposition was demonstrated in *Murdoch v The Queen, 2007 HCATrans 321* [64], however this third component within the photo-comparative technique must be treated as a support to the first and second components, rather than a stand alone analytical method; as it is a visual representation to highlight any similarities and differences.

One study conducted by Home Office Science Development Branch (2007) [68], initially obtained footage of POI, then later introduced a 'dummy' subject – a known person whose height and morphological details are calibrated can attend the scene to be captured by the same camera. Like-to-like images should be compared and if, for instance, security manually 'followed' a POI with the camera to record their activity, the position and zoom of





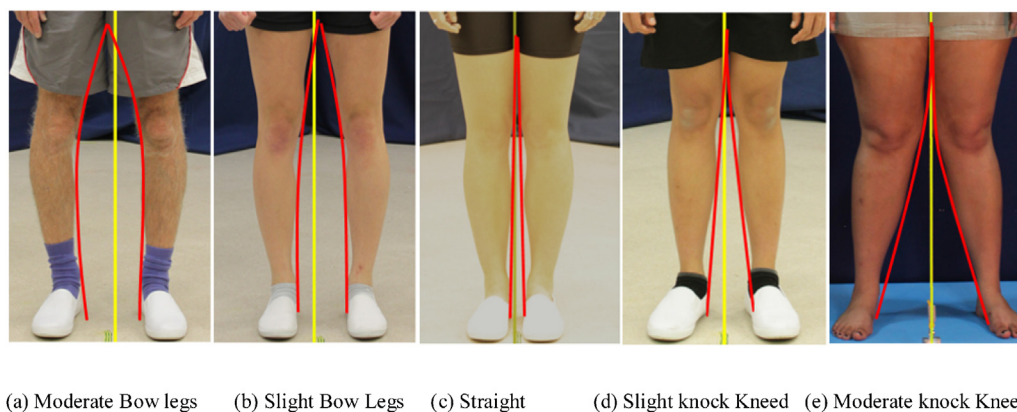
**Fig. 1.** The differing types of measurements/proportions analysed for gait.

The anthropometric measurements of the body (static and dynamic features) are applied for the assessment of gait. Static features (a) are defined as the geometrical measurements of the body, i.e. individual's length of whole leg, length of individual's knee to foot height etc. Examples of measurements taken are represented by lines. Dynamic features (b) are measurements related to gait. For instance, the distance between the left and the right toe during gait, distance between knees, stride length etc. The examples of such measurements are represented by the lines.

the camera need to be aligned to the original path of the POI when recording the 'dummy' as well [68]. A measuring stick is used by the 'dummy' with the base of the stick placed at the approximate feet of the POI and measured with a spirit level to ensure it is parallel to the ground. Following this, superimposition can be conducted via software in a more accurate manner (*ibid.*).

Geradts et al. [69] determined that when assessed within the sagittal plane the hip, knee, and ankle joint angle were not suitable for identification separately, but they offer some distinctiveness that can contribute to the strength of evidence. Schollhorn et al. [70] resolved that single variables or parameters of such variables cannot establish an identification of individuality. Therefore, more variables extracted from the offender (captured on surveillance) increases the reliability of the evidence [71]. Both Larsen et al. [71], and Jokisch et al. [72] determined that the most significant features examined are of the frontal view of the subject. Jokisch et al. [72] explored the recording angles of individuals to determine the optimal view in which friends and colleagues were recognised most easily; with results leading to the frontal angle being superior to half-profile and profile view.

