The utility of gait as a biological characteristic in forensic investigations – An empirical examination of movement pattern variation using biomechanical and anthropological principles.

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Declaration

I, Ioana Macoveciuc, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signature

Date 5 August 2020

With greatest love, for my parents …

This thesis is as much your accomplishment as it is mine,

Thank you

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Last, but certainly never the least, thank you to my one and only, whose love distance did not diminish.

Abstract

Forensic gait analysis is generally defined as the analysis of gait features from video footage to assist in criminal investigations. Although an attractive means to detect suspects since data can be collected from a distance without their knowledge, forensic gait analysis presently lacks method 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 addressed. 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 analysis of sagittal plane human motion in the bilateral shoulder, elbow, hip, knee, and ankle joints was conducted across complete gait cycles of twenty participants, to investigate the degree to which intraindividual variation impacts 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 movement asymmetry given body region and gait sub-phase, thereby challenging previous methods employing interchangeable use of bilateral motion data, 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 events. Given the findings of this thesis and paucity regarding empirical basis to support expertise, exerting caution when evaluating gait-based evidence admissibility is highly recommended, since the utility of gait in identification is currently limited.

Impact Statement

The findings of this thesis represent several novel additions to the field of forensic gait analysis, considering the current paucity in the afferent literature regarding scientific foundations, methodological framework, and empirical basis for utilising gait in identification (or for assisting in identification). Firstly, the predominant assumption of gait symmetry is refuted through the investigation of intraindividual variability across gait cycles of the same participants in five bilateral joints (shoulder, elbow, hip, knee, and ankle), results which illustrate that the degree of intraindividual variability differs between body sides. This find therefore indicates that gait data obtained from one body side cannot be utilised interchangeably with the other, thus highlighting a deficiency in previously published literature in which the gait of individuals was not necessarily discriminated according to body side. Likewise, the mean values of a set of gait cycles are not necessarily representative of an individual's gait throughout all gait events, in all joints and in both body sides. Previous indications as to a higher potential for upper body joints to be more discriminatory than lower body joints are also questionable, given that the results of the analysis in this thesis do not necessarily suggest this to be the case. Subsequent to submission, the work presented herein will be disseminated in the form of peer-reviewed journal articles in high-impact journals in forensic science and in specialist conferences.

The impact of the findings of this thesis is not only of importance to forensic gait analysis since it also emphasises the need to investigate the scientific foundations of forensic sciences in general, particularly those at incipient stages and those which make use of established methods from different fields modified for forensic use, as does forensic gait analysis with methodologies adapted from the medical field. The lack of an empirical bases for assumed scientific foundations in forensic gait analysis is highly problematic for legal proceedings, an aspect previously highlighted by a primer for courts published by the Royal Society, and in a critical review published by the author of this thesis and co-authored by the thesis supervisors. Although the dataset utilised in this thesis is not without limitations, the results underline that previously held assumptions may not hold true, and 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. Therefore, this thesis empirically demonstrates that considerable caution is to be exerted when utilising gait for identification, making recommendations for amendments in the code practice and for future research.

Contents

List of Tables

List of Figures

List of Plots

Section I – Research Rationale and the Foundations of Forensic Gait Analysis

Chapter 1 – Research Context and Scope

1.1 Introduction

Throughout recent decades, the legal standing of forensic science in criminal investigations has increased in importance in an effort to tackle the diversification in unlawful acts. Whereas judicial outlooks have altered with respect to the role of forensic science in the criminal justice system (Bitzer 2019; Edmond *et al* 2017; Evison 2018; Gennari 2018; Howes 2015; Roberts 2012; San Pietro *et al* 2019), the practicalities underpinning and interlinking legal requirements, scientific principles, and the state-of-the-art, remain unresolved. For instance, the 4-6 million Closed-Circuit Television (CCTV) cameras in the United Kingdom (British Security Industry Association 2013) and research dedicated to this aspect, have had little impact on societal perceptions of the role of CCTV (Farrington *et al* 2007; Home Office 2005; Keval and Sasse 2008; Scottish Government 2009). Despite the encouraging data from crime prevention research (e.g. Welsh *et al* 2009) and, more recently, from the utility of CCTV as an investigative tool (e.g. Ashby 2017), there remains a lack of clarity regarding the role and scope of public surveillance (Taylor 2010). Regardless of the intent of recent government publications to divorce the Orwellian perspective attached to public video surveillance (e.g. Porter 2016, 2018; Surveillance Camera Commissioner 2017) these offer little in the way of practical implementations (House of Commons Science and Technology Committee 2018a).

Such challenges have only recently been formally articulated in the UK, with respect to technological/digital services in the criminal justice system (Forensic Science Regulator 2014, 2016a,b), despite these permeating the arena of 'classic' forensic science for at least a decade (e.g. House of Commons Science and Technology Committee 2005). Combined with the plenitude of theoretical legal requirements and regulations, local, national and international standards of practice, guidance documents, and accreditation schemes from a multitude of agencies, as well as general and field-specific scientific rigour, it is unsurprising that the forensic sciences, as a whole, are in a paradoxical state of controlled disorder. This is further amplified by unrealistic and insufficiently informed judicial and societal expectations of forensic science outputs (e.g. Costa and Santos 2019; Dror *et al* 2018; Edmond 2013; House of Lords Science and Technology Select Committee 2019; Kirby 2013; Maeder and Corbett 2015), which have spurred strong international debates not only at legal and governmental levels (e.g. Rosenstein 2018) but also within scientific communities (e.g. Cole 2013a; Evett *et al* 2017; Hak 2019; McCartney 2019; Roberts 2015). Many of the topics currently tackled in forensic debates revolve around the theme of evidence admissibility criteria for ensuring fair trials and preventing injustices (e.g. Bolton-King 2016; Bowers 2019; Gill 2019; Smit *et al* 2018). This theme is a multifaceted one, involving divergent perspectives of the judicial and scientific communities predominantly due to a paucity in opportunities for collaborative engagement and financial input in research (Flanagan 2018; Home Office 2011; House of Lords Science and Technology Select Committee 2019; Morgan and Levin 2019). One basis for such debates, spanning years, is the need for conducting empirical examination of established and novel forensic methods alike, to ensure that reproducibility, reliability, and quality, are to the required standards when utilised in court (e.g. Morgan 2017b; Redmayne *et al* 2011; Risinger *et al* 2002). A multitude of documents have been published over the years in this regard, by practitioners in consultancy with governmental agencies, such as the President's Council of Advisors on Science and Technology (PCAST) (2016) and the National Research Council (2009) in the USA, and the House of Commons Science and Technology Committee (2013, 2016) as well as the Forensic Science Regulator in the United Kingdom (e.g.2019a). 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 the majority of 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 such example, with which this thesis is concerned, is forensic gait analysis.

1.2 Defining the Research Problem: Aims and Objectives

Forensic gait analysis is broadly defined as "*the analysis, comparison, and evaluation of features of gait to assist the investigation of crime*" as applied by forensic gait experts or scientists with experience in areas such as biomechanics and clinical gait analysis. The methodological approach generally involves analysis of two or more sets of video footage where obvious characteristics such as facial features and/or other personal identifiers are obscured or dissimulated, to conclude whether same individual is present in the videos (Forensic Science Regulator 2019b). Since gait characteristics can be collected without the knowledge or consent of the individual of interest, the potential applications of gait analysis are considered attractive since these can extend to all stages of an investigation, including surveillance and intelligence-gathering. Constructed (from a physiological perspective) from a series of (largely) repetitive, cyclic movements that are considered generally symmetric (Patterson *et al* 2012), gait can be observed from a distance (Boulgouris and Chi 2007) and cannot be entirely concealed or dissimulated (Bouchrika *et al* 2011). The role of forensic gait analysis is also of relevance to present trends because its underlying basis is digital in nature. Considering the ongoing advancement in digital and automated technology and current use of such approaches especially in airport security (e.g. facial recognition), it is reasonable to assume that the usage of gait analysis will increase in coming years.

Nevertheless, forensic gait analysis has yet to meet method validation and quality standards that are inherent to forensic practice, not only due to insufficient research but also because certain assumptions regarding its scientific foundations have not been examined. One such assumption around which forensic gait analysis methodologies are based, is that gait is unique to each individual. This may indeed be considered an educated premise based on current anthropological, physiological, and anatomical knowledge. For example, each individual will have a particular body segment ratio, body-mass index (BMI), height and weight, all of which will also depend on sex and age and/or presence of pathology. These features, combined with particular physical activities (or lack thereof), habitual shoe wear, use of shoulder bags and many other particularities, will most likely result in unique gait signatures, particularly when investigated at minute levels using state-of-the-art technologies. However, incorporating empirically unfounded assumptions into the design of forensic gait analysis methods (or any other forensic science), is an unsafe precedent for quality of evidence (Lord Chief Justice of England and Wales 2015; Parliament Office of Science and Technology 2005), as most recently observed in bitemark analysis (Bowers 2019; PCAST 2016; Saks *et al* 2016); its shortcomings are analogous to those in forensic gait analysis, which range from inadequately designed empirical studies lacking reported gait feature frequency (and absence of population databases with known demographic characteristics), insufficiently scrutinised methodological approaches, to overreliance on professional experience (The Royal Society 2017a). Considering that forensic science expectations have altered in recent years in light of miscarriages of justice (e.g. Robertson 2013), the claim of uniqueness also warrants empirical investigation in forensic gait analysis since current methods rely on vague, literature-based precedents. 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 thesis quantitatively explores the scientific foundations of forensic gait analysis through biomechanical investigation of human joint motion (i.e. kinematic analysis) that is most readily observed from CCTV footage, utilising joint angular data obtained from the Karlsruhe Institute of Technology, Germany, opensource database (KIT Whole-Body Human Motion Database 2019).

With a variety of human motions available from the KIT database, careful consideration was given to compiling a relevant dataset for analysing movements of the shoulder, elbow, hip, knee, and ankle joints (i.e. joint angles) in the sagittal plane (i.e. motion observable from the side) throughout full gait cycles, according to the following aims:

- to better understand the relationship between form (anatomy) and function (physiology) of normal human gait,
- to investigate the biomechanical basis for gait uniqueness by examining similarities and differences in joint angles, and,
- to build upon current theoretical foundations of gait-based human identification.

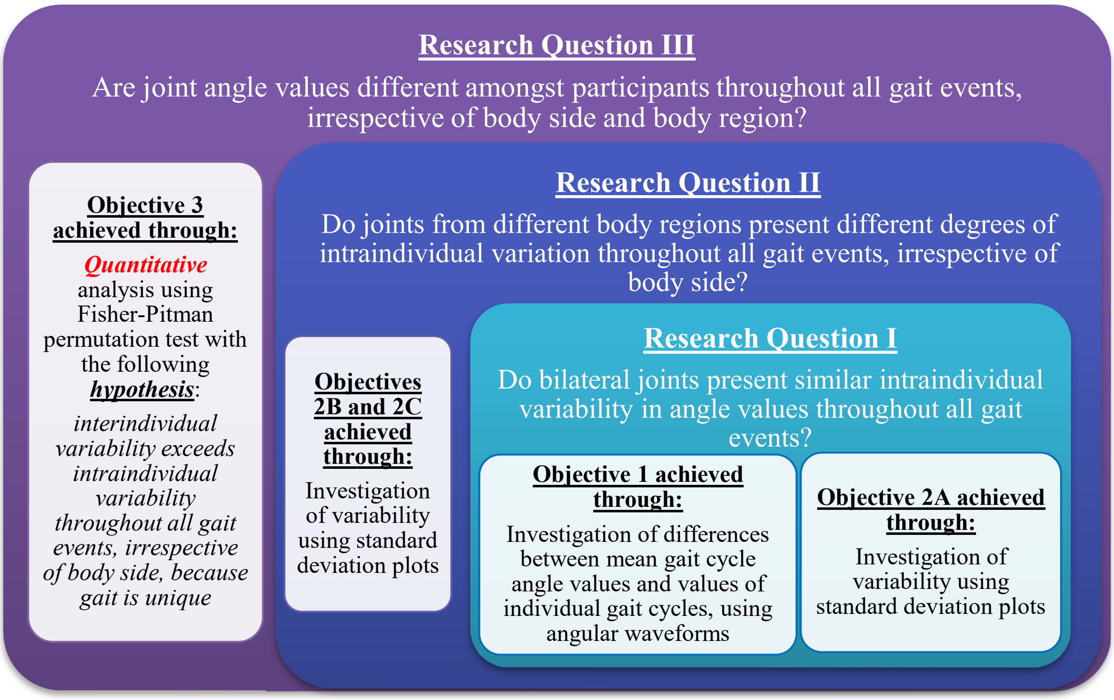
To achieve these aims, three *research questions* were formulated, each question designed to form the basis for the subsequent question, as follows:

I. Do bilateral joints (i.e. left and right body sides of the same joint) present similar intraindividual variability (i.e. variation within the same participant) in angle values throughout all gait events (i.e. sub-phases within a gait cycle)?
II. Do joints from different body regions present different degrees of intraindividual variation throughout all gait events, irrespective of body side?
III. Are joint angle values different amongst participants (i.e. interindividual variability) throughout all gait events, irrespective of body side and body region?

To fulfil the aims of the thesis through qualitative and quantitative analysis (where appropriate), the following three objectives were developed, as summarised in Figure 1.1*:*

(1) characterisation of upper and lower limb joint movements by assessing joint angle values throughout complete gait cycles;
(2) estimation of the discriminatory power of joint angles by comparing variation in the same participant (intraindividual variation):
    a. between the left and right sides of the body;
    b. amongst joints in the same body regions;
    c. amongst joints in different body regions;
(3) evaluation of the scientific utility of gait in human identification through the comparison of variability in upper and lower body joints of different participants (interindividual variability).

Figure 1.1 – Summary of Thesis Investigation Approach



Research Question III

Are joint angle values different amongst participants throughout all gait events, irrespective of body side and body region?

Objective 3 achieved through:

Quantitative analysis using Fisher-Pitman permutation test with the following ***hypothesis***:

interindividual variability exceeds intraindividual variability throughout all gait events, irrespective of body side, because gait is unique

Research Question II

Do joints from different body regions present different degrees of intraindividual variation throughout all gait events, irrespective of body side?

Objectives 2B and 2C achieved through:

Investigation of variability using standard deviation plots

Research Question I

Do bilateral joints present similar intraindividual variability in angle values throughout all gait events?

Objective 1 achieved through:

Investigation of differences between mean gait cycle angle values and values of individual gait cycles, using angular waveforms

Objective 2A achieved through:

Investigation of variability using standard deviation plots

1.3 Thesis Structure

1.3.1 Section I

Section I of the thesis provides the justification for the selected investigation approach by providing an in-depth review of the literature in Chapter 2, part of which has been previously published (Macoveciuc *et al* 2019). Since the theme of this thesis is the testing of scientific foundations in forensic gait analysis, Chapter 2, Section 2.2 begins with a characterisation of the general stages of forensic science process which delineates and emphasises the need for increased recognition of the scientific framework as one of the fundamental principles upon which all forensic science disciplines should be based, to support the value of scientific evidence in legal proceedings. Section 2.3 then presents these principles in the context of forensic gait analysis, where the knowledge basis, methodological approach, and forensic applicability are critically evaluated. The subjective nature of forensic gait analysis in practice is then addressed in Section 2.4 through an evaluation of current challenges which permeate the discipline, drawing attention to the foundational aspects which require further investigation and thus exemplifying the relevance of the investigation approach of this thesis to the body of literature. Chapter 3 introduces relevant anatomical and physiological principles of human gait which form the current knowledge basis of forensic gait analysis and which are used in the methodological approach of this thesis. Sections 3.2 and 3.3 describe and illustrate the anatomy and physiology of human gait, whilst Section 3.4 underlines the limitations associated with utilising these principles in the forensic science arena.

1.3.2 Section II

The second section of the thesis provides a detailed presentation of the materials utilised and methods employed. Chapter 4 presents the database from the Karlsruhe Institute of Technology (KIT) in Germany, which has been used for compiling a dataset relevant for the theme of this thesis. Section 4.1 provides a short introduction to the chapter, and continues with a general description of the available data from the KIT database in Section 4.2, and the manner of collection and processing conducted by KIT in Section 4.3, to provide a robust basis for evaluating the utility, relevance, accuracy, and precision of the data in later sections. Since only part of the data from the KIT database has been utilised, Chapter 5 presents this selection process in Section 5.2, followed by a description of additional processing steps which required implementation, in Section 5.3. The chapter concludes with Section 5.4 which justifies the rationale of the methodological approaches employed to answer the three research questions.

1.3.3 Section III

The third section presents, describes, and evaluates the results derived in addressing the three research questions of this thesis. Chapter 6 investigates Research Question 1, the intraindividual variability of the bilateral shoulder, elbow, knee, hip, and ankle. To facilitate the reading and comprehension of the data, the results of each joint are presented and discussed in separate sections within the chapter (Section 6.2 through to Section 6.6). Chapter 7 investigates Research Question 2, the intraindividual variability of different body regions, by comparing the degree of variabilities across the shoulder, elbow, knee, hip, and ankle joints from both body sides. The results are presented in Section 7.2, and discussed in Section 7.3, also in light of the results obtained in Chapter 6. The results of Research Question 3 which address interindividual variability are presented and evaluated in Chapter 8, Section 8.2. The discussion in Section 8.3 also considers the data obtained from Chapters 6, and 7, thereby resulting in a more integrated assessment of the potential of gait as an individualistic characteristic in forensic science.

1.3.4 Section IV

Due to the large amount of data and its associated complexity, Section IV synthesises the main findings of the analyses, highlighting and integrating their implications in the forensic science context. Chapter 9 presents a summary of all findings in Section 9.1 and integrates all of the data analysed in Section III with aspects which may have had an impact on the analysis of the data, not only limitations associated with the KIT database but also with those that may have originated from post-processing throughout Section 9.2; also, future directions are considered. The thesis concludes with Section 9.3 which emphasises the impact of the thesis results on the current body of literature in the field of forensic gait analysis.

Chapter 2 – The Scientific and Legal Standing of Forensic Gait Analysis

2.1 Overview

Chapter 2 presents and places the research problem into the general forensic science context and in the context of forensic gait analysis applications, parts of which have been previously published as a critical review (Macoveciuc *et al* 2019). Section 2.2 defines and debates the fundamental principles of the forensic science paradigm in the context of current 'disputes' on methodological approaches and evidence admissibility, thereby developing a framework for investigating the foundations of forensic gait analysis in Section 2.3. The knowledge basis of the discipline is introduced and critically evaluated in Section 2.3.1, followed by an appraisal of its forensic context in Section 2.3.2. The premise of gait uniqueness and the utility of gait features in identification are assessed in Section 2.3.3, as applied in the forensic context, and as related to the current knowledge basis. A critical assessment of current research in the discipline is presented in Section 2.3.4, in conjunction with approaches to method validation and foundational testing, whilst Section 2.3.5 discusses these approaches in light of cognitive biases associated with the qualitative nature of forensic gait analysis. The chapter concludes with Section 2.4 which investigates the use of forensic gait analysis in court cases (Section 2.4.1), providing a thorough examination on the challenges associated with admitting gait information as evidence (Section 2.4.2).

2.2 Science in the Legal Context

From a general perspective, 'science' is considered synonymous with objectivity, and for a field of study to be classified as a 'science', logic and rationality are some of the key requirements which drive data collection, analysis, and interpretation (Inman and Rudin 2002). Science is traditionally considered a means by which one can uncover 'truths' through methodical observation and experimentation (Howson and Urbach 2006). However, defining sciences as such is certainly not an absolute, particularly for those applied in legal contexts. 'Forensic' science is rather a balancing act between the raw evidence and the subjective, biased human who observes and conducts tests to reach a scientific 'truth'. Since forensic science is considered a "*vital instrument for the detection and deterrence of crime and the administration of justice*" (House of Commons Science and Technology Committee 2005), its governing standards must not only meet the science-based requirements but also those imposed by the law. Whilst forensic science is (in principle) ruled by logic, the process of applying pure rationality is undermined by factors which revolve around cognitive bias (unintentional, prejudicial errors) as part of the human 'condition' (Tversky and Kahneman 1974). As such, the 'correct' development of satisfactory protocols for collecting, analysing and interpreting data is therefore arguable due to challenges associated with the uncertainty problem that is inherent to science and implicitly, forensic science (Mennell 2006; Mennell and Shaw 2006; National Research Council 2009; PCAST 2016; Zapf and Dror 2017).

In general, the forensic science process remains somewhat founded on certain scientific 'laws' such as the Locard's Exchange Principle whereby every contact leaves a traces, Kirk's Concept of Individualisation whereby a contact made by an individual belongs to the said individual, and the Divisible Matter Principle whereby a trace recovered as evidence can be sourced back to the said individual (Inman and Rudin 2002), as depicted in Figure 2.1. Such an approach to the forensic science process has slowly shifted in recent years during which it has become increasingly recognised that these 'laws' may not adequately encapsulate and reflect the components of the process, and may not be applicable to all fields of study with forensic applications (Crispino *et al* 2019, Morgan 2019) especially those involving pattern matching such as forensic gait analysis.

Figure 2.1 – The Stages of the Forensic Science Process
(image taken from Inman and Rudin 2002)

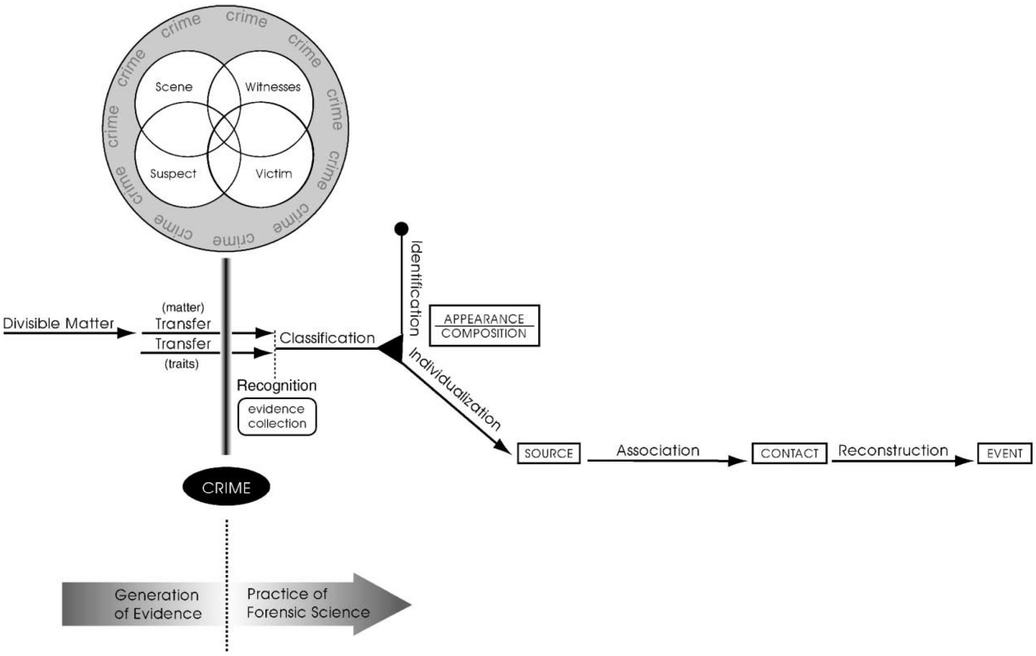


Figure 2.1 is a schematic representation of the forensic science process, starting from the crime and ending with the reconstruction of events for the courtroom.

The primary fundamental concept for a pattern-matching discipline as is forensic gait analysis, would be "individualisation", since "transference" and object "classification" have no particular use for video analysis (Figure 2.1). However, it can also be argued that "individualisation" cannot be achieved, and forensic gait analysis should rather focus solely on "identification"; in the framework depicted in Figure 2.1, "identification" is defined as the categorisation of an object into a class. Having limited empirical data on individualisation, forensic gait analysis cannot currently be used beyond a tool for potential identity 'confirmation', hence the aim of this thesis to investigate whether there is any basis for considering individualisation as a concept in the forensic gait analysis paradigm. This perspective is not consistent across academic publications, whereby some forensic gait experts define it as a method of identification founded on the individuality of gait (e.g. Birch *et al* 2013a, 2014) or provide contradictory opinions (e.g. Birch *et al* 2016a,b), thus eventually agreeing with other experts that forensic gait analysis is a 'class-level identification technique'

(DiMaggio and Vernon 2017; Larsen *et al* 2008b; Lynnerup and Larsen 2014). “Association” and “reconstruction” should also form the basis of the field whereby focus should not solely be either individualisation or person classification but also association of the individual to the crime scene and assistance in crime scene reconstruction. Since forensic information does not necessarily have to reach court (i.e. used solely for intelligence purposes rather than as evidence), evaluating the utility of forensic gait analysis as a means of intelligence is still advisable, although details regarding such an approach has only been briefly mentioned in the literature (Nirenberg *et al* 2018). This lacuna denotes a disjointed relationship between research and practice, whereby neither has been made available to the academic community in sufficient detail for appraisal and constructive criticism. Therefore, the standing of forensic gait analysis in the forensic science paradigm is uncertain, as is the form of knowledge which it proposes to yield.

Irrespective of the nature of the forensic science in question, the collection, processing, and analysis of crime scene materials is a complex endeavour composed of various stages which require collaboration between the forensic scientists and police, witnesses, crime scene technicians, and attorneys (Morgan 2018), as illustrated below in Figure 2.2. From a general perspective, the forensic science process begins at the crime scene where materials which may link an individual to the said crime may be found; for forensic gait analysis, this process would include identifying video cameras which may have captured relevant footage of a person interest, and obtaining the footage through different means (e.g. downloading onto a server, copying the footage onto a CD-ROM, etc.). Therefore, the manner of identification and collection of crime scene materials is pivotal, whereby their loss, destruction or contamination is irreversible and can have catastrophic repercussions in the outcome of a case (Harrison 2006; de Gruijter *et al* 2017).

Figure 2.2 – The Forensic Science Process from the Crime Scene to the Courtroom
(image taken from House of Lords Science and Technology Select Committee 2019)

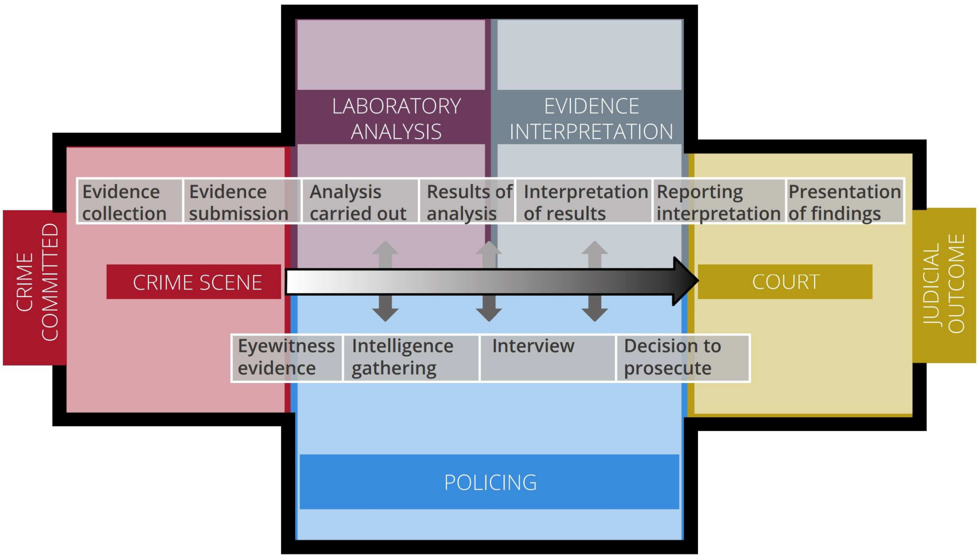


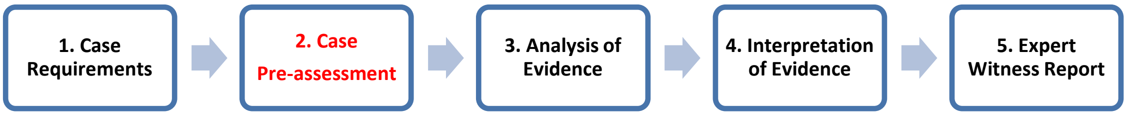
Figure 2.2 is a diagrammatic portrayal of the different steps of the forensic science process.

After collection, the crime scene materials are processed to determine the most appropriate line of analysis based on their nature and quality; in forensic gait analysis, this may include evaluation of the quality and quantity of footage. These materials may be compared with others subsequently collected by investigators to confirm or disprove associations between suspect and the scene (Jamieson 2004), a process that in itself is not free from producing false positive or false negative associations (Houck 2019). Finally, a reconstruction of events based on the evaluated crime scene 'materials' may be conducted for presentation in court in the form of crime scene 'evidence'. Therefore, when designing or adapting methods for forensic use, these stages should remain central to the methodological design where each procedure has been robustly investigated and accompanied by transparent error rates (Earwaker *et al* 2019; Martire *et al* 2017) to ensure proper analyses of crime scene materials and implicitly, accurate reconstruction of events (Morgan 2017a).

Another inarguable aspect of the forensic science process is that evidence collection, analysis, and interpretation stages are conducted using the scientific method (Crispino *et al* 2011). The central underpinning of the scientific method is the process of reasoning, and it is here that opinions diverge regarding how the stages of the forensic process are affected by cognition. Whilst there is an inclination to classify forensic science as a hypothetico-deductive model, elements of induction and abduction during early stages of evidence collection and during the interpretation stages respectively, are intrinsic to the model; a generalised approach at the start is necessary for developing an analysis plan. Also, drawing a set of likely explanations (given the evidence) is essential for interpreting the analysed data. However, the analysis stage requires a series of generally accepted and validated methodologies to ensure that the foundations of the interpretation stage are built upon empirically valid concepts (e.g. House of Commons Committee Science and Technology Committee 2013, 2016; PCAST 2016); this is another insufficiently tackled aspect in forensic gait analysis. Although cognition is inherently flawed, evidence interpretation would have no value in a greater legal context if the gap between observation and explanatory theory is not bridged through reasoning. Both theoretical and practical knowledge are invaluable since it is not possible to define a relevant examination approach solely through observation and without human judgement (Evett 1996, Lord Neuberger 2015), especially since forensic contexts are never identical (Morgan 2017b, 2018). Therefore, applying a restrictive approach to the reasoning process, and demoting the importance of professional experience should be avoided. Rather, the approach should be inclusive, seeking to identify, understand, document, and report cognitive biases in association with the evidence, to provide relevant interpretations and opinions for the court, and mitigate these wherever possible through robust designs and statistical analysis of results to support conclusions (Dror *et al* 2006; Towler *et al* 2018). Although various forensic gait practitioners have acknowledged this perspective, there generally seems to be a contradictory accompaniment of motives for which forensic gait analysis should not be discredited simply because it lacks these attributes (e.g. Nirenberg *et al* 2018).

Even at a reasoning level, forensic science should be approached from a multi-directional angle, and the reasoning process should be tailored according to the appropriate stage of the forensic process. Recommendations have been made by several scientists regarding methods of mitigating cognitive bias and one example, illustrated in Figure 2.3 below, proposes a Case Assessment and Interpretation (CAI) model (Cook *et al* 1998a).

Figure 2.3 – Model for Case Assessment and Interpretation (CAI)
(based on Cook et al 1998a)



The model works on the premise of developing an examination strategy (referred to as 'case pre-assessment') based on the information given by the authority requiring the evidence examination (e.g. police), including contextual information about the case. The pre-assessment component plays a central role in the model because it drives the forensic scientist to create a solid analysis plan and formulate hypotheses based solely on the presented information and evidence *prior* to the actual examination of the evidence. Recent studies have experimentally demonstrated that human decisions are cognitively dissonant in many forensic sciences (even as early as the crime scene procedures (e.g. van den Eeden 2016)) and hence biased due to the tendency of favouring information which confirms initial hypothesis and discarding information which may prove otherwise (Cole 2013b; Heyer and Semmler 2013; Smit *et al* 2018), thereby substantially reducing the purpose of the scientific method. By using the CAI model, the analysis and interpretation of the evidence would be conducted according to this initial plan and hypotheses and reduce the chances of the expert changing their interpretation *after* seeing the results (Cook *et al* 1998a,b).

Another approach, which forensic gait experts claim to utilise is the ACE-V(R) approach, as applied and described in DiMaggio and Vernon's 2017 book on Forensic Podiatry (DiMaggio and Vernon 2017), the sole 'academic' publication to describe how this approach is implemented in forensic gait analysis. The first step (Analysis) involves assessment of the unknown 'item' always prior to the known one, where observations, notes, and any measurements are taken using accepted approaches. In forensic gait analysis, this also includes an assessment of the quality and quantity of the footage to determine whether it is sufficient for the subsequent step. A Comparison is then conducted across the unknown and known items, also using accepted standards. This is then followed by an Evaluation of the analysis and comparison of the items expressed in the form of justified conclusions founded upon the prevalence of the observed features in a population which, as stated in the aforementioned book, can be "*obtained from literature, surveys, databases, and unpublished data*" and if non-existent, additional work needs to be undertaken for the "*purpose of that particular enquiry*" (DiMaggio and Vernon 2017, pg.169). As will be discussed throughout

Sections 2.3 and 2.4, published research on accepted standards and population prevalence of gait features is largely absent. Normally, a Verification stage would be undertaken by a second expert (if available) who is not made aware of any case contextual information to ensure that the quality of assessment is unbiased and follows the standards of the discipline. Finally, the witness Report or statement is prepared (if required).

At first glance, the CAI model is superior to the ACE-V(R) approach since the former encourages the expert to reflect on and develop a list of potential challenges which may be encountered during subsequent steps before conducting them. This supplies opportunity not only for performing an exhaustive study of the best available approach but also to constrain the possibility of the expert altering their opinion after completion of the analysis. In ACE-V(R), observations are directly conducted on the unknown material which inadvertently leads to the expert to already form an opinion on the nature of the data, thus introducing an a priori bias into the analysis of the known material. This also allows the expert to alter their method of analysis throughout the analysis and comparison stages and carry along an inherent bias throughout the entire process, thereby creating a bias snowball effect (Dror *et al* 2017). A more interesting approach to reduce potentially biased opinions throughout these stages is, for instance, the filler-control approach, whereby the expert would analyse the unknown and unknown footage, as well as at least one set of footage with no relevance to the previous two, to ensure that the match or non-match between the unknown and known footage is as accurate as possible (Wells *et al* 2013).

For ACE-V(R), the verification stage is also problematic, since, as stated in various forensic gait analysis publications (e.g. Birch *et al* 2013a,b), the field is a small one and it is likely that the expert performing the verification is a colleague of the expert who performed the analysis; hence, the independence characteristic of this stage is lost because the colleague would have likely been trained to follow similar standards and approaches as dictated by the authority under which they practice; therefore, there is potential for loss of transparency, an essential aspect especially in cases of differing opinions (Montani *et al* 2019). As a result, the verification stage loses its value, and quality assessment is rendered a trivial step in the process. Nevertheless, research is lacking with respect to which of these approaches (or others) would be most efficient for forensic gait analysis, considering that investigation is yet to be conducted to determine whether the current approach is indeed fit for purpose. This aspect therefore poses additional queries regarding the claim of gait uniqueness and its potential for individualisation since, regardless of whether the claim holds true, current methods are unsuitable for implementation in practice.

2.3 Theoretical and Practical Foundations of Forensic Gait Analysis

In the UK, there is no official accreditation process or specific regulatory body under which the 'forensic gait expert' operates and which defines the nature of the training required to allow a scientist to practice as a forensic gait expert. As stated by Birch and colleagues (2019), practicing forensic gait analysts in the UK are members of the Forensic Gait Analysis Working Group of the Chartered Society of Forensic Sciences, the aim of which is to advance the field and improve quality and standards. However, no specific accreditation scheme is currently associated with membership to this group to ensure that the methodologies employed are valid and founded on sound scientific evidence, particularly with respect to the main basis on which forensic gait analysis is founded, namely gait feature uniqueness. At present, forensic gait analysis is a recognised discipline of the Chartered Society of Forensic Sciences and 'regulated' by the Health and Care Professions Council (HCPC 2018), becoming only recently accompanied by a forensic code of practice published in December 2019 under the authority of the Forensic Science Regulator in collaboration with the College of Podiatry (Forensic Science Regulator 2019b). Nevertheless, there is yet to be a regulatory group specifically designated for forensic gait analysis or mandatory training of the gait analyst prior to conducting forensic casework and/or appear in court as an expert witness (Birch *et al* 2019).

Currently, the majority of information on forensic gait analysis is found in DiMaggio and Vernon' Forensic Podiatry textbook (DiMaggio and Vernon 2017) where a small chapter of less than 30 pages have been dedicated to a field of study which was utilised to provide evidence in court over 15 years before its publication in the case of R v Saunders 2000. In the aforementioned chapter, forensic gait analysis is defined as "*the analysis, comparison and evaluation of human gait including the components and features of gait, to assist the process of identification or to answer any other legal question concerning gait.* [This] *can involve the examination of recordings of moving images* [such as from CCTV] *and also sequences of foot and shoe prints* (DiMaggio and Vernon 2017, pg. 156). A different definition appears in a review article published by forensic gait experts that same year, which states that forensic gait analysis is defined as "*the identification of a person by their gait or by features of their gait, usually from closed circuit television (CCTV) footage and comparison to footage of a known individual*" (Burrow *et al* 2017, pg.2). The latter definition has been substantiated by previous publications also authored by forensic gait experts who have claimed that forensic gait analysis "*provide*[s] *evidence that individuals with experience in visual gait analysis are consistently able to* ***identify*** *individuals by their gait*" (Birch *et al* 2013b, pg.342). A variety of definitions regarding the scope and practice of forensic gait analysis are employed throughout the literature, although all are now superseded by the finalised code of practice definition which currently states that "*forensic gait analysis is the analysis, comparison and evaluation of features of gait to assist the investigation of crime*" (Forensic Science Regulator 2019b, pg. 4).

Preceding the code of practice, the publication of the forensic gait analysis primer has been an important step forward not only in strengthening the relationship between the forensic scientist and the legal system but also in presenting the court with the current limitations of the field (The Royal Society 2017a). It also draws attention to the difficulty in assigning an objective scale of comparison between video recordings whereby even a verbal scale of likelihood ratios would classify any data obtained from current methods as 'weak' (The Royal Society 2017a), considering the identification percentages obtained in the small number of published studies, and the absence of empirical data validated on an adequate UK population dataset. Whilst it can be debated that 'rougher' estimates of a verbal scale can be helpful to the court in the absence of large-scale population studies and that there can be high uncertainty even with large datasets (Norgaard and Rasmusson 2012), the problem of subjective uncertainty remains until further development of foundational bases for gait features in current use. A similar issue is also encountered with the claim of gait uniqueness and its potential for individualisation; in the absence of experimental data, its validity can only be considered "conjecture" (The Royal Society 2017a, pg.14). As discussed in the PCAST report (2016), case experience in pattern matching methods such as fingerprinting (and forensic gait analysis, which is not included in the report), cannot be a substitute for measured frequency of features in a given population (i.e. variability). The report also argues that such statements made in a legal context are scientifically invalid since the absolute truth cannot be known and therefore, use of verbal scale likelihood ratios in court should be prohibited (PCAST 2016). Considering these aspects, the UK forensic gait analysis primer for court (The Royal Society 2017a) is nevertheless an important step in ensuring that the gap between science and the legal system is not widened, whilst allowing judiciary members to make more informed decisions regarding admissibility criteria and weight of evidence from a more objective viewpoint, thus encouraging more transparent and fair trials.

2.3.1 Knowledge Basis

At present, forensic gait analysis draws methodological approaches mainly from the extensive clinical and biomechanical literature, despite claims that there is substantial ongoing research in the field, although the lines of investigation are not clearly stated, and these claims are only substantiated by personal communications (DiMaggio and Vernon 2017). The methods from clinical studies, although of high quality, are very different and cannot be extrapolated directly to a forensic context without adaptations necessary to forensic settings and implicitly, to meet validation and peer-review requirements that should be inherent to forensic practice. The setting of a clinical laboratory intended for research contrasts that of a crime scene, and consequently, the application of gait analysis knowledge is different and does not consider or incorporate the challenges a forensic setting might bring, in the methodological design. Whereas the clinical expert observes movement from an individual both visually, and/or on a computer which displays real-time numerical data, the forensics gait expert is required to interpret gait features based on low-quality, low frame-rate CCTV footage. Clinical gait analysis is undertaken under optimal conditions whereby, for instance, the physical 'availability' of the participant allows for repetition of movements of interest during extended periods of time, allowing for a large dataset to be built even from a single individual (e.g. Hollman *et al* 2016). Furthermore, the clinical subject would be wearing equipment for measuring various parameters such as gait cycle duration, foot pressure values, and muscular activity. This contrasts with the information available from CCTV, where factors such as total video sequence, lighting conditions, frame rate, partial obscuring of body regions, clothing, and so on, significantly reduce the value of the expertise (Larsen *et al* 2008b).

Appropriate terminology for forensic usage is also absent, despite an attempt made in 2015 to develop a 'list' of recommended, standardised terminology for use in practice (Birch *et al* 2015). However, the authors of the publication do not provide adequate examples from forensic practice to support their opinions regarding the importance of these recommendations. It also induces the reader to self-collate the claimed terminology in the absence of a clear presentation of the methods used in practice. For example, the authors state that the parameters commonly measured are spatial parameters such as step, stride, base of gait and toe out angle, and temporal parameters such as speed and cadence (Figure 2.4). However, the authors do not state the typical methods that practitioners utilise to obtain these measurements.

