The utility of gait in forensic human identification: an empirical investigation using biomechanical and anthropological principles.

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ABSTRACT

Forensic gait analysis is generally defined as the analysis of walking features of individuals from video footage, to assist in criminal investigations. Although an attractive approach to detecting suspects since data can be collected from a distance without their knowledge (e.g. from public CCTV cameras), this field of study currently lacks validation and quality standards not only due to insufficient research, but also because certain scientific foundations, such as the assumption of gait uniqueness, have not been adequately investigated. To test the scientific basis of this premise, a suitable dataset replicating an ideal forensic gait analysis scenario was compiled from the Karlsruhe Institute of Technology (Germany) database. Biomechanical analyses of human walking motion (i.e. gait cycles) in the left and right shoulder, elbow, hip, knee, and ankle joints of twenty participants was conducted using the R program. The purpose of these analyses was to investigate the degree to which differences between walking activities of the same participant (i.e. intraindividual variation) impact differences amongst participants (i.e. interindividual variation), according to the following aims: (1) to better understand the relationship between form (anatomy) and function (physiology) of human gait, (2) to investigate the basis of gait uniqueness by examining similarities and differences in joint angles, and (3) to build upon current theoretical foundations of gait-based human identification. The findings indicate different degrees of gait asymmetry given anatomical body region and gait sub-phase (i.e. component of a given cycle), thereby challenging previous methods employing interchangeable use of gait data irrespective of body side, and the use of 'average' gait cycles to represent the gait of an individual irrespective of body side. Furthermore, interindividual variability in all five joints is influenced by body side to different extents depending on gait sub-phase and body region, thereby challenging the claim of holistic uniqueness of gait features across all body regions and gait sub-phases. The results therefore underline that previously held assumptions may not hold true, and that their continued use irrespective of innumerable recommendations previously made and in light of novel research, may be detrimental to judicial situations where guilt or innocence is established based on such evidence. Given the findings of this research and paucity regarding empirical basis to support expertise, exerting caution when evaluating gait-based evidence admissibility in the courtroom is highly recommended, since the utility of gait in identification is currently limited.

KEYWORDS

forensic gait analysis; forensic human identification; forensic science; evidence admissibility.

ACKNOWLEDGEMENTS

The author wishes to express her gratitude to Dr. Herve Borrion (UCL) for his academic support, and Professor Tamim Asfour and Isabel Ehrenberger from the Karlsruhe Institute of Technology in Germany for their time in providing assistance with the KIT database.

1. Introduction

The legal standing of forensic science has considerably altered in past years due to the diversification of criminal endeavours. Accompanying this 'evolution' in the nature and circumstance of crime, strong debates have arisen in forensic science communities, many of which revolve around the theme of evidence admissibility (e.g. Bolton-King 2016; Bowers 2019**;** Gill 2019; Smit *et al* 2018). Of particular interest is the need for conducting empirical examination of established and novel forensic methods, to ensure that reproducibility, reliability, and quality are to the required standards when utilised in court (e.g. Morgan 2017; Redmayne *et al* 2011; Risinger *et al* 2002). Although there is some governmental and academic disagreement centred around the criticism of the current state of forensic science (arguably considered to be somewhat exaggerated and unfounded (Nirenberg *et al* 2018; Rosenstein 2018)), the opinions presented therein have sparked strong interest amongst forensic scientists with regards to empirically testing methodological assumptions and/or scientific foundations in their respective fields, and examples include forensic anthropology (e.g. Christensen and Crowder 2009; Langley *et al* 2018; Macoveciuc *et al* 2017), fingerprint analysis (e.g**.** Dror and Mnookin 2010; Stevenage and Bennett 2017), and bitemark analysis (e.g. Pretty and Sweet 2010). However, little research has been dedicated to methods that are seldomly observed in the courtroom, but that have, nevertheless, been deemed in past trials as appropriate for forensic use and admissible in court.

One example is forensic gait analysis, generally defined as "*the analysis, comparison, and evaluation of features of gait to assist the investigation of crime*"; the methodological approach largely involves analysis of two or more sets of video footage where obvious facial characteristics or other personal identifiers are obscured or dissimulated, to conclude whether same individual is present in the videos (Forensic Science Regulator 2019). Since gait characteristics can be collected from a distance (Boulgouris and Chi 2007) without knowledge or consent, potential applications of gait analysis are considered attractive across all stages of an investigation. Constructed (from a physiological perspective) from a series of (largely) repetitive, cyclic movements that are considered generally symmetric, gait can be observed cannot be entirely concealed or dissimulated (Bouchrika *et al* 2011). Furthermore, given ongoing advancement in automated digital technology and current use of such methods, particularly in airport security (e.g. facial recognition), it is reasonable to predict that the practice of gait analysis will increase in coming years. At present however, forensic gait analysis methodological approaches have yet to meet validation requirements and quality standards intrinsic to forensic practice (Macoveciuc *et al* 2019) due to insufficient research and evidence for the assumptions upon which they are founded, namely gait uniqueness. In the absence of experimentally derived anatomical and physiological foundations to support such assumptions and therefore justify the utility of gait in identification, any data obtained from validation studies conducted on current methods would be fundamentally weak. Therefore, this study quantitatively explored the scientific foundations of forensic gait analysis through biomechanical investigation of human joint motion that is most readily observed from CCTV footage. This approach involved examination of intraindividual variability (differences in the same participant) of joint angle data and its impact on interindividual variation (i.e. differences amongst participants) according to the following aims: (1) to better understand the relationship between form (anatomy) and function (physiology) of normal human gait, (2) to investigate the biomechanical basis for gait uniqueness by examining similarities and differences in joint angles, and, (3) to build upon current theoretical foundations of gait-based human identification.