Furthermore, the camera should be placed in profile and posterior views to determine any further joint, dynamic, or morphological related variables (*ibid.*). Geradts et al. [69] proposed the camera placement to be above the head, to film in a transversal view, thus recording the step length and degree of outward rotation of the feet. It is believed that this transversal angle in tandem with other views would increase the number of variables developed to enhance the assessment of gait analysis. Lucas and Henneberg [73] deduced eight facial and eight body measurements to determine which was more distinct within their database. This was conducted through the search for duplicates – where the duplicate measurement would mean that the numerical measurement of one individual was identical to another person's measurement of the same feature. A total of 3982 subjects were analysed and the body was determined to be more distinct than the face as less duplicates were seen in body measurements when compared to the face (*ibid.*). It is further questioned however, how this would perform with individuals captured on CCTV images rather than standardised images. Birch et al. [74] conducted a study which showed that varying frame rates affected the eight



**Fig. 2.** The morphology of the lower limbs.

Morphology consists of the qualitative (feature by feature) analysis of size, shape and form of human anatomy. The images indicate the differing orientation of the legs representing bow legs (a) and (b), straight (c) and knock kneed (d) and (e).



**Fig. 3.** The superimposition of the mock 'POI' and 'Suspect'.

Superimposition is defined as the overlay of images. As indicated in the above figure, the suspect (d) was superimposed on top of the POI (in pink) to determine similarities and differences. This technique is applied as more of a visual aid to determine similarities and differences. (a) is an image of the POI. Within (b) and (c), the suspect is gradually superimposed onto the suspect, and (d) is an image of the suspect (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

podiatrists' determinations of gait characteristics from the one participant. Thus, it was suggested that the CCTV cameras capture footage at as high of a frame rate as possible, as frame rates up to 25 frames per second indicated an increased positive effect on the analysis of gait by the podiatrists [74].

## 2.2. Gait recognition: computer based – human assisted

Improvement of the specifications of the capture systems will enable further access to distinctive features for the source level inference as well as continue to maintain the activity level inference as it is now. However, they are not all applicable for forensic gait analysis. One such example includes 'body markers', which follow body movements through placement of 'markers' upon specific landmarks of the body [75]. The markers can either be active (that may radiate sound, electrical waves, or light), or they can be passive (reflecting light, infrared, electromagnetic waves [75]). This method is unworkable when the source is unknown. Another technique applied for gait assessment includes tracking, where through estimation of body segment location, segments are separated from one another and 'tracked' [76]. Tracking commences once a person of interest is available for further assessment [77]. Varying types of tracking are available and explained in detail [77] as seen on Table 3. This method may be applicable for forensic evaluation and possibly to forensic intelligence, but not for investigative work.

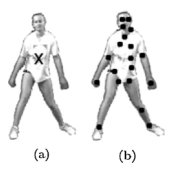
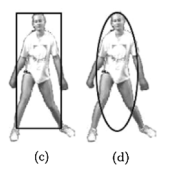
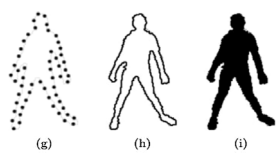


Tracking limits features available on the body and segments them into 'box-shapes' or 'elliptical shapes' [77], thus limiting variability that exists within the human form into said 'box-like' shapes. To provide an example, the bow-legged feature of an individual gait would be lost if segments of the body were to be tracked. Conversely, the use of anatomical landmarks of the body is ideal but use of the 'tracking' technology is not applicable to a POI captured by surveillance cameras as they are not in a controlled environment. This also applies to thermal CCTV cameras (sensors that detects heat signatures), which are used to visualise gait [78]. Thermal CCTV cameras mimic silhouettes, which obstruct features

of the body thus limiting feature analysis. Infrared provides benefits however, for allowing visualisation of an undetected POI (camouflaged within surrounding environment for example) [78].