Figure 2.4 – Spatial parameters of gait as defined by Birch et al 2015
(taken from Birch et al 2015)

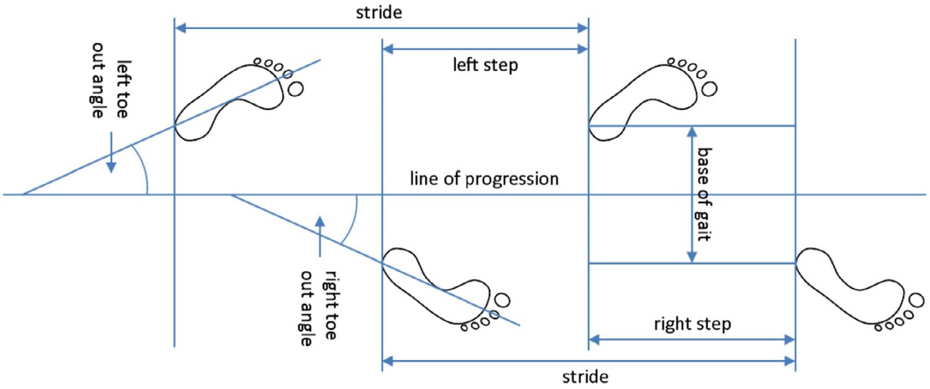
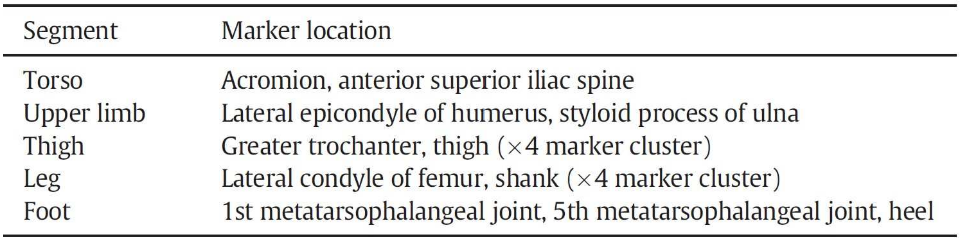


Figure 2.4 is a schematic representation of the characteristics which forensic gait analysts measure in space (spatial parameters). As defined in Birch et al 2015, *step* refers to the distance between the contact of the heel of the alternating left and right foot with the ground, *stride* refers to the point to point, successive contact of the heel of the same foot, *base of gait* refers to the distance between the rearmost points of the heels of the feet as measured in the line of progression (i.e. direction of walking) and the *toe out angle* is the angle between the longitudinal axis of the foot and the line of progression.

With respect to general movements at joint level (e.g. head, torso, upper and lower limbs), the authors state that such features are only described as seen in the video footage, and there is no specific reference as to whether joint angles are measured. In addition, the manner in which this description is performed for each body region is not mentioned, with the authors giving examples solely on which movements would be inappropriate to describe from video (i.e. minute movements which do occur but cannot be observed from video). An example as to how such a description would be conducted is provided in DiMaggio and Vernon's textbook (2017) whereby the right foot is described in two specific videoframes: "*Frame 15:30:16, despite the image being somewhat poor, the right foot is forward, seen at heel strike and is abducted; Frame 15:30:22, the right foot is forward and again abducted when compared to the pavement edge, with the forefoot being situated much nearer the pavement that the rearfoot*" (pg. 166). In the absence of actual measurements of the joint angles (or at least a description in association with spatial and temporal parameters), it is difficult to see how these types of descriptions can provide a solid basis for (assisting in) identification, as claimed by Birch and colleagues in a publication detailing how the professional gait analyst can accurately identify individuals based solely on observation (Birch *et al* 2013b, pg. 342). This aspect has been investigated in a different study by Birch and colleagues (2014) only secondary to their main aim which was to investigate the effect of video footage frame rate on the analysis of gait features. In the above-mentioned study, eight participants with 'knowledge of gait analysis' were asked to evaluate gait features from video footage obtained from a single subject using a single video camera. The subject was fitted with several body markers to also capture three-dimensional information from the body joints (Table 2.1), although the participants were not shown or asked to comment on this data.

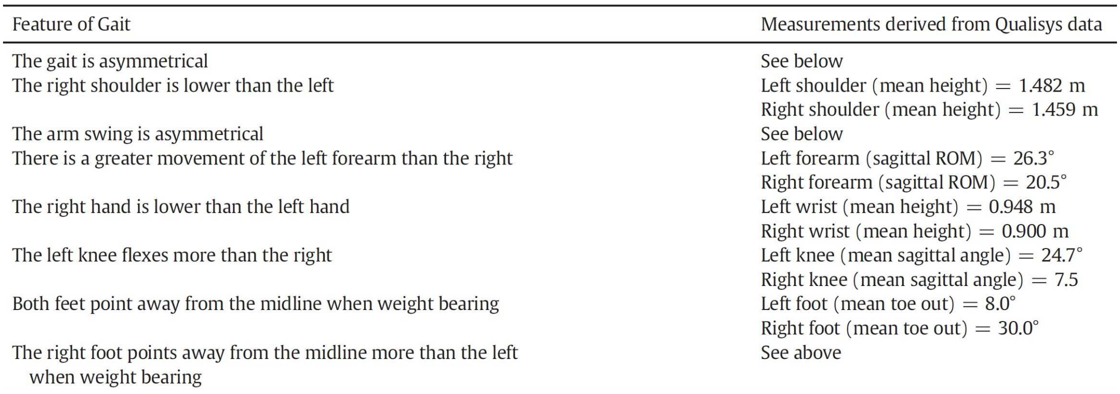
Table 2.1 – Locations of the body markers as presented in Birch *et al* 2014
(taken from Birch et al 2014)



Segment	Marker location
Torso	Acromion, anterior superior iliac spine
Upper limb	Lateral epicondyle of humerus, styloid process of ulna
Thigh	Greater trochanter, thigh (×4 marker cluster)
Leg	Lateral condyle of femur, shank (×4 marker cluster)
Foot	1st metatarsophalangeal joint, 5th metatarsophalangeal joint, heel

Table 2.1 describes the location of the markers as placed by Birch and colleagues in their study. No accompanying images or details are provided as to why the markers were placed at the respective locations and no references are provided regarding similar protocols in other studies.

Table 2.2 – The eight gait features and measurements from Birch *et al* 2014
(taken from Birch et al 2014)



Feature of Gait	Measurements derived from Qualisys data
The gait is asymmetrical	See below
The right shoulder is lower than the left	Left shoulder (mean height) = 1.482 m Right shoulder (mean height) = 1.459 m
The arm swing is asymmetrical	See below
There is a greater movement of the left forearm than the right	Left forearm (sagittal ROM) = 26.3° Right forearm (sagittal ROM) = 20.5°
The right hand is lower than the left hand	Left wrist (mean height) = 0.948 m Right wrist (mean height) = 0.900 m
The left knee flexes more than the right	Left knee (mean sagittal angle) = 24.7° Right knee (mean sagittal angle) = 7.5
Both feet point away from the midline when weight bearing	Left foot (mean toe out) = 8.0° Right foot (mean toe out) = 30.0°
The right foot points away from the midline more than the left when weight bearing	See above

Table 2.2 provides the list of observations pre-established by the authors of the publications, as well as the measurements taken from the motion analysis system (i.e. Qualisys). The table is meant to illustrate the corroboration between the observed feature from video and its respective measurement from motion analysis.

Since the aim of the study by Birch and colleagues (2014) was to evaluate effect of frame rate the purpose of obtaining three-dimensional observations from the subject was not addressed until the methods section of the publication; this purpose was to use these three-dimensional characteristics to serve as an 'empirical' template to independently evaluate the video footage observations obtained from the participants. However, these footage observations were not scored unless these corresponded with a pre-established set of eight observations deemed appropriate by the authors, as shown in Table 2.2, pg.28. This reduces the potential of establishing whether there are additional aspects which have been overlooked by the experiment designers, whilst also failing to highlight features which may have been erroneously interpreted by the participants. In addition, no information is provided as to (i) how this set of observations was established, (ii) why is it that only the measurements presented in Table 2.2 were taken, (iii) who performed the video and three-dimensional data capturing and measurements, and (iv) who performed the corroboration between the video features and the three-dimensional measurements. If the same person obtained both the video and three-dimensional data and performed the corroboration in the absence of verification by a second expert, then there is an inherent bias which renders the value of corroboration null because the former would already be familiar with all experimental conditions (i.e. confirmation bias). Another query which arises from this study (Birch *et al* 2014) is the reason for which other measurements were not taken.

Considering the information provided by Birch and colleagues in their publication on terminology in forensic gait analysis (2015), it is surprising that joint angles were not quantified to supplement the descriptive basis of movement observations and commence the development of an empirical basis for the claim of uniqueness and validate the individualisation potential of gait. Whilst joint angle quantification from video may not be feasible due to the associated difficulty of measurement (and implicitly, inherent error), other studies have demonstrated that there is a potential utility of measurements from video (e.g. Larsen *et al* 2008a; Lynnerup and Vedel 2005) including those of joint angles (e.g. Yang *et al* 2014b) and height (e.g. De Angelis *et al* 2007; Yang *et al* 2014a). Regarding height (or more appropriately, stature), a recent study has highlighted the possibility of using correlation and regression analysis for estimating stature from hand measurements, leg length, and length of gait stride, or hand measurements to predict leg and gait stride length with and without stature (Guest *et al* 2017); such studies therefore present the possibility of conducting measurements from video in forensic gait analysis. Most of these approaches are certainly not novel, yet none have been investigated in any depth in the field of forensic gait analysis. Although Guest and colleagues (2017) analysed data from 97 participants, validation is still required, particularly since these were not applied to video footage to observe the degree to which results are affected by, for instance, camera angle, distortions, distance from camera, or whether the number of measurements affect prediction accuracy. Therefore, there is potential to introduce a quantitative aspect within current observational forensic gait analysis methods to reduce the qualitative, subjective basis for developing conclusions.

Based on the aforementioned limitations, the expertise is currently hindered from extending beyond a 'potential confirmation' of identity or from simply 'assisting with identification', conclusions which, in fact, are based upon a highly suggestive environment where intelligence may already indicate to police that the person of interest is very likely to be the suspect. Such information prompts cognition to 'fill in the blanks' due to the suggestive context (contextual bias) that inadvertently leads the expert to form a prejudiced opinion (Edmond *et al* 2015) and therefore, interpret the data based on this opinion (confirmation bias) (Kassin *et al* 2013; Almazrouei *et al* 2019) rather than applying a more objective method in the comparison of videoclips. As such, the 'individualisation' potential of gait as an identification technique is reduced to a qualitative and subjective method of simply 'confirming' what is already known; at present, forensic gait analysis can, at best, include or exclude an individual from a pool of individuals with similar criteria (The Royal Society 2017a). Not being aware of the extent to which different features influence overall gait patterns, inclusion of an individual into a pool of 'similar' suspects will be inherently flawed, since the features of interest might in fact represent those which would be expected to be similar, rather than of use for individualisation Therefore, this thesis aims to contribute to current literature by investigating whether there is a extant basis for considering forensic gait analysis beyond its 'potential confirmation' status through the biomechanical examination of intra- and interindividual variability in joint angle values of the shoulder, elbow, hip, knee, and ankle during walking at self-selected, normal speed, in healthy adults. By utilising this investigation approach, this study may potentially contribute to future development of empirical databases and quantitative methodologies to forensic gait analysis, as well as to encouraging interdisciplinary collaborations.

2.3.2 The Forensic Context

Many of the foundational issues identified in other subjective, pattern-based forensic sciences such as bitemark analysis, parallel those of forensic gait analysis. As highlighted in the previous sections, the presumption of uniqueness, now demonstrated to be invalid in bitemark analysis, has not previously addressed in forensic gait analysis. There is a lack of a population database to provide a set of clearly defined, physiologically founded characteristics on which an expert may base their conclusions and implicitly, to provide a framework for calculating error rates. Information on false positives is currently unavailable, which brings into question the ability of the gait expert to support their decisions on excluding or including individuals from and into a pool of persons of interest, paralleling the challenging concept of 'absence of evidence is not evidence of absence' in trace evidence (Thompson and Scurich 2018).

Whilst the state-of-the-art has permitted significant advancements in the fields of biometrics and computer vision where identification of individuals using gait can be automated (i.e. gait recognition), the forensic setting complicates most of the sophisticated approaches to this problem (Seckiner *et al* 2018), including camera resolution, position and angle (Santos and Morimoto 2011; Xing *et al* 2016), lighting conditions (Moayedi *et al* 2015), clothing, shoes, and accessories of the person of interest/suspect (Guan *et al* 2012, 2015). In contrast to forensic gait analysis, biometric gait recognition is the automated comparison of CCTV footage to determine whether the same individual is found in the processed video clips (Nixon *et al* 2010). Gait recognition research therefore differs from forensic gait analysis in that its focus is the development of algorithms which render a high recognition performance in terms of identification but also in terms of, for example, age and sex estimation of the person of interest (Xu *et al* 2017). Nevertheless, forensic gait analysis and biometric gait recognition utilise the same basis of analysis (i.e. video footage) and yield a similar end-product (i.e. an estimation of how likely is the person of interest to be the suspect), but the methods by which analyses are performed are distinct, with gait recognition literature vastly exceeding that of forensic gait analysis in terms of originality, quality, methodological strength, and results. It might therefore be noteworthy to consider future collaboration between computer vision experts and gait analysts. For example, concepts from both fields are of relevance to one other whereby forensic gait analysts are (presumed to be) knowledgeable in the biomechanics of human movement, the forensic scene and the quality of footage to be expected in such circumstances, whilst gait recognition experts are well-versed in algorithm design, latest technological advancement, and can potentially provide innovative solutions for challenges related to, for example, the CCTV system layout. Such an interdisciplinary collaboration can have potential benefits not only by providing out-of-the-box perspectives on current issues but can sustain and develop gait into a more robust field of study.

In the UK, research on the scope and effects of CCTV has revealed that the intended purpose of crime reduction by instilling a sense of public safety has not been achieved (Home Office 2005). Furthermore, the UK is yet to voice an opinion in the form of method validation or specific standards for gait recognition, although it was recently mentioned (albeit briefly) during House of Commons Oral Evidence session of Biometrics Strategy and Forensic Services (House of Commons Science and Technology Committee 2018b). On the contrary, it has had the opposite effect whereby the public has been questioning their utility. Furthermore, the UK is yet to voice an opinion in the form of method validation or specific standards for gait recognition, although it was recently mentioned (albeit briefly) during House of Commons Oral Evidence session of Biometrics Strategy and Forensic Services (House of Commons Science and Technology Committee 2018b). Considering the available codes of practice in the UK, gait recognition would currently be suited in digital forensics, field which is defined in the general Code of Practice and Conduct of the Forensic Science Regulator as “*the process by which information is extracted from data storage media (e.g. devices, remote storage and systems associated with computing, image, image comparison, video processing and enhancement (including CCTV))”* (Forensic Science Regulator 2017). Whilst documents (and associated appendices) on method validation in digital forensics have already been published by the Forensic Science Regulator (2014, 2016a,b), specificity would be necessary should gait recognition evidence be used in court, since a recognition system is complex in terms of data processing and requires a trained specialist who should not only understand the system but who is also competent in analysing and interpreting gait-based data correctly and in presenting their conclusions in court together with assigning the appropriate weight to the evidence (Page *et al* 2019). For example, camera quality can cause loss of important anatomical information if depth cannot be captured (Gao *et al* 2015); in contrast, a camera with good depth acquisition can resolve problems posed by shadows and changes in lighting conditions (Aggarwal and Xia 2014).

In forensic gait analysis, footage quality is one of the few aspects (in addition to frame rate (Birch *et al* 2014)) which has been empirically tested, not solely for the use of the practitioner but also for ensuring universal understanding of footage quality for those involved in criminal proceedings associated with forensic gait analysis prior to requesting expert analysis. In a study by Birch and colleagues (2013b), the approach to footage quality analysis was based on the Delphi Strategy that is grounded on the principle of reaching an agreed consensus between experiment participants after several rounds of testing during which each participant voices their opinion. The participants were asked to individually identify which 'key factors and subfactors of CCTV footage' they considered of importance for footage quality assessment based on their experience. Four key factors were identified during the first round (quality of picture, lighting, direction of footage taken relative to the suspect, and the suspect), with an additional one (frame rate) agreed upon after the second round. For each of these five factors, several sub-factors were added; for example, sub-factors for 'suspect' included clothing, number of steps captured, and speed of movement. All the key factors with their accompanying sub-factors were then assigned a five-point Likert scale which allowed the practitioner to rate video footage (Table 2.3, pg.33).

The results of the tool presented by Birch and colleagues were deemed to have 'good reliability' after having been passed on to the participating experts for testing on their own casework, who in turn reported the tool to be "*fit for purpose*", producing repeatable results (Birch *et al* 2013b pg.917). Repeatability was also tested whereby the same participating experts were asked to evaluate one CCTV videoclip once a day for five days, with the results "*suggesting a good level of repeatability*" (Birch *et al* 2013b pg. 917). However, the authors acknowledge that the number of experts (three experts during the first set of rounds and another two experts for an additional round) who participated in the study was too low for a Delphi Strategy approach, yet they still concluded that the results "*suggest a good face validity of the tool*" (Birch *et al* 2013b pg. 917). This conclusion was also based on the 'positive feedback' received after a trial version of the tool was made accessible to other experts for casework use. However, the feedback is vague and unaccompanied by the case reports on which the tool was applied to demonstrate its utility in practice. Sparsely sourced and very brief, this tool, which is claimed to be "*suitable for use by anyone involved in criminal proceedings and not be reliant upon expertise in either gait analysis or CCTV surveillance*" (Birch *et al* 2013b, pg. 915), was developed based on the opinion of a small number of practitioners. No practice-based rationale is provided as to why and how each characteristic was deemed to be useful and whether (and which) others were excluded, except for statements regarding the vast experience of the participants involved in the tool development. The assignment of values for each characteristic is also highly subjective and complicates decision-making in cases where, for instance, the majority of the scored characteristics would lie at middle value. No information is provided as to what approach would be taken in such a case.

Table 2.3 – Video footage quality assessment tool
(modified from DiMaggio and Vernon 2017)

Characteristic	**Assignment of Value (5-point Likert Scale)**		
Picture	Very sharp	O O O O O	Very blurred
	Very good contrast	O O O O O	Very poor contrast
	Too bright	O O O O O	Too dark
Lighting	Very good lighting	O O O O O	Very bad lighting
	No shadow interference	O O O O O	Significant shadow interference
	No reflection interference	O O O O O	Significant reflection interference
	Direction of light source good	O O O O O	Direction of light source poor
Direction	Directly from the side	O O O O O	Directly from the front or back
	From below the subject	O O O O O	From above the subject
Frame Rate	Continuous flow of image	O O O O O	Series of still images
Subject	Whole of upper body in shot	O O O O O	None of upper body in shot
	Whole of lower body in shot	O O O O O	None of the lower body in shot
	Moving very fast	O O O O O	Moving very slowly
	10 steps or more in shot	O O O O O	2 steps or less in shot
	Clothing good for gait analysis	O O O O O	Clothing poor for gait analysis
Distance of subject to camera	Too close for gait to be viewed	O O O O O	Too far for meaningful analysis

Adapted from Table 1.6 (pg.163) of DiMaggio and Vernon's book (2017), Table 2.3 lists the characteristics which forensic gait analysts reportedly use to assess the suitability of video footage for analysis. This is based on Birch and colleagues tool published in 2013 (Birch *et al* 2013b). The choice of adapting this tool from DiMaggio and Vernon (2017) rather than directly from Birch and colleagues (2013b) is that the latter mostly provides written descriptions of how the tool is to be used but using insufficient detail and unaccompanied by meaningful tables or figures.

No addition to the aforementioned tool has been made since its publication; in DiMaggio and Vernon's 2017 book on forensic podiatry, these characteristics are listed and described, yet the authors do not critically evaluate their utility or mention any ongoing research in this aspect, either UK-based or elsewhere. It is nevertheless stated that the characteristics form part of an "*unpublished protocol*" of the Forensic Podiatry Unit at Sheffield Teaching Hospitals, UK (DiMaggio and Vernon 2017, pg.160). An electronic search of this unit provides little information on its role, accreditation, and affiliated practitioners or their on-going research (Sheffield Teaching Hospitals 2020). A similar result is observed when performing a search on forensic gait analysis services, whereby a single service appears, located in the UK and run by Professor Ivan Birch who has published the majority of the literature on forensic gait analysis to date (Forensic Gait Analysis Services 2019). There appears to be a much more significant level of detail with respect to the definition and scope of forensic gait analysis on this website, although no specific information is provided regarding ongoing research projects (encourages web visitors to contact them for details), and the majority of the references listed on the webpage are of gait recognition. The different streams of gait analysis research are indeed recognised; however, no statement is made regarding any ongoing interdisciplinary collaborations.

Another aspect of direct relevance to forensic gait analysis is the challenge associated with differing camera positions. This is listed as an important analysis component in DiMaggio and Vernon's book (2017) amongst other requirements such as (i) visibility of the entire body with no load carriage, clothed in a manner which does not hinder view of the lower limbs, (ii) a walking duration of at least 10 steps at a normal speed, (iii) a preferred angle of recording in the frontal or sagittal plane where the camera is not at a too great a distance from the individual, (iv) reasonably well-lit conditions and (v) reasonable video resolution and contrast. Two aspects are worth noting, one of which is the absence of criteria to quantify each of these conditions, hence the inevitability of disagreements amongst experts. Studies regarding quantification of observations have indeed been published (albeit in a small number), such as one by Larsen and colleagues (2008a) who examined the use of height and body segment measurements (i.e. photogrammetry) from video in forensic contexts, the results of which have highlighted that height may be a sufficiently reliable characteristic to assess from video footage, although it was reported that reproducibility of measurements at inter-observer level was lower than reproducibility at intra-observer level. However, the study involved only two observers with unreported experience in conducting gait analysis, or in utilising the software and conducting measurements, whilst the publication itself is poorly structured and difficult to comprehend; therefore, it is challenging to ascertain any valid conclusions regarding the aspect of poor inter-observer reliability. Nevertheless, poor inter-observer reliability for three-dimensional data analysis of joint motion (particularly in the elbow and ankle) was also noted by Sandau and colleagues (2016) who examined how reliable are manual joint centre annotations from three-dimensional reconstructions conducted by eight 'expert' observers. Although reproducibility was low, the authors reported that 72.6% of all participants were correctly identified, and that this approach is appropriate for forensic gait analysis. From a total of sixteen participants, this number is nevertheless low and does not bear sufficient weight for this claim since the approach has not been validated on a different set of participants and, as the authors state, the inter-observer reliability was low. Neither is it sufficient for the authors to claim that "*human gait is therefore concluded to be highly discriminatory and 3D reconstructions aid extraction of the relevant parameters. As the group of participants considered in this study is relatively narrow, the number of participants included should not limit the analysis in any severe way"* (Sandau *et al* 2016, pg.647).

These challenges, although unresolved, have already been recognised and investigated in the field of biometric gait recognition to a greater extent than in forensic gait analysis. For example, if video footage of the person of interest is captured from a high, posterior view, the gait cycle features are difficult to extract because the movements are not as obvious. From a side view where the person walks parallel to the camera, arm swing and step length can be clearly observed (e.g. Goffredo *et al* 2009; Murase and Sakai 1996). In their study, Iwashita and colleagues (2010) presented one method of combining data from two-dimensional video clips obtained from 16 cameras to reconstruct a three-dimensional model of a person of interest which could be used to estimate walking direction changes. Accuracy rate for identification was high (90%) only when the person walked parallel to the camera, whilst rates for the other three camera viewpoints did not exceed 40%. As such, gait recognition research has also begun to investigate approaches that are not necessarily designed to 'predict' direction change or origin or destination of a person but also view-invariant, meaning that accuracy rates would be uniform regardless of the camera position in relation to the person of interest (e.g. Jia *et al* 2018; Tong *et al* 2019; Wang *et al* 2019). This is important for inferring direction and as well as for identification because differences between video clips of the same person captured from different angles due to differences in camera positions can be greater than identical videoclips of different individuals (Bobick and Johnson 2001; Xing *et al* 2016).

For instance, Larsen and colleagues (2010) investigated the potential role of biomechanics in gait recognition in 21 individuals by obtaining three-dimensional joint angles of the hip, knee and ankle on two separate days (as well as segment angles and joint moments for which there is little detail provided regarding data collection), to observe whether time may influence gait patterns. The results have shown that the hip, knee, and ankle angles were the most discriminatory in the sagittal and coronal planes, with hip abduction/adduction angle producing the highest recognition rate (i.e. 90%). However, of note is the recognition rate for this same angle was 62% prior to corrections made for three-dimensional marker offset (i.e. error due to the marker being placed/moved during walking, outside the normal plane of motion). Unfortunately, there is little detail provided regarding how this correction was made and its purpose, whilst the discussion section is unclear. The authors state that the gait patterns were identical over the two-days of data collection, yet the patterns appeared to be shifted and numerical values did not coincide between the two days (the authors refer to this phenomenon as *DC-offset,* yet very little information is provided on the nature of this phenomenon). Although the premise that the results differ due to differences in marker position and/or due to markers having become displaced during the gait trials may indeed be valid, the study is insufficiently detailed regarding this aspect. For instance, only six out of 15 trials were selected for analysis in order to match the authors' selected velocity, with one gait cycle per body side, per trial. These gait cycles were then averaged intentionally, "*to reduce small casual variations from step to step because the main purpose of the study was to see whether or not a basic walking pattern could be recognised between days"* (Larsen *et al* 2010, pg.6). However, since differences in intraindividual variability in a given body region and between body sides were not previously quantified and evaluated with respect to their influence on interindividual variability, the progression towards the analysis of 'average' walking patterns is premature (although no substantial research was undertaken in the ten years since this publication); therefore, it is questionable whether this study provides evidence for the utility of gait in identification, despite the high recognition rates.

Since forensic gait data comparisons may be conducted between images or footage obtained at different points in time, it is also possible that the body regions appearing clearly in one footage, may be obscured in the other(s). Therefore, context in a forensic setting is also important, especially in situations where the aim is not solely focused on identification but also on tracking (Cong *et al* 2010) and recognising suspicious activities (Castro-Muñoz *et al* 2015; Chaurasia *et al* 2015; Hu *et al* 2004). Human identification (or rather assistance in human identification), as applied in forensic gait analysis, could also be extended to tracking missing individuals during intelligence-gathering operations where law enforcement needs to reconstruct the whereabouts of the victim or potential victims of a crime. The same principles as those in current use could be applied, whereby the forensic gait analyst could compare two or more sets of CCTV footage, at least one of which would present the facial features of the person of interest as obscured or concealed. At present, this or any other type of footage analysis requires the identity of the suspect or person of interest to be known to a certain degree for the comparison to be considered of investigative value. Arguably, this type of research should be conducted, if not before but at least concomitantly with experimental studies on the utility of gait for individualisation. Nevertheless, this avenue has yet to be explored in forensic gait analysis, as evidenced by the absence of academic publications on the subject. Related research has only been conducted in the field of automated gait recognition, where tracking algorithms are being developed to determine whether the same individual is present in the respective sets of footage, yet even in the field of biometrics, empirical investigation specifically dedicated to forensic application is scarce (e.g. Chaurasia *et al* 2015; Iwama *et al* 2013; Nixon *et al* 2010).

Many of the aforementioned limitations have the potential to be resolved through development of databases which should not only contain an adequate dataset, but also data from similar and different lines of research which would allow methodological comparison for determining accuracy rates of different methods, and development of universal approaches. In the UK for example, according to Birch and colleagues (2016b), there is ongoing development of a gait video database with (currently) roughly 1,000 individuals (59.5% males, 40.5% females, with the majority being in the range of 18-50 years of age and White), as summarised in Table 2.4, pg.37. However, according to the authors of the publication, the data was obtained covertly from adult members of the public, and all the demographic characteristics listed in the publication (available since 2016) are estimations; no subsequent publications have followed since.

Table 2.4 – Demographic characteristics of Birch *et al* 2016b database
(taken from Birch et al 2016b)

Demographic variable	Number in sample to date		Percentage of sample		Percentage of UK population (based on 2011 census)	
	Male	Female	Male	Female	Male	Female
Sex	599	408	59.5	40.5	49	51
Age group 18-30	290	222	56.6	43.4	50.1	49.9
Age group 31-50	233	150	60.8	39.2	49.6	50.4
Age group >51	76	36	67.9	32.1	47.3	52.7
White	783		77.8		87.2	
Black	87		8.7		3	
Asian	109		10.8		4.9	
South, East and Southeast Asian	19		1.9		2	
Other	8		0.8		2.9	

Table 2.4 presents the demographic characteristics of the UK database for forensic gait analysis. All demographic variables have been estimated by a single observer who "*had more than 35 years' experience in observational gait analysis*" (Birch *et al* 2016b*,* pg. 428).

Table 2.5 – Gait features observed in the database samples of Birch *et al* 2016b
(taken from Birch et al 2016b)

Sex	Male	Female				
Age	18–30	31–50	>51			
Height	Short	Medium	Tall			
Weight	Light	Medium	Heavy			
Ethnicity	White	Black	Asian	S, E and SE Asian	Other	
Gait	Symmetrical	Asymmetrical				
Base of gait	Narrow	Moderate	Wide			
Step length	Short	Moderate	Long			
Pelvic rotation	Limited	Moderate	Exaggerated			
Head/torso roll	More to left	None	Both	More to right		
Head tilted	Left	Forward	Back	Right		
Torso flexed	Left	Forward	Back	Right		
	Left	Right				
Shoulder lower						
Arm swing more pronounced						
Hip movement	Straight	Circumduct	Straight	Circumduct		
Knee points	In	Neutral	Out	In	Neutral	Out
Knee max extension	Flexed	Straight	Hyper	Flexed	Straight	Hyper
Foot points	In	Neutral	Out	In	Neutral	Out
Early heel lift						
Forefoot lift	High	Low	High	Low		
Forefoot slap						

Table 2.5 provides the list of gait features which were observed by Birch *et al* 2016b during the analysis of the individuals of the database.

In addition, the list of features which were analysed from the video footage of the individuals of the database (Table 2.5, pg.37), were agreed upon by four practitioners also using a Delphi strategy (as in Birch *et al* 2013b). The number of participating practitioners was argued to be appropriate since the UK only had six practitioners at the time (Birch *et al* 2016b). However, the argument is further sought to be strengthened by the claim that opinions of other practitioners on the listed gait features were obtained and confirmed at "*national and international conferences*" (Birch *et al* 2016b, pg. 427), despite no such conferences being named within the publication or as references. Furthermore, if one was to compare the published terminology list by Birch *et al* 2015, 2019 and the details of current forensic gait analysis methods discussed in Sections 2.3.2 and 2.3.3 of this thesis, it is difficult to see how the features listed in Table 2.5, pg.37, have any relation (foundational, methodological, or otherwise) to the methods forensic gait analysts claim to currently employ. For more accurate assessments of inter-individual variation and implicitly, more accurate quantification of uncertainty levels in an expert report, known demographic variability in the population (e.g. age, sex, weight, height, body proportions (BMI)) of a dataset is evidently necessary for building databases, as highlighted by studies in clinical gait research (e.g. Chehab *et al* 2017). Hence, the interpretative stage of the forensic gait analysis process can only be classified as observational, descriptive, and debatable where the reasoning employed is scientifically unfounded to support conclusions.

In contrast, gait recognition has a multitude of ongoing databases, such as the OU-ISIR database from Osaka University, Japan, the largest one yet, with 63,846 participants of known age and sex (Osaka University 2018, Xu *et al* 2017). Other notable examples include CASIA in China (CASIA Gait Database 2005) and SOTON in Southampton, UK (Seely *et al* 2008) which include several covariates such as different clothing combinations, different environments and camera angle views but which do not contain detailed demographics such as age, as does the OU-ISIR database. Considering the abundance of data available, it is evident that further research will follow; also, other projects recently completed from which further publications are expected, include the IDENTITY project at the University of Warwick, which sought to "*consolidate the integration of multimedia forensics into the forensic sciences*" by extending the use of biometrics to include gait as well (University of Warwick 2017). Despite this substantial international progress in terms of database size, and covariate analysis, only a small number of studies specific for forensic/crime application have been published to date (e.g. Condell *et al* 2018; Larsen *et al* 2008b; Lu *et al* 2014; Ludwig *et al* 2016; Lynnerup and Larsen 2014). One of such studies includes a recent pilot system with an easy-to-use user interface developed for person verification intended for users who do not have any professional training in gait analysis, such as the police force (Iwama *et al* 2013). This system was designed to assist in criminal investigations, whereby the user examines the list of matches presented by the system, rather than the system offering the 'correct' match (Iwama *et al* 2013). Whilst promising in the sense that it is the first system of this nature to be published, it was evaluated by a small number of participants (10 non-specialists and only one gait specialist).

Demonstrating that a gait analysis system is user-friendly is an important achievement of this biometrics research, as are the various databases available, in contrast with forensic gait analysis. However, a fair comparison of whether a non-specialist performs better, the same, or worse than a gait specialist in conjunction with the gait analysis system, cannot be conducted. Also, no information is provided regarding the training of the gait specialist in the study of Iwama and colleagues (2013), their qualifications and their experience in either forensic or clinical gait analysis. Therefore, no conclusions can be drawn regarding differences between types and levels of training and experience of those who created the system. Further research is yet to be published regarding method validity, more elaborate error rates, level of uncertainty, etc., and it is unknown whether this gait recognition tool can demonstrate similar competence in, for instance, more complex scenarios (e.g. crowded shopping mall), or across populations of different ancestral background and demographic variability. Nevertheless, considering this wealth of information, sharing data and expertise across forensic gait analysis and gait recognition disciplines could have a significant impact on the current forensic standing of both.

2.3.3 Utility of Gait Features in Identification: The Question of Individuality

In forensic gait analysis, the individualisation potential of human movement has been generally considered scientifically robust (e.g. Birch *et al* 2013b; Burrow *et al* 2017, Krishan *et al* 2015), and the uniqueness and potential for individualisation of gait taken as scientific 'truth', despite lack of clear empirical data to justify this premise. A recent clinical study on biomechanics using force plates to obtain information of ground reaction forces (i.e. forces exerted during foot contact with the ground) from 128 participants (52 females, 76 males), has indicated that not only do individuals present unique gait patterns which produce a 99.85% correct classification using support vector machines (i.e. machine learning), but also that aspects of gait patterns are consistent across 7-16 months (Horst *et al* 2017b). This study, as opposed to forensic studies with much smaller sample sizes, provides valuable results for forensic science with respect to the concepts of uniqueness and individualisation, by highlighting associated principles such as the consistency of gait patterns across time (persistence), and implicitly, the value of gait patterns as a potential means for (assisting in) identification. Although such state-of-the-art data cannot be generated from video, there is potential for this data to be extrapolated by performing comparisons against characteristics which can be examined from video, such as height and other body measurements, as well as joint angles; this could provide a basis to test and compare which video extractable features are most individualistic and which are most suitable and stable relative to camera angle, distance from camera, number of gait cycles in a footage and so on.

Additional data regarding individuality has also been produced in the gait recognition field, where, for example, Lin and colleagues (2010) measured the joint angles of the hip, knee and ankle in ten male subjects, to determine whether differences in joint angles between subjects is greater than within subjects, and therefore develop a method of algorithm-based recognition with angles which show the highest interindividual variability. The data on which these conclusions were developed were 350 gait trials, from which 20 trials per subject were used to determine the degree of variability between and within subjects; the remaining 15 trials per subject were utilised to test the developed algorithm. Based on a p-value of <0.05, Lin and colleagues (2010) found a higher variability between subjects than within subjects in all joint angles examined, the highest having been observed for hip rotation. Although this study provides some interesting results for the question of individuality in gait, the differences amongst gait cycles of the same individual (intraindividual variation) were not specifically tested. To represent a single trial for each participant, all cycles were averaged, also a common approach to ‘big data’ reduction in clinical gait analysis (Phinyomark *et al* 2018). However, the extent to which mean joint angle values are representative of the gait of an individual has not been previously investigated (neither prior, or subsequent to, the publication of the above-mentioned study), with no data to validate the proposition that a mean gait cycle can accurately encapsulate associated intraindividual variability. This aspect is central to the concept of uniqueness and the potential for individualisation of gait; if the intraindividual variability exceeds interindividual variability, then there is not utility for gait to be utilised in discriminating individuals from one another. In addition, analysis of symmetry between the left and right body sides was not conducted, and no females were included in the study. Although evidence for asymmetry has been provided by clinical research (Kuhtz-Buschbeck *et al* 2008; Schwartz *et al* 2014), no further evaluation of its impact on interindividual variation has been conducted in forensic gait analysis; this may also differ given body region due to differences between form and function (further discussion on this aspect is provided in Chapter 3). To address these lacunae, this thesis will therefore investigate both the degree to which the ‘average’ gait cycle encapsulates intraindividual variability and the extent to which movement asymmetry contributes to this variability (Research Question 1) given body region (Research Question 2) to evaluate the scientific utility of gait in identification (Research Question 3).

Another accompanying variable to the question of individuality in observational forensic gait analysis is whether humans are indeed inherently skilled at recognising the gait of others. Earlier studies in psychological perception using point-light displays, have shown that individuals can identify others from gait, albeit to different degrees. For instance, one of the earliest study to investigate this was conducted by Cutting and Kozlowski (1977), who collected joint position data from six participants who knew one another, by attaching retroreflective markers on joints of the upper and lower limbs and filming the participants in order to produce abstract displays (i.e. point-light display, Figure 2.5, pg.41).

Figure 2.5 – Point Light Display Images
(taken from Cutting and Kozlowski 1977)

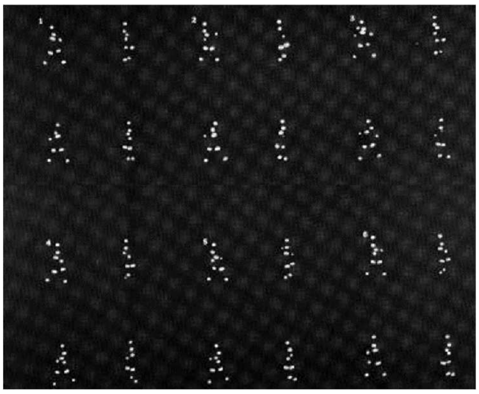


Figure 2.5 illustrates examples of point light display images. Each of the white clusters represents sagittal plane views of individuals in different poses such as walking from left to right, arms outstretched or closer to the body. Although the still images appear difficult to comprehend, the images would actually be presented to participants in the form of moving images, from which movement and shape is much easier to discern.

The six participants, as well an additional participant, were then asked to return two months post-data collection and examine a series of point-light displays from the collected data, to determine whether individuals can identify acquaintances and themselves from the displays. Although the participants did comment on specific characteristics such as speed, walking rhythm, and arm swing degree rather than provide a general explanation for why they concluded a match, the rate of correct matches was low (between 20% to 58%), results also supported by more recent studies (e.g. Troje *et al* 2005). Interestingly, results for self-recognition were not significantly better than the results from recognition of others, find also supported by other studies such as that of Jokisch and colleagues (2006), who also found that self-recognition is view-independent, whilst recognition of others is improved in the coronal and half-profile view. This data parallel sex recognition from gait; in a study where human motion in point-light display was synthesised using measurements from 20 males and 20 females, the four participating observers were able to differentiate between male and female gait by the degree of sway of the shoulder and hip, although percentages of accuracy were not clearly presented (Mather and Murdoch 1994). From an evolutionary standpoint, ability to differentiate between the sexes may be biologically rooted, considering the biological drive for reproduction.

The low person recognition from point-light displays may stem from the difficulty of human ability to perceiving the motion but may also indicate that lay people tend to focus on a combination of overall appearance, identifiable visual cues and associated motion rather than on the motion itself, as forensic gait expert claim to do. This implicitly introduces the question of whether gait experts may have similar tendencies and be implicitly biased towards overall appearance rather than performing an objective analysis of gait. Hence, this represents another solid motive not only for conducting cognitive bias tests, but also for method validation and evaluation of the scientific foundations underpinning these methods. Therefore, the main conclusions which can be drawn from point-light display studies is that humans may possess different degrees of ability to recognise others, rather than that gait is unique or that gait can be used for individualisation; it is also important to note that such studies investigate how humans perceive motion rather than intending to demonstrate the extent of gait uniqueness. This can certainly be reinterpreted in favour for supporting the premise of accuracy in subjective, observational forensic gait analysis, but doing so abolishes the foundations of the scientific method which should rely on a logical framework (e.g. Evett 2015), and implicitly, the role and scope of forensic science altogether.

It is also important to note that gait is highly behaviour-dependent (emotions, mental state, inebriety etc.), aspect which may have a two-sided impact on analysis; given an accompanying analysis of behavioural cues from video, this has the potential to augment the discriminatory power of gait but in its absence, it may have a negative impact on video footage comparison. In forensic gait analysis, emotion effects on gait have only been examined with respect to whether lay people can identify emotions from others, yet no research has been dedicated to understanding the degree to which emotions introduce variability in gait patterns and their implication for forensic gait analysis. Birch and colleagues (2016a) for instance, published a study testing how well lay people can identify emotions from gait, whereby university students and members of the public (n=30) were asked to analyse video files of three males and three females, but did not include a test group of practicing forensic gait experts. Nevertheless, the authors of the publication conclude that the results "*suggest*" that emotions can be identified from gait, with the mention that additional research is required to understand the effects of emotions on gait and how they are actually identified (Birch *et al* 2016a), but no accompanying propositions as to how this may be conducted, or how these effects can be examined with respect to gait inter- and intra-individual variation. Considering the paucity of data in this regard, it may be worth considering a more thorough investigation of how emotional cues can be interpreted, thus not only improving current forensic gait analysis methods, but also understanding the perpetrator and the criminal context, resulting in a more accurate reconstruction of past events and implicitly contribute to improved approaches to crime.

As such, at the present moment, gait analysis as performed by forensic gait experts fails to satisfy the main requirements of an identification method, which are: solid knowledge of how unique the trait used is (scientific knowledge), the level of variability of gait features in a given population, standardised gait features used consistently by experts, and appropriateness of the method forensic cases. These requirements form some of the main underpinnings of reliable expert testimony (Risinger 2007). Different forensic methods can yield different degrees of individual differentiation and the purpose is to clearly define what those are, prior to employing the respective method in the courtroom. The presumption that a forensic method is fit to be utilised in human identification should be directly dictated by the potential of its constituent features to differentiate one individual from another, rather than solely on the extent of professional experience in applying the said method, its ease of use, technological appeal and so on. Such characteristics should be considered secondary only to strong empirical evidence of its scientific foundations, as defined by the scientific method; regardless of the many quality assurance guidance documents and accreditation schemes (which may or may not be useful depending on how they are presented), any results obtained using flawed approaches and assumptions will be inherently invalid. Deviation from a scientific approach, as evidenced by a vast number of international guidance and accreditation documents, academic literature, and published case reports, can have serious consequences on civil liberties. Examples are vast and include not only the recently demoted field of bitemark analysis, but also the investigation of methods of more established forensic sciences such as fingerprint analysis. The latter discipline has demonstrated, through a large number of studies on cognitive bias, that even disciplines with significant history in forensic practice are fallible, a known aspect in the general sciences for over 40 years (e.g. Tversky and Kahneman 1974).