2. Methodological Approach

2.1 Dataset Selection and Processing

The joint dataset was obtained from a freely available online database managed by the Karlsruhe Institute of Technology (KIT Whole-Body Human Motion Database, Mandery *et al* 2015). The data of interest constituted joint angle data from complete gait cycles (i.e. repetitive periods during normal walking which start when one foot touches the ground and end when the same foot makes contact with the ground once again). The type of locomotory activity selected was *straight walking on flat, even ground at self-selected speed* from 20 adult participants (Table 1), each of whom performed the activity on four occasions. Given the paucity of data regarding gait variability for forensic purposes and the current possibilities of forensic gait analysis methods, preference was given to a more basic, uncomplicated gait setting to allow for baseline values to be developed. The joint type and associated movements chosen were sagittal plane movements (i.e. side-view movements, namely flexion/extension) of the right and left shoulder, elbow, hip, knee, and ankle (dorsiflexion/plantarflexion for the latter). The dataset size falls within the remit of previous forensic gait analysis research in which the total dataset sizes have not exceeded twenty subjects (e.g. Larsen *et al* 2008; Yang *et al* 2014a, Yang *et al* 2014c), whilst others have drafted findings from less than ten participants (e.g. Ludwig *et al* 2016; Yang *et al* 2014b), or only from males (e.g. Yang *et al* 2014a,b,c). All processing steps were conducted in the R program in a systematic and identical manner for all data files of the five joints which resulted in a total of over 1,300 gait cycles. A gait cycle was defined as the period of time between two consecutive heel strikes of the same foot, considered a standard convention in clinical gait analysis and has been reported to be in use in forensic gait analysis (Birch *et al* 2015). Following extraction, each of the cycles were standardised according to percentage gait sub-phase (i.e. distinct periods within a gait cycle) by applying linear interpolation which involves the reconstruction of the overall gait curve based upon the data points already available to a total of 101 points (i.e. 100%, the first point starting at 0% and the last point ending at 100%).

Participant	Sex	Age (yrs)	Weight (kg)	Height (m)
n=20	*n=16 (m)* *n= 4 (f)*	*27.25* *±6.32yrs*	*71.60* *±11.36kgs*	*176.4* *±8.97cm*

TABLE 1. Summary of participant demographic characteristics.

2.2 Data Analysis

One methodological trend observed in the literature is the utilisation of mean gait cycles to evaluate interindividuality irrespective of body side (e.g. Yang *et al* 2014b), despite that body asymmetry is an aspect often highlighted in clinical research (e.g. Kuhtz-Buschbeck *et al* 2008; Schwartz *et al* 2014). To evaluate the influence of this trend on interindividual variability and examine the extent to which flexion/extension movements are symmetric, mean joint angle values for each bilateral joint of each participant and their respective standard deviations were calculated. Although gait-associated motion has been previously shown to be largely symmetric (e.g. Patterson *et al* 2012), the degree of this symmetry requires quantification with respect to its potential impact on interindividual variability, a previously untested approach. In addition, the quantification of the intraindividual variability of gait cycles of the same body side was also of interest, given that one of the concepts upon which individualisation is founded is persistence of a feature regardless of crime scene setting or circumstances. Since forensic gait analysis is a discipline which employs a holistic analysis of body movements (e.g. Birch *et al* 2019), a comparison of joints from both upper and lower body regions was necessary to investigate whether certain body regions and/or specific joints present greater or smaller intraindividual variation given body side. To evaluate the impact of intraindividual variation on identification, interindividual variation was then tested using Fisher-Pitman permutation tests via the Monte-Carlo approach (10,000 permutations) in R, for each of the five joints. Four tests were conducted for each one of the five joints on the: (i) data from left body side, (ii) data from right body side, (iii) combined data from both body sides, and (iv) combined data from both body sides, accounting for 'body side' as an additional variable. The purpose of this was to compare and contrast the effects of intraindividual variability on the potential for differentiating amongst individuals and provide evidence for or against the validity of interchangeable use of left and right body side data to characterise 'average' gait of an individual.

3. Results

3.1 Intraindividual Variability

3.1.1 Upper Body Joints

The range of flexion and extension values observed in the angular waveforms of left and right shoulder joints were generally similar, particularly towards the end of the stance phase (~45-55%) during which maximum shoulder flexion is achieved (FIG.1A). In addition, the majority of the waveforms present similar overall shape, with the majority of participants presenting a larger range of values for the left shoulder than for the right shoulder during maximum flexion. Furthermore, the right shoulder mean values were generally grouped towards a more positive range of values during maximum extension at the start and at the end of the gait cycle (-10 degrees to -2 degrees) as opposed to the left shoulder values (-20 degrees to -6 degrees). For the elbow joint however, the angular waveforms were most similar during the first and final 20% of the gait cycles (FIG.1A). Also, the elbow exhibited less uniformity in the timing of maximum flexion and no specific trend of peak flexion location common to both the left and right elbow joints could be identified. Overall, the right elbow waveforms were generally more consistent throughout all gait events than those of the left elbow.