One gait study conducted by Collins, [79] evaluated silhouettes to determine body measurements and gait patterns. It is debated in the study whether the use of silhouettes for analysis creates limitations, as morphological features of the body are overlooked, as technically the outline of the body and the subsequent features analysed. The use of various angles within Collins study however, provides analysis of anterior/posterior and both profile views, thus increasing the value of the information brought by this technique [79]. The opposite approach was applied by Gabriel-Sans et al. [80], where the whole study was conducted by assessing from one camera view (profile view) only, thus disregarding the asymmetrical nature of the body, limiting it to a single side, thus limiting the overall assessment. In another study, Cheng et al. [2], allowed nine subjects to walk such that all angles of the body (quarter views – midpoint between a frontal and profile view and posterior and profile view) were able to be seen, in which the subjects walked diagonal within the camera view rather than parallel or perpendicular to it. The assessment of diagonal walking is beneficial for gait analysis as all views of the body are viewed for assessment. Commonly, persons recorded from CCTV footage are not only walking perpendicular or directly parallel to the camera, but rather, in all directions, resulting in quarter views of the person being recorded. Therefore, it is essential for further research and development into quarter view studies, or as Birch et al. [81] refers to them: 'oblique' views. A total of 13 subjects were assessed in another study conducted by Birch et al. [82] where various clinical experts (podiatrists and physiotherapists) assessed the volunteers' gait patterns. Although each feature from different body parts contain some distinctiveness associated to some strength of evidence, with no sufficiency threshold, this study determined that the analysis of the upper body is useful for analysis also, following the finding that the primary feature that aided in the analysis was the arm swing [82]. This reinforces that the assessment of the whole body rather than just the lower body

**Table 3**

Various tracking methods [77]. Each represents the differing types of tracking methods that are applied to assess the gait of a subject. (a) Single centroid point, (b) multiple points, (c) rectangular patch (d) Elliptical patch (e) part based multiple patches – articulations (f) object skeleton (g) multiple control points on object contour (h) whole object contour (i) silhouette of subject. Used with permission.

Types of tracking	Graphical representation
Points: The subject is characterized by a single central point (Fig. 3a) or by multiple points assigned for tracking (Fig. 3b)	
Primitive geometric shapes: The subject is embodied by an ellipse or rectangle (Fig. 3c) and (Fig. 3d), used for tracking both rigid and non-rigid objects	
Subject silhouette and contour: The boundary of a subject is outlined through contour representation (Fig. 3g) and (Fig. 3h). Inside this boundary, is the silhouette (Fig. 3i)	
Articulated shape models: Ellipses and cylinder represent the parts of the body, particularly where the articulations within the body are present (Fig. 3e), for instance the gleno-humeral (shoulder) joint to the torso	
Skeletal: Once the silhouette is obtained, a subject skeleton is applied through medial axis transform (Fig. 3f)	

can increase the feature set. Various techniques applied within experiments which were conducted previously, favoured analysis of the lower body, thus limiting the feature set assessment of the upper body. It was suggested by Veres et al. [3] that upon the assessment of silhouettes, the static component is focused upon as it is considered the essential component, whereas the dynamic component measuring the swing of the arms and legs are ignored as it is considered less important – which can reduce recognition rate. All features of the body are important, however it is thought that some features would be more distinct than others. Veres et al. also utilised three separate databases to increase the pool of data so assessment on a larger pool of subjects can be analysed, which increases the robustness of the study [3].

One study disregarding the upper body for gait analysis was that of Zhao et al. [62] where the upper body was totally eliminated from the analysis as a result of measurements being deemed unreliable, following unsuccessful tracking of the upper limbs. Another study on the other hand by Birch et al. showed that standardised clothing provided consistency amongst the subjects which was beneficial for the analysis process [82]. Moreover, shadows existing within the silhouette limits comprehensive gait analysis which was pointed out in the same study by Birch et al.

[82]. Liu and Sarkar [83], showed that detecting shadows and noise, differentiating, then extracting them from genuine gait is necessary as there was too much distortion affecting the gait observed the shadows, and noise were resolved by manual artefact removal to allow precise analyses. Therefore, it is highlighted that shadows existing within the silhouette limits may impact upon the study, compromising its reliability. A total of 71 subjects evaluated within the study contributed to the robustness of the experiment [83]. Consequently, combinations of biometric and morphological techniques were thought to enhance analysis of gait. Features that were appearance-based were derived from a video sequence of subjects walking, which was captured in differing conditions (i.e. indoors and outdoors) [84]. The outer contour width of the binary silhouette was considered the basic feature (*ibid*). Thus, to align temporally the gait sequences, various features were extracted (from width vector), followed by the application of dynamic time warping (DTW) (*ibid*). Lee and Grimson [85] were successfully able to eliminate some background noise within the silhouettes in their study, thus improving the reliability of the analysis.