Rather than adopt a mistrustful or defensive perspective regarding the status of forensic science or of a specific discipline (e.g. Rosenstein 2018), both the scientific and legal communities should support the testing and validation of new and established forensic disciplines alike and make a stronger contribution to developing a forensic research culture (Koehler and Meixner 2016; Mnookin *et al* 2011) where science is at the centre (DesPortes 2018; Morgan 2018). Likewise, a more balanced and robust relationship should be established between the scientific and legal communities to ensure that the definition, development, and implementation of current and future forensic methods is achieved in a manner which ensures transparency, effectiveness and efficiency. The UK forensic system for example, has taken an important step forward in scientific-legal communication with the publication of the forensic gait analysis primer (and the DNA primer) by providing the court with accessible documents which succinctly discuss methodological utility and associated limitations. However, this advantage is somewhat undermined by the leeway offered to law enforcement in making decisions regarding the type of evidence to be collected and analysed from a crime scene (Tully 2018) and in processing certain types of evidence such as digital evidence (Collie 2018). Although only a selection of items from a crime scene will have evidentiary value, all will nevertheless have varying degrees of value for reconstruction of events. Perhaps this is one of the explanations for why only a small number of cases bearing forensic evidence reach the courtroom to be debated (Home Office 2016; Government Office for Science 2015; Tully 2018), an additional problematic subject which warrants further investigation. Solutions to such circumstances appear simple and evident, although the practical means of achieving them are much more complex and can only be resolved through communication and collaboration amongst all involved parties to developed transparent, and implementable alternatives (Coyle 2018; Morgan 2018; Roberts 2012). Given that, as it stands, forensic gait analysis may be employed for evidentiary purposes in any one of the small number of cases reaching UK courts, this thesis intends to contribute to a greater understanding of the physiology of gait for identification purpose (Aim 1) by providing a biomechanical basis for the utility of gait for individualisation (Aim 2), and extend the theoretical foundations of current methods (Aim 3), thereby implicitly promoting future testing of the claim of uniqueness on a more extensive scale.

2.3.4 Method Validation

As previously discussed, the collective paradigm observed in the forensic gait analysis literature is that the field is an established forensic science, has a defined protocol, has been used in court successfully, and the experience of the practitioner is sufficient for conducting the analysis (e.g. Birch *et al* 2013b, Nirenberg *et al* 2018). The negative aspects of such claims in the absence of experimental evidence were deemed universally problematic by Mnookin *et al* (2011) who discussed how forensic sciences should move toward a 'culture' founded on sound scientific principles, methodological transparency, quantifiable error rates, mitigation of cognitive bias, and continuous professional constructive criticism. Method validation is one evident solution to building robust techniques that would serve the justice system in the most competent manner from a scientific viewpoint and, in theory, it is (generally) recognised as indispensable for transparent and fair trials (Forensic Science Regulator 2015; 2017; 2019a,c). In countries with an adversarial system such as the UK and the US, much of the practical aspect of the decision-making process with regards to the type evidence that is admitted in a trial remains at the latitude of the judge. Therefore, it is imperative not only to bridge collaboration between the judiciary and the forensic scientists, but also to improve upon and resolve disagreements within scientific communities. Considering that evidence admissibility guidelines do not necessarily reflect those which regulate the practice of a particular discipline (and vice versa), amendments to current approaches are required.

An attempt at method validation in forensic gait analysis was recently conducted by Birch and colleagues (2019). The purpose of the study was to investigate the repeatability (i.e. same participant on different occasions) and reproducibility (i.e. results of different participants for the same data) of the Sheffield Features of Gait Tool (Table 2.6, pg.45), the first study to test actual methods employed in forensic gait analysis casework; as stated in Section 2.3.2 of this chapter, the Sheffield protocols have only been briefly mentioned before this publication, with no others explicitly presenting the protocols. Fourteen participants completed the full study (recent graduates of the School of Health Sciences, University of Brighton), who have not previously utilised the tool or received training, nor conducted forensic case work, nor had any experience in forensic gait analysis; the approach was considered appropriate by the authors since "*there is currently no requirement for a person wishing to undertake gait analysis in the forensic context to undergo training prior to embarking on casework*" (Birch *et al* 2019, pg.2).

Table 2.6 – Four Sections of the Sheffield Features of Gait tool
(taken from Birch et al 2019)

A1	symmetrical gait			
A2	asymmetrical gait			
A3	erratic gait			
	symmetry of gait could not be determined			
B1	no significant rolling of the head and torso			
B2	rolling of the head and torso			
B3	rolling of the head and torso, more to the right on right steps than to the left on left steps			
B4	rolling of the head and torso, more to the left on left steps than to the right on right steps			
	frontal plane motion of the head and torso could not be determined			
B5	no significant yawing of the torso			
B6	yawing of the torso, right side forwards on left steps, left side forwards on right steps			
B7	yawing of the torso, right side forwards on right steps, left side forwards on left steps			
	transverse plane motion of the torso could not be determined			
B8	vertical movement of the head and torso on each step			
C1	head held approximately in line with the midline of the torso in the frontal plane			
C2	head held tilted to the right relative to the midline of the torso in the frontal plane			
C3	head held tilted to the left relative to the midline of the torso in the frontal plane			
	frontal plane alignment of the head could not be determined			

Table 2.6 presents the first four sections of the Sheffield Features of Gait tool, as shown in Birch *et al* 2019. These first four sections are part of a total of 15 sections containing 113 gait features, not presented in the publication.

The participants were presented with footage in the form of modified, computer-generated avatars produced using three-dimensional motion capture data from a single human subject. Six pieces of footage of approximately six seconds displaying different avatars were constructed based on the motion obtained from the single human subject; each avatar presented a different version of walking, with different gait features but identical clothing, oriented from the left side, frontal oblique view; the choice for this view angle was argued by the authors to be a typical view found in forensic casework. A pair of these six avatars were then assigned randomly to participants on six separate occasions spaced one week apart and accompanied by the full Sheffield Gait tool which consists of 15 sections containing 113 gait features. The repeatability scores of the participants, avatar and Sheffield tool sections were then calculated for all 14 participants. The lowest repeatability of the tool was observed for features related to the frontal view of the torso, whilst the highest was observed for arm swing. The latter is in accordance with a previous study by Birch and colleagues (2013a) in which the authors suggest that the upper limb produces higher identification rates. For reproducibility however, only four participants completed analysis of all the six avatars, and the accompanying scores were 84.72% (highest) and 63.19% (lowest) (Birch *et al* 2019). In this case, highest reproducibility was observed for ‘base of gait’ features and the lowest for ‘knee at heel strike’ feature. Although the use of avatars is suitable in the sense that the method is solely focusing on the identification of features, there are other aspects which require further testing. The applicability and efficiency of the tool requires validation in actual casework, where video footage presents additional challenges to the gait analysts such as poor lighting conditions, obscuring of certain bodily regions, and position of the individual with respect to the camera (including both body sides). In addition, a higher number of participants is required to test tool reproducibility and implicitly, those participants should be practicing forensic gait analysts. However, at present, the features employed in the Sheffield tool have no fundamental scientific basis to justify their use.

An earlier method validation attempt was also made by Birch and colleagues (2013a) to test accuracy rate of identification by gait, yet it did not specifically employ the Sheffield protocols; although the pool of participants (n=7) for the study included three analysts which had "*some engagement with forensic gait analysis, none were engaged in this area of work as their core professional practice*" (Birch *et al* 2013a, pg.340). Participants were asked to view video clips of 'suspect walkers' and 'target walkers' and determine whether the suspect is a match for the target walker, producing accurate matches 124 out of 175 times (Birch *et al* 2013a). However, despite the small number of participants and the absence of practicing forensic gait experts, the conclusion drawn by the authors was that the study "*provides evidence that individuals with experience in visual gait analysis are consistently able to identify individuals by their gait"* (pg. 342). In addition, the authors also state that *"better rates of correct identification are achieved by experienced analysts than by inexperienced…*[which] *supports the continued role of experienced gait analysts as expert witnesses in criminal proceedings"*(pg.342). As cited in the article, the authors base the latter conclusion on the findings of another study by Stevenage and colleagues (1999) who investigated the ability of lay people to identify others by their gait. However, the sole conclusion which can be drawn from these two studies is that individuals with some experience in forensic gait analysis may perform better than lay people, since Birch and colleagues (2013a) clearly state that none of the participants in their study were practicing forensic gait analysts. Furthermore, Stevenage and colleagues (1999) tested the visual ability of lay people in identifying others, not a specific method employed in forensic gait analysis applied by individuals trained in gait analysis; in addition, only 24 out of a total of 48 observers matched the unknown and known walkers correctly. This aspect was somewhat clarified in a recent study by Birch and colleagues (2020) who compared the aptitude and degree of confidence of gait analysts with and without experience to conduct analyses and comparison of gait features from video. Interestingly, the results showed no statistically significant differences between experienced and non-experienced analysts with respect to the number of correct identifications but that non-experienced analysts made more false-positive than false-negative identifications and experienced analysts made more false-negative than false-positive identifications (Birch *et al* 20). These findings are of paramount importance to forensic gait analysis as a field of study, since these bring into question the role of the forensic gait analyst as an expert witness, in court. Therefore, the foundational basis for claiming that experienced practitioners should continue their role as expert witnesses is unsupported and requires further investigation to elucidate the reasons for these results. Whilst the higher level of confidence in non-experienced analysts may be justified given their unfamiliarity with the methodologies employed and their associated limitations, the small differences in the number of correct identification decisions may indicate fundamental flaws in the methods employed, inherent issues with the training of the experienced gait analysts, or both.

Additional aspects are also raised from the study of Birch and colleagues (2013a), where the lowest identification score was achieved by participants who focused on the lower body (64%), whilst the highest score was obtained by one participant who mainly used upper body features to perform the identification (80%). No mention is made as to why this one participant performed better using upper body data, and no physiologically founded discussion is provided as to why the upper body may be more useful in identification, hence the approach to investigate both upper and lower body joints in this thesis. Also, according to the definition provided by DiMaggio and Vernon's book published in 2017, the forensic gait analyst is one who operates under the remit of podiatry (DiMaggio and Vernon 2017), which is a field that mainly concerns the lower limb. However, a review also published in 2017 concisely described that "*the Forensic Podiatrist will take a holistic view of the whole body and how movement, position, structure and function of other areas of the body affect the functioning foot, and again vice-versa*" (Burrow *et al* 2017). In contrast, the Forensic Gait Analysis Code of Practice and the primer for courts, state that "*forensic gait analysis is the analysis, comparison and evaluation of features of gait to assist the investigation of crime"* (The Royal Society 2017a, Forensic Science Regulator 2019a). Amendments to definitions, methods, and interpretation strategies in light of new research are necessary to ensure good practice and should be at the core of all forensic sciences since legislations demand keeping the expert testimony within one's area of expertise (Ministry of Justice 2020). However, as it currently, stands, the code of practice is vague and generally present similar lists and descriptions to DiMaggio and Vernon's book (2017). Neither does it present nor suggest specific criteria for empirical studies to examine the scientific foundations of forensic gait analysis nor does it question in sufficient depth current methods applied in the field. Hence, further clarifications are required regarding the definition of forensic gait analysis, the qualifications required of the expert, expertise limits of the gait analyst, methodological validation other than with black-box studies (which are nevertheless insufficient to determine how experts reach 'correct' conclusions (e.g. Champod 2014)), and suggestions regarding investigation of the scientific foundations of the field. Likewise, a new issue on image comparison for prosecutors and investigators from the Forensic Science Regulator is also needed, since the one in current use does not include any details on image comparisons in gait analysis (Forensic Science Regulator 2016b).

2.3.5 Cognitive Bias

Cognitive biases, or unintentional errors in data interpretation due to the brain taking 'short-cuts' to reduce information processing (House of Parliament 2015; Stammers and Bunn 2015), are major factors of concern widely discussed within the forensic science and legal communities (Cooper and Meterko 2019). As emphasised in the 2016 PCAST report (PCAST 2016), this is of special importance in subjective, pattern-matching methods (as is forensic gait analysis), where expert judgement is heavily relied upon. Human decisions are cognitively dissonant and hence biased due to prejudices arising from professional training, work environment, experience, case context information and reference materials, and the evidence itself (Zapf and Dror 2017), more so when there is paucity in the fundamental science upon which the forensic science field should rest. Recommendations across a variety of forensic disciplines have been made for several years now regarding methods of reducing the subjectivity of data interpretation, such as hypothesis and analysis plan formulation prior to evidence examination, reducing irrelevant case information, and peer-review (Cole 2013b; Dror and Hampikian 2011; Elaad 2013; Haber and Haber 2013; Heyer and Semmler 2013; Mattijssen *et al* 2016; Roberts 2017; Stevenage and Bennett 2017; Triplett 2013), amongst many others, as discussed throughout this chapter. As previously stated in Section 2.2.1, forensic gait experts reportedly use the ACE-V(R) approach whereby the expert first analyses the original footage, followed by the reference footage obtained of the suspect (DiMaggio and Vernon 2017). As described in DiMaggio and Vernon's book, the ACE-V procedures include (i) general observations to describe the conditions and context of the footage, and (ii) a thorough evaluation of the unknown and known footage to identify and document gait that is characteristic of a pathology or simply the features of gait by playing the video at slow and fast speeds and documenting observations for each frame of the video. However, there is little evidence in the scientific literature to demonstrate that critical evaluation of current gait analysis protocols has been conducted, despite the debates on cognitive bias and the 'correct' development of satisfactory protocols for collecting, analysing, and interpreting data (Mennell and Shaw 2005). Also, only a few formal case reports have been published to explain and critically assess how and whether a particular protocol was effective (e.g. DiMaggio and Vernon 2017, pg. 319; Larsen *et al* 2008b).

As detailed in the previous section, only a small number of experimental studies have been published in forensic gait analysis which seek to imply good method reliability (e.g. Birch *et al* 2013a, 2014, 2015, 2016a,b), although other experts who have applied gait analysis techniques in the field refute the claim altogether that gait-based expert evidence is sufficiently reliable for forensic use (e.g. Iwama *et al* 2013; Larsen *et al* 2008a,b). The error rates presented in this small number of studies should be interpreted with caution because the sample number is predominantly very small, the data are not analysed based on a standardised analysis protocol (or no explicit analysis protocol at all), experimental conditions are insufficiently tested for cognitive bias or other sources of error, and the methodological approaches are not fundamentally based on the scientific method. Therefore, it is unknown whether the error rates presented are due to the training of the practitioner, inherent flaws of the analysis protocol, or whether there is an issue in the assumptions on which the method is based (Dror 2013; Kassin *et al* 2013; Martire and Kemp 2018; OSAC Human Factors Committee 2018). Although a challenging endeavour to separate each one of these potential sources of error (Dror and Charlton 2006), neither has been explored in any level of detail to date; therefore, this thesis aims to fill some of the current gaps by investigating assumptions of gait-based methods. It is also very challenging to provide solid comments on currently employed forensic methodologies since those provided in peer-reviewed publications are vague and unclear. As a result, constructing study designs to test methods employed in casework cannot be achieved.

The same issue is present in the sole textbook which provides details on forensic gait analysis, published by two established podiatrists (DiMaggio and Vernon 2017). A second book focusing solely on forensic gait analysis by Haydn Kelly, claiming to provide details on current methods was due to be published in 2017, yet an online search of the item produces an 'out of stock' response on various websites, and appears to be absent from the intended publisher's website (i.e. CRC Press). Therefore, in-depth information for academics outside the field or practice is unavailable.

In March 2018, a review article has been published (Nirenberg *et al* 2018) in which the authors acknowledge the challenges discussed in the forensic gait analysis primer and throughout this thesis chapter, agreeing that further research into protocol design and expert training is required to ensure that methods are used and applied according to the robust standards required by forensic science and by extension, the court. However, there is persistence in attempting to prove that as it stands, forensic gait analysis should not fall into disrepute just because it lacks these standards, and the authors appear to adopt a view that evidence should not necessarily be scientific, rather, it should be "*sound*" evidence (Nirenberg *et al* 2018). Considering how forensic science has changed with time, this perspective is one from which the academic community has attempted to move away (Mnookin *et al* 2011; Morgan 2017a), precisely to improve the 'science' and by extension, to be able to provide stronger, more reliable evidence. The premise should be to empirically test methodologies given new technology, make use of appropriate statistical tests to support conclusions, publish case reports which describe the utility of both new and existing methods of forensic analysis, and reflect and mitigate cognitive biases (Dror 2017; Dror and Cole 2010; Morgan 2017b). For instance, while completing a project on human–robot interaction, an undergraduate student at the Massachusetts Institute of Technology (MIT) discovered racial bias in a generic facial recognition algorithm which failed to recognise individuals of African American ancestry; when interacting with the robot which was equipped with a camera and a facial recognition software, the incorporated algorithm failed to identify the face of the student, and implicitly, her presence (Buolamwini 2017). A similar issue is present (though yet to be acknowledged) in gait recognition studies, where data are predominantly obtained from small number of participants (notable exceptions are the Osaka University datasets, although the population is largely of Asian ancestry), usually adult males of 20–35 years of age with 'average' height and weight, with unreported ancestral background (e.g. Al-Tayyan *et al* 2017; Li *et al* 2018; Yu *et al* 2017). However, even with large datasets, no extrapolations can yet be made regarding how and to what extent are these algorithms designed to process human variability, how their design influences the decision-making process of the biometric system and to what extent other human cognitive biases are inadvertently introduced into their design. Some of these aspects are explicitly discussed in a document drafted by the Science and Technology Committee published by the House of Commons, with respect to automated face recognition, and serve as the basis for recommending "*action on the governance and oversight of both forensics and biometrics. . .* [because these] *underpin essential confidence in the administration of justice*" (House of Commons Science and Technology Committee 2018a).

As discussed in Section 2.2.2, high levels of objectivity are possible when developing and testing methodologies especially if multiple hypotheses are drafted before the evidence is analysed, and the expert seeks to refute (rather than confirm) the hypotheses which they inadvertently favour (pre-conceived opinions), thereby contributing to transparency in the decision-making process and a reduction in confirmation bias (Dror *et al* 2006; Heuer 1999a,b; Kukucka *et al* 2017; Simon *et al* 2001). If irrelevant information is also removed (reducing contextual bias), a stronger quality assurance protocol through peer review can be implemented, thus allowing stronger evaluation of available data (Ballantyne *et al* 2017; Dror and Rosenthal 2008). In addition, reflection on prevention of methodological failure rather than solutions for failures after the fact, combined with continual self-critique, can stimulate the mind to reflect on alternative perspectives, improve performance and prevent over-confidence (Heuer 2008). Such examples of approaches challenge the expert to think in ways other than those in which they are accustomed and instil a greater sense of self-critique which reduces the tendency of the brain to take cognitive 'short-cuts'. To improve the legal and scientific standing of forensic gait analysis, approaches such as these should be implemented in a manner most suitable for efficient and effective forensic application.

2.4 The Gait Expert Witness and Boundaries of Practice

2.4.1 Published Casework

The first case to report use of expert-based gait evidence in the courtroom was that of *R v Saunders* in 2000 in the UK, although it was not until 2011 that the admissibility of this kind of evidence was brought to a broader attention after it formed the grounds of an appeal in *R v Otway* (DiMaggio and Vernon 2017). The evidence given by the expert witness withstood the admissibility 'test', and was accepted despite being qualitative in nature, with no empirical support for the applied method and for the conclusions drawn. By definition, an expert is one who not only possesses practical (including tacit) knowledge, but also the necessary qualifications which serve as 'authentication' of this knowledge, and who provides expert opinion on evidence pertinent to their field of expertise (Forensic Science Regulator 2019c; The Crown Prosecution Service 2019). In addition to academic contradictions on the definition of forensic gait analysis previously discussed in this chapter (now superseded by the code of practice), there also seem to be unclarities regarding the remit and nature of the expertise, which so far, has only been presented in DiMaggio and Vernon's book and, most recently, (albeit much more vaguely), in the code of practice (Forensic Science Regulator 2019b). For example, DiMaggio and Vernon (2017) state that the gait expert witness is not to discuss or employ debatable or unvalidated methods and be cautious with respect to present limitations, recommendations which are contradictory both to other statements made in the chapter but also other published work. This contrasts a discussion on a case (R v Ferdinand and others 2014), where the experts seem to agree with the court perspective that there should be "*support* [of] *the role of professional experiences as opposed to solely scientific approaches to forensic podiatry practice*" (DiMaggio and Vernon 2017, pg. 207). Furthermore, the judge of the aforementioned case also stated that, as long as the court can observe the features highlighted by the expert witness, there is no specific need to explain how the quality of the footage is assessed, despite defence objections regarding the poor quality of the images (R v Ferdinand and others 2014). Although the UK legal system has long since dismissed the value of expert witness testimony based solely on experience (more in theory than in practice), principles remains ambiguous in the case of forensic gait analysis, since expert testimony of this nature has been accepted in court as 'forensically valid' evidence. What is also interesting is that Birch and colleagues (2013b) state the "*gait analysis from closed circuit camera footage is now commonly used as evidence in criminal trials*" (pg.915). Considering that no other case reports have been published to date (absent also in the Forensic Gait Analysis Primer for Courts where it is reasonable to assume that these would have been included), this statement is contradictory from two perspectives. Firstly, if gait evidence is indeed 'commonly' employed, then the rest of academic community is left in the dark since no academic publications are available to provide detail on this aspect. Secondly, it adds further concern to the premise of regulating the forensic validity of gait evidence, especially since the statement is unclear regarding whether the evidence has reached the courtroom and has been debated or whether the evidence was utilized in a case presentation where the suspect settled for a lesser sentence and/or admitted their guilt. It is therefore unclear where, how and to what extent gait as evidence has increased in criminal trials.

Prior the R v Saunders 2000 case, gait expert evidence was an unknown in the legal arena. Rather than following systematic steps of foundational and methodological testing for validation and recognition in the peer-reviewed scientific community, forensic gait analysis appears to have become a forensic science field because of this first case in which it was applied. Only a small number of articles appeared in the scientific literature, albeit their questionable analytical frameworks, small sample size, absence of control groups, and lack of accounting for observer bias, amongst other limitations. Nevertheless, accuracy of identification is reported to be as high as 79% (Birch *et al* 2013a), and caution as to the applicability of gait-based evidence is mentioned only in some (e.g. Larsen *et al* 2008a,b). Moreover, as previously stated, gait analysis is highly sensitive to multitude of factors, ranging from the video camera position and angle (Zhang and Troje 2005), to the video quality, frame rate and duration (Matovski *et al* 2012) and to factors associated with the individuals appearing in the footage. For the latter, variation is highly dependent on the context of movement speed such as walking or running, a long-known aspect (Kirtley *et al* 1985), movement type such as picking up or dropping objects, and emotional and behavioural influences (Yingliang *et al* 2006). These are further complicated by inherent physiological differences, including age, sex, height, weight, and overall body proportions. These differences have not been adequately addressed with respect to the threshold at which analysis and interpretation become difficult and to what extent. In the absence of systematic criteria, reasons as to how and why analysis is affected, remain vague, with no valid options of resolving these effects adequately discussed in the literature.

Gait analysis has also been used as evidence in court in a 2005 case in Denmark concerning a bank robbery, when the police requested this type of expertise because the perpetrator was disguised and they "*thought that* [he] *had a unique gait*" (Larsen *et al* 2008b, p.1149). The robbery recording was obtained via two cameras, one of which was located at the entrance to the bank and the other behind the cashier desk. The recordings of the former were used to analyse the suspect's gait, as it gave a frontal view of the perpetrator's movements, entering, committing the crime, and leaving the bank; the camera behind the desk was not placed sufficiently strategic to allow gait analysis but was used to obtain body measurements (i.e. photogrammetry technique) such as stature, eye-level height, and shoulder-level height. The robbery recording was analysed first, according to a protocol the experts devised which was based on a detailed physiological description of the entire body of the perpetrator (e.g. body angles, relative rotations of certain body regions associated with gait etc.) and on the aforementioned measurements. The experts then compared these recordings with additional recordings of a suspect obtained by the police which led them to the conclusion that there were some similarities between the two sets of recordings, which included "*restless stance, anterior positioning of the head showing a neck lordosis and inversion of the ankle joint*" (Larsen *et al* 2008b, p.1150).

However, the robbery recording was short, the perpetrator had his hands in his pockets which created an abnormal shrugging posture, and the feet were partially obscured; nevertheless, the suspect had a limp which was concluded to be a match to that of the perpetrator, despite the experts having based the quantification of this variability on a previous study with only 11 participants. The experts concluded that besides the limp, there were insufficient characteristics for a stronger analysis to be performed, acknowledged that the analysis they conducted cannot establish the identity of the individual and stated that they did advise the court of this matter; nevertheless, the suspect was still found guilty. This is another aspect to consider when determining whether evidence based on unfounded scientific principles should be admissible; regardless of whether the expert outwardly declared the limitations of the method, the court still made a decision based on this evidence. In the haste to bring the guilty to justice and close a case, the court has a tendency to accept 'second-rate' evidence in situations where no other evidence is available (i.e. the best available evidence suffices (e.g. Smith and Bull 2014)). Therefore, cooperation between the forensic scientist and the court cannot be overstated: it is necessary for the scientist to be able to refuse to present evidence in court if the method is weak, and for the court to have all the necessary information (e.g. documents such as the UK primer for courts) to confer appropriate weight to the evidence (van Asten 2014). Therefore, cooperation and collaboration between the legal and scientific arenas and between different scientific disciplines, are indispensable for ensuring transparency from all involved parties throughout all stages of the forensic science process (including access to materials through post-conviction disclosure for appeals (McCartney and Shorter 2019)), to ultimately ensure fair trials (Evett *et al* 2000; Passalacqua *et al* 2019).

2.4.2 Admissibility of Gait Evidence

Whilst visual analysis is not a weak method within itself, conclusions should not be considered of much scientific use in the absence of a systematic way which describes how the analysis criteria are applied. For example, forensic anthropology is a field largely based on visual, subjective analysis which heavily relies on the aptitudes and experience of the expert. However, the discipline benefits from ongoing research in defining and clarifying the scope and boundaries of practice, method validation and development (Macoveciuc *et al* 2017), population-based adaptations of current methods, cognitive bias studies, and interdisciplinary collaborations such as virtual assessment of skeletal remains (e.g. Francisco *et al* 2017; Nakhaeizadeh *et al* 2014; Nakhaeizadeh *et al* 2020; Urbanova *et al* 2017). It is therefore unsatisfactory to state that one aspect of a competent forensic gait expert is to make use of 'appropriate methods' (DiMaggio and Vernon 2017) in the absence of an adequate basis for the said methods. Divergence of opinion is inherent in all forensic sciences, but more so in those based mainly on untested, qualitative principles, since it is difficult for experts to unanimously agree on characteristics which largely depend on their observational capabilities. Such disagreement can only be reduced (certainly not eliminated) through development of mandatory and transparent, protocols to govern the processes of knowledge-building, data collection, analysis, and interpretation, founded upon collaborative engagement (Ross 2015). Considering these matters in association with the paucity in cognitive bias data, courts should be much more reluctant in accepting gait-based expert witness evidence of this kind, especially since it contradicts the core requirements of validity and reproducibility of data, as applied in most of other forensic science evidence types (Lord Thomas 2015). Criteria of admissibility of evidence in the courtroom are and should remain complex, especially in cases pertinent to new technologies, methods and/or fields of study. However, this complexity should only refer to the rigor of method testing for ensuring high-quality results, and implicitly, of evidence (O'Brien *et al* 2015) rather than to imposing unnecessary difficulty in the evidence admissibility process. If one is to consider, at least in theory, the purpose of the legal system, both overcomplication and oversimplification of this process can lead to similar results of injustice. For instance, forensic gait analysis has seen substantial contribution from fields other than that under which it is classified, especially computer science; paradoxically, only a very small contribution has originated from the forensic sciences. Instead, research has been centred around the development of algorithms for the advancement of gait analysis as a biometric technique without concomitantly developing forensic methods for the courtroom.

To successfully meet evidential criteria and ultimately achieve their intended purpose, the forensic sciences should work towards stronger cooperation in planning and formulating quality assurance protocols, develop and/or expand existing training programs, and strengthen collaboration between the scientific and legal communities to improve information exchange, matters discussed (amongst many others) in various governmental documents published over the years in the US and UK. The concern, as with any forensic science, is not that there is not 'enough' research being done *per se*, but rather *how* it is done; the purpose of evidence delivery in court should be to demonstrate proficient knowledge of the accuracy and precision of a method given its present scope and boundaries rather than the presentation of an inexistent, 'perfect' method (Christensen and Crowder 2009). Considering the current state of the discipline, courts should remain cautious when accepting gait evidence, as they should be with any type of evidence obtained using untested methods with unquantified error rates, unregulated by a detailed code of practice without statutory powers and without clear applications in forensic contexts, as highlighted by Rt Hon Sir Brian Leveson (2015) well before the publication of forensic gait analysis code of practice.

Further research should also be extended to court/jury perceptions of evidence, and the expert witness, particularly in light of the multitude of television programmes portraying an unrealistic picture of what forensic science can achieve in practice. With 101 participants and a well-balanced male to female ratio, the results of a recent study by Ribeiro and colleagues (2019) who examined jury beliefs regarding the degree of human judgement input and error rates at every step of 16 different forensic techniques (including DNA and fingerprint analysis), highlighted that individuals are generally aware of the potential of errors in forensic science and consider that human judgement is extensively employed throughout all stages of the process. It is important to note that only 16 out of 101 participants served as jurors prior to the study being conducted. The perspective presented by Ribeiro and colleagues (2019) has been previously validated in a similar study by Smith and Bull (2014) who highlighted that the majority of their study participants (200 in total) were less likely to deliver a conviction in cases where there was lack of evidence. Rather, the participants were more likely to convict if there was weak, but nevertheless present evidence (a similar occurrence in the case of the bank robbery in Denmark discussed in Section 2.4.1), especially if their beliefs rested heavily with the prosecution from which the evidence originated in the given scenarios (Smith and Bull 2014).

One potential limitation to the aforementioned studies is the lack of realistic expectations of most participants regarding the associated pressures to establish innocence of guilt given the available or absent evidence. However, the criticism of jury perception research which does not involve actual jury members (e.g. Thomas and Balmer 2007; Wilcox and NicDaeid 2018) should be approached with caution and deeper reflection should be conferred towards the research questions driving the respective studies. Evidently, an experienced juror will have a different outlook when making a judgement about the credibility of an expert witness and implicitly, the strength of evidence (Wilcox and NicDaeid 2018), but experience will not necessarily have an impact on one's prejudicial characteristics which can be tested equally accurate in individuals who have not acted as jury members. In a two-part study by Hernandez and Preston (2013), the impact of belief on information processing has been tested to determine whether preconceived political beliefs have an impact on how individuals perceive new information and whether verdicts in a mock trial are affected by the degree of fluency of the presented case and evidence. The study has highlighted that individuals are less likely to convict if the summary of a crime is disfluent, based on the presumption that there is a higher engagement of the cognitive processes to understand the presented summary, leading to a more accurate assessment of the case and therefore, a decreased chance to deliver convictions. This is an interesting premise regarding how current expert witness report and statements are prepared for the court, and how the expert witness prepares for their appearance in court.

Nevertheless, inappropriate pooling of participants in such studies may introduce bias which will incorrectly reflect trends of a juror population, as may the failure to include both prosecution and defence expert witness reports, as indicated in a study by Wilcox and NicDaeid (2018) who investigated juror opinions of expert witness credibility. Nonetheless, the challenge for jurors and the court to evaluate expert witness credibility and implicitly differentiate between strong and weak evidence, is a matter with which the judicial system should concern itself by ensuring that the participating legal actors in a trial are prepared and adequately informed of current research and its limitations. This is of special concern for the forensic sciences which make use of likelihood ratios such as DNA analysis; whilst the in-depth mathematical aspects are of no concern for the court, the jury should be made aware of their utility in evidence delivery as well as of the difference between an expert's best evaluation of the evidence and an expert's attempt to deliver faultless evaluation of the evidence by presenting the likelihood ratios as absolute truth (Gittelson *et al* 2018). Interestingly, social psychology research of a non-forensic nature has highlighted that individuals tend to categorise clearly written textbooks as "simplistic" and consequently, of a lesser quality and persuasiveness than those which appear more complex (Galak and Nelson 2011). This is a crucial aspect to consider with respect to expert credibility both in the verbal and written delivery of the evidence, as well as the fluency of the delivery. Jurors should also be informed of the main aspects of cognitive bias which can affect the experts as well as themselves, and how to interpret the difference in logic between solving a problem and explaining a fact (Pelillo *et al* 2015). Hence, an overreliance of juror decision-making on the professional experience of the expert witness is a potentially dangerous precedent in the absence of a clear presentation of the governing guidelines of the expert's respective field, which is why forensic gait analysis imperatively requires further research.

However, it is often argued that the subjective forensic sciences cannot incorporate a strict set of guidelines to drive the methods of analysis, evaluation, and interpretation due to the heavy dependence on human judgement to conduct these processes. It is also argued that such disciplines cannot be validated except through black-box studies which would examine expert performance; nowhere is it stated or proposed that subjective methods require foundational testing of the knowledge on which the discipline is built. As recently observed with bitemark analysis which also falls into this category, there are serious pitfalls to this approach which can lead to complacency and, in the long run, miscarriages of justice. Although there is paucity in data regarding the frequency with which forensic gait analysis is employed in the courtroom worldwide, there appears to be increasing interest in accepting the field as a 'valid' forensic science, at least in the UK, with the publication of the code of practice (Forensic Science Regulator 2019b). Based upon the contents of this code of practice, it is difficult to see the potential in it driving future improvements in the field for extrapolation in practice.

On the same note, research into academic peer-review has also discussed the shortcomings of current systems, the most evident one being that the integrity of the submitted manuscript lies with the author, rather than with the review committee who generally operate under the assumption that the research is valid (Ballantyne *et al* 2017). This issue has been raised previously by a document of the Home Office in which recommendations are made regarding the need for the Forensic Science Regulator to "*encourage appropriate journals to establish independent robust peer-review processes for their publication*" (Silverman 2011, pg.3) For the courts, this validity uncertainty can have serious implications, which is why the primers for court are paramount in ensuring that the judiciary members are properly informed by a team of established forensic experts regarding current literature on forensic methods, and validity and accuracy of published scientific opinion (with more to follow in the future (Black and NicDaeid 2018)). To propose replication as part of publication peer-review is evidently outlandish, but the core issue is not to undertake such an approach but to instil scientific rigor at educational level in order to promote graduates with strong ethical foundations, as well as develop platforms for post-publication critical analysis. The key components required to ensure that this occurs, mirror those required in forensic casework peer-review: (i) rigorous review of current literature, (ii) solid methodologies developed using suitable research designs, (iii) appropriate analysis given the parameters of the design and methodology and, most critically in the forensic context, (iv) accurate presentation of conclusions given the extent and scope of the applied methods and clear description and evaluation of error rates. However, the challenge remains in properly defining the requirements of these components; further publications on this matter, additional to the vast number of 'guidance' documents already available, confuse rather than provide quality assurance (Wilson-Wilde 2018). This is of importance in the UK, where closure of the Forensic Science Services has led to a disintegrated forensic service delivery system where some services are provided by the police and some by private firms (Evison 2018). National governing regulations are mostly in the form of guidance documents provided by the Forensic Science Regulator with no statutory powers for enforcement (Tully 2018), which has, in part, led to a system where research funding is insufficient (Morgan and Levin 2019) and cost effective solutions are sought at the expense of financial and logistic investment in research, with scientific advancement and input flattened into disjointed analytical tests which miss the contextualisation of evidence (Flanagan, 2018; Resnikoff *et al* 2015; Tully 2018). Erroneous perspectives of forensic science and its associated legal proceedings are ultimately circular, whereby societal imperfections reflect the failures of the judicial system and vice versa.

Whatever the degree of practical emulation studies on jury perceptions presume in their methodological approach, the critical basis of this type of research is that it assumes evidentiary validity. Perhaps an interesting avenue would be to explore perceptions of the judiciary on biased versus non-biased expert witness reports to evaluate the degree of belief alteration (or absence thereof) with respect to strength of evidence and witness credibility. Similarly, the manner in which evidence itself is presented in court should be addressed to determine the extent to which jury perceptions may be affected by, for instance, the order in which the evidence and associated information is presented (Charman 2013). This should also be evaluated in light of the recently published primers on gait analysis and DNA to investigate their value in supporting court endeavours. However, in the absence of empirical research on the science behind employed methods, such recommendations are premature for forensic gait analysis. Prioritisation of evaluating a forensic discipline is a crucial aspect in the process towards the goal of confirming or disproving certain assumptions. Hence, the purpose of this thesis is to tackle part of the challenges in forensic gait analysis (present even in established forensic sciences) at the core, by investigating the presumption of gait feature uniqueness and the potential for individualisation through the kinematic analysis of joint angles of the upper and lower body which are most readily observed and which present potential for quantification from CCTV footage. To develop an in-depth basis for this approach, Chapter 3 presents and describes the anatomical and physiological aspects of gait.

Chapter 3 – Anatomy and Physiology of Human Gait

3.1 Overview

Chapter 3 discusses the anatomical and physiological underpinnings of human gait. Section 3.2 provides a general introduction of the accepted clinical terminology of movements which occur at the joints of the shoulder and elbow (Section 3.2.1), and hip, knee, and ankle (Section 3.2.2). For simplicity, the accepted convention is to discuss each of these physiological components in isolation, although gait involves concomitant movement of multiple biomechanical systems. Section 3.3 describes the biomechanical aspects of the gait cycle, section in which the methods of forensic gait analysis are also contextualised. Section 3.4 evaluates factors which influence gait such as sex, and age, and discusses the implications these factors may have on the analysis of gait in forensic settings.

3.2 General Principles of Anatomy

From a structural and functional viewpoint, gait is a highly complex interaction amongst multiple physiological systems, involving psychological, neurological, muscular, and skeletal input, altogether achieving spatio-temporal displacement of the body. From a biomechanical perspective however, the main physiological components on which displacement depends, are the hips, legs, and feet (Hall 2012). The motion of these joints is also accompanied (albeit secondarily) by movements in the upper limb such as in the joints of shoulder and elbow which sustain the balance of the body and contribute to the forward propelling of the body (Meyns *et al* 2013). As detailed in the previous chapter, the forensic gait analysis approach to 'identification' is described as being holistic, whereby the analyst observes and describes motion of the entire body. Therefore, in this thesis, the investigation of the utility of gait in forensic investigations will not only include biomechanical analysis (i.e. kinematic analysis) of the hip, knee, and ankle joints but also of the shoulder and elbow, all in the sagittal plane (i.e. flexion-extension and the equivalent in the foot (i.e. dorsiflexion/plantarflexion)). Whilst movements also occur at the level of the head, neck, and torso, these are difficult to quantify from video, especially in the case of lower quality CCTV and will not be discussed. Despite this, a holistic investigation of the entire body would have provided a more solid basis for investigating individuality in gait from a physiological perspective; however, this data was not available from the database utilised in this thesis (a more thorough discussion of this rationale will follow in Chapter 4 – The KIT Whole-Body Human Motion Database).

Joint motion in kinematic analysis is described in terms of rotation, translation, and curvilinear motion in the sagittal, coronal, and transverse planes which refer to standardised perspectives from which one observes and describes a body region and its associated movements when the body is in anatomical position (Standring 2008). Figure 3.1 below illustrates the human body in anatomical position and depicts the three anatomical planes of reference. The sagittal plane divides the body into right and left halves, the coronal plane into anterior (front) and posterior (back) regions, and the transverse plane into superior (up) and inferior (down) regions.

Figure 3.1 – Anatomical Planes and Directions
(modified from Standring 2008)

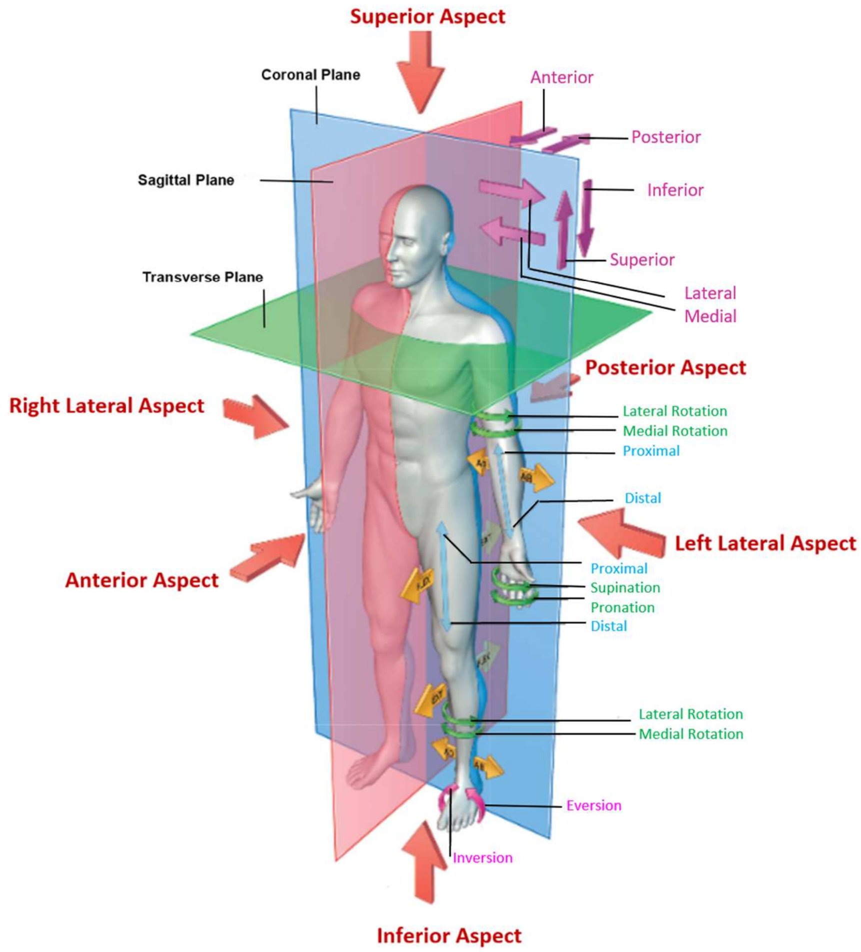


Figure 3.1 summarises the planes and directions used to describe human body anatomy. The body can be divided in the coronal, sagittal or transverse planes. Joint motion is therefore described in terms of how the body component moves in relation to these three planes.