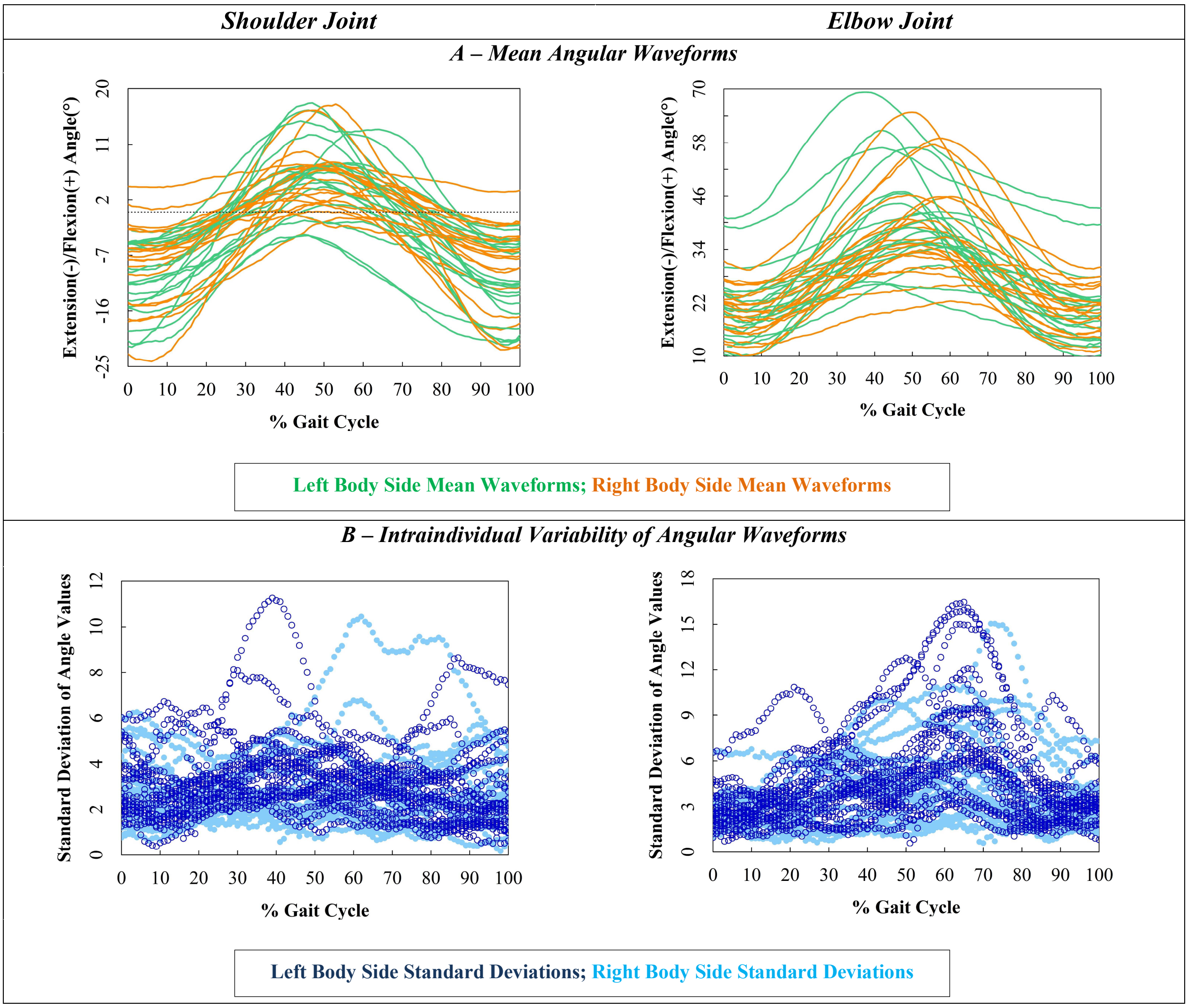

FIG.1 Intraindividual variability of flexion/extension movements in the upper body joints. The mean gait cycle waveforms of the left and right shoulder and elbow joints of all 20 participants (A) are accompanied by their corresponding standard deviations (B). In Fig.1A, each one of the 20 participants is represented by one green line and one orange line corresponding to their mean gait cycle waveform for the left and right body sides, respectively; the black horizontal dashed line represents a y axis value of zero. In Fig.1B, the dark blue circles and light blue circle represent the standard deviations of the left and right body sides respectively, at every 1% of the gait cycle.

To investigate the degree to which the mean waveforms of the 20 participants reflect the characteristics of singular gait cycles and evaluate whether the differences in the means is negligible for the data of the bilateral joint to be considered interchangeable, analysis of variability using descriptive statistics was conducted. For the shoulder joint, the intraindividual variability of the angle values across all gait cycles for each one of the 20 participants was generally small in both body sides (FIG.1B). The standard deviations throughout all gait events were mostly clustered in the range of 1 to 5 units. The largest variability of approximately 11 standard deviations was found in the left shoulder during the latter half of the stance phase (~40%), and the second largest variability of approximately 10 standard deviations during early swing (~60%) in the right shoulder. In contrast to the shoulder, the elbow joint presented different variability ranges and trends. During the first 20% of the gait cycle and during the final 10% of the gait cycle, the standard deviations of the bilateral elbow were largely similar, not exceeding 1-5 standard deviations. However, the range the largest variability was larger than in the shoulder, particularly in the latter half of the cycle. Variability close to zero standard deviations was only found in two participants.

3.1.2 Lower Body Joints

The bilateral hip joint exhibits a more consistent shape, synchronicity, and value ranges in most participants across most gait events (Fig.2A), in contrast to the shoulder and elbow joints. Nevertheless, one common characteristic was the inconsistency in the timing of maximum extension (i.e. maximum flexion equivalent of the upper body joints) which, in general, occurred earlier in the cycle for the left hip waveforms (~55-57%) and later for the right hip waveforms (~60-68%). Maximum extension values were more consistent than observed in the upper body, irrespective of body side. The bilateral knee joint also exhibits some common characteristics to both the upper limb joints as well as to the hip, such as differences in values and timing of peak angles. In contrast, maximum extension values were more consistent across all 40 waveforms at the start and end of the cycle. Also, the values of the right knee waveforms were generally lower than those of the left knee values throughout all gait events. In the ankle joint, the synchronicity of maximum dorsiflexion during stance and maximum plantarflexion during swing differs between the two body sides. The gait cycle region with the highest degree of bilateral similarity (shape and synchronicity-wise) was the first 35% stance, whilst elsewhere, the right ankle joint gait events generally occurred later than those of the left ankle joint. In addition, certain anomalies were present, such as flattened peak dorsiflexion. Overall, both body sides present with similar interval of values across the stance phase. Nevertheless, as previously observed in the shoulder, elbow, hip, and knee joints, the overall shapes are similar, despite lack of synchronicity and in some regions, differences in values.