### 3. Uses of gait analysis

As mentioned in section 2, 'Forensic Use', biometric technology can be applied to a variety of forensic processes, where in consequence, the value of gait analysis will be relative to its purpose:

**Forensic investigation** – Biometric technology can contribute by comparing traces (such as fingermarks and prints) to the database – where the persons whose data are most similar to the mark are shortlisted [54]. Results are then refined where reference specimens are excluded based on the data, leaving only those individuals whose data most closely related to the mark [54]. The forensic investigation process is very valuable within gait analysis. For instance, generating a list of candidates and exclude unrelated persons within the database is possible from the gait, however, it is currently not scalable in the same way as an Automated Fingerprint Identification System (AFIS) and requires further development [54]. Such improvements can be the incorporation of high quality surveillance cameras (such as the work of Neves – who determined that automatic height estimation is achievable within surveillance scenarios [86]), as limitations of camera distortion and clothing are present within gait assessment and require further research before they can be overcome [54].

**Forensic intelligence** – Biometric technology can be applied in forensic intelligence scenarios to detect patterns of interest, especially when they are linked to abnormal and potentially security-related situations and behaviours. When forensic science is applied within the forensic intelligence context, the aim is to develop efficient strategies and concrete operations to disrupt or prevent from criminal activity, as well as to link traces related to the same source [87], which complements the conventional use of forensic science to be used in court outcomes [87]. In the case of gait analysis, forensic intelligence also depends on the main question being addressed, for example it is based on the activity (movements of POI in surveillance footage) or source (person related features observed on POI) level inference [54]. A typical example is linking cases involving someone who has a limp for instance, or is on crutches. It is recognized that gait analysis requires further development before this technique can be used to its full potential, with development of standardised intelligence databases [87], to allow traces to be linked from various different cases.

**Forensic evaluation** – Forensic biometric evidence at source level comprises the application of biometric technology to exclude the



POI or assess the strength of the evidence resulting of the comparison of the trace and reference specimens for the reporting in court proceedings [54]. Development and application of a probabilistic approach within gait analysis will allow the examiner to provide a description of the strength of evidence to the trier of facts in court [54]. Additionally, challenges also exist within the estimation of intravariability (within source variability for several persons), intervariability (feature variation between all persons of a population) within-source variability (feature variation of one person at different times) and between-source variability (feature variation of a person regarding a population) for gait, which will be further developed in future publications.

### 3.1. The legal system

Forensic gait analysis has faced substantial obstacles and criticism within legal settings, where the problem lies not within gait analysis, but rather the lack of scientific validity and evaluation by the forensic examiner and poor understanding of the fundamental principles and of the forensic inference process. Internationally, not all legal systems rely on admissibility criteria to accept evidence in court; in the inquisitorial system it remains for example the province of the trier-of-fact. The two major legal systems are common law (adversarial) and civil law (inquisitorial) [88]. In short, the adversarial system is reliant on the courts role of an impartial referee between the prosecution and defense whereas an inquisitorial system relies on the court investigating the proof of facts of a case [89]. The common law system is found predominantly in Australia, United Kingdom, America and Canada [90], whereas the civil law system is found in most of Europe, all of Latin America and parts of Africa and Asia [91]. However, rather than focusing on whether a rule is either adversarial or inquisitorial, importance on a fair trial, assisting tribunals to achieve tasks whilst abiding by fundamental fair trial standards [89] and specifically for gait analysis, forensic evaluation of the evidence whilst upholding scientific validity and reliability as the result of forensic evaluation is not a decision of identification, but a description of the strength of evidence. Admissibility is not involved with the formulation of the forensic evaluation conclusion, but rather the legal rules in order to accept evidence. The result of the examination provides support to one of the alternative hypotheses; (H1) the trace and reference material originate from the same person, or (H2) the trace and reference material originate from different persons.