Associated with these planes are axes which bear the same names (i.e. sagittal, coronal, and transverse) and which are utilised to express the nature of the joint angular motions in the form of a three-dimensional coordinate system (Figure 3.2). The coordinate system is an accepted means which physiologists, biomechanists and clinical experts use to simplify description and implicitly, analysis, in order to allow for a universal understanding across various disciplines (Wu *et al* 2002, 2005). This is, in part, due to the complex nature of the motion of joints and therefore, the need for simplification. For example, joint kinematics are defined according to whether the movement is rotational, translational, or curvilinear, whereby movement occurs around an axis, along an axis, or around and along an axis, respectively.

Figure 3.2 – Coordinate System

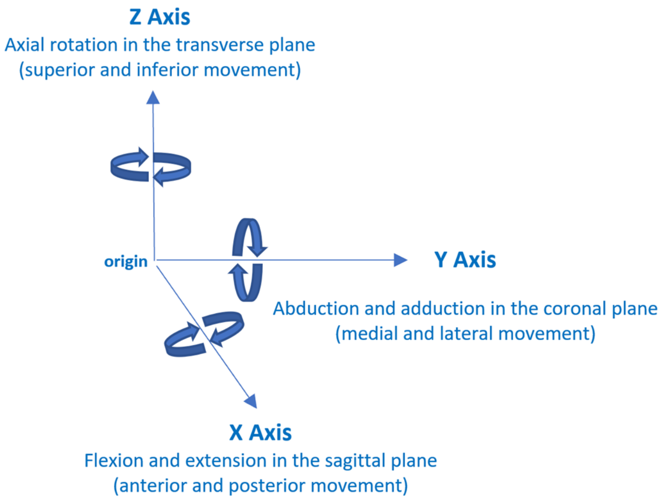


Figure 3.2 is a schematic representation of the coordinate system for movement description utilised in this thesis. The x axis represents movement in an anterior/posterior direction, the y axis represents movement in the medial/lateral direction and the z axis represents movement in the superior/inferior direction.

However, in practice, these movements do not happen in isolation; they will occur in different ways and to specific degrees depending on the joint type. This aspect is crucial for clinical practice, where physiotherapeutic or surgical treatments for medical conditions such as scoliosis (Syczewska *et al* 2012; Vergari *et al* 2015), stroke (Reissman *et al* 2018), Parkinson's disease (Rennie *et al* 2018), and multiple sclerosis (Roening *et al* 2015), require a thorough investigation of human motion. In forensic gait analysis, translational and curvilinear movements are difficult to observe and quantify in the absence of equipment fitted onto subjects of interest and therefore, have no application in the forensic context except in the form of theoretical knowledge. As a result, the focus of this chapter is rotational movement as exemplified in Figure 3.2, whereby (i) motion in the sagittal plane occurs around the coronal or x axis, (ii) motion in the coronal plane occurs around the sagittal, y axis, and (iii) motion in the transverse plane occurs around the longitudinal, z axis. Each one of the three constitutes one degree of freedom, meaning that (from a simplistic viewpoint and without taking into consideration translational and curvilinear movements) the maximum number of degrees of freedom of a joint is three.

The terminology associated with these motions are flexion-extension (dorsiflexion-plantarflexion equivalent in the foot), abduction-adduction, and axial rotation, respectively. Given that sagittal plane movements are most readily observed from video (e.g. abduction and adduction are difficult to observe in most body regions despite their utilisation in forensic gait analysis (e.g. DiMaggio and Vernon 2017)), only flexion/extension will be investigated in this thesis, whilst coronal and transverse plane movements will only be addressed from a theoretical perspective. Of note is that there are also other conventions in use where, for instance, movement around the z axis occurs in the coronal plane and movement around the y axis occurs in the transverse plane; however, such specifications remain at the latitude of the user, provided that these are well-defined throughout. For this thesis, the format of the coordinate system will be implemented as described Figure 3.2, pg.60, corresponding to the same coordinate system utilised by the researchers of the KIT database from which the dataset for achieving the thesis research aims was obtained. For the description of flexion and extension angle values in a given joint in kinematic analysis, the former is generally designated by positive angle values whilst the latter by negative angle values; a value close to zero denotes a neutral joint position, a large angle value in the positive range denotes increased flexion, and a large angle value in the negative range denotes increased extension. The same principles are applicable to the foot, whereby dorsiflexion is represented by positive angle values and plantarflexion by negative values.

3.2.1 Upper Limb Motion

From physiological perspective, the upper limb is composed of the upper arm, lower arm and hand, defined according to the three major joints which provide movement namely, the glenohumeral joint (shoulder) which connects the entire limb to the torso, the elbow joint which connects the upper arm with the lower arm, and the wrist joint which connects the hand with the lower arm (Figure 3.3). The shoulder joint is one of the most flexible joints in the body due to the largely soft tissue-based connection of the arm to the torso.

Figure 3.3 – General Upper Limb Anatomy
(modified from Drake et al 2009)

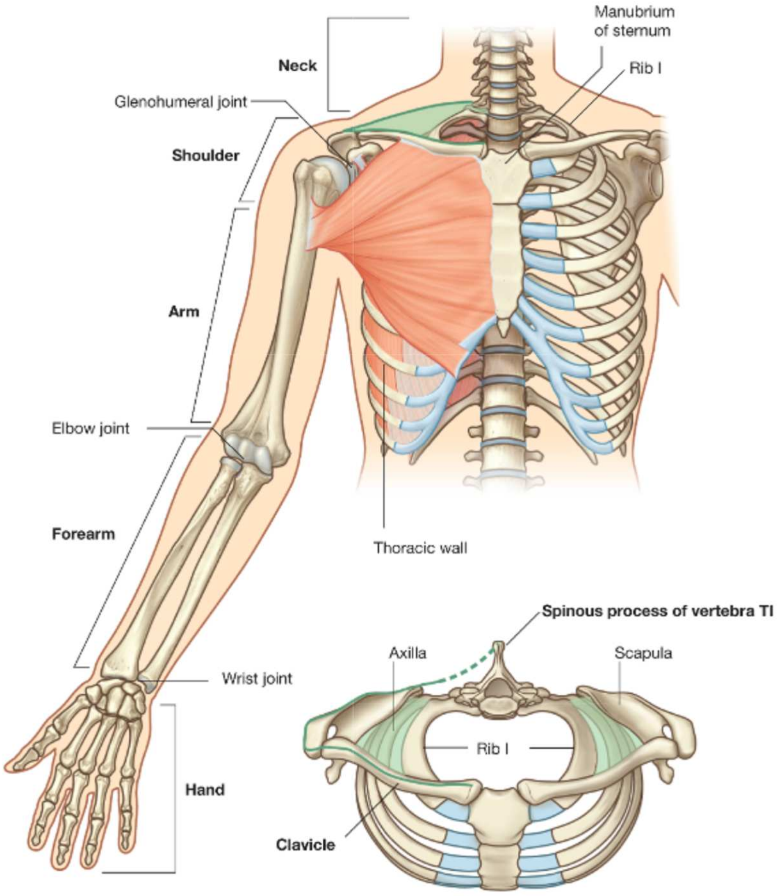


Figure 3.3 illustrates the general anatomy of the upper limb which is composed of the humerus (arm), radius and ulna (forearm) and the hand. The upper limb is attached to the torso via the glenohumeral joint (shoulder joint) which is composed of the head of the humerus, scapula and clavicle.

The types of motion of the upper limb are complex and include flexion/extension and abduction/adduction which are the main, gross movement types occurring during gait. Medial/lateral rotation and circumduction do not constitute movements which would be typically observed during normal gait (these are nevertheless dependent on the body region in question) and therefore will not be specifically investigated in this thesis. However, it is important to note that none of these movements in the body occur in isolation; flexion/extension will be accompanied by a certain degree of abduction/adduction, and in theory, the appropriate terminology would be that the movement occurring is circumduction. However, in general, the description of joint motion requires focus on the principal movements being observed to facilitate the explanatory process and reduce complexity, especially in fields such as forensic gait analysis where the majority of the video examination process is based upon descriptive analysis. For example, if video footage shows the individual from a lateral viewpoint (i.e. sagittal plane), description can only be conducted on the motion which is observed from that particular viewpoint. In the case of the shoulder, motion analysis from the sagittal plane allows discussion solely on the flexion and extension of the shoulder because abduction/adduction, rotation and circumduction cannot be observed since the footage is in two dimensions.

In the shoulder (Figure 3.4A-D pg.64), flexion/extension is generally required for arm swing which provides additional support in propelling the body forward, whilst abduction/adduction may or may not occur. The degree of flexion/extension and of abduction/adduction will therefore differ amongst individuals, depending on the style of an individual's gait (Pontzer *et al* 2009) as well as on their physical limitations, carrying of items and/or pathological conditions. Although important with respect to gait efficiency (Meyns *et al* 2013) and balance (Shishov *et al* 2017), the upper limb evidently does not perform a direct function in gait, whereby no major differences have been found in the movements of the hip, knee and ankle in the sagittal plane in the absence of arm swing except that more bodily energy is spent in the absence of arm swing (e.g. Umberger 2008). Therefore, there may be a higher degree of variability across individuals in the movement of the upper limb. For identification however, it is an interesting aspect to investigate precisely because of this inherent variability which has been previously suggested to provide better results than the lower limb (Birch *et al* 2013a).

Figure 3.4 – Shoulder Joint Motion

(modified from Drake et al 2009)

A – Flexion/Extension

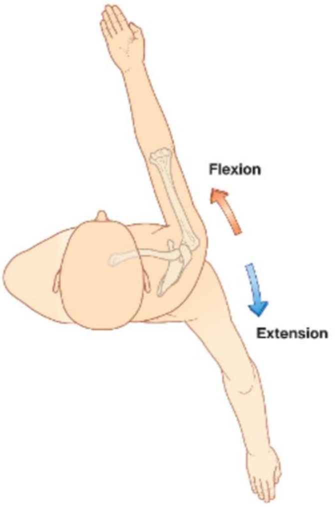


Figure 3.4A depicts flexion and extension of the shoulder joint in the sagittal plane. Anterior movement of the arm relative to the torso represents flexion (red arrow) and posterior movement relative to the torso represents extension (blue arrow).

B – Abduction/Adduction

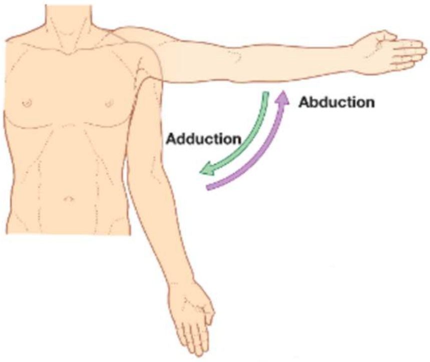


Figure 3.4B depicts abduction and adduction of the shoulder joint in the coronal plane. Lateral movement of the arm away from the torso represents abduction (purple arrow) and medial movement towards the torso represents adduction (green arrow).

C – Medial/Lateral Rotation

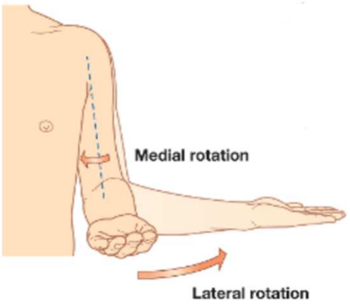


Figure 3.4C depicts medial and lateral rotation of the shoulder joint. With the elbow in the flexed position, the movement of the lower arm away from the midline of the body represents lateral rotation and movement of the lower arm towards the midline of the body represents medial rotation.

D – Circumduction

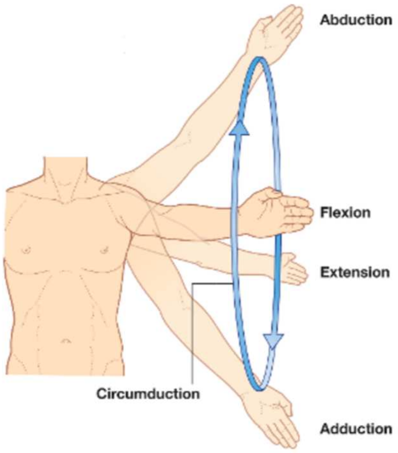


Figure 3.4D depicts the range of motion (and the complexity) of the shoulder joint. Circumduction combines movements in the sagittal and coronal planes, thus resulting in an interrelated flexion/extension and abduction/adduction of the entire arm, relative to the torso.

Unlike the shoulder joint, the principal movement of the elbow is flexion-extension (Figure 3.5A). Pronation/supination also occurs (Figure 3.5B), although this movement is mainly related to the movement of the hand, whereby pronation allows the palm of the hand to face posteriorly and supination allows the palm to face anteriorly (anatomical position). However, it is included as elbow motion due to the head of the radius (bone of the lower arm) rotating against the distal end of the humerus (bone of the upper arm); to allow this movement to occur, the radius is connected to the elbow only by soft tissues, the ulna (medial bone of the upper arm) being the only bony component directly articulated with the humerus.

Figure 3.5 – Elbow Joint Motion
(modified from Drake et al 2009)

A – Flexion/Extension

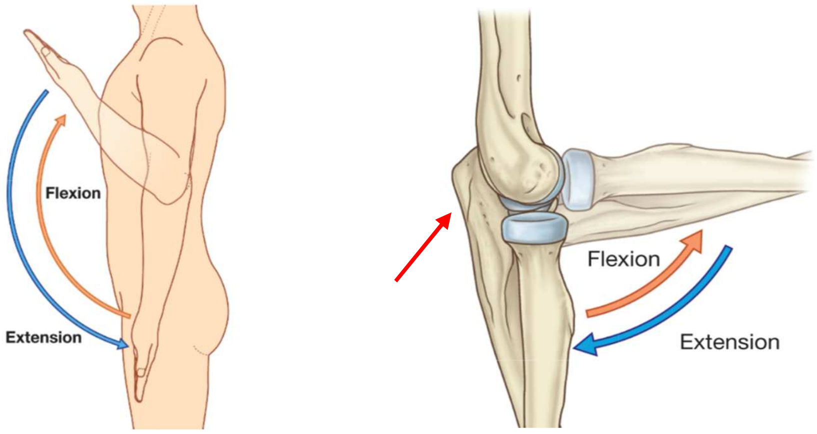


Figure 3.5A depicts flexion and extension of the elbow joint in the sagittal plane. With palms facing anteriorly (supination in anatomical position), superior movement of the lower arm represents flexion (orange arrow) and inferior movement of the lower arm represents extension (blue arrow). Flexion and extension are the principal movements occurring at the elbow joint and are produced by the radial head sliding across the distal humerus and the 'hook' of the proximal ulna (red arrow) sliding along the distal humerus.

B – Pronation and Supination

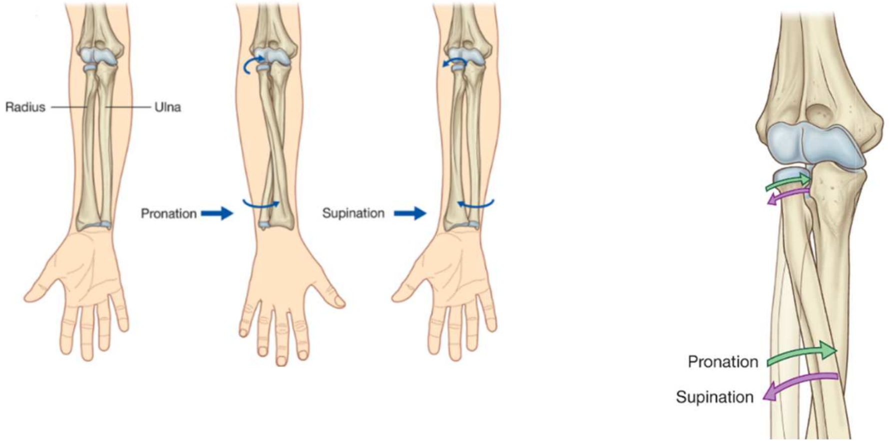


Figure 3.5B depicts pronation and supination of the lower arm, where the radius slides over the ulna to allow the palm to face anteriorly or posteriorly. This movement can only be observed along the lower arm and evidently, according to which way the palms are facing, but it is included as movement of the elbow joint because of the 'sliding' of the radial head along the distal humerus (bone of the upper arm).

As with the shoulder joint, elbow motion is important in gait from a stylistic viewpoint. Although flexion or extension is not specifically required to produce arm swing, some individuals may exhibit a slightly flexed elbow during arm swing whilst others may swing the arm with a fully extended elbow. Whilst individuals do tend to exhibit some degree of shoulder motion in the form of flexion/extension by performing arm swing during walking, movement in the elbow is much less specific as a gait feature. Therefore, it warrants further investigation, especially to observe whether individuals are consistent in their degree of movements. With respect to pronation/supination, this will not be investigated in this thesis because from an anatomical standpoint, it does not have an implicit role in arm swing and cannot be readily observed from video (unless the hand is also visible), but it can serve as an additional component in investigating gait styles.

3.2.2 Lower Limb Motion

From a functional standpoint, the components of the lower limb which accomplish locomotion are the femur, tibia and foot, defined according to the joints involved in producing gait namely, the hip joint which connects the upper leg (femur) with the pelvis, the knee joint which connects the femur with the lower leg (tibia), and the ankle joint which connects the tibia with the foot (Figure 3.6A-C, pg.67). Although from an anatomical perspective the hip is not part of the lower limb, the hip joint plays a critical role in gait and therefore has been included under the section for the lower limb for simplicity. The hip joint is a ball-and-socket type of joint, similar to the shoulder joint in terms of motion complexity, allowing a range of movements to occur (Figure 3.7A-D, pg.68). Unlike the shoulder joint, the hip requires efficient stabilisation from the soft tissues to maintain balance during standing and implicitly, to efficiently maintain and alter the centre of gravity of the body as required, during locomotion (Drake *et al* 2009). As a result, the hip motion which occurs during gait is much more restricted and less visible; rather, it is the movement of the pelvis itself which can be seen, rather than movement at the joint. For example, during hip flexion and extension, the superior portion of the hip moves posteriorly and anteriorly, respectively. Concomitantly, as the pelvis moves posteriorly, it also projects superiorly, whilst when moving anteriorly, it also projects inferiorly, thereby also producing adduction and abduction, respectively. These types of ‘global’ pelvic movements are referred to as *anterior, posterior, or lateral tilt* (Standring 2008), and accompany flexion/extension and abduction/adduction; therefore, from a visual perspective, flexion/extension and abduction/adduction can only be inferred based on the nature of the pelvic tilt, and evidently, also based on the position of the leg and foot. Although the movements themselves cannot be directly observed from video footage, the overall motion of the pelvis can be, hence its importance in forensic gait analysis.

Figure 3.6 – General Lower Limb Anatomy

(modified from Drake et al 2009)

A – Hip

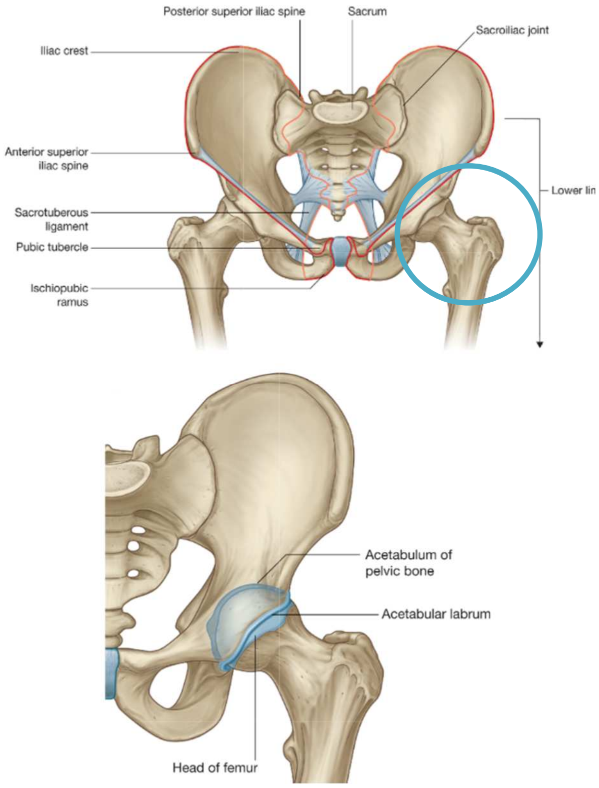


Figure 3.6A illustrates the pelvic complex composed on the two os coxae (pelvic bones) and sacrum. The os coxae articulate with the femur at the hip joint via a ball-and-socket-like joint (circled area in blue, with a close-up below), to each other via the pubic symphysis and to the sacrum via the sacroiliac joints.

B – Knee

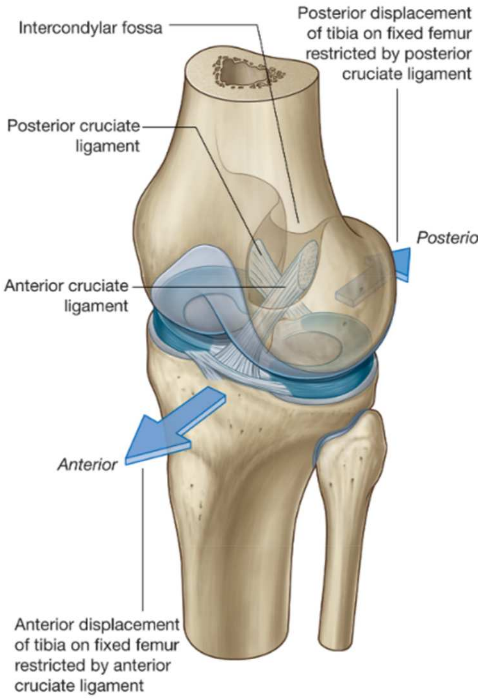


Figure 3.6B illustrates the knee joint from an anterolateral viewpoint. Of note is the flat nature of the tibia, rounded off solely by soft tissue (menisci).

C – Ankle

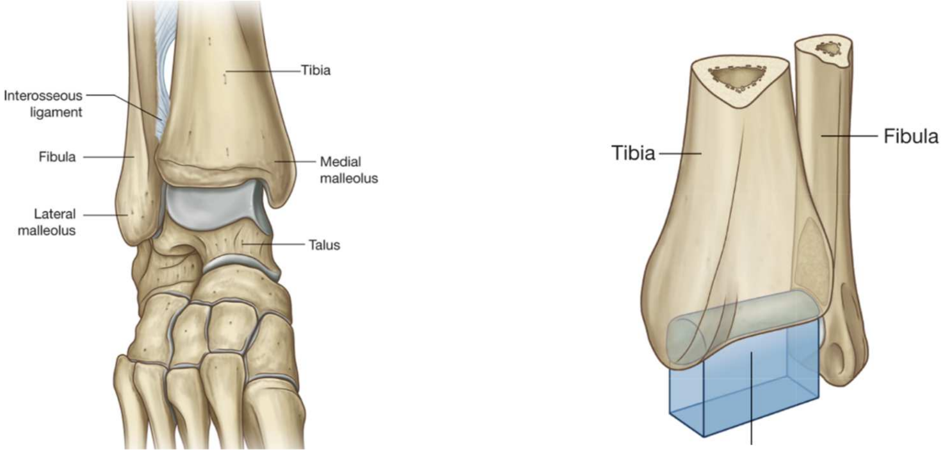


Figure 3.6C illustrates the right ankle joint from an anterior viewpoint. The tibia and the talus are the major contributors of the ankle joint, also represented schematically on the image to the right. As in the knee, the principal movements are flexion and extension, with the tibia sliding over the articular surface of the talus. Of note is the greater articular congruency in the ankle comparing to the knee.

Rotation of the hip also accompanies the aforementioned movements, since it is required for adequate placement of the foot during gait (Figure 3.7), however, this movement is minute by comparison and can only be inferred with respect to the placement of the foot on the ground whereby internal rotation of the hip is associated with medial displacement of the foot whilst external rotation of the hip is associated with displacement of the foot laterally. Visually, this can be difficult to observe from video and therefore, will not be investigated in this thesis.

<u>Figure 3.7 – Hip Joint Motion</u>
(*modified from Drake et al 2009)*

A – Flexion/Extension

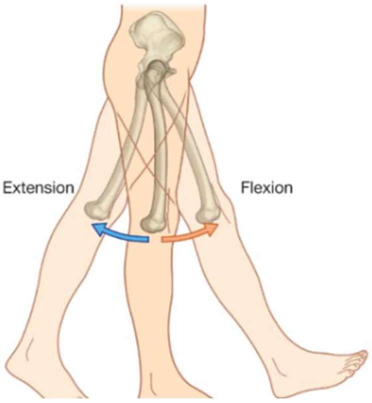


Figure 3.7A illustrates flexion and extension movements of the hip in the sagittal plane along the coronal (x) axis. The orange arrow depicts anterior movement of the hip joint (flexion) and the blue arrow depicts posterior movement of the joint (extension).

B – Abduction/Adduction

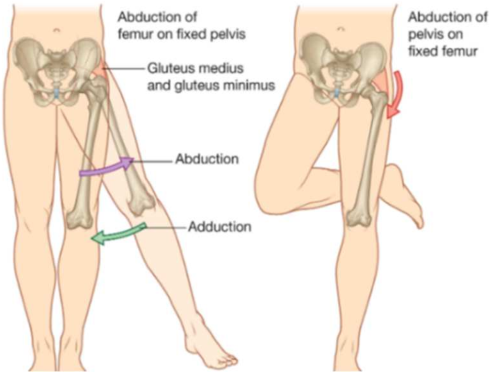


Figure 3.7B illustrates abduction/adduction of the hip joint in the coronal plane along the sagittal (y) axis, on a fixed femur and fixed pelvis. The purple arrow depicts movement in a lateral direction (abduction), and the green and red arrows depicts movement in a medial direction (adduction).

C – Internal/External Rotation

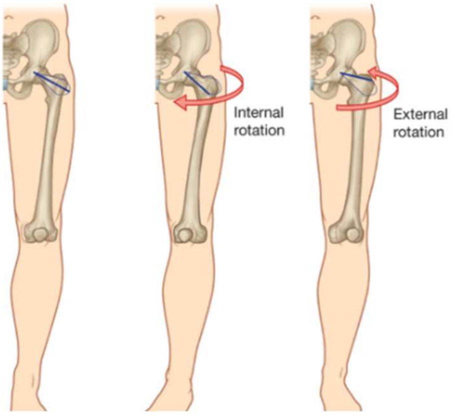


Figure 3.7C illustrates internal and external rotation of the hip joint.

D – Circumduction

Figure 3.7D depicts the range of motion of the hip joint. As in the shoulder joint (with obvious functional differences) circumduction combines movements in the sagittal and coronal planes, thus resulting in an interrelated flexion/extension and abduction/adduction.

Anatomically, the hip also plays a highly important role in sex differentiation as a result of the differing demands between males and females with respect to parturition (Lewis *et al* 2017). As depicted in Figure 3.8, the female pelvis is more rounded and laterally displaced, with a larger, more rounded pelvic inlet to facilitate childbirth, whilst the male pelvis is narrower and 'heart-shaped', with a constricted pelvic inlet. Whilst the same type of movements will occur in both females and males during gait, the associated range and style of motion at the hip joint will differ, as will the overall appearance of the movement whereby females tend to swing their hips to a greater degree than men (Chumanov *et al* 2008). From an observational viewpoint, sex estimation could therefore be a simple endeavour. Of note is that such a description represents the 'average' male and female but is certainly not representative of all populations (Betti 2017; DelPrete 2019). Depending on ancestral background, physical activities, and other factors, either sex may present some characteristics of the other, and by extension, the 'typical' female and male gait will differ to a certain degree. As discussed in the previous chapter, resolving such challenges can be achieved by population studies and compilation of adequate population datasets which can accurately represent an overall range of variation to be expected in a specific population, and the associated error rate of erroneously including or excluding an individual into or out of a specific population.

Figure 3.8 – The Female and Male Pelvis
(modified from Drake et al 2009)

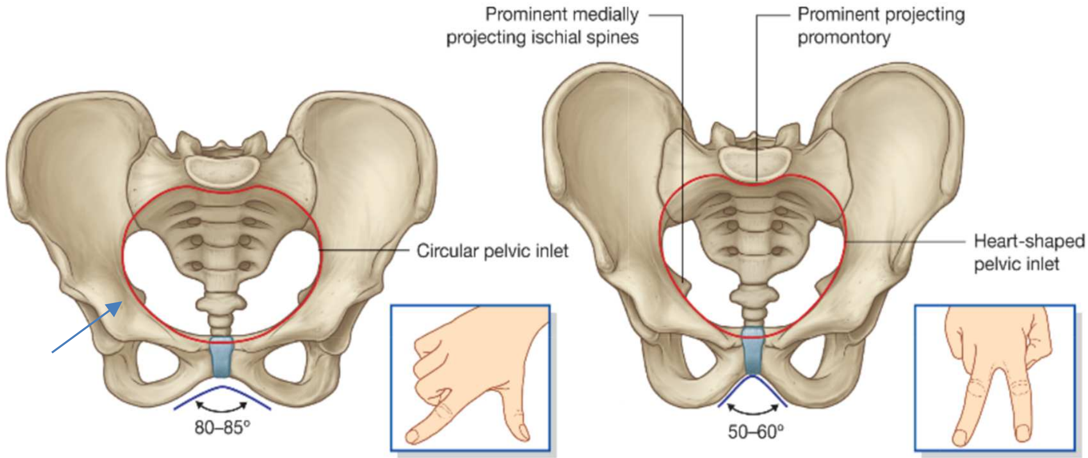


Figure 3.8 depicts the female pelvis (left) and the male pelvis (right). Note the overall smaller size of the female pelvis, as well as the larger, more rounded pelvic inlet, wider subpubic angle (80-85°) and more superolateral position of the acetabulae (blue arrow).

In simple terms, the knee is a modified hinge joint, complex in terms of movement types because it involves the femur, tibia, as well as the patella (kneecap). However, the knee is maintained in position solely by soft tissues because the articular surfaces of the distal femur and proximal tibia are not as congruent as in the ball and socket joint of the hip (Figure 3.6 – General Lower Limb Anatomy, pg.67), an essential anatomical characteristic without which locomotion would not be as efficient. This means that the axis of rotation is less restricted, and flexion and extension will occur in conjunction with some degree of axial rotation and abduction-adduction (Clement *et al* 2018), as illustrated in Figure 3.9B. These are necessary to ensure that the foot is placed towards the midline in order to maintain centre of gravity. However, if it were considered a typical hinge joint, flexion and extension are standard movements and the most obvious visually (Figure 3.9A).

Figure 3.9 – Knee Joint Motion

A – Flexion-Extension
(modified from Drake et al 2009)

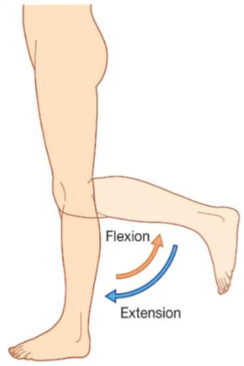
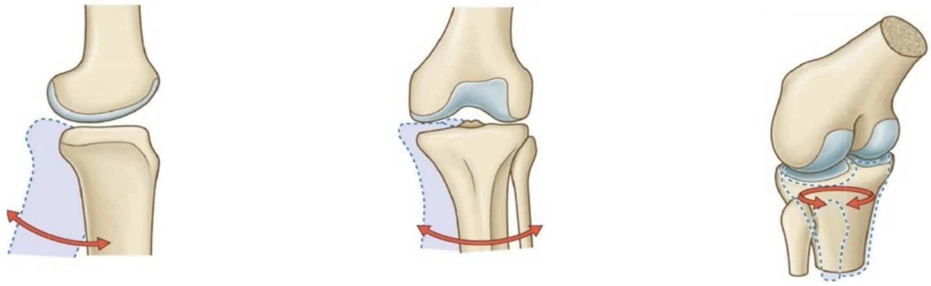


Figure 3.9A illustrates flexion and extension movements of the knee in the sagittal plane along the coronal (x) axis. The orange arrow depicts posterior movement (flexion) and the blue arrow depicts anterior movement of the joint (extension).

B – Movements in all Three Planes
(modified from Standring 2008)



Flexion-Extension

Abduction/Adduction

Internal/External Rotation

Figure 3.9B depicts the movement types at the knee joint. Flexion and extension occur in the sagittal plane (lateral view), abduction/adduction occur in the coronal plane (anterior view) and internal/external rotation occurs in the transverse plane (posterolateral view). The main type of motion during walking is flexion-extension. However, internal, and external rotation will also occur, coupled with abduction and adduction. The permitted movements are essential for an efficient upright gait.

The ankle is closer to a typical hinge joint (see Figure 3.6 – General Lower Limb Anatomy, pg.67), whereby the tibia slides over the talus of the foot to produce dorsiflexion (flexion) or movement of the foot superiorly and plantarflexion or movement of the foot inferiorly (extension), as illustrated below in Figure 3.10. However, it will also exhibit some degree of axial rotation, as required for the feet to maintain a slightly medial position to ensure balance. As a result, the head of the talus of the foot is convex and rounded whilst the distal tibia is concave. During plantar or dorsiflexion, the tibia slides over anteriorly or posteriorly, thereby creating a sliding motion typical of a hinge joint. The soft tissues sustaining the joint restrict these movements to the sagittal plane, making it more stable that the knee, but despite this and greater articular congruency, additional rotation will still occur, although as in the knee, these will not be visible and will therefore not be analysed in this thesis. The movements occurring in the foot are also of interest in gait from a clinical standpoint, however, these will not be included due to the visual unavailability of such motion from video footage.

Figure 3.10 – Ankle Joint Motion
(modified from Drake et al 2009)

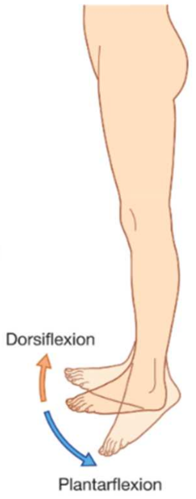


Figure 3.10 illustrates dorsiflexion and plantarflexion movements of the ankle in the sagittal plane. Dorsiflexion (or simply flexion) is the superior movement of the ankle joint where the foot points superiorly (orange arrow). Plantarflexion (or extension) is the inferior movement where the foot points inferiorly (blue arrow). Dorsi- and plantar- refer to the surface of the foot touching the ground.

3.3 The Gait Cycle

3.3.1 General Physiology of Gait

The physiology of human movement is a well-documented area of research, with a plethora of methodologically robust data available, including biomechanical and predictive motion models (e.g. Leboeuf *et al* 2019; Martin and Schmiedeler 2014, Skubich and Piszczatowski 2019). Body stability is an important and indispensable attribute in both quiet stance (i.e. standing upright with both feet on the ground), and as well as during walking or related activities, more so that the development of stability precedes that of mobility (Yaguramaki and Kimura 2002). Considering that most of the body weight is located in the upper half and supported by the relatively small surface area of the pelvis, maintaining balance is a complex task (Jian *et al* 1993; Pitt and Chou 2019; Virmani *et al* 2018). Whilst standing, energy consumption is normally low in a healthy individual, achieved by the efficiency of the posture itself. Distribution of the weight of the upper half of the body is such that muscles of the legs and pelvis are not required to engage in active contraction and relaxation. The body's centre of mass (COM; i.e. total body mass) is projected vertically onto the ground as the centre of gravity (COG), requiring an even distribution over the area which is occupied by the portions of the feet which touch the ground and during alternating foot ground contact whilst walking (Lu *et al* 2017; Williams and Martin 2019). The COM projects vertically and counteracts the opposite and equal vertical force exerted by the ground (i.e. GRF, ground reaction force) at the centre of pressure (COP), as illustrated below in Figure 3.11.

Figure 3.11 – Motion of the Hip and Leg During Heel Strike
(image modified from Standring 2008)

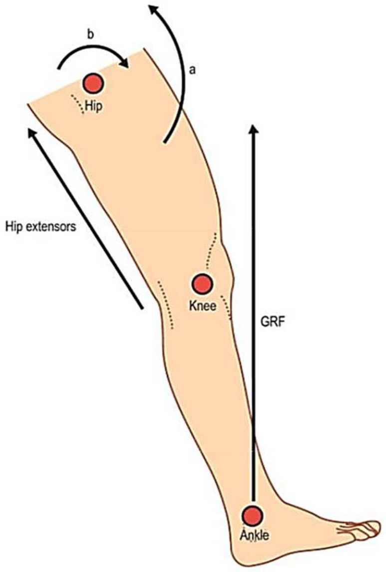


Figure 3.11 illustrates the motion of the hip and leg during heel strike of the stance gait phase. The ground reaction force (GRF) produced by the heel strike travels along the leg and causes the hip to flex. In response, the hip extensors respond in an antagonistic manner by contracting, to prevent the body from toppling over.

The COM varies according to the activity undertaken due to differences in forces to which the body is subjected. During standing, the forces involved originate from gravity and air pressure, and therefore, are much lower when compared to walking; no active, mechanical forces are produced by the muscles because the body remains relatively still. Locomotion requires additional mechanical forces for forward thrust and braking, and the COM position changes due to alternating contact of the feet with the ground; at any one time, the entire body weight rests only on a single foot, and as a result, the forces are much higher (Morasso and Sanguineti 2002). Therefore, stability requires a much more active involvement of the entire body. These aspects have long been known and recent research has also demonstrated that gait-like movements begin as early as in the weeks after birth, a direct result of spinal cord development and implicitly, increased neural activity (Scheuer and Black 2000). The changes in overall body posture throughout infancy and childhood are brought about by alterations in the angle between the vertebral column and pelvis, and by the formation of the vertebral column curvatures, especially the curvature of the inferior portion of the vertebral column (i.e. lumbar lordosis) (Scheuer and Black 2000). As the infant learns to walk, a shift in the centre of gravity of the body occurs, causing the lumbar lordosis to increase progressively with age (Giglio and Volpon 2007) and ‘relocates’ the centre of gravity such that once skeletal maturity is achieved (Figure 3.12), it becomes positioned posteriorly to the hip and lower portion of the vertebral column (Gardocki *et al* 2002).

Figure 3.12 – Centre of Gravity Position in Adults
(taken from Drake et al 2009)

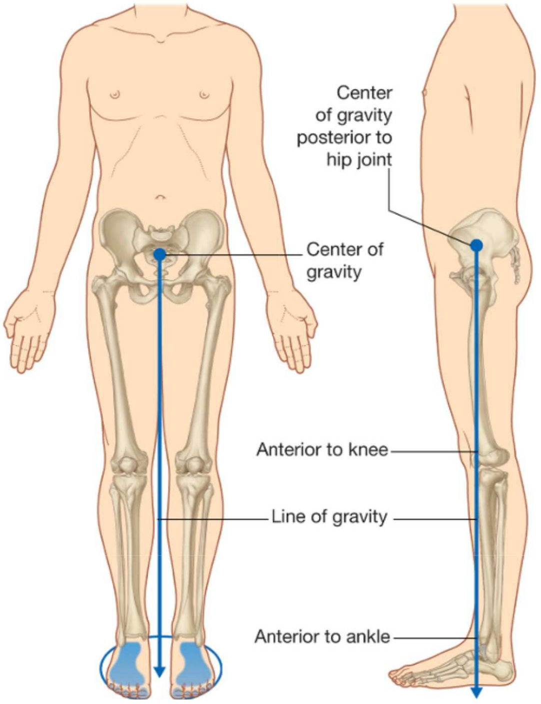
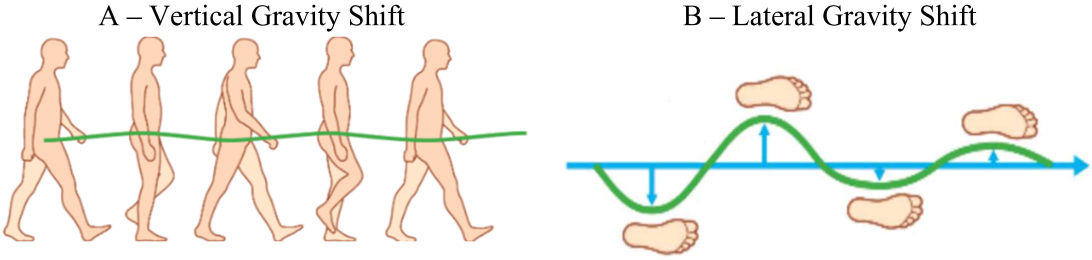


Figure 3.12 illustrates the position of the centre of gravity in adults. In order to efficiently distribute body forces, the centre of gravity is positioned posterior to the hip joint (and the vertebral column) to allow the line of gravity to ‘act’ anterior to the knee and ankle. This allows for the feet to evenly distributed these forces and permit the body to maintain balance during standing and during locomotion.

Since gravity acts posteriorly to the hip joint and to the vertebral column, the weight of the head, arms, and trunk becomes located anteriorly to the line of gravity, thereby resting on the centre of the vertebral bodies (Saunders *et al* 2005; Thomsen *et al* 2002). This position is also efficient with respect to musculature, since the back muscles are not required to contract for maintaining this posture but contribute passively (Hall 2012), allowing smooth distribution of forces and change of the centre of gravity position during walking (Figure 3.13).

Figure 3.13 – Changes in the Centre of Gravity
(modified from Drake et al 2009)



A – Vertical Gravity Shift

B – Lateral Gravity Shift

Figure 3.13 is a schematic representation of the vertical (A) and lateral (B) changes in the centre of gravity.

3.3.2 The Gait Cycle Phases

As illustrated in Figure 3.14, the gait cycle is composed of two main phases, the *stance* phase, and the *swing* phase, each of which is further sub-divided into a set of stages (Standring 2008). Essentially, both the stance and swing phase involve the same type of actions but in reverse order, whereby the left and the right sides of the body are mirroring one another. The stance phase is the period from when foot touches the ground to when the same foot lifts off the ground, whilst the swing phase is the exact opposite, and therefore, both phases receive similar contribution from the leg joints (Gunther *et al* 2009). During first contact of the foot with the ground in the stance phase, the leg is lowered by the contraction action of the flexor muscles of the ankle and the foot contacts the ground at the heel (heel strike). Full ground contact (foot flat) is achieved by the muscles of the hip which help extend the flexed lower leg during this phase, cancelling its swing (Hamill *et al* 2015). This occurs together with the muscles and tendons of the foot which contract to maintain the anatomical arch of the bottom of the foot, thereby undergoing plantarflexion, while the thigh muscles contract to ensure that the leg remains extended; in their absence, the knee would flex, resulting in the body buckling to the ground (Kimura *et al* 2005; Stewart *et al* 2008). The opposite is true for the swing phase when the hip and leg mostly undergo flexion and the foot is dorsiflexed.