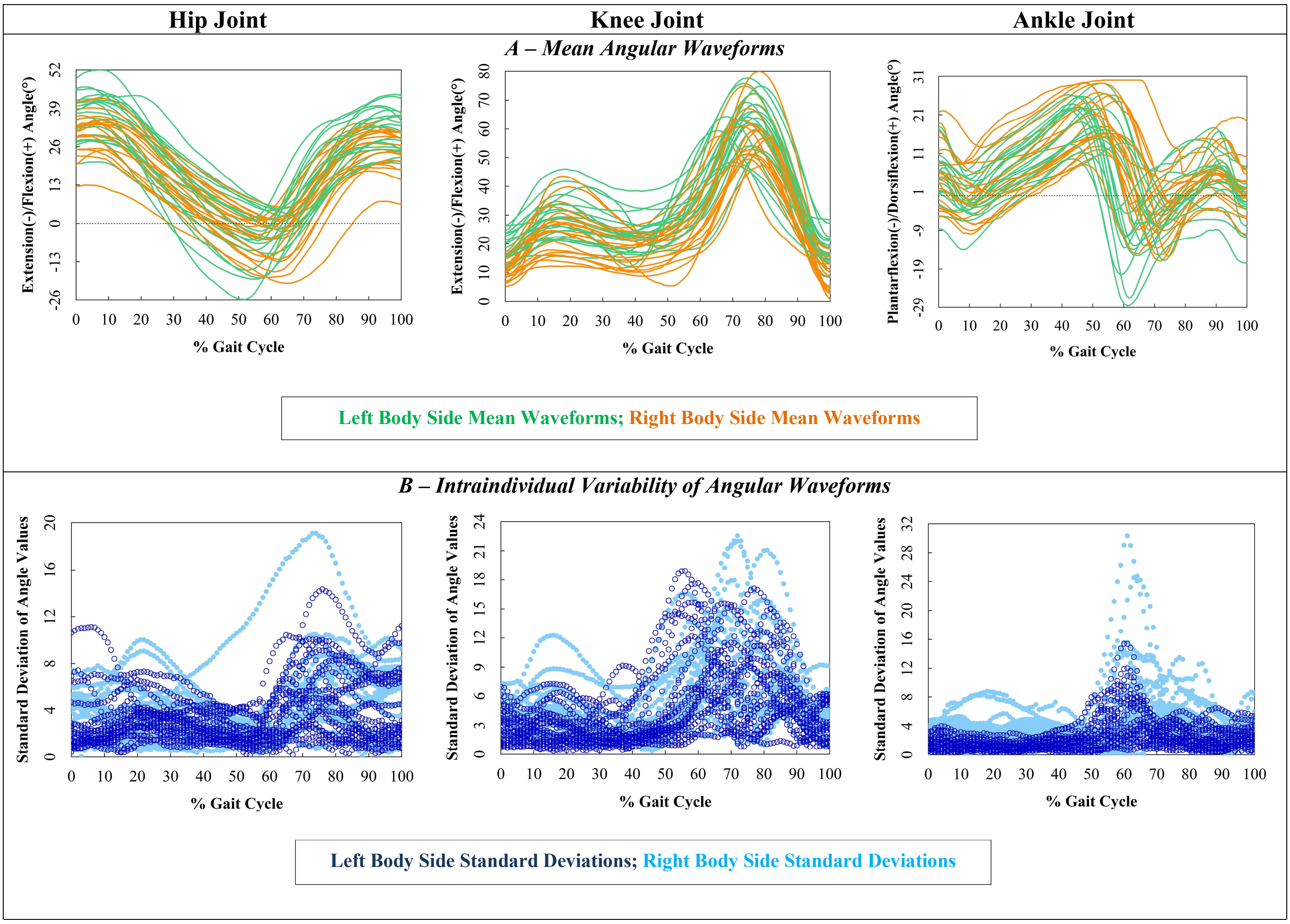

FIG.2 Intraindividual variability of flexion/extension movements in the lower body joints. The mean gait cycle waveforms of the left and right hip, knee, and ankle joints of all 20 participants (A) are accompanied by their corresponding standard deviations (B). In Fig.2A, each one of the 20 participants is represented by one green line and one orange line corresponding to their mean gait cycle waveform for the left and right body sides, respectively; the black horizontal dashed line represents a y axis value of zero. In Fig.2B, the dark blue circles and light blue circle represent the standard deviations of the left and right body sides respectively, at every 1% of the gait cycle.

When examining intraindividual variability, the differences amongst the lower body joints (and in comparison to the shoulder and elbow) become more notable (FIG.2B). The overall variability trends of the hip joint differ to those of the upper body whereby the swing phase generally presented a higher intraindividual variability range than the stance phase (0-54%), where the variability generally did not exceed approximately 8 units. In the knee joint, the lowest intraindividual variability range across most participants was found throughout mid-stance (1-6 units) and during the final 10% of the gait cycle. This contrasts the latter half of the cycle (~46-90%) where intraindividual variability range was high bilaterally for all participants, with no clearly discernible trend. Throughout late mid-swing, only a single participant presented with low variability in the left knee. As opposed to the intraindividual variability found in the previous joints, the intraindividual variability of the ankle joint across the gait cycle was more narrowly clustered around lower values. Whilst the variability was generally lower and more constant across most gait events for the left ankle, the variability of the right ankle fluctuated to a higher degree in some participants.

3.2 Interindividual Variability

3.2.1 Upper Body Joints

The Fisher-Pitman permutation tests on shoulder and elbow joint data yielded *statistically significant* results ($p<0.01$) throughout the entire gait cycle in all three conditions, as illustrated in FIG.3 below (i.e. left body side (A), right body side (B), left and right body sides combined (C)).