Experts in podiatry and medical practitioners are considered as qualified to present evidence of gait analysis within the United Kingdom courtroom – an example would be that of *R v Saunders [2000] VSCA 58 a* [92], where the expert was a podiatrist whose expertise was in gait analysis (*ibid*). Although the podiatrist's knowledge was necessary for the examination, the forensic knowledge is also an imperative component which needs to be fulfilled not only in gait examination but also in other transdisciplinary forensic fields. The practitioner compared both suspect and POI images by vigorous frame by frame assessment where the same body planes for both image were analysed and compared (front, rear and side views) [92]. This was the first time that gait analysis was deemed admissible in the Old Bailey Central Criminal Court in London – thus making legal history (*ibid*). A Swedish case *Mijailo Mijailovic, Supreme Court of Sweden (2004)* involved the assassination of Swedish Minister for Foreign Affairs [93]. Facial comparison, as well as gait and body measurements, were measured and assessed between the accused and a person of interest (obtained from surveillance footage) – and contributed to the conviction of the accused [94]. Another example of this is the matter of *Regina v Aitken, 2008,1423. BCSC* a Canadian case where

body analysis evidence was accepted as an identification, since the *Daubert*<sup>6</sup> test was satisfied [95], which requires the expert to demonstrate suitable levels of study, training, and experience [96]. Additionally, the expert's theory must be tested, error rates determined, standardised protocols established, peer reviewed, publications to be available, and finally, the scientific community must generally accept the technique [96]. In Europe however, rather than the *Daubert* standards, it is advocated that method is validated and accredited. Another case from the UK is that of *R v Otway [2011] EWCA Crim 3*, whereby identification evidence of the suspect's gait was compared to reference sequences [97]. It was criticised by the defence, however, that there were no statistical database and no scientific basis of the method as support for its inclusion (*ibid*). An appeal was raised on these grounds, but it was rejected and gait analysis was admissible (*ibid*). Moreover, in 2003, the 'Bromby Scale' was recommended to experts and applied the same year for use in the British criminal courts (Table 4), for the purpose of standardisation of evidence presented [98]. The issue that lies within the Bromby scale 'however, is that the scale provides support to the hypothesis, and not to the evidence, given the hypothesis (defined as prosecution's fallacy).

In Australia, forensic gait analysis, can only be presented as similarities and differences by 'Ad hoc' experts [99]. *Ad hoc* experts can only provide opinion-based evidence of the anatomical and forensic imagery experience obtained, and are limited to only providing evidence of similarities and differences, unlike experts who can provide evidence of identification [99]. Using techniques of photo comparative analysis and morphological classification of the POI and suspect(s), evidence of this type in Australia is presented by experts within the forensic anatomy and imagery fields [65]. This was established in the matter of *R v Hien Puoc TANG, 167. 2006, NSWCCA* whereby body examination evidence was not deemed admissible in court, as a result of the expert expressing the POI and suspect were 'one and the same' [100]. This highlights that the issue lay within the poor understanding of the fundamental principles by the 'expert'; thus questioning the expertise of the appointed practitioner. This landmark case established that the requirements of section 79 of the Evidence Act were lacking due to lack of science supporting the 'opinion' evidence, but rather based on the judgement of the expert; thus differing significantly from evidence of 'fact' [65]. Section 76 of the Evidence Act (1995) is also known as the 'Opinion Rule' where the lack of fact combined with the absence of expert experience/qualification results in inadmissibility of evidence [101]. Subsection 79 of the Evidence Act (1995), is an exception to this rule, known as 'the expert opinion rule' [101]. For this rule to be satisfied, the forensic practitioner must possess specialised knowledge obtained by training, experience or study, specifically an academic degree in a relevant field (primarily forensic science) [101]. Furthermore, the opinion presented must be based wholly or substantially on the area of said specialised knowledge (in combination with the disclosure of methods) [101].