Figure 3.14 – Schematic Representation of the Gait Cycle Phases
(*taken from Standring 2008)*

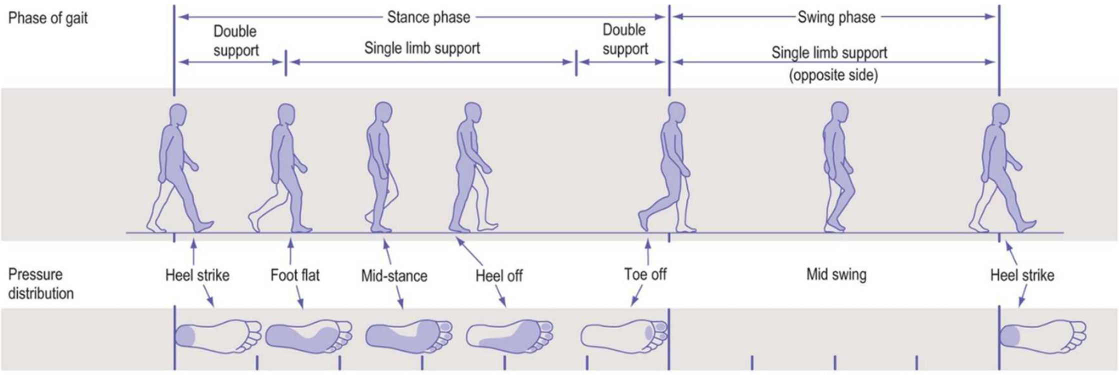


Figure 3.14 is a schematic representation of the phases of a single gait cycle accompanied by pressure distribution in the foot. The stance phase begins with support from both feet, with one foot striking the ground with the heel (heel strike), with the other losing contact with the ground from the toe area (toe off). During the toe-off period, the foot performing the heel strike will increase contact with the ground until achieving full contact (mid-stance). After mid-stance, the foot starts to lose contact with the ground again at the heel and the cycle is one again repeated in the same manner contralaterally.

Muscle action for hip and leg extension during stance is important as this allows the body to prepare to weight-bearing through knee stabilisation (Figure 3.15). Similarly, the action of plantarflexion of the foot acts as a braking system by reducing the speed and therefore controlling the mass of the body. During swing, the movements are antagonistic, the purpose being to accelerate the body and propel it forward in conjunction with arm swing which increases axial rotation of the spine (Whittle and Levine 1999).

Figure 3.15 – Movements of the Knee Joint During Walking
(modified from Standring 2008)

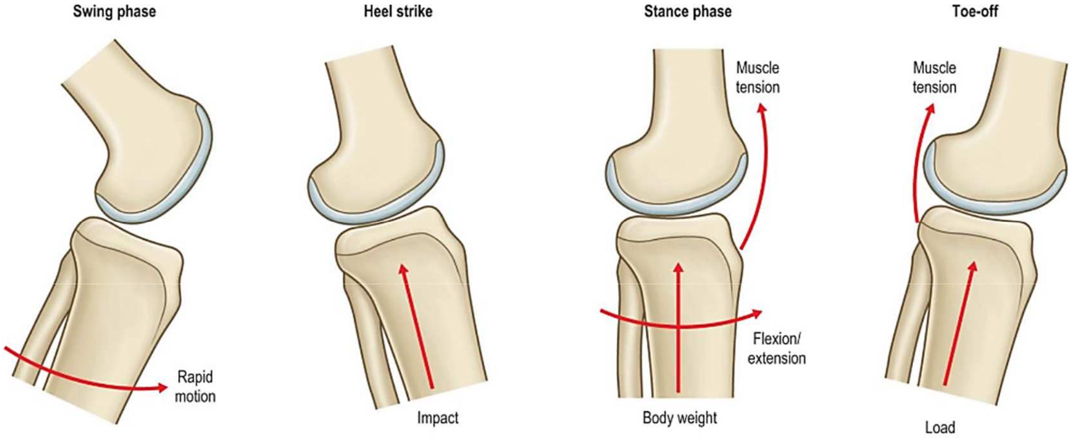


Figure 3.15 illustrates the movements occurring at the knee during the gait cycle phases. During the swing phase, the knee is in flexion, and extension is achieved by the swinging action required for the foot to make initial contact with the ground at heel strike. Full extension is achieved in the stance phase when there is foot-ground contact. After foot-ground contact, the leg begins to return to the flexed position to prepare for the swing phase and repetition of the entire cycle.

At the beginning and end of the stance phase, the feet are both on the ground for a short time, immediately after one foot touches the ground and the other begins to lift off the ground. This repetitive action alternates between the feet during walking, however it is never that both feet are off ground at the same time; this only occurs in running, and is referred to as *double* float as opposed to *double support* when both feet are in contact with the ground during walking (Hamill *et al* 2015). Although the variations of the joint angle in the sagittal plane are the same for both running and walking, their values differ for obvious reasons; in running for instance, the angle of the thigh should be analysed in relation to the position of the trunk, since the latter will also participate by adopting a forward bend caused by the shift in the body’s centre of mass. Similarly, the importance of arm swing is more relevant since it aids in forward propelling by helping the body gain and balance momentum (Kaddar *et al* 2015) which has been noted in children as early as age five, period during which gait begins to resemble those of adults (Chester *et al* 2006; Lythgo *et al* 2011; Samson *et al* 2009). This represents a good indicator of the innate aspect of gait especially since full skeletal development of the lower limbs is far from complete and therefore, temporal and spatial characteristics of gait are yet to fully develop (Ganley and Powers 2005; Hallemans *et al* 2005; Muller *et al* 2012, 2013). For instance, research has revealed that infants complete the swing phase by placing the heel of the foot first on the ground, rather than planting the entire foot flat onto the ground, thus biomechanical differentiation is possible, particularly in the sagittal plane (Bisi and Stagni 2016); hence, age estimation from gait would be an interesting avenue for future forensic gait analysis. It is also important to note that, whilst each stage of the gait cycle can be delineated according to the aforementioned principles, none of these stages, including their associated movements, occur in isolation; these are interrelated and overlap to prevent an otherwise robotic and abnormally appearing gait. The transitions between these actions are indeed difficult to quantify but are important to consider when investigating why gait cycles differ between individuals. This is of importance for forensic gait analysis: by considering this smooth transition amongst gait phases, classification between normal and abnormal gait stemming from pathology or attempt of disguise has the potential to be achieved.

3.4 Physiological Factors Affecting Gait

As discussed earlier in this chapter, gait requires a holistic contribution from all joints systems, each of which performs a specific function to allow for efficient locomotion. Currently however, forensic gait analysis is methodologically limited with respect to the movements which can be used for analysis (and implicitly, with respect to which features are most relevant for individualisation). Video footage comparison is also further complicated by other factors which are difficult to be found consistent. For instance, as highlighted by Yang and colleagues (2014c), gait speed inconsistencies across known and unknown forensic footage can reduce the accuracy of identification. Although the type of movements occurring in higher or slower speeds are identical, the value of the joint angles will implicitly differ. Higher walking speeds will be accompanied by a higher range of joint angle values due to larger footsteps being required; additionally, arm swing will also be more obvious since a larger input would be required from the upper limb to propel the body forward quicker and will also be dependent on a certain degree of asymmetry (e.g. Schwartz *et al* 2014). In a study investigating walking speed relationship between the upper and lower body joints in 20 healthy subjects, Romkes and Bracht-Schweizer (2017) found that the degree of shoulder and hip flexion increases with higher walking speeds, thereby also sustaining the importance of arm swing in achieving a higher speed gait. This aspect is endorsed by studies which have found that upper limb constraints not only impede individuals to walk at higher speeds due to poor upper/lower limb coordination but also decreases trunk, thoracic and pelvic rotation in the transverse plane (e.g. Ford *et al* 2007).

Of note is that for normal speeds, studies have shown that the differences in lower limb joint angles are not much greater with or without arm swing during normal walking (e.g. Umberger 2008) and that asymmetries in the upper and lower limbs are not necessarily correlated in sagittal plane movements (e.g. Kuhtz-Buschbeck *et al* 2008). Furthermore, the range of motion appears to be larger in the left elbow in both men and women (Bruening *et al* 2015). Therefore, arm swing may represent a functional requirement that is also speed dependent (Hejrati *et al* 2016) rather than solely influenced by sex or limb dominance and will result in abnormal limb coordination when it is not used as demanded by gait speed. Also, such data refer to differences solely during normal gait (i.e. walking), and do not apply to jogging or running. During walking, the legs are mostly straight, especially during the middle of the stance phase; in running, the knees are bent and there is an overall higher joint motion due to increased speed than during normal walking. Also, speed is dictated by swing and therefore, this phase will be shorter than stance during walking and vice versa for running. In addition to the reduced contact time between the foot and the ground, as well as instances where both feet have no ground contact at all, differences in leg position also occur in running. These distinctions are important in forensic gait analysis because these will influence the initial process of assessment which involves determining whether the movements captured on video can be utilised for analysis. Currently, forensic gait analysis is designated solely for walking and has not been reported to be of use in instances where the person of interest is running, ascending, or descending stairs or other such circumstances. Given that the individualisation potential of these gait features in current use has not been addressed, this thesis focuses solely on walking in order to develop a solid baseline prior to addressing more complex scenarios. Locomotory activities other than walking still require solid knowledge in the form of experimental studies to provide rationale for their lack of utility in forensic cases, thus warranting future research.

The implications of the aforementioned aspects in walking are therefore important in forensic gait analysis whereby these highlight the importance of also analysing the movements of the upper body rather than focusing solely on the lower limb, especially since Birch and colleagues (2013a) have provided some evidence that the upper body movements may be more discriminatory than those of the lower body. The reason for this may be related to the inherent variability of upper limb motion which, as previously stated, serves as a mode of sustaining a more efficient gait rather than performing a direct role. Considering that the upper limb motion is not as restricted to specific gait phases as is the motion of the lower limb, there is a higher potential for individual-specific characteristics to be observed, yet more challenging to quantify, precisely due to the stylistic variability. The relationship between the upper and lower body at different gait speeds may also be worth considering, given the results of Romkes and Bracht-Schweizer (2017). This could contribute to the development of a standardised approach to forensic gait analysis, whereby the analyst not only considers different joint systems in isolation but also in relation to the others, to examine upper/lower body coordination and differences between different joints at different points during the gait cycle. For example, certain individuals may perform arm swing during different gait sub-phases, earlier or later than others, and in conjunction with an earlier or later knee flexion/extension. There may be a vast number of combinations such as these, thus highlighting their potential to differentiate individuals from one another, thereby requiring further empirical investigation. In addition, such characteristics increase in complexity when considering the nature and degree of symmetry of the left and right sides of the body. Whilst symmetry appears not to be affected by age in adults (Patterson *et al* 2012), some degree of body asymmetry is a normal physiological characteristic (Kuhtz-Buschbeck *et al* 2008). Since video footage can be captured from any angle depending on the position of the camera, empirical data is required to validate the premise of negligible differences in symmetry to allow for uniform conclusions to be drawn irrespective of the side of the body. Investigation of body symmetry therefore constitutes the first thesis objective, as presented in Section 1.2, pg.16.

Clinical studies have also empirically demonstrated that certain features of gait are influenced by sex and age in certain circumstances. In a study which investigated sexual dimorphism in upper and lower body joint angles in 100 adult participants (36 females, 55 males), Bruening and colleagues (2015) have shown that this is present at whole-body level. These differences occur particularly at the elbow, ankle and hip, where women exhibit a greater range of motion than men, with differences specifically found in movements such as shoulder peak flexion and elbow peak extension, hip abduction/adduction, hip rotation during the loading phase of gait and ankle dorsiflexion/plantarflexion, including knee abduction and adduction as supported by numerous studies (e.g. Chehab *et al* 2017; Kobayashi *et al* 2016; Stansfield *et al* 2018). Such differences in range of motion are to be expected, especially with respect to the functionality of the pelvis in women, although these differences are not consistent across all adult age groups, due to the degenerative processes which occur during ageing (McKay *et al* 2017). For instance, some studies have shown that there are no sex differences with respect to the step length/cadence ratio except at higher walking speeds, where women were found to have a lower ratio than men (Bogen *et al* 2018). Coordination amongst gait phase movements of the lower limb were also found to be age-dependent especially in the hip and ankle during terminal swing which showed an increased variability in younger individuals (Hafer and Boyer 2018), a similar find in a study on age-related changes in arm swing (Van de Walle *et al* 2018). This may stem from the larger range of motion in younger as opposed to older adults, due to inherent joint and muscular flexibility which facilitates maintenance of balance and the physiological necessity to conduct the locomotory activity. All of these aspects are yet to be addressed in forensic gait analysis.

In addition to demographic characteristics, there are a wide variety of conditions in forensic contexts where aspects such as clothing, shoes, carriage (e.g. purse, rucksack), type of ground (e.g. slope, stairs, flat ground), can affect the gait of an individual and thus render the premise of uniqueness moot, especially since there is insufficient data to allow forensic gait experts to correct for such factors and support the principles which govern the field of study. For example, Ludwig and colleagues (2016) investigated the effect of shoe type on gait variability for forensic application in eight subjects using cyclograms (i.e. graphs in which one angle is plotted against another) and have shown that there was a quicker decrease in knee angles and larger hip angles at foot contact with the ground in individuals walking barefooted versus those walking with shoes. Furthermore, the coordination of the knee-foot angles was also affected by combat boots as opposed to walking barefooted. Although the sample size is too small to draw solid conclusions, the overall trend appears to be that there is higher variability between the experimental conditions than there is between individuals, thus bringing into question the premise of individuality of gait for forensic application. Such confounding factors can therefore render the identification process difficult; if two sets of footage belonging to the same individual wearing different shoes are analysed, the degree of difference between the two videos might be too large to conclude that it is the same individual appearing in both videos, as previously highlighted (Ludwig *et al* 2016). Conversely, when analysing footage of different individuals who present similar build, body proportions and environmental conditions, the results might indicate a smaller degree of difference between the two individuals, than between the same individual wearing two different types of shoes. Further challenges are introduced by the time lapse between the two (or more) sets of footage; clinical data has recently demonstrated that the general assumption of gait pattern consistency might be erroneous since patterns are inconsistent during the same day, but more so across several days (Horst *et al* 2016). These represent just some of the categories of the multitude of potential challenges a forensic gait analyst might encounter, for which there are no empirical means available for quantification to determine whether uniqueness and the potential for individualisation are detrimentally affected to the point of lacking utility, a concept tackled in the forensic sciences for at least a decade (Cole 2009). Based upon current knowledge and empirical data on these confounding factors, it is difficult to understand how these matters are resolved in practice.

Adjusting for the aforementioned factors has also been shown to be important in a study by Roislien and colleagues (2009) who analysed age and sex differences using joint angles; due to the interrelated nature between age, sex and body proportions and their concomitant effects on gait, the understanding of specific variables such as age in isolation is challenging, and solid evidence for their specific roles in gait cannot be provided without employing mathematical approaches to take such factors into consideration when these are not being tested directly. This would be problematic in forensic contexts and can lead to inconclusive or erroneous interpretations if not considered, especially if further confounded by, for instance, clothing (Scoleri *et al* 2014). Whilst height varies amongst adults of similar ages, between the different sexes, and across different ancestry groups and populations, body mass is much more difficult to categorise, but nevertheless has been shown to have an impact on the sagittal and frontal plane movements of the pelvis and hip, as well as on the movements of the knee in the frontal plane (e.g. Chehab *et al* 2017), and in the sagittal plane during early stance (Hora *et al* 2017), including in children (e.g. Mahaffey *et al* 2018); body mass is very difficult to estimate across populations because its variation mostly depends on the individual and their personal weight preference, fitness level, diet, environment, genetics, and disease. Although challenging to incorporate in forensic gait analysis methodologies, it is important to at least have empirical evidence on whether there exists a basis for uniqueness, to then proceed to investigate how different body proportions influence range and types of motion in individuals of different overall build, particularly for avoiding misappropriating normal characteristics as pathological in origin.

Section II – Materials and Methods

Chapter 4 – The KIT Whole-Body Human Motion Database

4.1 Overview

Chapter 4 presents the origins of the secondary data utilised in this thesis. Section 4.2 describes the general contents of the database from which the dataset was compiled, including information regarding previous applications, and is accompanied by a discussion on its suitability for this thesis. Section 4.3 defines the procedures employed by the researchers who developed the database to collect and process the data and discusses associated caveats with respect to motion capture systems and the biomechanical model employed in calculating joint angles.

4.2 Database General Contents

The dataset for this thesis was obtained from a freely available online database managed by the Karlsruhe Institute of Technology (KIT) in Germany (Mandery *et al* 2015). The database consists of data previously collected by KIT and several internationally reputed academic institutions and utilised in European-funded projects for robot development and human-robot interaction research from which various publications have arisen. Examples of projects include:

- Koroibot: enhance human-like locomotion of robots;
- WALK-MAN: development of humanoid robots which can operate in hazardous conditions (e.g. damaged buildings following natural and man-made disasters);
- Xperience: development of automated introspective, predictive, and interactive understanding of actions and dynamic situations in robots;
- SecondHands: designing robots which can assist maintenance technicians.

The database consists of various data forms (e.g. ground reaction forces and joint angles), depending on the motion examined and the type of project contributing the results; for the dataset selected for this thesis (further details are provided in Section 5.3, pg. 91), the data type of interest are only in the form of joint angle values since no associated ground reaction forces or other data forms are provided in the database for compiling a dataset relevant to forensic gait analysis (i.e. normal walking). Although its intended application is for modelling human motion for robotics, the type of data captured is universal and was therefore deemed advantageous for this thesis due to several reasons. Firstly, three-dimensional human motion data collection is a highly expensive endeavour (for which a funding application would not have been achievable for this thesis), requiring numerous experts and technical staff to help prepare and calibrate the equipment. Due to the high number of cameras and the difficulty of calibration, a room of suitable dimensions would have required permanent booking for an extended period of time. Also, the processing required to compute joint angles is laborious and challenging, requiring substantial experience in biomechanical modelling and in utilising relevant software to ensure accuracy of results; although this could have been resolved with assistance, the amount of data would have been substantially reduced given time constraints, including the number of potential volunteers. Other logistical challenges would have also included the need for an additional room adjacent to the experiment room where participants would have been required to change clothing and be fitted with appropriate equipment to record motion; this aspect, coupled with physical contact during fitting of the equipment, would have also posed additional challenges in obtaining ethical approval which would have delayed and therefore restricted the time available for data collection. Considering the aforementioned challenges, the opportunity to demonstrate that data exchange can occur not only within disciplines (an intention stated by the researchers who developed the database (Terlemez *et al* 2014) but also across disciplines, presented itself. In this manner, this premise can also be tested with respect to how valuable and valid is secondary data for application other than that for which it was intended, as well as highlight any potential deficiencies which the developers of the database may have not previously considered. As highlighted throughout Chapter 2, lack of standardisation and interdisciplinary collaborations can impede progress since many of the methods and approaches are developed independent of a thorough investigation and validation of existing methods and data, leading to an abundance of unsubstantiated data.

The KIT database, as a basis for choosing a dataset for this thesis, is also appropriate because the numerous projects in which it was utilised, were conducted at a large scale and were approved and funded by the European Union; this demonstrates that the data have been collected in an ethical manner and that the standards employed were monitored. The transparency of the database is also highlighted by a well-organised user-interface where data can be searched for according to the area of the body relevant to the motion, type of project, institution, subject number and according to the object kit involved in the motion. In addition, detailed evidence is provided, accompanied by informed illustrations regarding how the equipment accessories were fitted and any additional measurements obtained from the participants. The data are available in various formats such as raw data (i.e. marker locations in three-dimensional space used to reconstruct joint angle values) in excel format, c3d format (i.e. universal format of three-dimensional data) and video format (.avi) with obscured facial features, as well as processed data in XML format containing joint angle values (format utilised in this thesis). Currently, it consists of data from 210 participants (93 males and 36 females with reported demographics) with most motion types generally comprising at least 5-10 trials per participant, although not all motion types are performed by all 210 participants, a limitation which impeded the use of data from all available participants. Motion data from each participant is stored on the KIT website in anonymised form.

4.3 Procedures for Data Collection and Processing

The KIT data were captured indoors, under laboratory-based conditions, using a marker-based three-dimensional motion capture system (Mandery *et al* 2016), As exemplified in Figure 4.1 below, reflective markers were placed onto the body suit and other accessories such as those of the head, hands and feet, at locations which would allow for a holistic biomechanical representation of the motions of each joint of the participant in three-dimensional space (Mandery *et al* 2016). In general, (and as conducted by KIT), the markers are fitted at anatomical locations (usually, projecting surfaces of bone which can be felt through the suit) according to specific protocols which are standardised for all subjects participating in a given experiment, as well as for the same subject who is participating multiple times in the experiment. Although it appears unrealistic to utilise data from an indoor experiment for forensic application, this is necessary to minimise the impact of variables which have the potential to confound the results and reduce the potential to identify, estimate, and evaluate the impact of intraindividual variation on interindividuality. In addition, marker-based motion capture systems currently represent some of the most accurate means available for obtaining motion data in a non-invasive manner.

<u>Figure 4.1 – Reference Marker Set-up for Data Collection</u>
(taken from Mandery et al 2015)

Figure 4.1 illustrates the standard protocol of marker locations as applied by KIT. Each white spherical object represents one marker and is placed onto specific surfaces to allow as accurate a reconstruction of each body segment as possible (e.g. upper arm, lower arm, upper leg, lower leg etc.) which would then allow for calculation of joint angles.

The manner in which the system used by KIT functions, is that the motion capture cameras emit infrared light which is reflected off the markers placed onto the body suit at anatomically relevant locations; the cameras capture these individual reflections and the recordings of the cameras containing these reflections are then compared in order to determine the location of these reflections in three-dimensional space (i.e. triangulation) (Mandery *et al* 2016). The location of each individual reflection in space therefore represents the location of the marker which is saved as a three-dimensional 'point cloud' in c3d (raw) format (Mandery *et al* 2016). The changes in location of this point cloud data informs the researcher of the changes in location of the markers themselves (i.e. marker trajectories), and these are labelled according to the pre-established marker set, as illustrated below in Figure 4.2.

Figure 4.2 – MMM Reference Model Configuration
(taken from Mandery et al 2016)

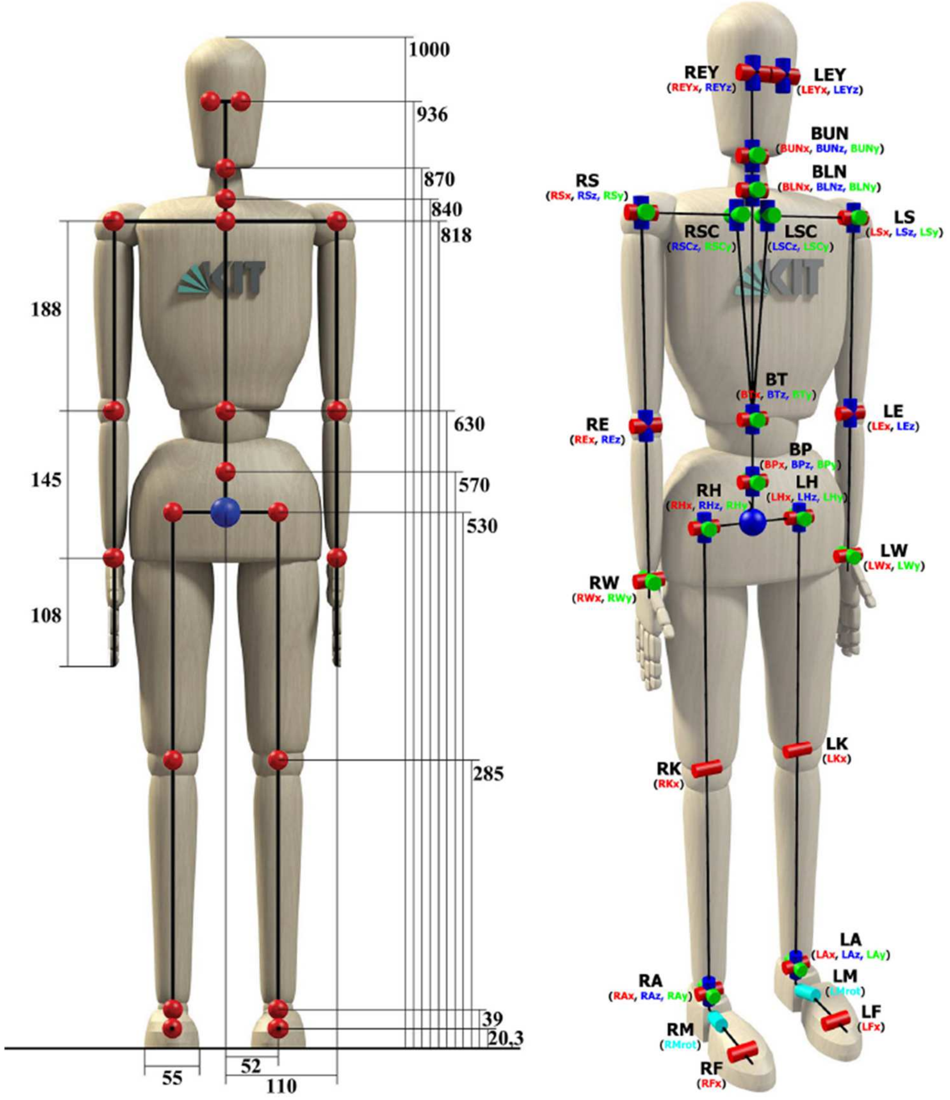


Figure 4.2 illustrates the MMM model, where the left image shows the scaling of each body segment and the right image illustrates the position and names of each body joint, as well as the axes of rotation; these are found in brackets, below each joint and represent rotation around the X axis (red), rotation around the Y axis (blue) and rotation around the Z axis (green). *For this thesis, the joints of interest are the right and left shoulder joints (RS and LS), right and left elbow joints (RE and LE), right and left hip joints (RH and LH), right and left knee joints (RK and LK) and right and left ankle joints (RA and LA). The movement of interest is in the sagittal plane, around the X axis, and is indicated in red (e.g. RSx).*

Hence, the additional purpose of standardised marker location is to allow accurate labelling of each marker in space for meaningful interpretation of the motion. Since the data obtained are in the form of marker locations, further processing is required to calculate angles because in isolation, the marker locations do not represent body regions. As a result, the implementation of a well-defined biomechanical protocol is required to define how each set of markers represents a specific body region (i.e. body segment). There are a variety of ways in which body segments can be modelled from motion capture data for joint angle calculations; for the KIT data, the protocol and the three-dimensional model (referred to as Master Motor Map (MMM) model) for joint angle calculations were custom-made for the purpose of creating a standardised approach which could be applied for a variety of motions from various motion capture systems; therefore, one of the intended purposes of the model and the KIT database was to facilitate replication of human movement in robots, as well as encourage data exchange across different institutions (Terlemez *et al* 2014). As stated in publications authored by researchers who contributed to the development of the KIT database, the MMM model is based on a rigid body system (i.e. body system which does not deform, therefore an idealization of the human body), often used in human motion pattern recognition, including human-robot interaction and action recognition (e.g. Chen *et al* 2019; Guo *et al* 2018; Kameshima and Sato 2006; Zhou and Ming 2016). As illustrated in Figure 4.2, pg.84, the model has varying numbers of joint degrees of freedom (those of relevance to this thesis were the bilateral shoulder, elbow, hip, knee, and ankle in the sagittal plane). The coordinate system employed for movements of the model (Figure 4.2) is the same as previously presented in Figure 3.2, pg.60. Therefore, the model (and implicitly, the placement of the markers), is important in obtaining physiologically relevant data from each body region to allow for a most accurate of the joint locations and angles in three-dimensional space (Wren *et al* 2008).

In the context of obtaining data from three-dimensional marker-based system, there is no gold standard regarding the type of model (particularly in the case of rigid model types (e.g. Nester *et al* 2007)) implemented in data analysis since each model type, including the MMM model, will carry inherent error. The features of the model are mainly decided by what each researcher considers the best approach to obtain as high a quality as possible from each marker given the application of the intended model; this has, in part, lead to a multitude of available models of varying accuracy (e.g. Ferrari *et al* 2008), the data from which are difficult to compare and evaluate, thus also warranting standardisation (e.g. Kontaxis *et al* 2009; Leardini *et al* 2017), and further research with respect to comparative accuracy (e.g. Andersen *et al* 2010) across all joint types (e.g. Potvin *et al* 2017). Nevertheless, the ‘perfect’ model is unlikely to be achieved considering that the motion obtained is nevertheless an approximation of the true motion at the joint and anatomical differences between individuals may anyway influence the accuracy of any model. Also, another decision point is how limiting the area of interest (e.g. the ankle) is in terms of the difficulty in placing the markers and whether these remain in place, and if not, to what degree do these move during data capture as a result of skin movement over the underlying bone which displace the markers to different degrees (i.e. soft tissue artefacts). Evidently, accuracy of the model is of high importance to ensure that the approximated motion is as true as possible to the actual joint motion, however, anatomical and computational restrictions will nevertheless impede the development of an ideal model for motion analysis, and further research for the development of evaluation protocols for such artefacts is recommended (e.g. Cereatti *et al* 2017).

Considering these inherent limitations, a standardised approach to anatomical body segment definitions, marker placement, and model consistency in a given experiment, is imperative to ensure reliability (Kaufman *et al* 2016; Gorton III *et al* 2009); in its absence, large differences will result not only between participants but also in the same participant (Borhani *et al* 2013), and therefore, intraindividual variation cannot be adequately estimated. One assumption upon which three-dimensional motion capture relies is that the markers will move in unison with the anatomical landmarks upon which they are placed. Therefore, the marker is assumed to be representative of the actual motion produced at that particular landmark. In practice however, the marker will move, since it is not permanently fixed upon the landmark, a source of error which is widely recognised (e.g. Barré *et al* 2015; Peters *et al* 2010; Stagni *et al* 2005). However, this can be mitigated by ensuring that the participant is wearing a properly fitted suit that the markers are securely attached in locations chosen by the researcher, and that the biomechanical model is appropriate (De Rosario *et al* 2017). With respect to the impact of this error, gross displacement may render the recorded trial unusable, whilst small displacements (e.g. less than a few millimetres depending on the joint location and the type of movement being investigated) do not create errors with a significant impact on the reconstruction of joint angles (Begon *et al* 2017) for the purpose of overall movement analysis (Ferrari *et al* 2008), particularly in the lower limb sagittal plane (Fiorento *et al* 2017). Unfortunately, such errors have been large enough to contribute to the unsuitability of some of the data from the KIT database and are discussed in more detail in Section 9.2

Despite standardised protocols, placing the markers in exactly the same location for every participant is an extremely challenging task, considering that these are placed over body suits and the anatomical locations (i.e. the underlying bones) have to be estimated through palpation of the landmarks through the suit; thus, the joint locations for marker placement are estimations of the true joint locations. As a result, the marker locations cannot be identical every time for every participant. Nevertheless, following an established, step-by-step, detailed anatomical set-up can help reduce this source of error. This represents a more problematic aspect when investigation of minute changes in joint angles is necessary (Lamberto *et al* 2017), and this is usually the case only for clinical/surgical research where precision is crucial for the application and efficiency of specific treatments. For this thesis (and forensic gait analysis research in general) however, such small errors do not represent a major detrimental effect on the quality of the results because such errors do not affect the overall gait pattern. Also, since this thesis is concerned with sagittal plane movements (i.e. flexion/extension), the arrangement of the marker set appears to create a significant impact only coronal and transverse plane movements (e.g. Schulz and Kimmel 2010). Furthermore, minute differences cannot be directly observed from video footage nor measured using video software tools, and as a result, are not very useful as a characteristic for assisting with identification.

Whilst gait may indeed be unique if examined in sufficient detail, the degree of this ‘uniqueness’ is relevant for identification only if it remains within the parameters of the data which can be obtained from current forensic gait analysis methods. Therefore, the intention of this thesis is to contribute further knowledge with respect to whether the uniqueness of gait is discernible from gait patterns as can be examined by current methods, rather than attempting to confirm or disprove the assumption of gait uniqueness in general. It is also important to note that any methods short of invasive procedures, such as attaching markers directly onto bone, is a representation of joint motion rather than the exact motion truly occurring at the joint. Therefore, at the present moment, three-dimensional motion capture systems remain the most accurate, non-invasive means for estimating human motion.

Chapter 5 – Thesis Methodological Approach

5.1 Overview

Chapter 5 presents the methodological approach adopted in this thesis. Section 5.2 outlines the methodological approach for selecting the dataset from the KIT database and Section 5.3 details the additional processing steps required prior to data analysis, whilst also discussing any associated challenges. The analysis approach, including the statistical package chosen, are then discussed in Section 5.4 for each one of the three research questions.

5.2 Selection of the Dataset

To investigate the three research questions posed in this thesis utilising joint angle data from the KIT database, the type of locomotory activity selected for analysis *was straight walking on flat, even ground at self-selected speed*. With over 1500 motion experiments available from the KIT database (KIT Whole-Body Human Motion Database 2019), the selection and collation of the dataset required approximately 35 hours. The conditions of chosen locomotory activity were based upon the criteria generally requested by forensic gait analysts when performing forensic comparisons, as discussed throughout Chapter 2, Section 2.3. The conditions of the chosen dataset can therefore replicate the ideal circumstances favoured by forensic gait analysts. The purpose of analysing ideal rather than complex forensic scenarios was to allow investigation of baseline values for intraindividual variation; the more complex the conditions of a dataset, the more difficult the isolation of sources causing the intraindividual variation. Furthermore, it was also important to determine whether these 'ideal' conditions can indeed provide these baselines values or whether there is an inherent issue with the currently accepted conventions. Intrinsic differences such as age, sex, BMI, height, general body proportions, already represent complex challenges with respect to obtaining a uniform dataset, regardless of the overall size of the dataset. As a result, the external conditions of the scenario (e.g. type of walking surface, walking direction, speed, etc.), have to be simplified in order to estimate more confidently that the observed degree of intraindividual variation is originating from the individual rather than from an external source. Evidently, since the data has been previously collected, it is difficult to exclude external sources impacting gait cycle patterns that have not been reported on the database website and are unrelated to the specified experimental conditions such as lack of attention or interest of the participants, or discernible/reported fatigue. As a result, careful consideration was given to collating a uniform dataset to minimise experimentally related error sources which could confound analysis of variation. These aspects fulfil the first two aims of this thesis (previously detailed in Chapter 1, Section 1.2, pg.14).

To improve upon the level of confidence with respect to the origins and uniformity (or lack thereof) of intraindividual variation, this approach could have been further expanded through the examination of differences in intraindividual variation under various conditions such as speed (slow, normal, fast), walking direction, and walking surface (e.g. stairs, narrow ledge, etc.), in order to determine whether certain conditions (single or in a specific combination) present different degrees of intraindividual variation. This could have served for making recommendations as to which conditions are more likely to result in erroneous matches than others; also, since current forensic gait analysis methods rely solely on normal walking on flat ground, investigation of other walking conditions could have contributed to widening this scope. However, as stated in Chapter 4, Section 4.2, the KIT database is a collation of different projects; although the data collection and subsequent processing of the MMM models were conducted in a similar manner, the subjects performing a specific locomotory activity are not necessarily the same subjects performing other such activities. Hence, analysis of intraindividual variability for a specific activity could not be compared with those of all other activities available from the database across the same participants. In the cases where certain subjects participated in more than one activity, their number was insufficient for robustly testing variability differences (e.g. less than five participants). Nevertheless, the single locomotory activity chosen remains valid for meeting the thesis aims through the established objectives because it parallels the scenario most favoured by forensic gait analysts and therefore, can provide insight as to whether intraindividual variation can potentially affect the accuracy and precision of conclusions drawn by forensic gait analysts given current guidelines (or lack thereof).

The number of subjects that executed this type of locomotion amounted to a total of *20 adult subjects* (Table 5.1, pg.90); each subject performed the 'walking' activity on four separate occasions, at closely-spaced time intervals (i.e. four trials per participant). The number of trials was important with respect to dataset selection since a larger number of trials allows for extraction of a larger number of gait cycles, thus increasing the size of the data available for analysis. The initial methodological plan was to also quantify the degree to which consecutively obtained gait cycles (i.e. same trial) differ from gait cycles obtained during different instances (i.e. different trials) and its impact on interindividuality. However, issues with the quantity and quality of the data available impeded this approach and the method was modified to include as many cycles as possible from the available trials. Nevertheless, this modification posed no direct issue given that uniqueness and individualisation rely on foundations such as the persistence of a feature irrespective of context. The main assumption relevant to this thesis is that gait remains 'unique' to an individual irrespective of whether the gait cycles originate from different trials and/or whether the gait cycles were captured consecutively from each experimental trial. Recent research utilising machine learning approaches have provided evidence regarding alterations of gait patterns over time, with some remaining persistent over weeks or years (patterns obtained using vertical ground reaction forces (Horst *et al* 2017b)) and others changing as early as several days (e.g. overall shape of angular waveforms of the lower limb (Horst *et al* 2016, 2017a)). However, these studies do not quantify specific characteristics of gait patterns which could qualify as "*features of gait*" from video, given current methods in forensic gait analysis. To build an empirical basis regarding the scientific foundations of gait features currently employed in forensic gait analysis, this thesis addresses one of the many types of characteristics of gait which could be considered “features”, namely joint angular data, thereby representing one step towards solidifying lacking scientific underpinnings of current methods and in encouraging future research on multiple fronts. Whilst studies using pattern-based approaches are also of importance in building this knowledge basis and in prompting novel research areas within forensic gait analysis, differences in forensic contexts (given the multitude of factors which may affect gait) supersede differences which may be introduced by the findings of the aforementioned studies. As discussed throughout Chapter 2, examples include different behavioural patterns under stress of committing a crime, associated clothing which may impede visualisation of the same body regions from the same angle in different sets of footage, quantity, and quality footage, amongst many others. Therefore, differences between periods as short as several days are less pressing to address given the multitude of contextual circumstances which will exacerbate differences in walking patterns of the same individual irrespective of time lapse, and given the previously discussed paucity in the fundamental science of employed methods.

Table 5.1 – Summary of Participant Demographic Characteristics

Participant	Sex	Age (yrs)	Weight (kg)	Height (m)
1	M	27	66	1.80
2	M	25	69	1.82
3	M	24	74	1.92
4	M	25	84	1.82
5	M	28	70	1.81
6	F	23	55	1.69
7	M	24	60	1.70
8	M	21	85	1.70
9	F	25	52	1.63
10	F	25	61	1.63
11	M	44	85	1.81
12	M	24	80	1.88
13	M	27	87	1.77
14	M	44	85	1.81
15	F	25	72	1.67
16	M	29	65	1.88
17	F	25	58	1.64
18	M	26	87	1.74
19	M	33	72	1.86
20	F	21	65	1.70

For each trial, data was captured every centi-second (i.e. every 0.01 second), with each trial lasting between five and eight seconds, thereby resulting in at least 500 data points per trial. This sampling interval is of importance because it allows for capturing of the transitions between movements, thereby allowing for a more accurate representation of the movement (Robertson *et al* 2014); lower sampling intervals affect this representation by rendering the captured movement more robot-like, thereby reducing the accuracy of the joint angle values throughout the gait cycles. In conjunction with the sampling interval, the trial duration is also relevant since (in general, and depending on speed), the longer the duration, the higher the number of complete gait cycles. Since this thesis investigated the influence of the intraindividual variation on the individualisation potential of gait, the number of complete gait cycles which were extractable from the trials in the dataset was of high importance, although the intended number (at least five gait cycles per subject) could not be achieved for all subjects due to issues associated with data quality. These matters are discussed in more detail in Section 5.3, and in Section IV.

As shown in Table 5.1, pg.90, the main demographic ranges of the selected twenty participants are 24-27 years of age, 1.70-1.82 m height, and 55-74 kg weight. 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* 2008a; 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). Of the twenty subjects, six are female and fourteen are male, an unintentional sex bias in many studies of the kind, which is dependent on the individuals who choose to volunteer, rather than on the researchers' choice (e.g. Sarkar *et al* 2005). Whilst a dataset with a larger number of participants with a wider age range and equal sex distribution would have been ideal, the dataset selected remains advantageous over other datasets for the purpose of examining intraindividual variability; other studies examining gait variation have analysed data only from males (e.g. Yang *et al* 2014a,b,c), hence an additional advantage of this dataset, despite the sex disparity. In addition, since this thesis does not seek to directly test and/or develop a sex or age estimation method from gait, the existing biases are not directly problematic for the interpretation of the results with respect to intraindividual variation. Since the dataset for this thesis exceeds the dataset size (including number of cycles) and demographic characteristics commonly employed in relevant literature, this approach also addresses the third aim of this thesis which is to build upon current theoretical foundations of gait-based human identification.

5.3 Processing of the Dataset

The initial intended approach to intraindividual variation analysis from gait for this thesis was to obtain a holistic perspective of the motion of all the computed joints from the constructed MMM model data from the KIT database, amounting to 16 joints including left and right sides of the body (except eye position) and 25 movements in total, as previously illustrated in Figure 4.2, pg.84. However, whilst conducting the additional processing of the dataset collated from the database, the joint angle values of many of the joints (particularly movements in the coronal and transverse planes) were unusable due to various errors (e.g. improper marker fitting, marker movement, incorrect reconstruction of data points, etc.) which resulted in either erratic data points, absence of data points, or joint angle values and overall gait cycle patterns that were excessively out of bounds for the expected ranges for human gait; these aspects are discussed in more detail in Sections III and IV. Therefore, the number of joints and associated movements selected for analysis was reduced to a total of five bilateral joints, with one movement type per joint (i.e. flexion/extension in the sagittal plane).