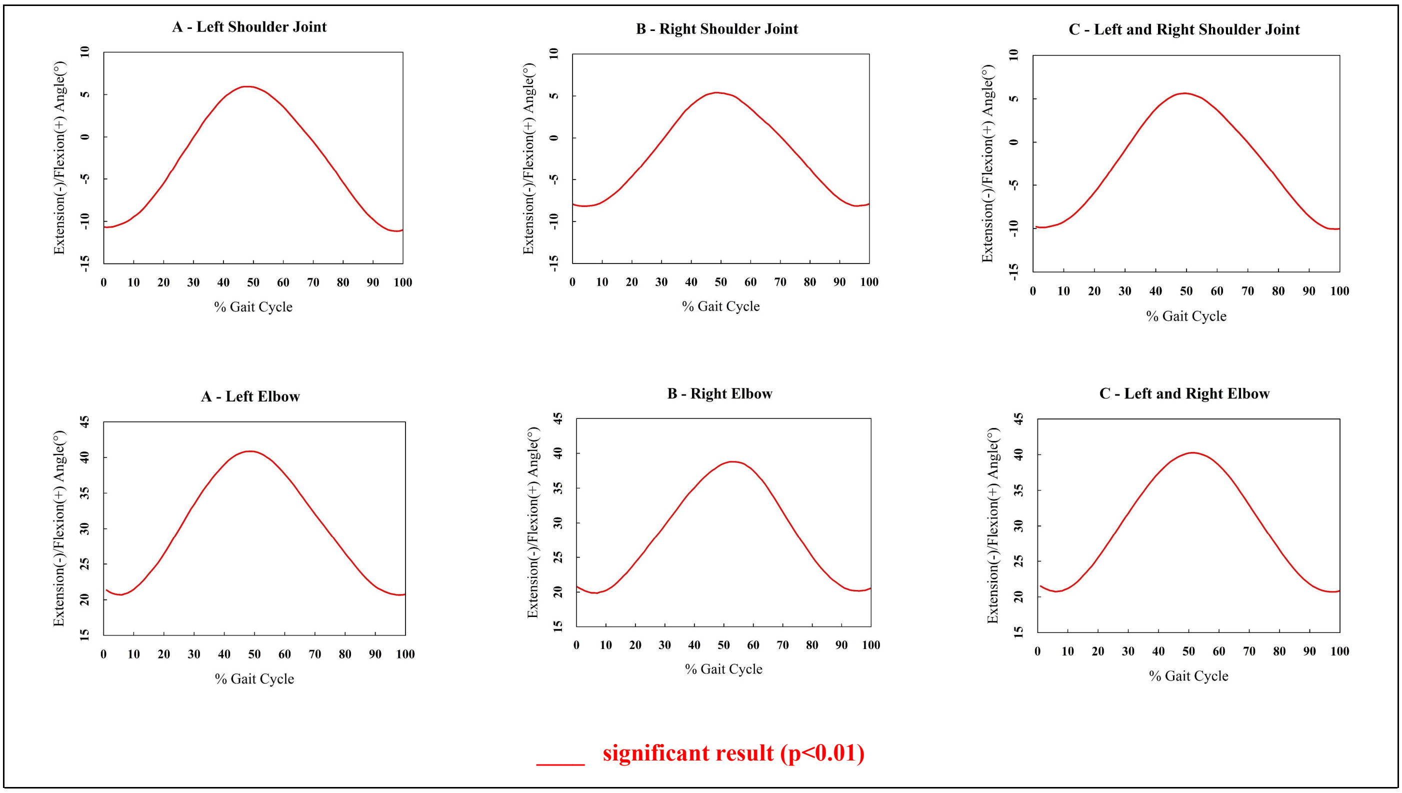

FIG.3 Interindividual differences in the shoulder and elbow indiscriminate of body side. Statistically significant results indicate differences amongst participants.

In contrast, the results for the tests that test whether body side influences discrimination amongst individuals are *statistically significant* only throughout specific gait segments (FIG.4). For the shoulder joint, statistically significant results were obtained throughout early stance and late swing (~0-16%, 77-100%), whilst for the elbow, throughout approximately half of the gait sub-phases (~4-51%). Hence, only a small proportion of the gait cycle was *statistically significant* in both joints, namely part of the heel strike and loading response (4-16%).

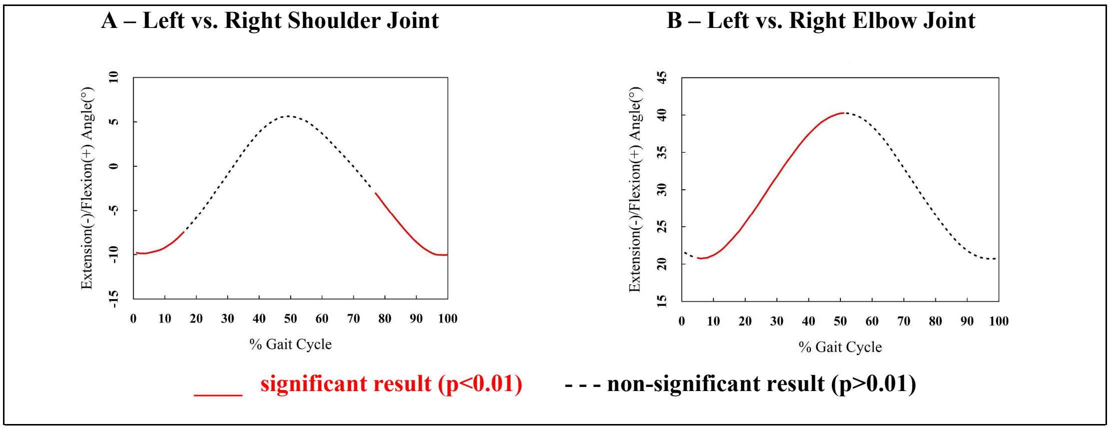

FIG.4 Interindividual differences in the shoulder and elbow given body side. A statistically significant result indicates that body side influences discrimination amongst participants whilst a statistically insignificant result indicates no influence of body side on the discrimination amongst participants.