Therefore, to be declared admissible in Australia, experts presenting evidence of forensic gait analysis must demonstrate they must exhibit appropriate training, experience, or study, whilst also understanding the forensic inference process. This was emphasised within the matter of *Smith v The Queen, HCA 50, 2001* whereby police officers were not deemed appropriate to present evidence of identification due to lack of expertise [102]. Likewise, within *Regina v Jung, 658, NSWSC, 2006* it was determined that distortions must be considered upon analysis of a POI by experts when presenting evidence of facial comparison [103].

<sup>6</sup> *Daubert v Merrell Dow Pharmaceuticals, in 509. [1993], U.S. 579*



**Table 4**

A guide for an expert witness [98]. The level of support for identification evidence of image comparison, are provided within the table (ranging from 'Lends no support' to 'Lends powerful support').

Level	Description
1	Lends no support
2	Lends limited support
3	Lends moderate support
4	Lends support
5	Lends strong support
6	Lends powerful support

The admissibility for body analysis was established within the Australian High court as seen in the landmark homicide case of *Murdoch v The Queen*, HCATrans 321, 2007 and *Murdoch v The Queen NTCCA, 2007*, where the appeal pursued by the defence was quashed with the original ruling sufficing [64,104]. Nevertheless, scrutiny of forensic body examination continues to restrict opinions to similarities and differences, an issue once again raised in the case of *Regina v Dastagir*, SASC 26, 2013 [105]. This case highlighted the criticisms within the science including the lack of [1] standardised protocol, [2] population database, and [3] frequency statistics (including the probabilities of the presence of features in a population) [105]. It is thought that the development and improvement of these aspects will allow forensic body examination evidence to be credible. Further credibility to a method is thought to be established through validation of an accepted protocol, compiled in a validation report that is peer-reviewed at the moment of the accreditation.

#### 4. Conclusion

In the introduction it was stated that any type of observation, such as gait analysis from CCTV footage could potentially be used for investigative and forensic intelligence purposes, and as evidence in court proceedings if the most correct strength of evidence is provided.

Forensic investigation and forensic intelligence based on gait analysis is possible now, but more work is needed to further advance automated comparison systems for generating a list of candidates from their gait, and linking traces related to the same source. From this, not only will forensic examination be more efficient for narrowing the suspect pool, but through improvement of the forensic evaluation process, the strength of evidence can be assessed, and empirical substantiation attained. After the examination has been completed, if the Likelihood Ratio is 1, indicating the results are of no value, this may be indicative of the inability of the method or the lack of information in the observation.

In legal settings currently, assessment of gait material has been criticised for its lack of scientific validity through lack of ACE-V (Analysis, Comparison, Evaluation and Verification) protocols and inference models i.e. likelihood ratio. Specifically, courts have questioned the appropriateness of providing evidence of identification in court without the sufficient protocols, statistics and database available for the scientific community to determine the reliability of the method. As highlighted in 'Forensic Image Analysis: CCTV Distortion and Artefacts' [1], forensic examination of such material ultimately aims at evaluating the strength of evidence at source and activity levels and that this strength is inferred from the trace, obtained in the form of CCTV footage [1]. Therefore, forensic practitioners appointed as experts to present evidence of gait examination must understand the forensic inference process and also demonstrate their expertise within both forensic anatomy and forensic imagery; thus it makes clear

the role given to them in the context of the case [106]. The experts must also keep in mind the current limitations within the varying types of techniques, not only from influences that may alter the manner in which a person walks but also from CCTV distortion, however, the technique can be developed through further studies and research.

A possible way forward is firstly, determining the estimation intervariability and intravariability for gait, and establishment of a standardised CCTV gait database with accompanying controls in place with high quality DSLR cameras. Additionally, isolation and development of how varying influences impact upon the gait may determine certain patterns in each influence type. Furthermore, determining any trends or distinct features within various age, sex, and ancestry groups and the frequency of such features, may improve understanding of gait within each subpopulation. Finally, the development and application of a probabilistic approach within gait analysis, to provide a description of the strength of evidence whilst upholding scientific validity and reliability, is thought to contribute to unlocking the full potential of forensic gait examination.

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