The joint type and associated movements chosen were right and left shoulder (RS and LS), right and left elbow (RE and LE), right and left hip (RH and LH), right and left knee (RK and LK) and right and left ankle (RA and LA) flexion/extension, as illustrated in Figure 5.1 below. Therefore, the movements chosen, investigate intraindividual variation of human motion in the sagittal plane, thereby the forensic gait analysis application of the results presented in Section III of this thesis are constrained to analysis of gait from a side/oblique view. Although it would have been more advantageous to examine all constructed joints of the MMM model, a frontal/oblique of a person of interest is favoured by forensic gait analysts, and the movements most readily observed from such an viewpoint are of flexion/extension, as discussed throughout Chapter 3. Therefore, the results of this thesis would be directly applicable to preferences considered most ideal in forensic gait analysis.

<u>Figure 5.1 – MMM model displaying the abbreviated joint names</u>
(taken from Terlemez et al 2014)

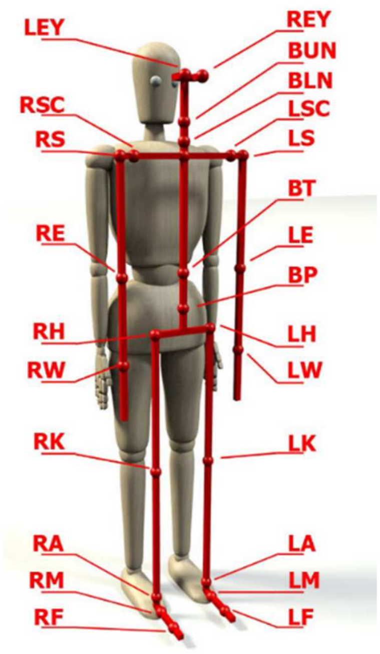


Figure 5.1 illustrates the MMM model with the associated joint names in abbreviated form.

The joints of interest for this thesis were:

- RS/LS – right/left shoulder
- RE/LE – right/left elbow
- RH/LH – right/left hip
- RK/LK – right/left knee
- RA/LA – right/left ankle

As stated in Chapter 4, the data available from the KIT database are in various formats and the format of interest for this thesis was XML, which contains the constructed joint angle values of each MMM models for each participant. For the purposes of analysis of gait cycles, the data could not be analysed in this configuration and format, requiring additional processing steps to isolate the relevant lines of data. To prepare the file for manual extraction of the gait cycles, the first processing step was to import each XML file into Microsoft Excel. The overall format of the data in the file was retained when imported; this was checked every time this procedure was conducted to ensure that none of the data were lost or altered in any way. These steps were laborious and as a result, the length of time required to conduct the data download, dataset collation, and this section of data processing was over 65 hours. Following the arrangement of the data into a format that was simple to visualise and importable into other software, the processing progressed to extracting the gait cycles. The software of choice for the gait cycle extraction (and for the subsequent results visualisation and analysis in Section III) was R software (R Core Team 2020). This was favoured over more traditional approaches such as SPSS due to the nature of the data. Firstly, each gait cycle had to be manually extracted from the data files since as previously stated, these were not annotated within the XML files and no accompanying data of this nature was available for the chosen dataset. Additionally, since the R software relies on programming, any type of command can be given provided that the command follows the established conventions of the R language, thereby rendering the software 'unlimited' with respect to data processing approaches, type of graphical plots that can be generated, and statistical tests.

The subsequent processing was conducted in a systematic and identical manner for all data files, each of which contained angular data of all joints presented in Figure 5.1, pg.92. The full R code for these procedures can be found in Appendix A where it is presented according to joint type. The code was developed using the basic commands of the R language (termed 'base R'); other types of code called 'packages' could have been utilised as alternatives to the 'base R' commands, however, this was not required since any type of command can be written using 'base R' provided that the semantics of the R language are known. Since each file contained data from all joints, the data of each participant was separately imported into R by selecting the relevant column (e.g. Participant 11, Trial 3, right knee (RK) column). The gait cycle extraction then proceeded by plotting the full trial and manually selecting the values corresponding to each separate gait cycle in a given trial; all complete gait cycles were extracted to ensure that the amount of data for analysis is as large as possible. Overall, the total number of manipulated gait cycles in this thesis was in excess of 1,300 cycles. Considering the potential of the R software, this process could have been automatized by developing custom-made lines of commands, however, the expertise of the thesis author in programming with R has only been recently developed. Nevertheless, the automatization of this process would have still required manual adjustments for each joint and for each participant through visual observation since angle values, and total trial duration were not identical. Furthermore, manual extraction is also more accurate in this context since each datum point could be immediately visualised in a plot, thus reducing the error of selecting an inaccurate start or end of the extracted gait cycle. Although there is potential for small degrees of asynchronicity to be artificially introduced through this approach, the cycles were continually evaluated to ensure this source of error was minimised. Also, the joint angle values at the start and end of each gait cycle were selected according to published literature for confirmation, by defining one gait cycle as the period of time between two consecutive heel strikes of the same foot. Gait cycles can also be defined using other points throughout the gait phases, however, the 'heel strike' approach (Figure 3.14, pg.75) is generally considered a standard convention in clinical gait analysis and has been reported to be in use in forensic gait analysis (Birch *et al* 2015), thus facilitating comparison with a wider range of publications. Since there are only a very small number of studies analysing gait variation in forensic gait analysis, no conclusions can be drawn as to the nature of any adopted convention; the aspects which can be noted are that certain studies have utilised 'toe off' to define the start and end of the gait cycle (e.g. Yang *et al* 2014b), whilst others have utilised other approaches to quantifying variation such as cyclograms (Ludwig *et al* 2016).

Following extraction, each of the cycles were standardised according to percentage gait phase by applying linear interpolation which involves the reconstruction of the overall gait curve based upon the data points already available. This implies that if the length of one gait cycle is approximately 1.5 seconds and the sampling interval is 100 points per second (i.e. one data point every 0.01 seconds), then there would be 150 data points in total for one gait cycle. When applying linear interpolation, the 150 data points would be adjusted such that each data point would correspond to 1% of the gait cycle, thus reducing the 150 data points to a total of 101 points (i.e. 100%, the first point starting at 0% and the last point ending at 100%). Considering that the gait cycles were not identical with respect to duration, and implicitly, with respect to the total number of points, standardisation in terms of interpolation was necessary to allow comparisons amongst different gait cycles. For a higher sampling interval, such as was the case with the data from the KIT database, linear interpolation was appropriate since there were sufficient data points to prevent alterations of the original gait cycle during reconstruction of the overall gait cycle waveform; comparisons with other more complex methods such as spline interpolation, which are usually required in lower sampling intervals (Robertson *et al* 2014), were conducted and it was noted that linear interpolation was the most appropriate approach for maintaining the original characteristics of the 'raw' gait cycles.

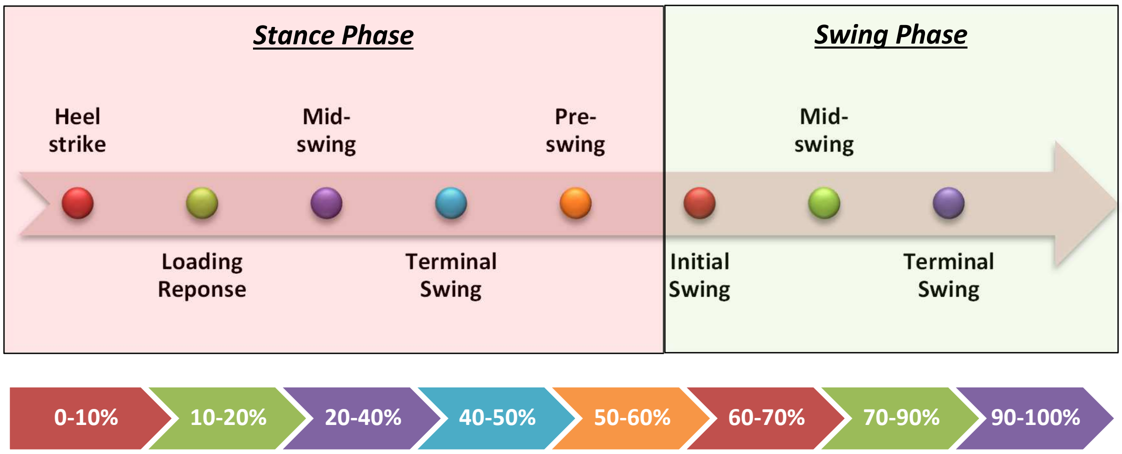
For graphical visualisation of the gait cycles, standardisation also involved modifying the X axis from displaying time in seconds to displaying a percentage of the total gait cycle, whereby the beginning of gait cycle (0%) would be represented by the first heel strike and the end of the gait cycle (100%) would be represented by the moment immediately prior to the subsequent heel strike of the same foot, thus allowing for each of the joint angle values to represent a percentage of the gait cycle. This was also conducted because the trial recordings do not necessarily begin precisely when the participant started performing the locomotory activity; there will always be a small degree of lag time (e.g. 1-1.5 seconds) for the raw recordings of motion capture data due to obvious reasons. Since the files from the KIT dataset have only been processed with respect to joint angle reconstruction, additional adjustments had to be made to ensure that the data are relevant to gait analysis. A simpler alternative would have been to have accompanying data as that from a force/pressure plate (i.e. instrument which measures ground reaction forces or pressure exerted by the feet) which would have allowed synchronisation with the joint values to pinpoint the time when, for example, the heel strikes occurred (analogous to the pressure 'map' presented in Figure 3.14, pg.75). This would have simplified the data processing stages, however, there would not have been a significant improvement in the accuracy of the gait cycle extraction process since data from force plates are still estimations of true movement. Standardisation was also necessary in order to allow meaningful comparisons to be made amongst different gait cycles of the participants and well as to facilitate interpretation of the results in light of the previously published literature. The standardisation and the chosen approach (i.e. linear interpolation) are common in the clinical (and forensic) literature, although other more complex functions could have been applied as alternatives to linear interpolation (e.g. functional Fourier Transform (Yang *et al* 2014b)); however, by opting for a more simple approach to data processing, much more meaningful comparisons with previously published results can be made by maintaining a higher degree of methodological consistency, considering that the aim of this thesis is to test the assumption of gait uniqueness and the potential for gait to be used for individualisation.

5.4 Dataset Analysis Approach

Subsequent to the gait cycle extraction, the resulting data required re-arranging for further analysis in R. Adjustments are necessary in a code-based software such as R because every step is user-defined, and every analytical procedure is dependent upon a specific format, thus requiring the data to be arranged in a manner which would allow correct application of these procedures. The phase subsequent to gait cycle extraction was the calculation of mean joint angle values for each bilateral joint of each participant, followed by calculation of their respective standard deviations. This phase (Research Question 1) constituted the central aspect of investigating the physiological basis of gait uniqueness in this thesis. 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), given that body asymmetry is an aspect often highlighted in clinical research (e.g. Kuhtz-Buschbeck *et al* 2008; Schwartz *et al* 2014). As a result, mean joint angle values were compared to joint angle values of all individual gait cycles for each participant and each one of the five bilateral joints, and intraindividual variability was then assessed amongst gait cycles of both body sides (Research Question 1). 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 (Research Question 2). Finally, to evaluate the impact of intraindividual variation on human identification from gait obtained from Research Questions 1 and 2, interindividual variation was tested using a Fisher-Pitman permutation test for each of the five joints (Research Question 3).

Since all three research questions investigate the assumption of gait uniqueness across all gait events, Figure 5.2 on the subsequent page presents in detail, the structure of a single gait cycle which was implemented for all analyses conducted in this thesis. As described in Chapter 3, Section 3.3.2 and illustrated in Figure 3.14, pg.75, the gait cycle is divided into the *stance phase (0-59%)* and the *swing phase (60-100%)*, and each one of these two phases can be further partitioned into several sub-phases. Although the percentage gait cycle corresponding to each sub-phase can also vary slightly, the percentages displayed below represent generally accepted standards (e.g. Birch *et al* 2015; Standring 2008); each colour of a given gait sub-phase corresponds to the same colour in percentage form. This framework was employed in all research questions in order to facilitate description and evaluation of intra- and interindividual variation.

Figure 5.2 – Graphic Representation of the Gait Cycle Phases as Utilised in Thesis Analysis Approach



5.4.1 Research Question 1

The first stage of data analysis of this thesis tackled the assumption of gait uniqueness by examining whether movement is symmetric between the left and right body sides through the analysis of joint angle values of the bilateral shoulder, elbow, hip, knee, and ankle. 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 to the best of the author's knowledge. This aspect is of importance particularly since both clinical and forensic gait analysis generally employ methods which describe the 'average' gait of an individual without necessarily discriminating between body sides. In addition, the quantification of the variability of gait cycles of the same body side was also of interest, given the persistence concept upon which individualisation is founded. Given the complexity of Research Question 1 with respect to the quantity of data it has generated (200 graphs in total), examples of angular data from several participants for each bilateral joint are presented in a separate section; Sections 6.2, 6.3, 6.4, 6.5, and 6.6 contain the results of the shoulder, elbow, hip, knee, and ankle joints, respectively. Each section contains two graphs summarising general characteristics observed all 20 participants across all gait events using the gait cycle framework presented in Figure 5.8; one graph provides the mean waveforms of all 20 participants (i.e. mean angular waveform plot) at every 1% of the gait cycle and the other illustrates the variability of their associated values (i.e. standard deviation plot) at every 1% of the gait cycle. All summary graphs were created in the R program using a manually tailored code (Appendix B). Although the data can be relatively well represented through such summaries, these are insufficiently detailed for investigating intraindividual variability. Obtaining additional data on the degree to which mean waveforms represent individual gait cycles serves to construct an empirical basis to evaluate whether it is appropriate to utilise mean values to represent general gait patterns and can provide evidence with respect to whether data from either body side can be used interchangeably to represent the gait of individuals. However, due to the large number of graphs produced, only several participant examples were selected for each joint, based on the characteristics observed for the given joint (e.g. graphs to exemplify differences between normal and anomalous gait cycle features of a participant). The complete set of results for all 20 participants are found in Appendix H1A-H5A for the shoulder, elbow, hip, knee, and ankle, respectively.

The examples presented in each of the sections titled 'Results', consist of separate angular waveform plots of specific participants, designated as 'Plot A'; their associated commentaries investigate the assumption of similarity in mean waveforms of one of the five joints by visually evaluating differences in shape, values and overall synchronicity. Each angular waveform plot was produced in the R program using a manually written code found in Appendix C. The nature of the contents are identical for each participant and every joint, whereby the angle values of all extracted gait cycles (method detailed in Section 5.3) were plotted onto the same graph, accompanied by mean values waveform of the left and right body sides as well as a grand total mean which combines the values of both body sides (e.g. Figure 5.3, pg.98). In graphs belonging to males, the cycles are coloured in blue and those for females in pink/purple. There are several reasons for opting for this approach. For example, the concomitant visualisation of all gait cycle angular waveforms for each participant allows for a more thorough evaluation of their common characteristics as well as their differences, much of which are lost when only their respective mean waveforms are examined, a common limitation in current literature. As exemplified in Figure 5.3, pg.98, differences can originate from the lack of synchronicity of specific gait events (red braces, inverted), and/or differences in values (red arrows), or general shape. By observing both the individual gait cycle waveforms and their respective mean waveforms, a more solid judgment can be made regarding whether the mean waveform can encapsulate the features of the individual cycles, or whether (and which) certain features may be lost when considering general gait patterns. The grand total mean was also plotted onto the same graph for similar reasons, to highlight the degree to which it can represent the features of both body sides.

Figure 5.3 – Example Angular Waveform Plot A for Research Question 1

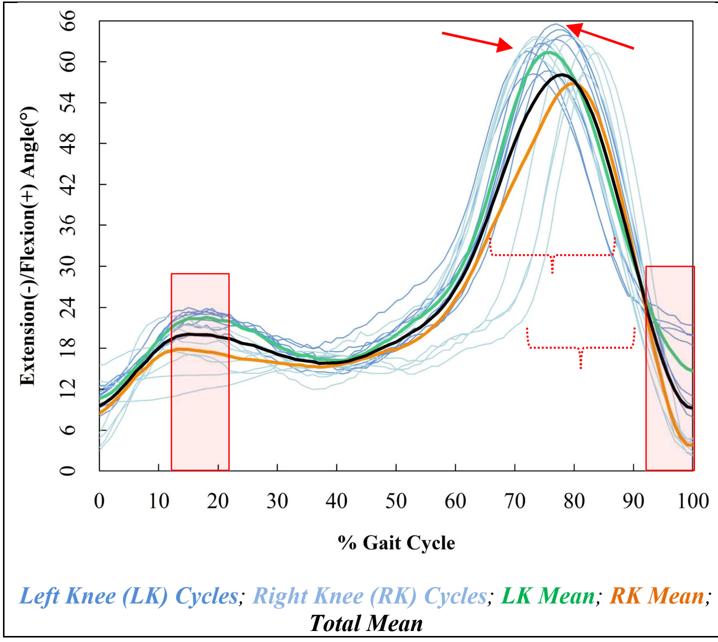


Figure 5.3 illustrates an example of the angular waveform plot of the knee joint of Participant 4.

The dark blue waveforms represent the left knee cycles, the mean of which is the thicker, green line. The light blue waveforms represent the right knee cycles, accompanied by their respective mean, in orange. The grand total mean is represented by the black line, combining the values of both body sides.

Note that the cycles are not all identical. There can be several reasons for this difference such as differences in specific values (arrows), lack of synchronicity (inverted dashed braces) and differences in position and range of values (red boxes).

Since angular waveform plots do not directly quantify variability, standard deviation plots (designated as ‘Plot B’) were utilised to accompany the angular plots (e.g. Figure 5.4, pg.99); this type of plot was preferred since it is directly comparable to the angular waveform plots and as such, both plot types can be viewed and evaluated in unison according to a common framework of the gait cycle sub-phases. This allowed for more in-depth comparisons to assess the magnitude of variability differences between the left and right body sides, whether there is an absence of variability during certain gait events, and whether these differences or absence of differences are located during similar gait events. Individual analysis of each participant to produce data regarding intraindividual variability was therefore essential for developing an evidential basis for the interchangeable use of the left and right joint data in previously published literature. As with the angular waveform plots, only a selection of standard deviation plots were selected (the full set of plots is found in Appendix H1B-H5B).

These variability plots depict the standard deviation of the angle values of all cycles for each body side separately, at every 1% of each gait event; this was calculated based on the values of all gait cycles which were extracted for each participant, each body side and each joint. A separate R code was written to calculate this descriptive statistic, as well as to create the plots (the code is found in Appendix D). As with the angular waveform graphs, the nature of the contents of each of the graphs is identical for each participant and joint to facilitate comparison. In addition to the variability of each body side, a combined variability was also calculated, analogous to a grand total mean. The purpose of the combined variability was to illustrate potential differences in range of angle values between the two body sides; a combined variability which does not exceed the variability of either body side demonstrates that the left and right body sides share a common range of values, as exemplified in Figures 5.3 and 5.4. Conversely, a combined variability which exceeds the variability of both body sides (Figure 5.4, black arrows), highlights distinct ranges of angle values for each body side, as highlighted Figure 5.3 (red boxes). Hence, the angular waveforms directly complement the standard deviation plots since these constitute a means of identifying the origin of the variability, such as whether the variability originates from a lack of synchronicity or from true differences in value.

Figure 5.4 – Example Standard Deviation Plot B for Research Question 1

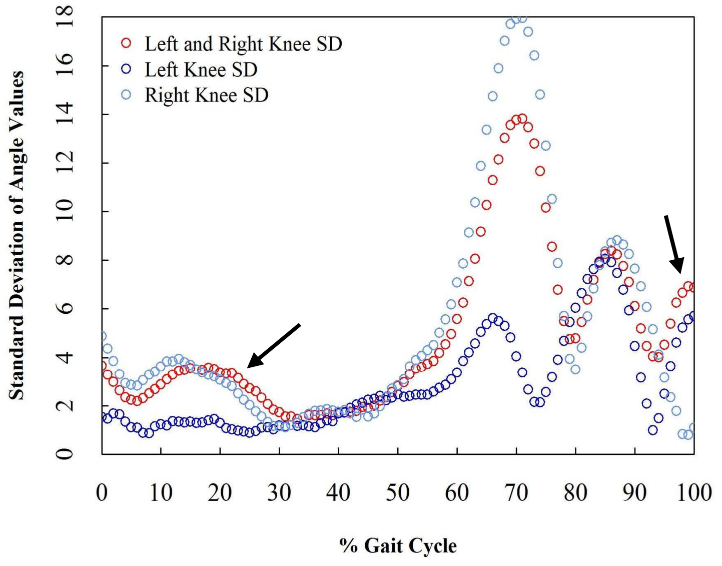


Figure 5.4 illustrates an example of a standard deviation plot of the knee joint of Participant 4. The dark blue circles represent the standard deviation (SD) of all left knee cycles at every 1% of the gait cycle. The light blue circles represent the standard deviation of all right knee cycles. The red circles represent the total variability of the combined left and right knee angle values at every 1% of the gait cycle.
The two black arrows emphasise a combined variability that is larger than the variability of either body side during mid-stance (20-30%) and terminal swing (~94-100%). When examining the angular waveform (Figure 5.9), the differences in location and range of values of the two body sides are confirmed.

5.4.2 Research Question 2

The second stage of data analysis of this thesis builds upon Research Question 1 by exploring potential patterns in variability across all five bilateral joints and compares the differing degrees of intraindividual variability throughout the gait cycles of each of the 20 participants. Given that previous forensic gait analysis research has indicated that the upper limb joints may be more discriminatory than lower body joints (Birch *et al* 2013a), and since the upper limb role in gait is more passive than those of the lower limb given reduced physiological constraints (as discussed throughout Chapter 3, Sections 3.2 and 3.4), a comparison amongst body regions was also required to address these previously untested aspects. Hence, the purpose of this second approach was to attempt to answer *Research Question 2* and fulfil the three thesis aims previously presented in Chapter 1, Section 1.2.

The analysis for Research Question 2 generated 40 graphs in total, each containing the standard deviations of all five joints for each one of the 20 participants (the standard deviations presented herein were previously obtained for the analysis of Research Question 1, as described in Section 5.4.1). As with Research Question 1, only several standard deviation plots for each body side were presented in the thesis (Chapter 7); the remainder are found in Appendix I1-I2. These example plots are preceded by a separate summary plot for each body side containing the data of all 20 participants for all five joints. This method was opted for in order to allow concomitant examination of which regions of the gait cycle present the largest number of joints with the lowest variation given body side, which combination of joints present the lowest variation in a given gait sub-phase(s), and whether there is any general difference in variability between the upper and lower body joints. All graphs were created in the R program, also with a manually tailored code (Appendix E). The data of the two body sides were analysed conjointly in Section 7.3 to investigate the extent to which the two body sides are similar, given similar and different body regions. An example of a standard deviation plot and accompanying analysis for Research Question 2 is presented in Figure 5.5.

Figure 5.5 – Example Standard Deviation Plot for the Left Body Side (Research Question 2)

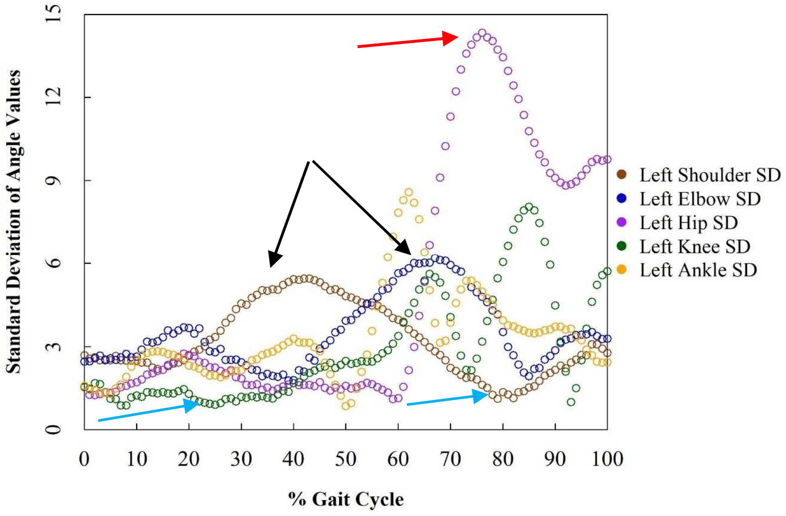


Figure 5.5 illustrates an example of standard deviation plot of all five joints of the left body side in Participant 4. Each group of differently coloured circles described in the afferent legend, correspond to the standard deviations of the shoulder, elbow, hip, knee, and ankle at every 1% of their respective gait cycles.
The red arrow emphasises the joint with the largest variability during the swing phase, the black arrows highlight a similar overall variability trend with a mirroring effect in the shoulder and elbow (i.e. same shape but peak variability occurring during different gait segments, and the blue arrows emphasise the joints with the lowest variability in the stance and swing phases.

5.4.3 Research Question 3

The third and final stage of data analysis of this thesis quantifies and investigates the degree to which bilateral intraindividual variation influences interindividual variation across gait events of sagittal plane movements of the shoulder, elbow, hip, knee and ankle, to provide evidence for, or against the assumption of gait uniqueness and implicitly, the utility of gait in forensic identification. The analysis therefore integrates the finds of the previous two research questions in order to answer *Research Question 3*, and fulfil the three thesis aims previously presented in Chapter 1, Section 1.2. The Fisher-Pitman permutation test was utilised for the analysis of each bilateral joint (full R code in Appendix F), an alternative to the one-way ANOVA F-test test of differences in the means, which is suitable for datasets that do not satisfy the condition of equality of distributions (Berry *et al* 2002). Hence, the research question is extended upon the following hypothesis: *interindividual variability exceeds intraindividual variability throughout all gait events, irrespective of body side, because gait is unique.* The dataset of this thesis is not uniform with respect to the total number of cycles per participants for each joint and body side, as presented in Table G, Appendix G. Also, the total number of participants is small and unequal when considering their varied physiological characteristics which may influence gait patterns such as weight, height, age and sex; as a result, classical significance tests would yield inappropriate results given the purpose of the analyses in this thesis. The permutation characteristic of the test is also appropriate since it allows for the values of each joint at each percent of the gait cycle of all 20 participants to be 'shuffled' given a user-defined number of times, thereby artificially 'increasing' the size of the dataset by calculating the probability of obtaining values as extreme as those observed in the dataset (Hothorn *et al* 2006).

The Fisher-Pitman permutation test is based upon a similar framework to the ANOVA F-test in that it tests for differences in sample means to determine whether the means are significantly different from one another, but utilising the reshuffling principle (i.e. exchangeability of the data) irrespective of the nature of the data distributions. This exchangeability assumption is valid for the gait dataset of this thesis since angles produced by normal upper or lower limb movements of healthy individuals can only take values that are within the range of the physiological parameters of the human body. Since the assumption of exchangeability is met, and the dataset is small, with unknown distributions, the Fisher-Pitman permutation test is a valid alternative to the ANOVA tests (Hayes 2000). However, the test also assumes an equality of variances (Neuhauser and Manly 2004) in order to provide valid results with respect to differences in the mean. Despite this potentially influencing assumption on the validity of the results, this approach was chosen since variability would already be available from the results obtained from Research Questions 1 and 2. In addition, a statistical significance due to inequality in variances with or without a difference in the means is as relevant to the data analysis of this thesis as is a 'true' difference in means, since the research aims revolve around the influence of variability and body symmetry on the discriminatory power of joint angles in identification. For example, in a scenario where the results of Research Question 1 yield large differences in body symmetry with respect to the degree of intraindividual variability in a particular joint, a *statistically significant* result for interindividual variation for that joint given body side thus reflects body asymmetry; this would therefore suggest that interindividual variation is influenced by the differences in variability between the two body sides. The 'true' difference in means becomes less pertinent to the analysis because there would be evidence to suggest that regardless of whether there is a difference in the means or not, the large intraindividual variability given body side, does not allow for a valid calculation of the difference in means, thus indicating that identification is affected by intraindividual variability due to body asymmetry.

The purpose of the need to also quantify interindividual variation in addition to intraindividual variability was to evaluate whether intraindividual variation may be higher in certain gait cycle regions in specific joints which would reduce the value of interindividual variation and implicitly, the discriminatory characteristic of gait in identification. To answer Research Question 3, the data previously prepared for the preceding two research questions were re-arranged in Excel in a suitable format for the R program package utilised, namely the *coin* package (Hothorn *et al* 2008; Strasser and Weber 1999); this step was necessary since different packages in the R program require specific data formats in order to apply the user-defined functions accurately. For each joint, the data of all participants were added to three Excel files namely, one file for the left body side, one file for the right body side, and one file for both body sides, for simplicity in conducting the significance tests. After importing the data in R and running the *coin* package, the *one-way test* function (i.e. Fisher-Pitman permutation test) was applied to each of the three files, once for the left body side, once for the right body side and twice for the file containing the data from the two body sides. For the latter, one test was conducted on all of the data of all 20 participants collated irrespective of body side, and a second to investigate the role of body side by discriminating between the data of the left and right body sides. The purpose of evaluating each body side in isolation and in collating all data irrespective of body was to allow for a more robust evaluation of the importance of body side in discriminating individuals from one another.

The *one-way* tests were conducted using 10,000 permutations (Monte-Carlo) approach for a p-value of 0.01; this p-value was chosen to minimise non-rejection (Type II error) of the null hypothesis. The number of permutations was chosen since after several trials, an increase in the number of permutations or opting for a different approach did not alter the obtained p-values beyond the second decimal place (Kaiser 2007); hence, when rounding the p-value to the second decimal place, the overall value was not altered. Following the significance tests, the data were plotted onto four different graphs (also in the R program) for each joint, to illustrate the regions of the gait cycle which presented significant and non-significant p-values for the left and right body sides separately, for the combined left and right body sides and for the body side-dependent data. The R code for all the aforementioned steps is found in Appendix F. The data obtained using the Fisher-Pitman permutation tests are presented and evaluated in Chapter 8; Section 8.2.1 and 8.2.2 present the results of the upper and lower body joints respectively, whilst Section 8.3 compares and contrasts the results of all five bilateral joints given all data obtained from Research Question 3, as well as from Research Questions 1 and 2.

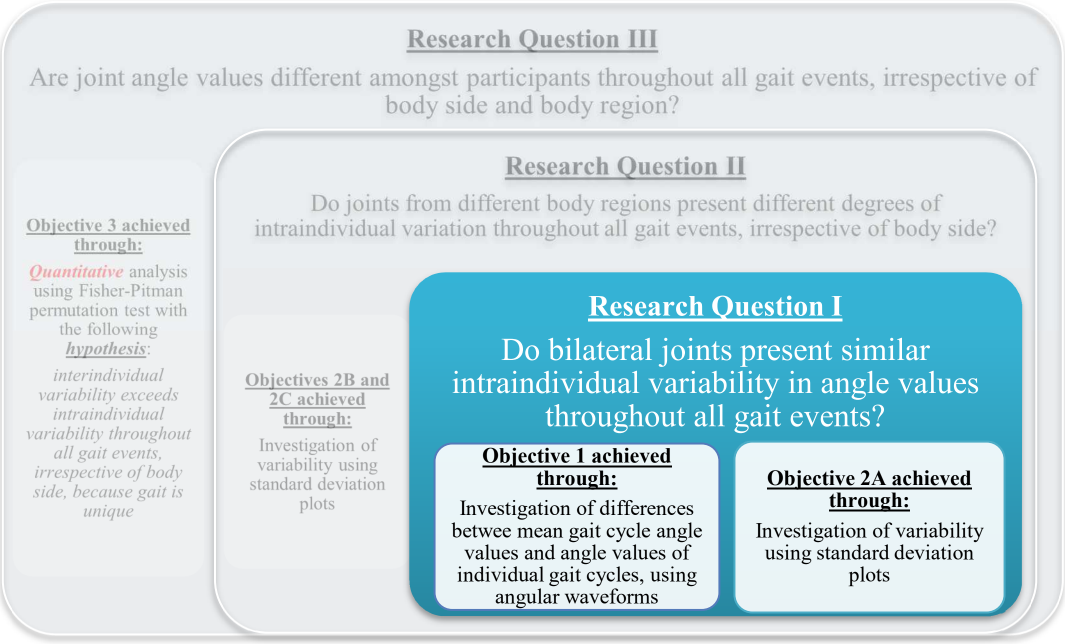
Section III – Variation in Gait

Chapter 6 – Intraindividual Body Side Variability (Research Question 1)

6.1 Overview

Chapter 6 presents and describes the findings of Research Question 1. As previously discussed Chapter 5, Section 5.4.1, and reiterated below (Figure 6.1), Research Question 1 constitutes the centre phase of the thesis investigative approach towards fulfilling the aims and objectives presented in Section 1.2, Chapter 1. The results are presented and discussed separately for each joint (Sections 6.2 to 6.6 for the shoulder, elbow, hip, knee, and ankle respectively).

Figure 6.1 – Thesis Investigation Approach (Research Question 1)



6.2 Left and Right Shoulder

6.2.1 Results

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, with values largely clustered around 5 degrees to -5 degrees, as shown in Figure 6.2A. From the 40 waveforms (20 participants, one waveform per body side), only seven surpass the aforementioned range. 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). Likewise, the gait sub-phases were generally synchronised across both the left and right shoulder joint waveforms, although maximum shoulder flexion was observed to occur either earlier or later in the cycle for some of the waveforms, particularly for the left shoulder. Anomalous waveforms were found in most of the participants to different extents, with two examples highlighted in Figure 6.2A, corresponding to P5 (full blue arrows), P17 (red arrow), and P18 (dashed blue arrow).

To investigate the degree to which the mean waveforms of the 20 participants presented in Figure 6.2 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. The intraindividual variability of the angle values across all gait cycles for each one of the 20 participants was generally small in both the left (dark blue) and right body sides (light blue), as depicted in Figure 6.2B. The standard deviations throughout all gait events for both body sides were mostly clustered in the range of 1 to 5 units, including three of the previously presented participants (P5, P6, and P18). The largest variability of approximately 11 standard deviations was found in the left shoulder during the latter half of the stance phase (~40%), corresponding to P17, and the second largest variability of approximately 10 standard deviations during early swing (~60%) in the right shoulder, corresponding to P14 (Figure 6.2B, red arrows). Interestingly, variability close to 0 standard deviations (i.e. no variability) was only found in the left shoulder during early stance (~9-10%) in P2 and in the right shoulder during late swing (~96-99%) in P12, as indicated by the green arrows.

Figure 6.2 – Research Question 1: Summary of the Bilateral Shoulder Joint Data

A – Left and Right Shoulder Mean Gait Cycles

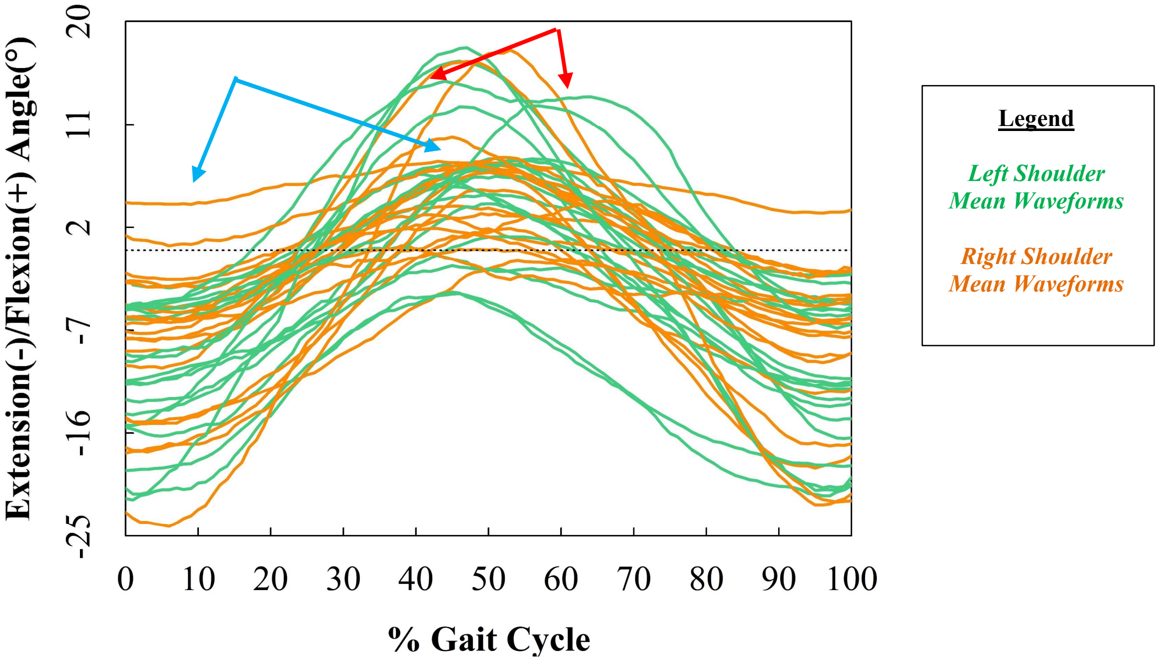


Figure 6.2A illustrates the mean gait cycle waveforms of the left and right shoulder joints of all 20 participants. Each one of the 20 participants is represented by one green line and one orange line corresponding to the mean gait cycle waveform for the left and right shoulder joints, respectively. The black horizontal dashed line represents a y axis value of zero. The **red** arrows indicate an example of **double peak** effect in the left shoulder (P17), and the **blue** arrows a flat overall shape in the right shoulder for P5.

B – Variability in the Left and Right Shoulder

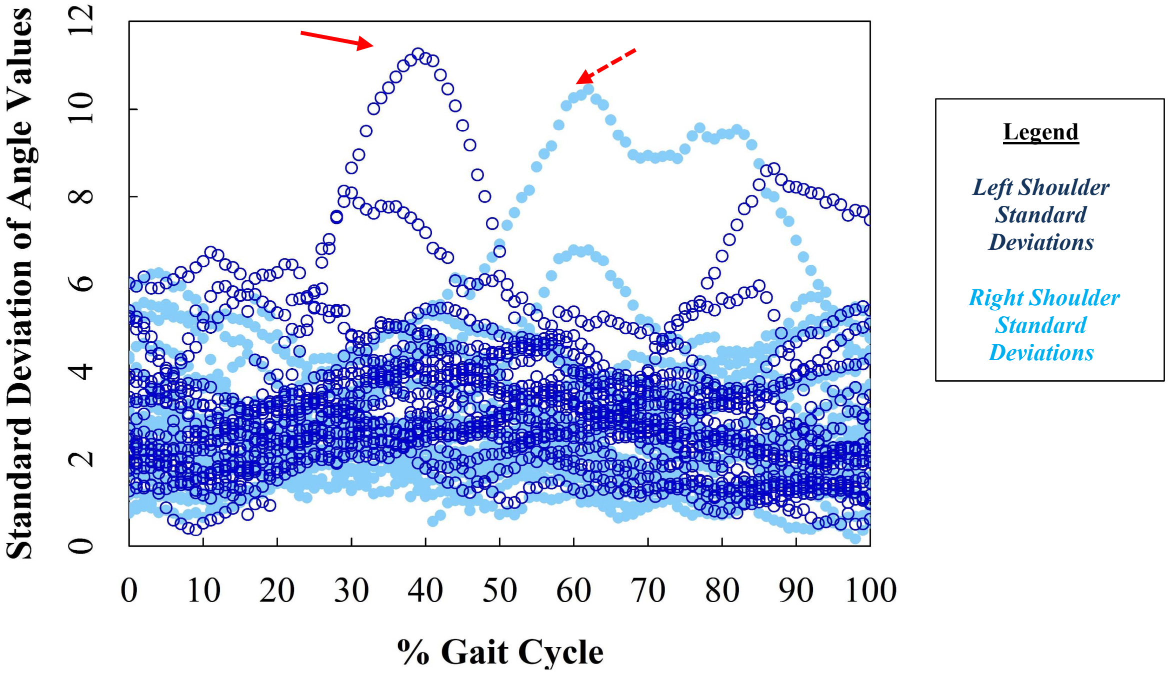


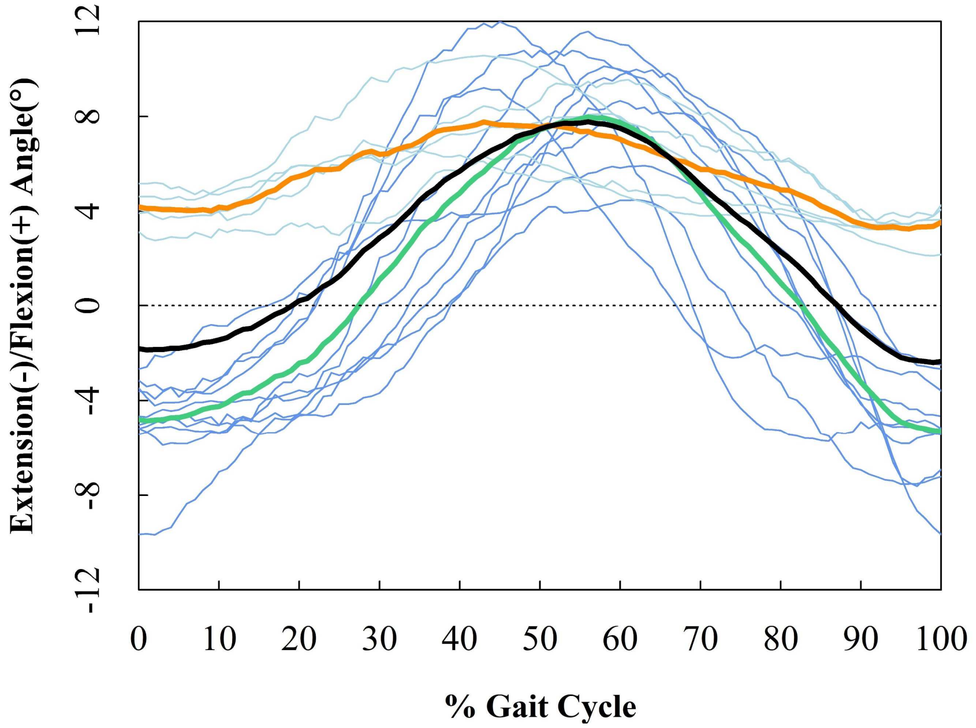
Figure 6.2B illustrates the standard deviations of the values of all bilateral gait cycles for each of the 20 participants. The dark blue circles and light blue circles represent the standard deviations of the left and right shoulder joints respectively, at every 1% of the gait cycle, for each one of the 20 participants. The **red** arrows indicate the **largest** intraindividual variability in a given gait phase; full red arrow corresponds to P17, and dashed red arrow to P14.