3.2.2 Lower Body Joints

As observed in the upper limb, the hip, knee, and ankle likewise yielded statistically significant results (p<0.01) in all gait cycle regions when not discriminating between body sides (FIG.5).

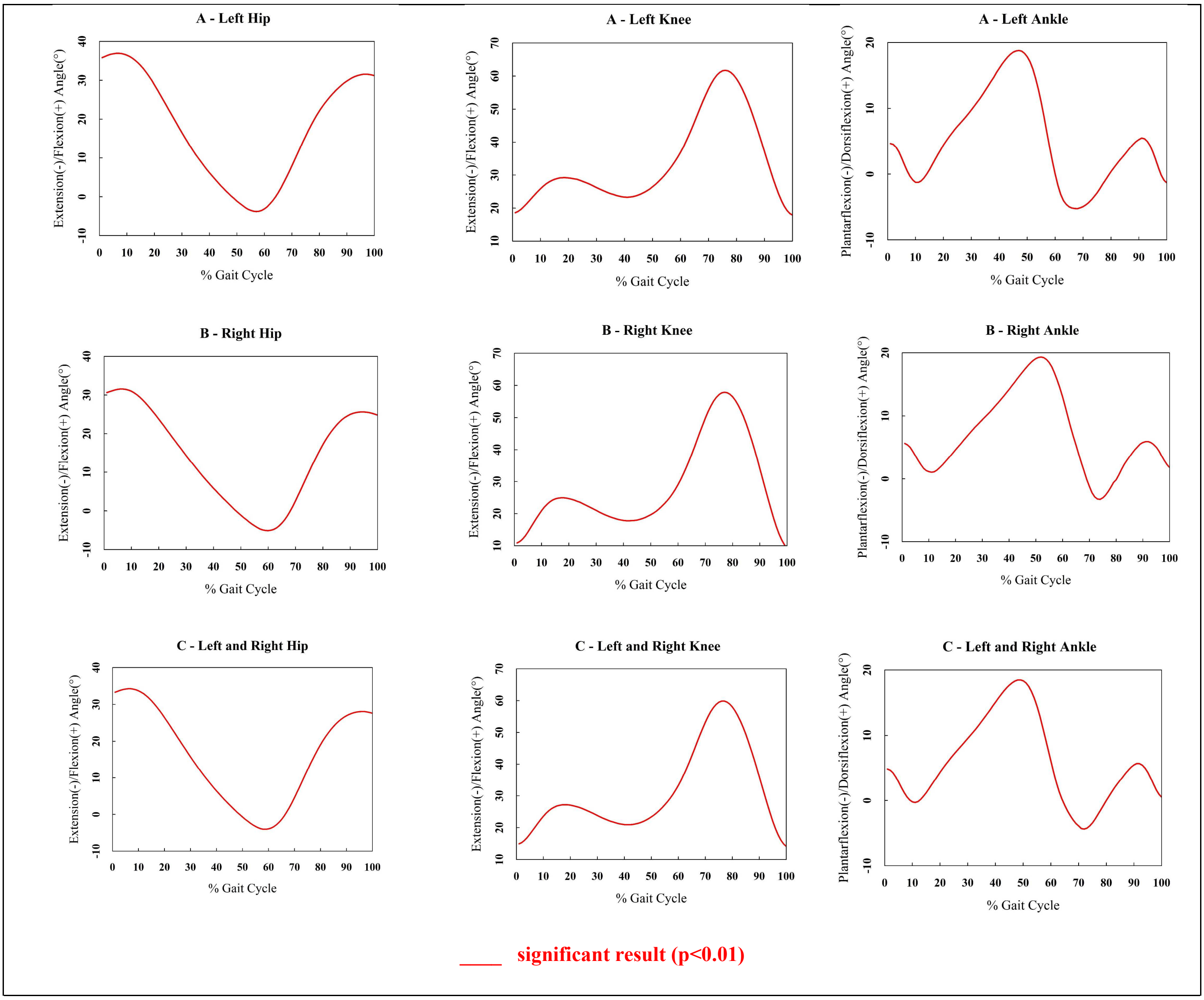

FIG.5 Interindividual differences in the hip, knee, and ankle indiscriminate of body side. Statistically significant results indicate differences amongst participants.

For the hip joint (FIG.6), the tests that investigate the influence of body side on interindividual variability amongst participants are *statistically significant* for the majority of gait sub-phases (0-31%, 59-100%). The *statistically significant* region of the gait cycle common to both the upper body joints and the hip is the latter half of *heel strike* and *loading response* sub-phases (4-16%). In contrast to the upper body joints and the hip, the knee joint presents a very large proportion of the gait cycle with *statistically significant* results (0-75%, 90-100%). Overall, similarities in statistically significant gait segments are greater between the hip and knee joints (0-31%, 59-75%, 90-100%), than the similarities amongst the hip, knee, and upper body joints (4-16%). However, in comparison to all previous joints, the ankle presents the smallest proportion of *statistically significant* gait cycle regions (~6-16%, 38-45%, 51-70%, 96-100%). Therefore, the ankle presents small similarities in *statistically significant* gait segments to both the upper body joints (4-16%) and to the hip and knee joints (6-16%, 59-70%, 96-100%).

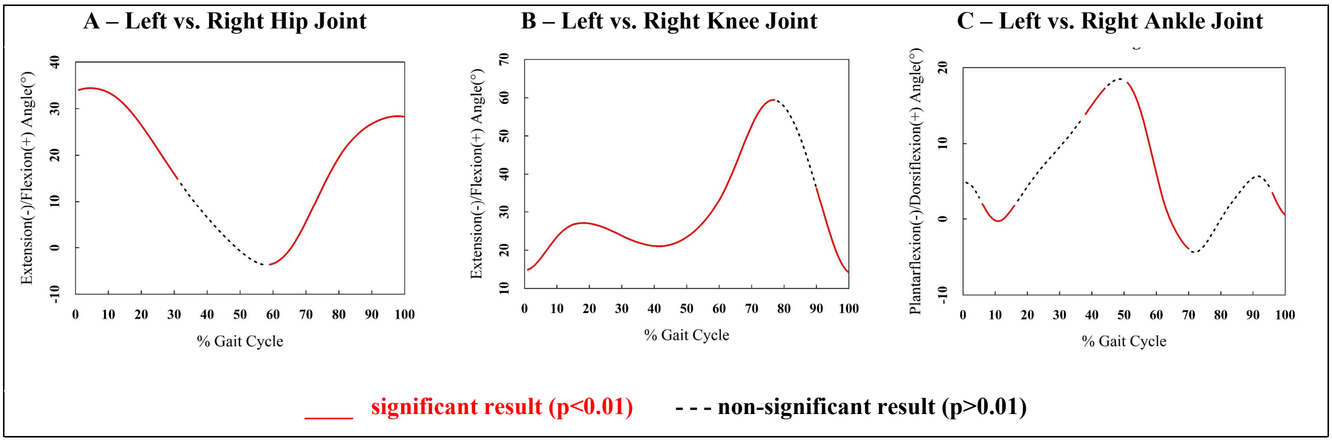

FIG.6 Interindividual differences in the hip, knee, and ankle given body side. A statistically significant result indicates that body side influences discrimination amongst participants whilst a statistically insignificant result indicates no influence of body side on the discrimination amongst participants

4. Discussion and Conclusions

The findings of this study exemplify that intraindividual variability is present in differing degrees amongst the 20 participants in the shoulder, elbow, hip, knee, and ankle. Bilateral movement asymmetry was noted and predominated the gait events of all five joints, albeit to differing degrees. Upper body intraindividual variability was similarly large bilaterally throughout all gait events to different extents in different participants and depending on body side and gait sub-phase. In contrast, lower body intraindividual variability was found to be absent/low in all three joints, although asymmetry was more pronounced than in the upper body. As a result, the importance of body side in interindividual variability fluctuated depending on gait cycle sub-phase, and differences were found not only between upper and lower body joints but also amongst joints of the same body regions. Interindividual variability was found to be least affected by body side in the shoulder and ankle joints, and most affected by body side in the knee joint. This study therefore highlights that, given the innumerable conditions in which gait can vary, particularly in a forensic setting, the concept of an 'average' gait of an individual is fundamentally weak from a kinematic perspective. Similarly, in cases where the sets of footage to be compared do not present the individual of interest in an identical pose, error can be further introduced if data are not obtained from the same body side.

To improve upon the findings of future studies in investigating the scientific basis of gait in criminal investigations, several aspects have to be considered. For example, a larger number of trials should be obtained from participants containing a 'sufficient' number of gait cycles for extraction (the threshold for the latter is an aspect which has yet to be investigated). The number of extracted gait cycles should also be equal across all trials, to allow analysis of differences between trials and within trials. This would provide further evidence regarding the consistency of the movements of a given individual at similar and different points in time. Also, gait cycles at the start and end of trials should be examined with caution since participants can be influenced by the request to start and stop the trial in laboratory-based conditions. Coordination amongst upper and lower body regions should be investigated to evaluate whether there is potential to increase accuracy of identification given specific combinations of motions, considering that none of the joint movements occur in isolation, particularly regarding body sides. Since experimental conditions can rarely replicate real-world conditions accurately, their simulation should be carefully designed and evaluated to be of use in forensic investigations. Therefore, human identification from gait using current methods should be conducted with increased caution, given the multitude of physiological factors which may influence results (in addition to behavioural factors, the control of which is challenging). Despite that the definition of forensic gait analysis states that it is a field of study which *assists* in the investigation of a crime, further emphasis should be implemented in the code of practice and implicitly, in the education and regulatory process of early career and professional practitioners alike, to prevent the usage of forensic gait analysis as an identification technique, given currently limited knowledge.

Based upon the analyses undertaken, the following conclusions can be drawn regarding the *current* utility of gait as a biological characteristic in forensic investigations:

i. The degree of intraindividual variability is body-region and body side-dependent in sagittal movements of the shoulder, elbow, hip, knee, and ankle, in a normal walking condition, at self-selected speed and on flat ground;

ii. Intraindividual variability does not impact interindividual variability when examining unilateral sagittal plane movements under the conditions presented in point (i), thereby providing evidence for the claim of uniqueness and for the potential of gait for individualisation;

iii. Movement asymmetry affects interindividual variability in a given gait sub-phase to different extents depending on body region, thereby rendering the claim of uniqueness and the potential for individualisation body-side dependent.

REFERENCES

Birch, I., Birch, M., Rutler, L., Brown, S., Burgos, L.R. et al. 2019. The repeatability and reproducibility of the Sheffield Features of Gait Tool. *Science and Justice*, **59(5)**:544-551.

Birch, I., Vernon, W., Walker, J., and Young, M. 2015. Terminology and forensic gait analysis. *Science and Justice,* **55(4)**:279–84.

Bolton-King, R.S. 2016. Preventing miscarriages of justice: a review of forensic firearm identification. *Science and Justice,* **56(2)**:129-142.

Bowers, C. M. 2019. Review of a forensic pseudoscience: Identification of criminals from bitemark patterns. *Journal of Forensic and Legal Medicine*, **61**:34–39.

Bouchrika, I., Goffredo, M., Carter, J., and Nixon, M. 2011. On using gait in forensic biometrics. *Journal of Forensic Sciences,* **56(4)**:882-889.

Boulgouris, N.V. and Chi, Z.X. 2007. Human gait recognition based on matching of body components. *Pattern Recognition*, **40(6)**:1763-1770.