To demonstrate the range of characteristics amongst participants, several illustrations are provided; the full set of results are found in Appendix H1, Plots H1.1A,B to H1.20A,B. As indicated in Figure 6.2A, and presented in Plot 6.1A, Participant 5 (male, 28 years, 70 kilograms, 1.81 metres) presents minimal flexion in the right shoulder, with no discernible maximum flexion peak. Also, the left and right shoulder mean waveforms highlight left shoulder mean values which are generally lower than those of the right shoulder in the majority of the gait phases. Overall, these mean differences reach 8-9 degrees during heel strike (~0-10%) and terminal swing (~95-100%) and originate from the differences in location of the interval of values. Whereas the extension values of the 5 right shoulder cycles are clustered around positive values during early stance (~0-25%) and terminal swing (~89-100%), all 10 left shoulder cycles are found in the negative range, between -3 degrees and -9 degrees. These discrepancies are reflected in a higher combined variability of approximately 5 standard deviations which exceeds the variability of both body sides (Plot 6.1B, red). Implicitly, the total mean values do not reflect the range of values observed in the bilateral shoulder. The two mean waveforms also differ in shape whereby the right shoulder waveform does not display a distinct maximum flexion peak; rather, the right shoulder is maintained in a slightly flexed position throughout all gait events, starting at 4 degrees, increasing to a maximum of 7 degrees during terminal stance, and decreasing to a minimum of 4 degrees towards the end of the swing phase. Due to this small interval of values, the variability of the right shoulder is maintained under 2 standard deviations throughout all gait events, as shown in Plot 6.1B, approaching zero variability at the start of terminal swing (~90-92%).

In contrast, the 10 left shoulder cycles present dispersed and inconsistent maximum flexion peaks spread across terminal stance, pre-swing and initial swing, and a larger interval of values during the latter half of the gait cycle, including maximum flexion values. Due to these phase shifts, the corresponding variability values are highest, but this variability is misleading because it does not originate from differences in value (evident from Plot 6.1A) but rather from lack of synchronicity of the gait events in these cycle segments. For the same reason, the variability trends of the two joints differ in those regions, as shown in Plot 6.5B. Hence, the start of terminal stance (~40-42%) and mid-swing (~78-80%) present the highest variability differences of 2 and 3 standard deviations, respectively. Conversely, the lowest differences in variability between the two body sides (close to zero) were found to be during the loading response phase/mid-stance (~18-24%) and at approximately 50% of the gait cycle. Overall, the lowest variability of close to zero units was found in the right shoulder during terminal swing (~89-95%).

Plot 6.1 – Variability in the Left and Right Shoulder (**Participant 5**)

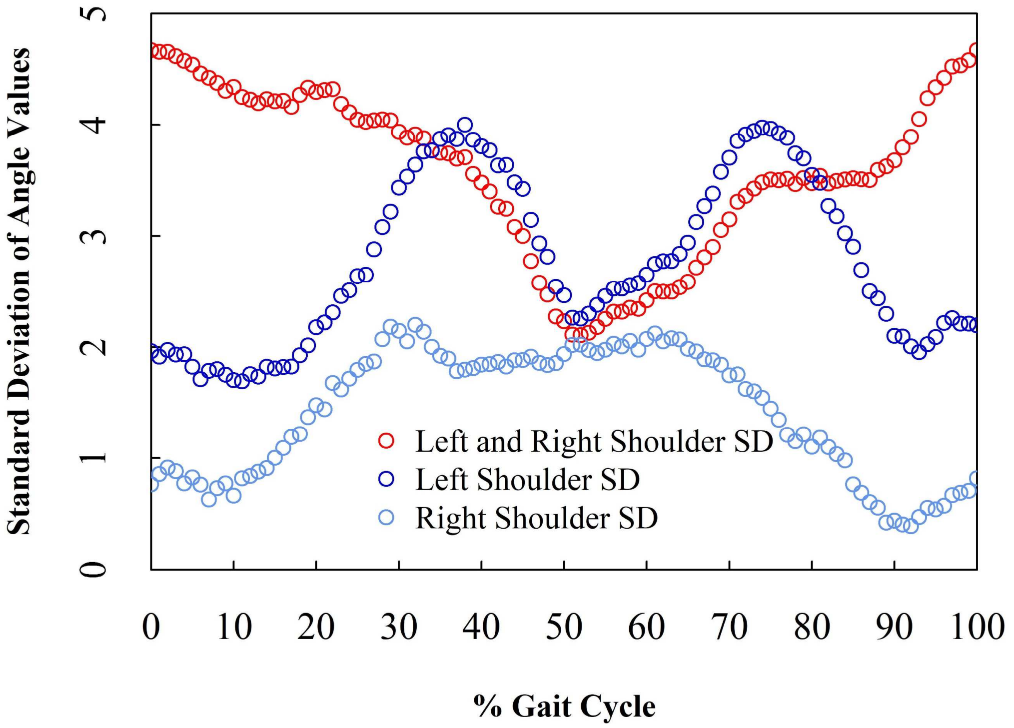
A – Gait Cycles of the Left and Right Shoulder of Participant 5



Left Shoulder (LS) Cycles*; **Right Shoulder (RS) Cycles**; **LS Mean**; **RS Mean**; **Total Mean***

Plot 6.1A illustrates the gait cycles of the left (LS) and right shoulder (RS) joints of Participant 5, together with their respective means (green and orange respectively), as well as their combined mean (black). The LS joint (dark blue) is represented by a total of 10 cycles and the RS joint (light blue) by 5 cycles. The black horizontal dashed line represents a y axis value of zero.

B – Standard Deviation Plot of Participant 5



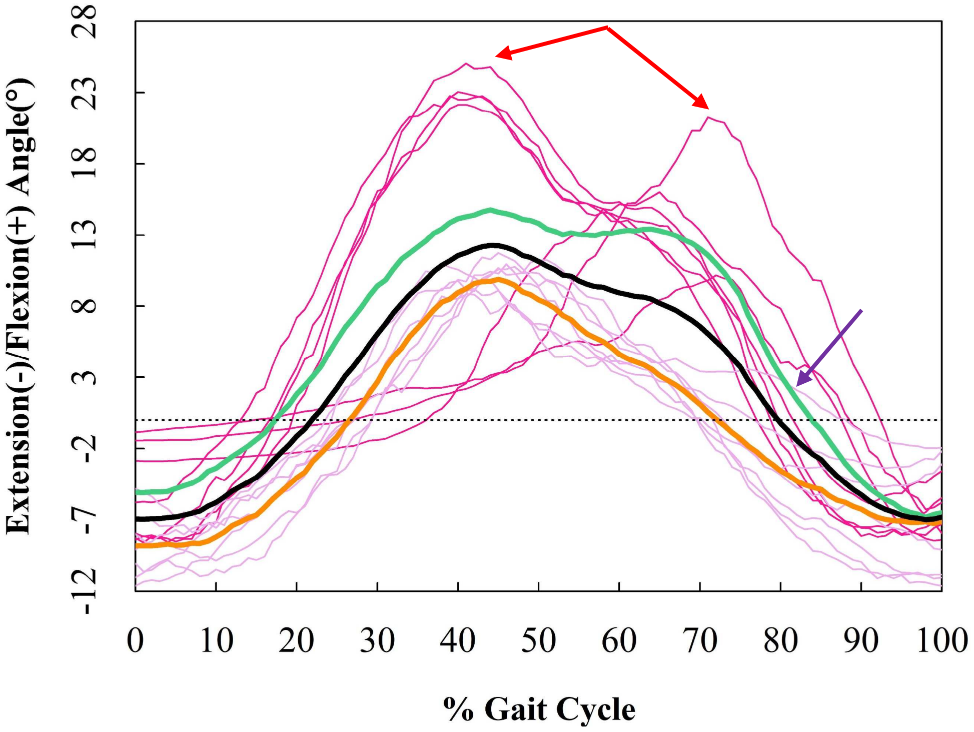
Plot 6.1B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 5 for the left and right shoulder joints (dark blue and light blue respectively) as well as the combined standard deviation for both joints (red) for each 1% of the gait cycle.

As previously indicated in Figure 6.2A (red arrows), Participant 17 (female, 25 years, 58 kilograms 1.64 metres) presents a unique anomalous characteristic, whereby one of the seven left shoulder mean waveforms display two peak flexion events. In addition, as indicated in Figure 6.2B (full red arrow), P17 also presents the largest intraindividual variability. As shown in Plot 6.2A in more detail, overall, the shapes of the mean waveforms are incongruent, whereby the left shoulder mean waveforms displays two peak flexion events (red arrows), as opposed to the single peak of the right shoulder mean waveform. Generally, the differences in means between the left and right shoulder do not exceed 5 degrees, with the exception of initial swing (~60-70%) where the largest difference of approximately 9 degrees was observed, and the final 5% of the gait cycle where the differences are negligible. In contrast to the other participants, the left shoulder mean waveform of P17 displays maximum shoulder flexion twice, once during terminal stance (~40-42%) and again during mid-swing (~70%), a characteristic also reflected in the total mean waveform, implicitly resulting in a combined variability that is higher in value than either body side, as shown in Plot 6.2B. Also, the maximum flexion values constitute some of the highest observed.

When examining the individual waveforms (7 gait cycles per body side), this double peak flexion is found only in 2 out of the 7 left shoulder gait cycles but is nevertheless encapsulated by the mean waveform due to the phase shifts occurring in the remaining 5 cycles where maximum shoulder flexion is achieved at a later period during the gait cycle (~65-70%). Therefore, the substantial variability of 11 standard deviations in the left shoulder (Plot 6.2B) stems from the delay in peak flexion in 3 out of the 7 cycles rather than from truly lower peak flexion values. Similarly, the 6 standard deviations variability during mid-swing also corresponds with this phase shift, as well as to the second additional peak effect. Conversely, the shape and values of the 7 right shoulder cycles are much more uniform and consistent throughout most of the gait cycle. Therefore, the variability trend is maintained more constant and under 2 standard deviations for most of the gait events (~0-72%). The final 28% of the swing phase however presents a higher variability of 4 standard deviations in the right shoulder due to one of the 7 cycles which presents an additional, albeit flatter peak (Plot 6.2A, purple arrow). Overall, the lowest variability of just under one standard deviation was found at the start of terminal stance in the right shoulder (~40-41%).

Plot 6.2 – Variability in the Left and Right Shoulder (**Participant 17**)

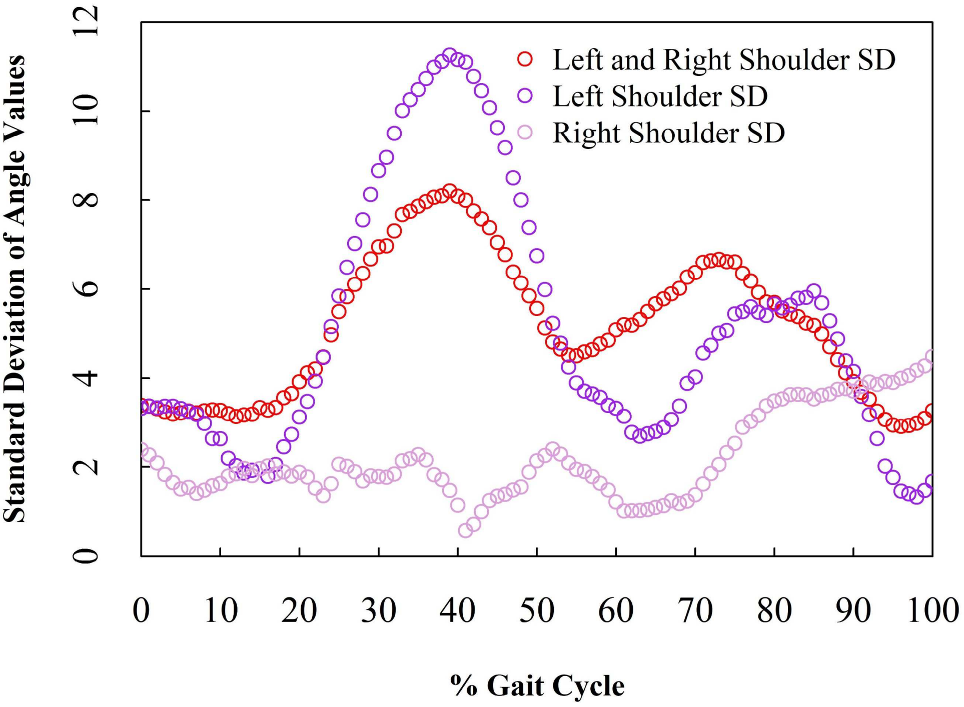
A – Gait Cycles of the Left and Right Shoulder of Participant 17



Left Shoulder (LS) Cycles; Right Shoulder (RS) Cycles; LS Mean; RS Mean; Total Mean

Plot 6.2A illustrates the gait cycles of the left (LS) and right shoulder (RS) joints of Participant 17, together with their respective means (green and orange respectively), as well as their combined mean (black). The LS joint (dark pink) is represented by a total of 7 cycles and the RS joint (light pink) also by 7 cycles. The black horizontal dashed line represents a y axis value of zero. The purple and red arrows highlight the double peak effect in the right shoulder and left shoulder respectively.

B – Standard Deviation Plot of Participant 17



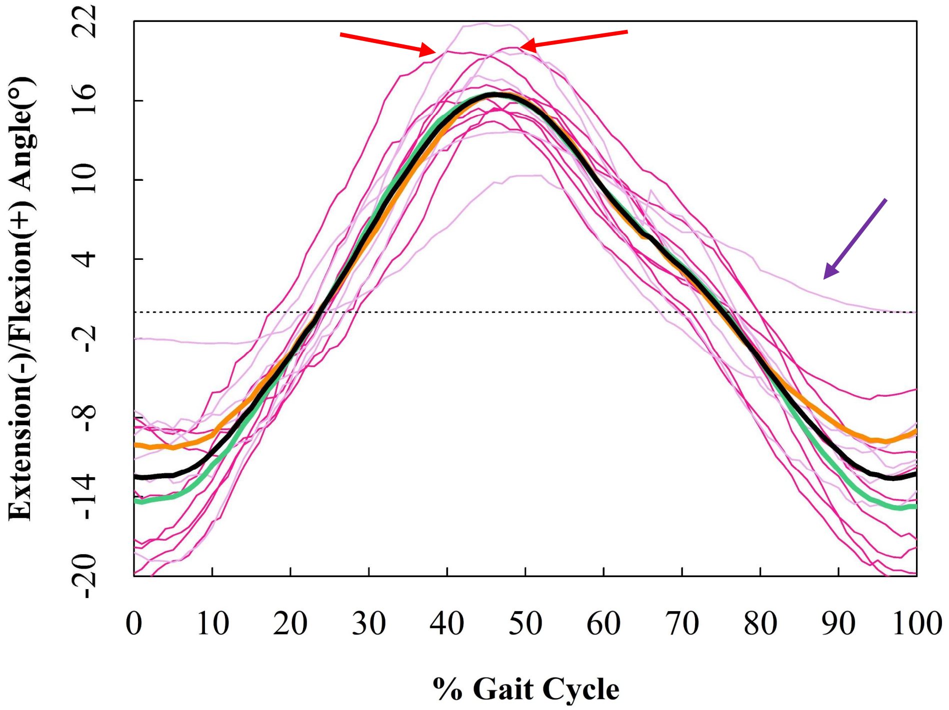
Plot 6.2B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 17 for the left and right shoulder joints (dark purple and light purple respectively) and the combined standard deviation for both joints (red).

Participants 5 and 17 represent two of the multiple examples of anomalous gait cycle characteristics encountered in at least one cycle of at least one of the two body sides. On the other hand, Participant 6 (female, 23 years, 55 kilograms, 1.69 metres) constitutes one of the few examples with high degree of synchronicity across all cycles for both body sides. Plot 6.3A highlights a predominantly consistent relationship throughout the majority of gait events between the left and right shoulder mean waveforms, the exceptions being the first 15% of the stance phase and the final 15% of the swing phase where the left shoulder mean values are lower by 6-7 degrees, as illustrated in Plot 6.3A; this participant also presents the largest flexion and extension values observed thus far. With the exception of 2 out of the 6 left shoulder cycles (red arrows) which display differences in peak flexion, and one out of the 6 right shoulder cycles which displays the highest extension values and which differs in shape, and synchronicity (purple arrow), the cycles of the bilateral shoulder share common characteristics throughout all gait events. As a result, the differences in variability between the two body sides are negligible (less than one unit) throughout most gait events. The sole exception is terminal stance (~45-47%), where a difference of approximately 3 standard deviations was noted (Plot 6.3B), stemming from a minor peak flexion shift and lower value of one of the right shoulder cycles which resulted in a higher right shoulder variability.

Separately, the left shoulder values were generally less variable than those of the right shoulder, however, similar bilateral trends of variability increase/decrease were found throughout the gait cycle, with the exception of the mid-stance and pre-swing phases (~35-55%) where the variability of the left shoulder decreased whilst that of the right shoulder increased. In addition, the variability of both joints was highest at the start and end of the gait cycle (just under 6 units). As depicted in Plot 6.3A, both the left and right shoulders display a greater range of values during these gait phases, thus translating into higher variability. Nevertheless, the combined variability (Plot 6.3B, red) is maintained within the range of both body sides, as is the total mean (Plot 6.3A, black line). Overall, the lowest variability of 2 standard deviations was found solely during the right shoulder terminal stance (~44-45%), as opposed to previous participants for whom the minimum variability was less than 2 units.

Plot 6.3 – Variability in the Left and Right Shoulder (**Participant 6**)

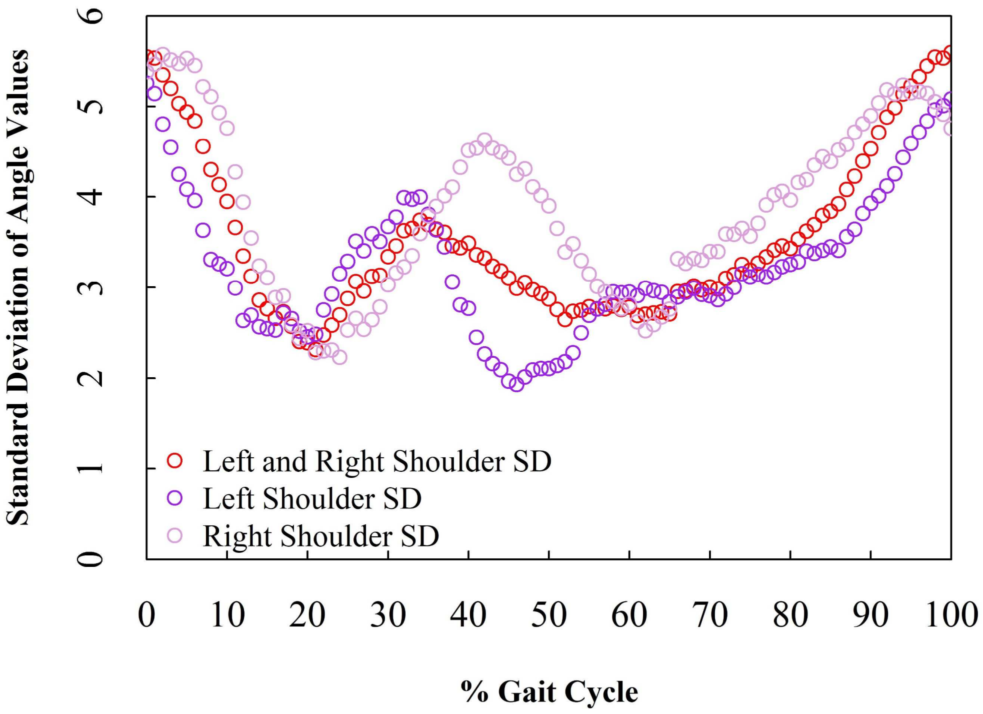
A – Gait Cycles of the Left and Right Shoulder of Participant 6



Left Shoulder (LS) Cycles*; **Right Shoulder (RS) Cycles**; **LS Mean**; **RS Mean**; **Total Mean***

Plot 6.3A illustrates the gait cycles of the left (LS) and right shoulder (RS) joints of Participant 6, together with their respective means (green and orange respectively), as well as their combined mean (black). The LS joint (dark pink) is represented by a total of 8 cycles and the RS joint (light pink) by 6 cycles. The black horizontal dashed line represents a y axis value of zero. The red arrows indicate asynchronicity in two left shoulder cycles whilst the purple arrow indicates the right shoulder cycle with highest extension value.

B – Standard Deviation Plot of Participant 6



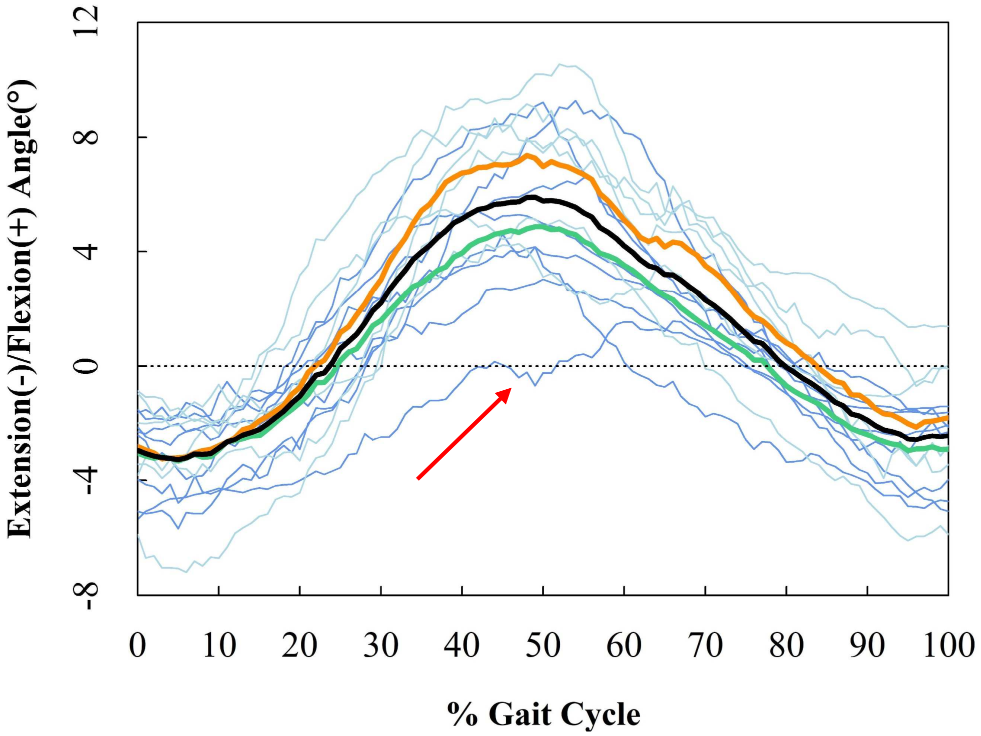
Plot 6.3B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 6 for the left and right shoulder joints (dark purple and light purple respectively) as well as the combined standard deviation for both joints (red) for each 1% of the gait cycle.

To also illustrate the range of variability amongst participants, a contrasting example is that of P1 (male, 27 years, 66 kilograms, 1.80 metres), who presented the lowest overall variability in both body sides, depicted below in Plot 6.4 in more detail. The shapes of the left and right shoulder mean waveforms obtained from a total of 8 cycles and 6 cycles respectively, present some similarities. The left shoulder mean values are predominantly lower than those of the right shoulder (~30-100%), but only by a maximum of 3 degrees throughout terminal stance and pre-swing (42-52%); elsewhere, the differences are less than 2 degrees, and therefore negligible. This characteristic is sustained when examining the individual cycles, whereby the values of the 8 left shoulder cycles and the 6 right shoulder cycles are generally interspersed, rather than clustered into distinctly higher or lower value group. One exception is the middle region of the gait cycle (~31-62%) where one of the 8 left shoulder cycles presents lower values thus corresponding with the aforementioned maximum difference (red arrow, Plot 6.4A). The differences in value were exacerbated by the lack of synchronicity (i.e. phase shift) of the peak event (i.e. maximum flexion) across the cycles, thus resulting in a fluctuating variability across the gate events (Plot 6.4B, dark blue). This aspect was also observed in one of the 6 right shoulder cycles, although the duration of peak flexion in the right shoulder appears to be longer for the majority of the 6 cycles as opposed to the left shoulder. As a result, maximum flexion for the right shoulder mean waveform begins earlier and is maintained for longer (~40-50%) than maximum flexion in the left shoulder (~50-51%), thus resulting in a wider peak. Also, the right shoulder values are clustered within a larger interval of values during early stance (~0-20%) and during most of the swing phase (~70-100%), a feature also reflected by the highest degree of variability of 2-3 units, as shown in Plot 6.4B (light blue).

Conversely, the variability of the left shoulder is maintained low at just over one standard deviation during these gait events, due to the narrower range of values. In contrast, the middle region of the gait cycle displays a reduction in right shoulder variability and an increase in the variability of the left shoulder to 3 units, due to the previously discussed two shoulder cycles with lower values. Nevertheless, the differences in variability between the two body sides are just above one standard deviation throughout most gait events, as expected from the small differences in the values of the mean waveforms, except during terminal swing (~90-100) where the largest difference in mean value of 3 degrees was also noted and therefore, where the difference in variability is largest (2 units). Therefore, for P1, the combined standard deviation (Plot 6.4B, red) falls within variability range of both body sides and implicitly, so does the total mean throughout all gait events. Furthermore, the overall variability trends of both joints are similar throughout all gait events, although these alternate. Lastly, the region with the lowest variability of one unit was left shoulder mid-swing (~82-86%).

Plot 6.4 – Variability in the Left and Right Shoulder (**Participant 1**)

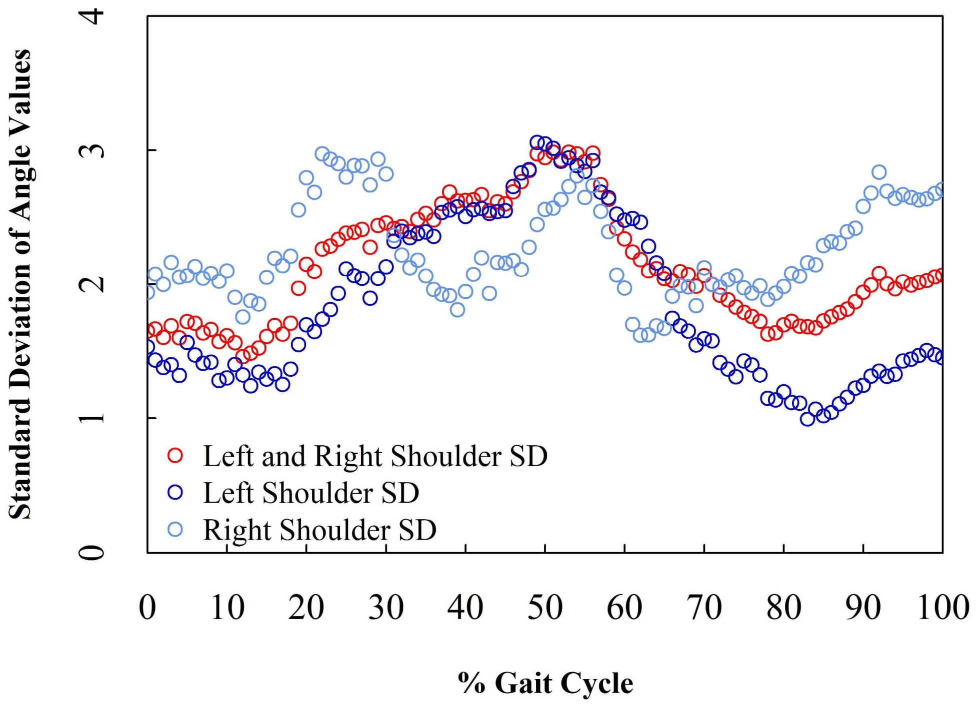
A – Gait Cycles of the Left and Right Shoulder of Participant 1



Left Shoulder (LS) Cycles**; **Right Shoulder (RS) Cycles**; **LS Mean**; **RS Mean**; **Total Mean

Plot 6.4A illustrates the gait cycle waveforms of the left (LS) and right shoulder (RS) joints of Participant 1, together with their respective means (green and orange respectively), as well as their combined mean (black). The LS joint (dark blue) is represented by a total of 8 cycles and the RS joint (light blue) by 6 cycles. The black horizontal dashed line represents a y axis value of zero. The red arrow indicates the shoulder cycle with the lowest values.

B – Standard Deviation Plot of Participant 1



Plot 6.4B illustrates the standard deviations at each 1% of all of the gait cycle of Participant 1 for the left and right shoulder joints (dark blue and light blue respectively) as well as the combined standard deviation for both joints (red) for each 1% of the gait cycle.

6.2.2 Discussion

In the shoulder joint, the range of variability of the left body side is largely similar to variability range of the right body side (1-4 standard deviations) across all of the 20 participants, but not throughout the full length of all gait cycle phases and not for all 20 participants to the same extent, as shown in Table 6.1, pg.115. The participants were grouped according to whether they exhibit similar bilateral variability (light orange) OR bilateral *and* combined variability (dark orange). The 'similarity' constitutes a difference amongst the variabilities of one standard deviation or less. This threshold was chosen since it translates to an angle value difference of less than 2.5 degrees that is as negligible a quantity as possible so as to ensure appropriate extrapolation of the subsequent conclusions for building a biomechanical (scientific) basis for forensic gait analysis methodologies, as well as adequately testing the premise of gait uniqueness. The grouping of participants in Table 6.1 is also important since the value of the combined variability is indicative of whether the range of values of a given body side is grouped at a different interval than the range of the contralateral body side. In cases where the combined variability exceeds the variability of both body sides, the utilisation of bilateral gait data interchangeably is unrecommended since the total mean cannot be accurately representative of bilateral values given the differences in the location of the range of values between the two body sides. Hence, the two categories in Table 6.1 are mutually exclusive to ensure clarity regarding such characteristics.

Therefore, the analysis of the shoulder joint data (277 bilateral cycles in total) indicates that intraindividuality of angle values is not similar bilaterally throughout all gait events (Research Question 1). As illustrated in Table 6.1, pg.115, *initial swing* is the gait phase where the largest number of participants (n=8) presented similar bilateral and combined variability, thus highlighting that in less than half of the participants, both body sides also share a common range of values (dark orange). Since the number does not constitute a majority, this indicates that the movements in the shoulder joint across the majority of gait events are largely asymmetrical and therefore, the utilisation of the total mean or unilateral joint data is unsuitable to represent the 'average' gait of an individual, given the differences in intraindividual variability between the two body sides in the shoulder joint.

Table 6.1 – Gait Cycle Regions with Similar Intraindividual Variability in the Bilateral Shoulder Joint

	Participant Index									
Right and Left Shoulder Intraindividual Variability	P3 P5 P7 P11 P12 P19	P3 P4 P5 P7 P17 P18 P19	P2 P7 P10 P18	P1 P2 P7 P10 P20	P2 P13 P20	P2 P11 P18 P20	P2 P10 P11	P3 P10 P11 P13 P19	P2 P3 P10 P11 P19	P2 P6 P7 P10 P11 P12 P19
Total Number of Participants	6	**7**	4	5	3	4	3	5	5	**7**
Right and Left Shoulder Intraindividual Variability + Combined Intraindividual Variability	P1 P4 P14 P15	P1 P9 P11 P15	P3 P6 P11 P15 P19	P3 P11 P13 P15	P1 P3 P7 P9 P10 P14 P15	P1 P3 P5 P9	P1 P3 P6 P8 P9 P16 P19 P20	P1 P4 P6 P9 P16 P20	P1 P4 P6 P13 P15 P16 P18	P13 P15
Total Number of Participants	4	4	5	4	7	4	**8**	6	7	2
	Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
	Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.1 summarises the gait cycle regions of bilateral shoulder joint flexion/extension in all 20 participants where the intraindividual variability of the left and right body sides, as well as their combined intraindividual variability, are similar (i.e. difference of one standard deviation or less). The light and dark orange coloured boxes highlight the largest number of participants in a given category. Note that all 20 participants are found in the table, albeit differently distributed across gait sub-phases.

The second largest groups of participants (n=7) with similar bilateral and combined variability was found during *terminal stance,* and *late mid-swing* sub-phases. However, not all participant indices are consistent throughout the aforementioned phases; only P1 is present throughout all three gait sub-phases (i.e. also in *initial swing*), thereby suggesting that the higher number of participants with similar bilateral and combined variability may or may not imply that these gait sub-phases represent segments where symmetry is highest; this aspect warrants further investigation with a larger dataset for confirmation. Conversely, smallest number of participants (n=2) with similar bilateral and combined variability was found in *terminal swing*. This suggests that *terminal swing* is a gait segment with the least potential for interchangeability of left and right shoulder data, further highlighting the importance of body side during analysis. Since the number of participants with similar bilateral and combined variability does not constitute a majority in any of the gait phases, this aspect is additionally suggestive of lack of symmetry in shoulder flexion and extension during normal walking.

With respect to consistency of both bilateral and combined variability across multiple gait events, P1 and P15 are the sole participants for which bilateral and combined variability magnitudes are similar throughout most of the gait sub-phases (70%). However, both participants are not present throughout all of the same gait events; during *mid-stance* and *terminal swing* only P15 is present, whilst during *pre-swing* and *initial swing,* only P1 is found. High consistency across gait events (90%) was also noted in P3, however, for *heel strike, loading response,* and *mid-swing*, the bilateral variability was similar, but the combined variability differed, thus highlighting a difference in location of the range of values amongst these gait sub-phases. Given that only 3 out of 20 participants presented symmetric flexion and extension movements throughout the majority of gait events, this find may indicate that in general, flexion and extension movements in the shoulder joint are asymmetric.

The number of participants with similar bilateral and combined intraindividual variability can solely evaluate body symmetry, however, in the forensic context, body symmetry has to also be accompanied by an overall low intraindividual variability that is relatively stable across individuals and across gait phases, to allow for interindividual variation to be assessed meaningfully. Therefore, an analysis of which participants presented low variability across gait events was conducted to develop an empirical basis for interindividual variability analysis later in the thesis (i.e. Chapter 8). As presented in Table 6.2, pg. 117, the participants were grouped according to two categories: '*variability of one standard deviation*' and '*no variability'*. For the former category, participants were included only if the variability observed was equal to *and/or* just under one standard deviation, throughout an entire gait sub-phase; participants for whom low variability was found for very short gait segments (e.g. for 3-4% of a gait sub-phase) were not included since such brief gait cycle periods have no particular utility in developing an empirical basis for investigating gait uniqueness and implicitly, for addressing the potential of gait-based features for individualisation since no specific trends can be extrapolated and such minute movements would be difficult to observe from video. For the '*no variability'* category, participants were included if the observed variability was close to *and/or* equal to zero standard deviations; in gait sub-phases where such negligible variability was encountered in very short segments AND the remainder of the given gait sub-phase presented a variability of one unit or less, the participant was placed in both categories. In other cases where short gait segments with 'no variability' AND higher variability throughout the remainder of the gait sub-phase was encountered, the participants were not included in Table 6.2.

Table 6.2 below shows that only five of all twenty participants exhibit intraindividual variability of one standard deviation or less for the shoulder joint. Moreover, these participants are dispersed throughout multiple gait sub-phases and across the two body sides, rather than concentrated in specific regions of the gait cycle and/or according to body side; the largest number of participants in a given gait sub-phase was 2 participants in *terminal swing* of the right shoulder. Whilst low variability was also encountered in P1, P7, P11, P15-P18, the gait segments were too short to be of any utility for drawing solid conclusions and implicitly, of little use for forensic gait analysis. Overall, the intraindividual variability in the right shoulder is lower throughout a larger proportion of gait events (40%), as opposed to the left shoulder (30%) where a variability of one standard deviation was found during *heel strike, loading response* and *terminal swing,* with one (different) participant per category. For the right shoulder, two participants were noted during *terminal* swing, where zero variability was also encountered for a short segment of this gait sub-phase, in contrast to the left shoulder for which zero variability was found for a brief segment during *heel strike* in a different participant. Also, no participant presented low or zero variability bilaterally.

Table 6.2 – Gait Cycle Regions with Lowest Intraindividual Variability in the Bilateral Shoulder Joint

		Participant Index									
Left Shoulder Intraindividual Variability	**One Standard Deviation**	P2	P8								P9
	No Variability	P2									
Right Shoulder Intraindividual Variability	**One Standard Deviation**	P5							P2	P5	P5 P12
	No Variability										P5 P12
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.2 summarises the gait cycle regions of the left and right shoulder joint flexion/extension of all 20 participants which present with an intraindividual variability of one standard deviation or less. Of note is that participants P1, P3, P4, P6, P7, P10, P11, P14-P20 present intraindividual variability higher than one standard deviation and are therefore not found in this table. The light and dark red coloured boxes indicate the magnitude of the intraindividual variability (**light red – one standard deviation**; **dark red – zero variability**).

The evaluation of this dataset therefore suggests that the flexion and extension movements of the right shoulder are as highly variable as those of its contralateral counterpart, since the proportion of gait sub-phases with low variability in the right shoulder is not substantially larger than in the left shoulder. In addition, the majority of participants presented with a variability of greater than one standard deviation and, coupled with only a single gait sub-phase for which bilateral and combined variability were similar (i.e. *initial swing,* Table 6.1, pg. 115), the results suggest that the data of the bilateral shoulder cannot be utilised interchangeably, and that the total mean is not accurately representative of the variability observed in both the left and right body sides in the shoulder joint. Based on the obtained results, there are two approaches to the interpretation of this data. One is that, given the stylistic nature of upper limb movements and their (more) passive implication in the biomechanics of gait, the shoulder and elbow joints would be highly suitable for identification; individuals have more anatomical ‘freedom’ to opt for a personalised manner in which to conduct their arm movements because the upper limb joints (particularly the shoulder joint) are less constrained with respect to their anatomy and physiology, and less biomechanically relevant for achieving locomotion. To investigate this interpretation, the bilateral shoulder joint intraindividual variability required comparison not only with that of the bilateral elbow joint but also with the intraindividual variabilities in the lower body joints, namely the bilateral hip, knee, and ankle (found in Chapter 7 – Intraindividual Body Region Variability (Research Question 2)). On the other hand, the high intraindividual variability and lack of bilateral movement symmetry may pose issues during the individualisation process since it may exceed the degree of interindividual variability. Therefore, to quantify the impact of this intraindividual variability on the potential for individualisation, and test the claim of uniqueness, further analysis was required (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

Of note is that the majority of the shoulder joint angular data presented different types of anomalies, as evidenced, for instance, by the saccadic nature of the transition across the gait events which translated into lack of smoothness of the waveforms (e.g. Plot 6.4, pg.113); the origin of these anomalies are discussed in more detail in Chapter 9. Nevertheless, the lack of smoothness of the angular waveforms does not constitute a detrimental effect upon interpretation of the results since the overall shape and range of values are in accordance with previously published literature (e.g. Romkes and Brach-Schweizer 2017). Anomalies of interest for the evaluation of the results were found in the right shoulder of P5 and P12, the left shoulder of P17 and P18, and in the bilateral shoulder joint of P9. For P5 (Plot 6.1, pg.107) and P12, the right shoulder waveforms were flatter, with a distorted overall shape in comparison to their opposite counterpart, whilst for P17 (Plot 6.2, pg.109), the left shoulder waveforms exhibited additional peaks during the swing phase; since this feature is unique to this participant and found solely in a single gait cycle, it is likely that it originates from inadvertent flexion of the shoulder that is unrelated to the gait of the participant. For P18, the right shoulder waveforms were also flatter in comparison to the left shoulder which also presented a sharp, delayed peak flexion. For P9, all gait cycles presented a similarly erratic appearance irrespective of body side, with no definite peak flexion/extension events; as a result, the left and right body sides are comparable to one another but difficult to compare with other participants. In addition, P2, P11, P12, and P19 also exhibited the lowest degree of flexion; for P2, maximum flexion was rather decreased extension/neutral position for the left shoulder, whilst for P11, the gait cycles presented decreased extension rather than true flexion since all values were negative. For P12 and P19, the value of flexion did not exceed 9 degrees. Given that such features are prominent in 4 out of 20 participants (and to a similar, albeit smaller extent in others), these may represent a stylistic characteristic warranting future research.

Many of the participants also exhibited lack of synchronicity, thus resulting in a higher intraindividual variation, particularly during the swing phase which is generally most affected by a delay in maximum flexion. This aspect has impacted the interpretation of the degree of variability in certain participants since its origin is not necessarily a difference in angle value or shape, but rather a difference in position of the angle values. However, the angular waveforms are important for this analysis since the regions of highest variability can be matched to the angle values of particular gait cycle regions to evaluate the origin of variation. Given this approach, the results suggest that the lack of synchronisation may be an indication that certain individuals achieve maximum flexion in the shoulder joint during different gait events. For instance, asynchronicity is not present in all participants; Participant 6 (Plot 6.3, pg.111) displayed the highest degree of synchronicity and yet, the variability exceeds one standard deviation for both the left and right body sides due to larger ranges of value. Also, other participants with at least two units of variability present similar values despite the lack of synchronicity. Therefore, this aspect may constitute an additional variable to consider for future research to evaluate whether degree of synchronicity is a participant-dependent variable, whether it is a confounding factor originating from data collection, or whether it is a combination of both. Since the data was repeatedly revised by the author of this thesis, the asynchronicity characteristics may not necessarily originate from an improper extraction of the cycles which could have implicitly resulted in an artificial variability in the timing of gait events (although it was very challenging to ensure uniformity).

To provide further evidence for timing of gait events as an additional intraindividuality-related variable, research should be conducted using technology which measures gait events throughout the experimental trial in order to more accurately pinpoint the gait sub-phases and facilitate the isolation of this variable. Also, researchers should consider standardisation of how the gait phases are subdivided with respect to percentages; although it is agreed that the stance and swing phases constitute 60% and 40% one gait cycle respectively, there is more leeway regarding how different studies assign percentages to the sub-phases. This aspect has not impacted the thesis analyses given that the same framework of percentages was utilised (Figure 5.2; pg.96); however, this warrants future investigation to allow for more meaningful comparisons to be made across different studies. On a different note, P12 was the sole participant with the lowest number of extractable cycles (n=2) and an overall anomalous shape and yet presents a variability of one standard deviation during *late mid-stance* (Table 6.2, pg.117). This contrast suggests that the number of gait cycles utilised for analysis may also influence the degree of variability (for this participant, it reduced the associated variability), and as such, results from published literature which investigate intraindividual variation with small datasets, should be interpreted with caution.