Christensen, A.M. and Crowder, C.M. 2009. Evidentiary standards for forensic anthropology. *Journal of Forensic Sciences,* **54(6)**:1211-1216.

Dror, I.E. and Mnookin, J.L. 2010. The use of technology in human expert domains: challenges and risks arising from the use of automated fingerprint identification systems in forensic science. *Law, Probability and Risk,* **9(1)**:47– 67.

Forensic Science Regulator. 2019. *Code of Practice for Forensic Gait Analysis.* December 2019; **1**:1-48. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/851650/Forensic_Gait_Analysis.pdf (accessed October 16, 2020).

Gill, P. 2019. DNA evidence and miscarriages of justice. *Forensic Science International,* **294**:e1-e3.

KIT Whole-Body Human Motion Database. 2019. https://motion-database.humanoids.kit.edu/ (accessed October 16, 2020).

Kuhtz-Buschbeck, J.P., Brockmann, K., Gilster, R., Koch, A. and Stolze, H. 2008. Asymmetry of arm-swing not related to handedness. *Gait and Posture,* **27(3)**:447-454.

Langley, N.R., Jantz, L.M., McNulty, S., Maijanen, H., Ousley, S.D. et al. 2018. Error quantification of osteometric data in forensic anthropology. *Forensic Science International,* **287**:183-189.

Larsen, P.K., Hansen, L., Simonsen, E.B., Lynnerup, N. 2008a. Variability of Bodily Measures of Normally Dressed People using PhotoModeler® Pro 5. *Journal of Forensic Sciences,* **53(6)**:1393–1399.

Ludwig, O., Dillinger, S. and Marschall, F. 2016. Intra-individual gait pattern variability in specific situations: implications for forensic gait analysis. *Forensic Science International,* **264**:15–23.

Macoveciuc, I., Marquez-Grant, N., Horsfall, I. and Zioupos, P. 2017. Sharp and blunt force trauma concealment by thermal alteration in homicides: an in-vitro experiment for methodology and protocol development in forensic anthropological analysis of burnt bones. *Forensic Science International,* **275**:260-271.

Macoveciuc, I., Rando, C.J. and Borrion, H. 2019. Forensic gait analysis and recognition: standards of evidence admissibility. *Journal of Forensic Sciences*, **64(5)**:1294-1303.

Mandery, C., Terlemez, O., Do, M., Vahrenkamp, N. and Asfour, T. 2015. The KIT Whole-Body Human Motion Database. *International Conference on Advanced Robotics* (ICAR), 27-31 July 2015. Istanbul, Turkey. pp. 329 – 336. https://h2t.anthropomatik.kit.edu/pdf/Mandery2015a.pdf (accessed October 16, 2020).

Morgan, R.M. 2017. Conceptualizing forensic science and forensic reconstruction. Part II: The critical interaction between research, policy/law and practice. *Science and Justice,* **57(6)**:460-467.

Nirenberg, M., Vernon, W. and Birch, I. 2018. A review of the historical use and criticisms of gait analysis evidence. *Science and Justice*, **58(4)**:292-298.

Patterson, K.K., Kadkarni, N.K., Black, S.E. and McIlroy, W.E. 2012. Gait symmetry and velocity differ in their relationship to age. *Gait and Posture,* **35(4)**:590-594.

Pretty, I.A. and Sweet, D. 2010. A paradigm shift in the analysis of bitemarks. *Forensic Science International,* **201(1-3)**:38-44.

Redmayne, M., Roberts, P., Aitken, C. and Jackson, G. 2011. Forensic science evidence in question. *Criminal Law Review,* **5**:347-356. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/118921/forensic-science-article.pdf (accessed October 16, 2020).

Risinger, D.M., Saks, M.T., Thompson, W.C. and Rosenthal R. 2002. The Daubert/Kuhno implications of observer effects in forensic science: hidden problems of expectations and suggestion. *California Law Review*, **90(1)**:1-56. https://dash.harvard.edu/bitstream/handle/1/3199069/Rosenthal_Daubert%3AKumho.pdf?sequence=1&isAllowed=y (accessed October 16, 2020).

Rosenstein, R.J. 2018. Deputy Attorney General Rod J. Rosenstein Remarks. National Symposium on Forensic Science. August 2018. https://www.justice.gov/opa/speech/deputy-attorney-general-rod-j-rosenstein-delivers-remarks-national-symposium-forensic (accessed October 16, 2020).

Schwartz, C., Croisier, J-L., Rigaux, E., Denoel, V., Bruls, O. et al. 2014. Dominance effect on scapula 3-dimensional posture and kinematics in healthy male and female populations. *Journal of Shoulder and Elbow Surgery,* **23(6)**:873-881.

Smit, N.M., Morgan, R.M. and Lagnado, D.A. 2018. A systematic analysis of misleading evidence in unsafe rulings in England and Wales. *Science and Justice,* **58(2)**:128-137.

Stevenage, S.V. and Bennett, A. 2017. A biased opinion: demonstration of cognitive bias on a fingerprint matching task through knowledge of DNA test results. *Forensic Science International,* **276**:93−106.

Yang, S.X.M., Larsen, P.K., Alkjaer, T., Juul-Kristensen, B., Simonsen, E.B. et al. 2014a. Height estimations based on eye measurements throughout a gait cycle. *Forensic Science International,* **236**:170-174.

Yang, S.X.M., Larsen, P.K., Alkjaer, T., Simonsen, E.B., and Lynnerup, N. 2014b. Variability and similarity of gait as evaluated by joint angles: implications for forensic gait analysis. *Journal of Forensic Sciences,* **59(2)**:494-504.

Yang, S.X.M., Larsen, P.K., Alkjaer, T., Lynnerup, N. and Simonsen, E.B. 2014c. Influence of velocity on variability in gait kinematics: implications for recognition in forensic science. *Journal of Forensic Sciences,* **59(5)**:1242-1247.