Therefore, the main findings obtained from the analysis of the bilateral shoulder data from all 20 participants can be summarised as follows:

- *initial swing* may constitute the gait sub-phase with the highest potential for interchangeability in the shoulder joint;
- *terminal swing* represents the gait sub-phase with the least potential for interchangeability;
- only two participants (P1 and P15) presented with largely symmetric movements;
- intraindividual variability in the shoulder joint is similarly high bilaterally;
- intraindividual variability in the shoulder joint generally amounts to at least one unit;
- degree of synchronicity of gait events in the shoulder joint may constitute an additional, participant-dependent variable and should be independently considered in future studies;
- the utilisation of the total mean or unilateral shoulder joint data in differentiating amongst individuals is inappropriate, with the results obtained from this dataset highlighting the importance of body side during analysis of shoulder angular data in the sagittal plane.

6.3 Left and Right Elbow

6.3.1 Results

The flexion/extension values of the left and right elbow joints are most similar during the first and final 20% of the gait cycle, ranging from 10 degrees to approximately 30 degrees, as shown in Figure 6.3. This contrasts the shoulder joint (Figure 6.2, pg.105) where the most clustered range of values were found towards the end of the stance phase (~45-55%). Also, the elbow exhibits less uniformity with respect to the timing of maximum elbow flexion and no specific trend of peak flexion location common to both the left and right elbow joints can be identified. Generalisations can be drawn for each body side separately, whereby the right elbow achieves maximum flexion towards the end of stance/early swing, whilst the left elbow achieves maximum flexion during mid-stance/late stance. Value-wise, mean maximum flexion angles for most participants fall within the range of 30-45 degrees, although in some, these values are much lower or higher, aspect present bilaterally (e.g. Figure 6.3A, blue and red arrows). Similarly, maximum extension values fall within the range of 10-30 degrees for most participants, with the exception of the left elbow waveforms of two of the participants which present maximum values of 49 and 51 degrees. Overall, the right elbow waveforms were generally more consistent throughout all gait events than those of the left elbow.

Since the differences amongst bilateral cycles of the elbow joint were more prominent than those observed in the shoulder joint, the intraindividual variability was therefore expected to be higher. In contrast to the more uniform intraindividual variability of 1-4 standard deviations observed in the bilateral shoulder joint in Section 6.2 , the intraindividual variability of the elbow does not follow a consistent trend across the gait cycle phases, as illustrated in Figure 6.3B. During the first 20% of the gait cycle and during the final 10% of the gait cycle, the standard deviations of the left and right elbow joints are similar across most participants, with a value of approximately 1-4 units. Throughout the remaining phases of the gait cycle, the left elbow variability increases steadily to 6 standard deviations in most participants during stance and early swing phases (~20-72%), followed closely by the right elbow. The largest variability of approximately 16 standard deviations (Figure 6.3B, red arrow) was observed in the left elbow of two participants during early swing (~62-64%) and the second largest variability of just under 15 standard deviations during mid-swing (~72-74%) for the right elbow. Variability close to zero standard deviations was only found in left elbow during pre-swing (~51%) and in the right elbow during mid-swing (~69-72%).

Figure 6.3 – Research Question 1: Summary of the Bilateral Elbow Joint Data

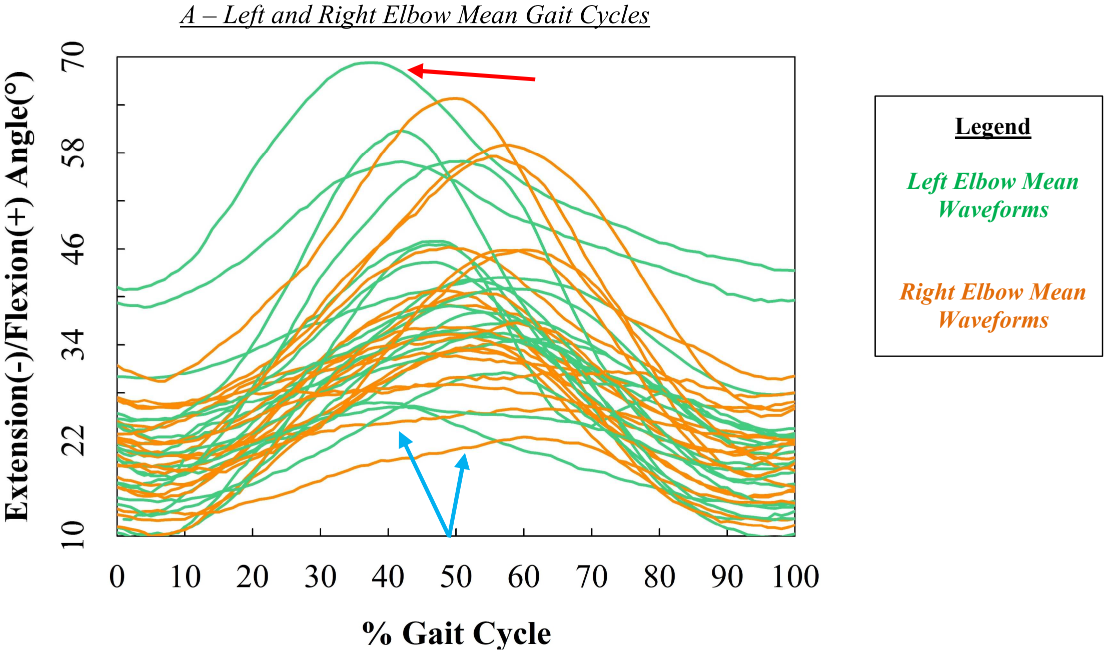


Figure 6.3A illustrates the mean gait cycle waveforms of the left and right elbow joints of all 20 participants. Each one of the 20 participants is represented by one green line and one orange line corresponding to the mean gait cycle waveform for the left and right elbow joints, respectively. The **red** arrow indicates the **highest** mean flexion value (corresponding to P11), and the **blue** arrows indicate right elbow mean waveforms with no discernible maximum flexion peaks (corresponding to P9 and P19).

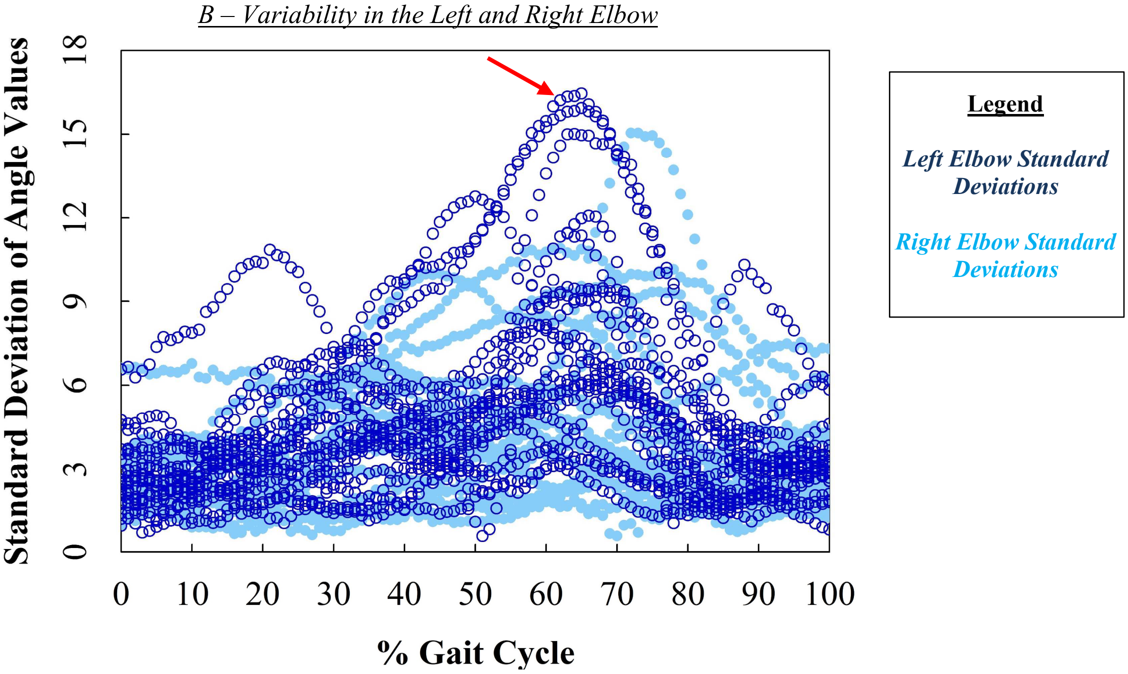


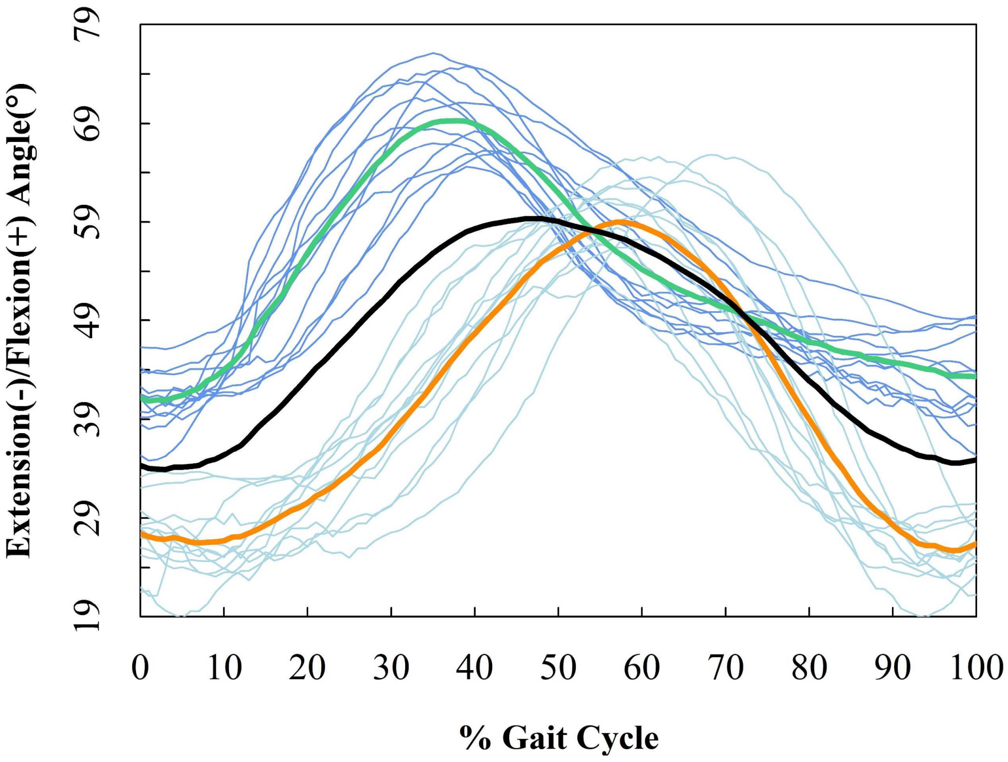
Figure 6.3B illustrates the standard deviations of the gait cycle values of each of the 20 participants. The dark blue circles and light blue circle represent the standard deviations of the left and right elbow joints respectively, at every 1% of the gait cycle. The **red** arrow indicates **highest variability** in the left elbow (P11).

To illustrate the different characteristics of elbow motion amongst the twenty participants, a selection of plots are provided. One example is that of Participant 11 (male, 44 years, 85 kilograms, 1.81 metres) who, as indicated in Figure 6.3 (red arrow), presented the largest degree of maximum flexion. As shown in Plot 6.5, P11 displays very different bilateral elbow mean waveforms, and implicitly, an inaccurately representative total mean waveform. Also, maximum flexion values are larger than previously observed in other participants. In contrast to the majority of the previous participants, each set individual cycles for each body side (12 left elbow and 12 right elbow cycles) are much more consistent to one another than to their bilateral counterpart with respect to shape and synchronicity of gait events (Plot 6.5A) and therefore, the differences between the two body sides are more delineated. For instance, maximum flexion in the left elbow occurs much earlier in the gait cycle (~38-39%) than in the right elbow (~58-59%). In addition, the left elbow remains consistently in a more flexed position throughout the swing phase than does the right elbow since the values are lower, regardless of the difference in peak flexion location. This characteristic was also observed during stance, where the largest differences of approximately 29 degrees were found between the two means. Therefore, the combined variability is much higher than the variability of either body side throughout most gait events, reaching 16 standard deviations during mid-stance (~29-32%), as shown in Plot 6.5B. Conversely, the smallest differences in value (3-4 degrees) were found during late terminal stance/pre-swing (~58-67%), and during the periods immediately preceding and following late terminal stance/pre-swing where the means are equal. In this particular case, the gait cycle segments with small mean differences and equal means correspond to regions where the combined variability is within bilateral elbow variability limits, a phase shift effect. This region is problematic, as is the remainder of the swing phase due to the lack of synchronicity.

As depicted in Plot 6.5B, the variability for each body side is relatively high; for the left elbow, the variability oscillates between 2-5 standard deviations throughout most of the gait cycle, the exception being a small segment of mid-stance (~20-25%) where the standard deviation is approximately 6 units, whilst for the right elbow, the variability is even higher. The overall patterns of variability for the bilateral elbow display a mirroring effect, whereby the left elbow shows a larger peak in variability during early stance and a smaller peak during pre-swing whilst the right elbow starts with a smaller peak during the stance phase, followed by a larger peak during mid-swing. The largest differences in variability of approximately 5 standard deviations were also recorded during mid-swing, whilst elsewhere these did not exceed 2-3 standard deviations. The lowest variability of 2 standard deviations was found in the left elbow during heel strike.

Plot 6.5 – Variability in the Left and Right Elbow (**Participant 11**)

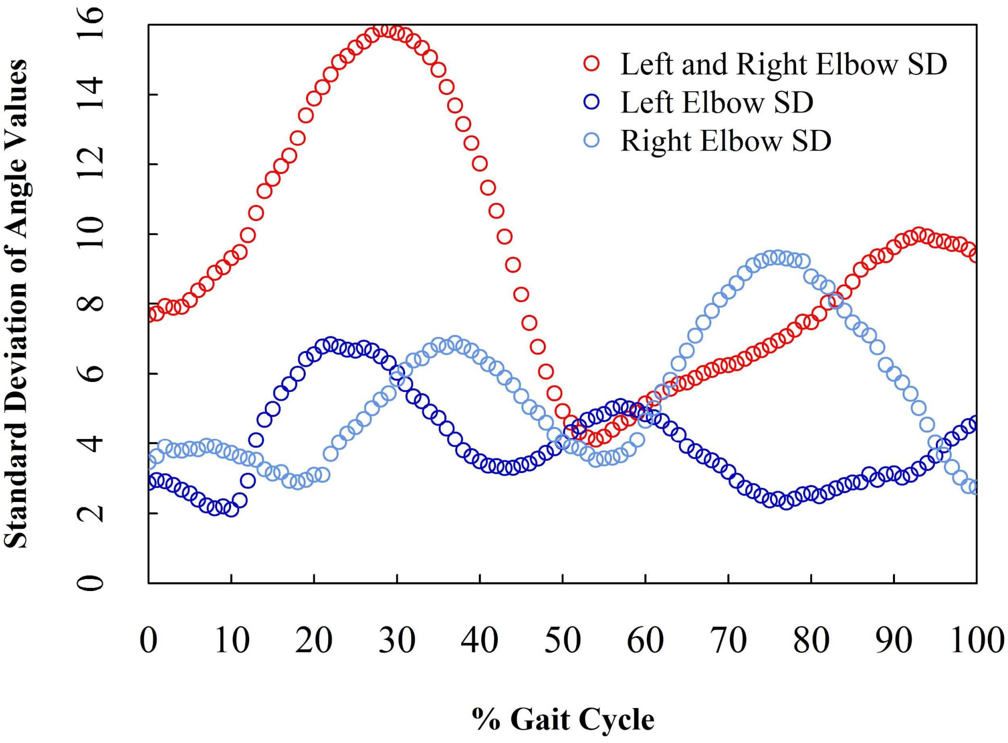
A – Gait Cycles of the Left and Right Elbow of Participant 11



Left Elbow (LE) Cycles; Right Elbow (RE) Cycles; LE Mean; RE Mean; Total Mean

Plot 6.5A illustrates the gait cycles of the left (LE) and right elbow (RE) joints of Participant 11, together with their respective means (green and orange respectively), as well as their combined mean (black). The LE joint (dark blue) is represented by a total of 12 cycles and the RE joint (light blue) also by 12 cycles.

B – Standard Deviation Plot of Participant 11



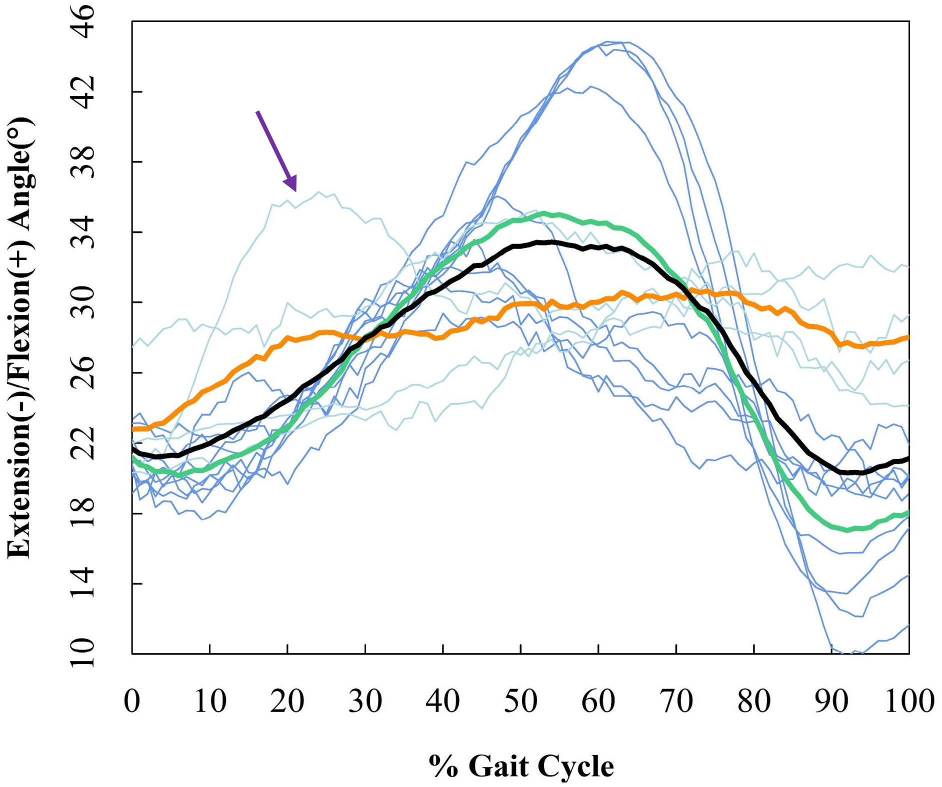
Plot 6.5B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 11 for the left and right elbow joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

In contrast to the high degree of flexion observed in P11, the mean waveforms and associated individual cycles of Participant 16 (male, 29 years, 65 kilograms, 1.88 metres) presented minimal flexion, with no discernible peak flexion event in the right elbow, as indicated by the blue arrows in Figure 6.3, pg.122. When examining the characteristics of the cycles in more detail, Plot 6.6 further emphasises these features, as well as the differences between body sides. The mean waveforms and the individual gait cycles display the largest bilateral differences with respect to shape and synchronicity than observed in many of the previous participants. The differences mainly stem from the right elbow waveforms (4 cycles in total) which, with the exception of one, do not possess definite maximum flexion and extension events, thereby appearing flat (Plot 6.6A). Instead, a small flexion event is noted during mid-stance (~20-22%), followed by 2-3 degrees of extension, after which the elbow remains in a gradually increased flexed position until the last 10% of the gait cycle where once again a 2-3 degree of extension occurred. This small peak flexion event (Plot 6.6A, purple arrow) corresponds with the highest right elbow variability of 6 standard deviations, as illustrated in Plot 6.6B. For the left elbow, only 4 out of the 9 gait cycles resemble the expected waveform shape (region corresponding to the highest variability in Plot 6.6B and least accurate total mean), and yet present with a more consistent timing and value of maximum flexion as observed in previous participants. The remaining 5 cycles are consistent with each other and with the right elbow with respect to maximum flexion timing, but not with the former 4 cycles which achieve maximum flexion at a later point in the gait cycle (~60-62%). This is also reflected in the large variability of the left elbow in this gait region which reaches 9 standard deviations (Plot 6.6B), as well as with the largest difference in variability between the two body sides. In addition, the range of extension values towards the end of terminal swing is also larger (10-17 degrees) but located at a lower scale than the right elbow values. As a result, the combined variability is higher than the variability of either body side (Plot 6.6B). During short segments of terminal stance (~48-49%), mid-swing (~80-81%), and terminal swing (96-100%), no differences in variability were observed, feature which is misleading since it stems from the phase shift effect rather than from true difference in value.

The overall trends of variability alternate throughout the first and last halves of the gait cycle; the variability is higher for the right elbow (0-45%), reaching a maximum of 6 standard deviations during late loading response/early mid-stance (~19-21%), whereas the variability of the left elbow does not exceed 2 standard deviations until late mid-stance/early terminal stance (~35-45%) where it increases to maximum of 4 standard deviations. During the latter half of the cycle, the variability of the right elbow decreases gradually to close to zero standard deviations (i.e. no variability) during early mid-swing (~69-72%), only to increase again throughout the remainder of the gait cycle to approximately 3 standard deviations. In contrast, the left elbow increases to 9 standard deviations during initial swing and decreases thereafter to 2-4 standard deviations, remaining higher than or equal to the variability of the right elbow cycles. The lowest variability of close to zero standard deviations was observed during a short right elbow gait segment of early mid-swing (~69-72%).

Plot 6.6 – Variability in the Left and Right Elbow (**Participant 16**)

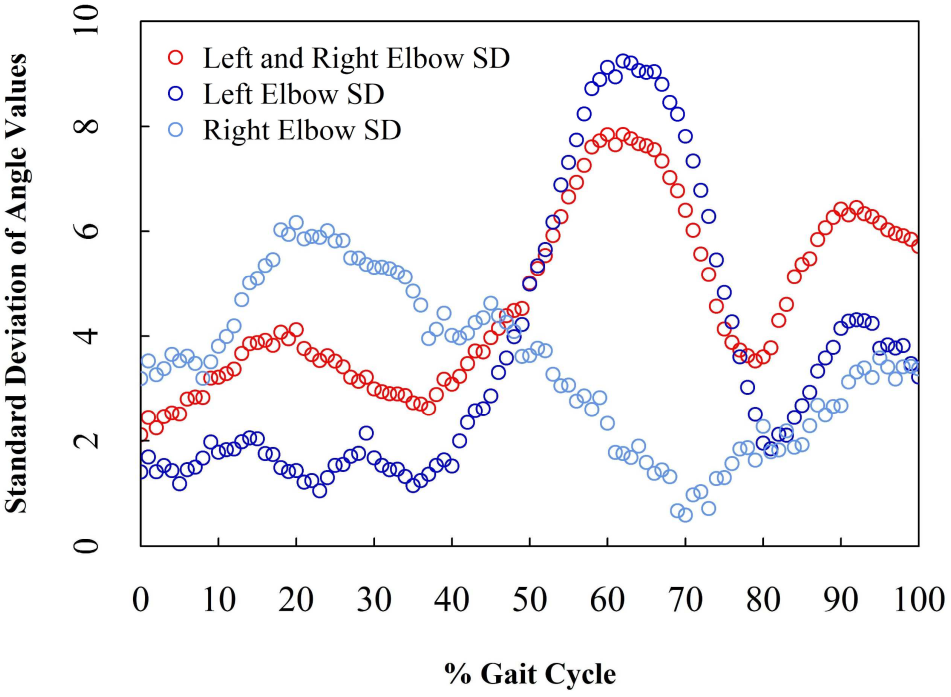
A – Gait Cycles of the Left and Right Elbow of Participant 16



Left Elbow (LE) Cycles; Right Elbow (RE) Cycles; LE Mean; RE Mean; Total Mean

Plot 6.6A illustrates the gait cycles of the left (LE) and right elbow (RE) joints of Participant 16, together with their respective means (green and orange respectively), as well as their combined mean (black). The LE joint (dark blue) is represented by a total of 9 cycles and the RE joint (light blue) by 4 cycles. The purple arrow indicates the right elbow gait cycle with peak flexion.

B – Standard Deviation Plot of Participant 16



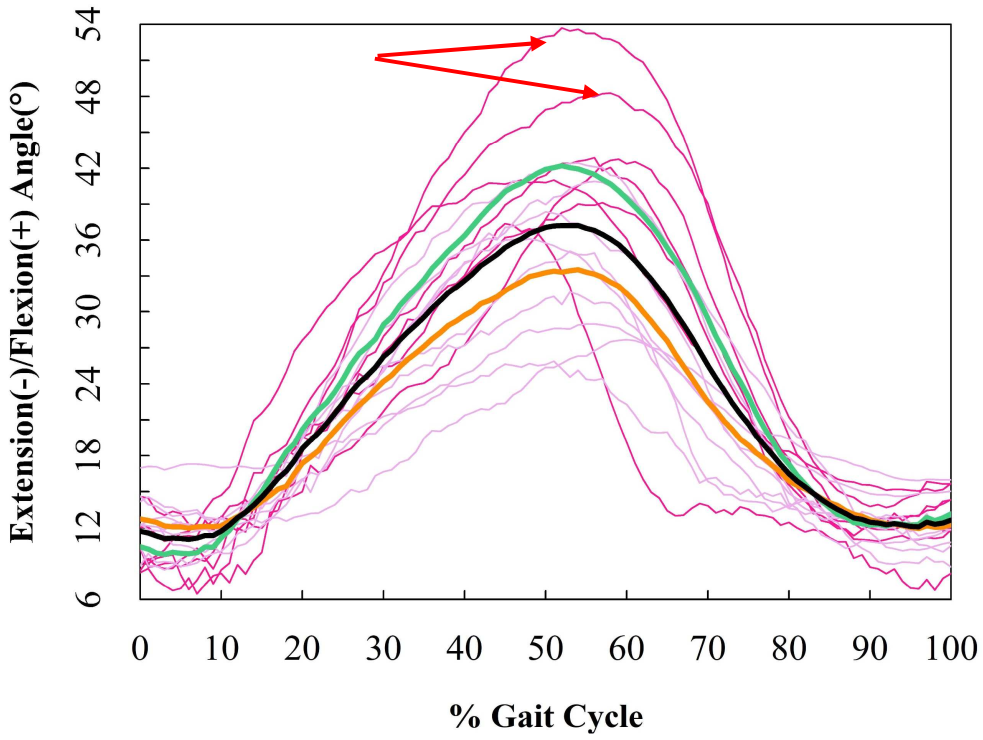
Plot 6.6B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 16 for the left and right elbow joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

As exemplified in the previous two plots, the bilateral elbow joint angular data presented substantial differences in synchronicity, values, and overall shape in all 20 participants to a greater degree than observed in the shoulder joint. Participant 6 (female, 23 years, 55 kilograms, 1.69 metres) is the only participant for whom similarities were found amongst cycles of both body sides. The left and right elbow mean waveforms of P6 (Plot 6.7A) are uniform in shape and synchronicity throughout the entire gait cycle. The largest differences in mean value amounting to approximately 8 degrees were observed during the progression towards maximum flexion and at the timepoint of peak formation (~50-55%). Throughout most of the gait cycle (including the aforementioned period), the values of the left elbow were larger than those of the right elbow; a reversal to this relationship was exclusive to the start of the gait cycle during heel strike (~0-10%). During loading response (~12-15%), and the latter half of the swing phase (~82-100%), a negligible difference between the two means was observed. The 9 right elbow cycles are better represented (shape-wise), by their respective mean waveform than the 7 left elbow cycles. In the latter, four of the gait cycles display evident phase shifts in maximum flexion, particularly during early swing, therefore, the total mean is most representative of the right elbow. The effect of phase shifts is also reflected in the higher variability of approximately 11 standard deviations during this gait segment (Plot 6.7B).

With respect to values, similar discrepancies are observed in both body sides; whereas the maximum left elbow flexion values of 2 out of the 7 gait cycles are higher by approximately 13 degrees than the respective mean (Plot 6.7A, red arrows), the maximum right elbow flexion values of four of the gait cycles are lower by 10 degrees than the respective mean. This contrasts the periods preceding and following maximum flexion, where the range in extension values are lower for both body sides, hence the similarly low variabilities (Plot 6.7B). Throughout most gait events, the differences in variability between the left and right elbow are close to negligible (one standard deviation or less) due to the similarity in ranges of values and implicitly, the synchronicity of gait events for most cycles (Plot 6.7B). As a result, the variability trend of both body sides is generally similar. This similarity is further strengthened by the combined variability which closely follows the trends and values of both body sides, except during terminal stance where the combined variability is higher due to the effect produced by the higher maximum flexion values in the left elbow (Plot 6.7A, red arrows). A concomitant increase was observed throughout the first half of the gait cycle and a concomitant decrease during the final 20% of the gait cycle. The exception was the start of the swing phase (~60-63%) where the difference in variability was largest (4-5 standard deviations). This stems from one of the 7 left elbow cycles which presented the highest degree of phase shift with respect to maximum flexion. For this participant, the lowest variability was just under 2 standard deviations during right elbow loading response (~15-18%).

Plot 6.7 – Variability in the Left and Right Elbow (**Participant 6**)

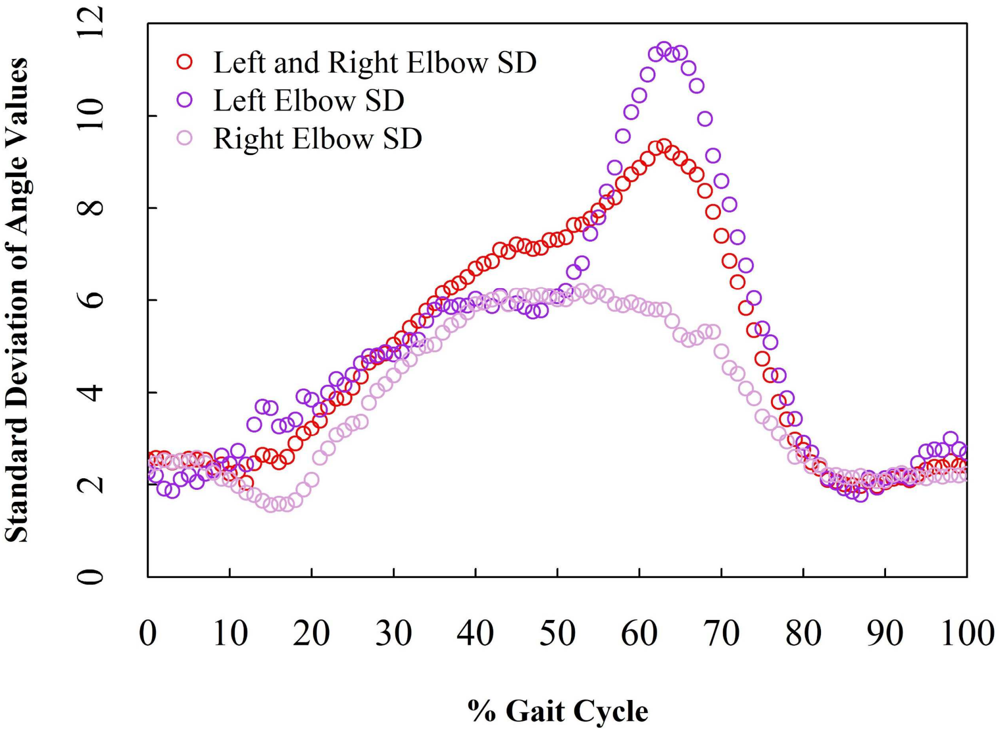
A – Gait Cycles of the Left and Right Elbow of Participant 6



Left Elbow (LE) Cycles**; **Right Elbow (RE) Cycles**; **LE Mean**; **RE Mean**; **Total Mean

Plot 6.7A illustrates the gait cycles of the left (LE) and right elbow (RE) joints of Participant 6, together with their respective means (green and orange respectively), as well as their combined mean (black). The LE joint (dark pink) is represented by a total of 7 cycles and the RE joint (light pink) by 9 cycles. The red arrows indicate the highest maximum flexion of the left elbow.

B – Standard Deviation Plot of Participant 6



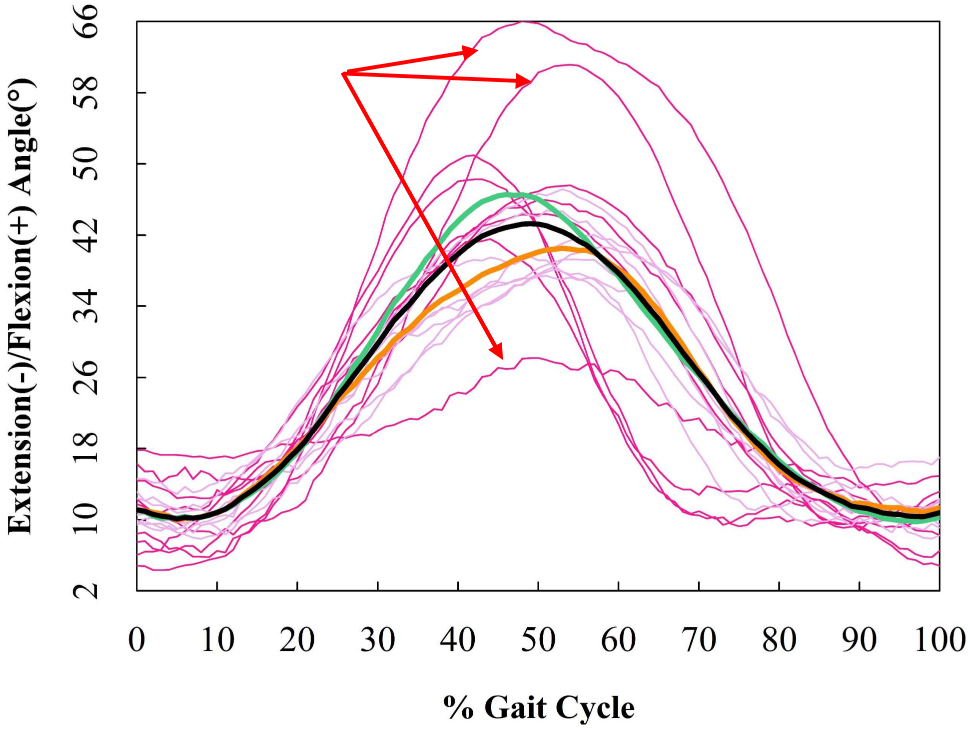
Plot 6.7B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 6 for the left and right elbow joints (dark purple and light purple respectively) and the combined standard deviation for both joints (red).

As indicated in Figure 6.3B, pg.122 (red arrow), the largest variability of 16 standard deviations was noted in Participant 10 (female, 25 years, 61 kilograms, 1.63 metres). Plot 6.8 illustrates this variability in more detail. The bilateral elbow mean waveforms are nearly identical in shape and value throughout the first 24% of the stance phase and throughout all of the swing phase (~59-100%). As shown in Plot 6.8A, due to the delay in maximum flexion of the right elbow (aspect not captured by the total mean), the intermediary period between the two phases (25-58%), displays a difference of approximately 8 degrees during maximum flexion of the left elbow (~45-46%), the largest difference between the mean values. However, the largest difference in variability occurs later in the cycle during pre-swing (~57-59%), corresponding not only with the impact of the phase shift but more so with the substantially higher peak flexion value range resulting from 3 out of the 9 left elbow cycles (Plot 6.8A, red arrows); hence, P10 presents the largest maximum flexion values. The right elbow is more restricted with respect to this maximum flexion range (34-45 degrees), as well for the extension angle value ranges during the stance phase (10-16 degrees). As a result, the variability of the right elbow increases above 3 standard deviations solely during early swing (~62-72%), but the combined variability remains within the limits of both body sides because the range of right elbow values is narrower and therefore ‘contained’ within the larger left elbow range of values throughout all gait events (Plot 6.8B).

Nevertheless, the aforementioned differences in ranges of value between the two body sides are also evident from Plot 6.8B. Throughout most of the stance and early swing phases, the variability differences between the two body side increase from one standard deviation (~28-29%) to 12 standard deviations (~64-65%) and decrease again throughout mid-swing to one standard deviation (~81-82%). During loading response/early mid-stance (~15-22%) and during terminal swing (95-100%), no variability differences were observed, corresponding to the highly similar range of values bilaterally. Individually, the variability in the left elbow is much larger than in the right elbow throughout most of stance and first half of swing (0-14%, ~25-82%), reaching a maximum of 16 standard deviations during early swing (~62%). Overall, the trends of the bilateral elbow joints are similar during first 20% of the stance phase and the final 30% of the swing phase, whilst the lowest variability of approximately 2 standard deviations was found during right elbow heel strike (~0-10%).

Plot 6.8 – Variability in the Left and Right Elbow (**Participant 10**)

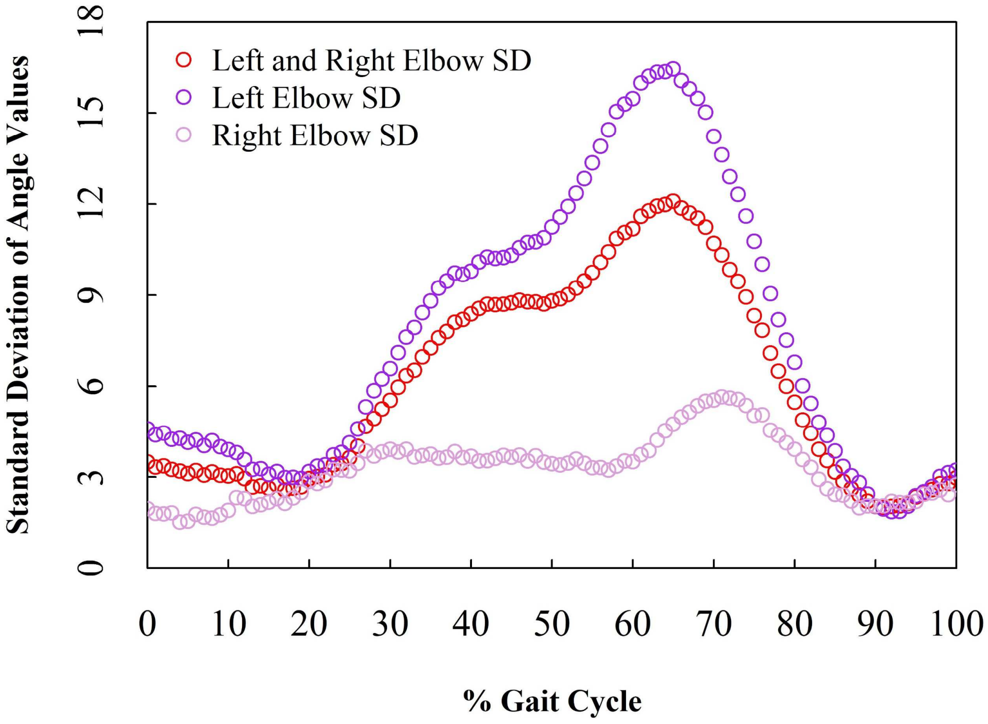
A – Gait Cycles of the Left and Right Elbow of Participant 10



Left Elbow (LE) Cycles**; **Right Elbow (RE) Cycles**; **LE Mean**; **RE Mean**; **Total Mean

Plot 6.8A illustrates the gait cycles of the left (LE) and right elbow (RE) joints of Participant 10, together with their respective means (green and orange respectively), as well as their combined mean (black). The LE joint (dark pink) is represented by a total of 9 cycles and the RE joint (light pink) by 8 cycles. The red arrows indicate the range of maximum flexion values in the left elbow.

B – Standard Deviation Plot of Participant 10



Plot 6.8B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 10 for the left and right elbow joints (dark purple and light purple respectively) and the combined standard deviation for both joints (red).

6.3.2 Discussion

In the left elbow joint, the intraindividual variability is generally similar to the intraindividual variability of the right elbow in all 20 participants, but not throughout all gait events and not for all 20 participants to the same extent, a similar find to the shoulder joint. Based on this dataset (325 bilateral gait cycles in total), the bilateral intraindividual variation is not similar across all gait events (Research Question 1). As shown in Table 6.3 below, the participants were grouped according to whether they exhibit similar bilateral variability OR bilateral *and* combined variability (i.e. difference of ≤1 standard deviation, as explained previously in Section 6.2.2 (Shoulder Joint)). *Early mid-stance* is the gait phase where the largest number of participants (n=9) presented similar bilateral and combined variability, thus highlighting that only less than half of the participants also share a common location of range of values (dark orange).

Table 6.3 – Gait Cycle Regions with Similar Intraindividual Variability in the Bilateral Elbow Joint

	Participant Index									
Right and Left Elbow Intraindividual Variability	P1 P5 P7 P11 P12 P13 P18	P7 P12 P15 P18 P19	P5 P8 P12 P15 P18	P4 P6 P12 P15 P18	P1 P4 P6 P12 P15 P18	P1	P8 P13	P1 P7 P13	P1 P9 P12 P15 P16 P19	P1 P11 P12 P13 P14 P16 P18
Total Number of Participants	**7**	5	5	5	6	1	2	3	6	**7**
Right and Left Elbow Intraindividual Variability + Combined Intraindividual Variability	P2 P3 P6 P8 P15 P17 P19	P1 P3 P8 P9 P10	P1 P2 P3 P4 P6 P7 P17 P19 P20	P1 P2 P7 P13 P14 P17 P20	P2 P3 P7	P11 P15	P15 P18	P4 P6 P8 P9 P17 P18	P2 P3 P6 P10 P17	P5 P6 P9 P10 P15 P17 P19
Total Number of Participants	7	5	**9**	7	3	2	2	6	5	7
	Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
	Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.3 summarises the gait cycle regions of bilateral elbow joint flexion/extension in all 20 participants where the intraindividual variability of the left and right body sides, as well as their combined intraindividual variability, are similar (i.e. one standard deviation or less). The light and dark orange coloured boxes highlight the largest number of participants in a given category. Note that all 20 participants are found in the table, albeit differently distributed across gait sub-phases.

However, since the number of participants remains is less than half, this find is only suggestive of potential for interchangeability, thus implying that analysis of movement during this gait sub-phase is likely to be affected by body side. The second largest group of 7 participants with similar bilateral and combined variability was found during *heel strike, late mid-stance,* and *terminal swing*. Conversely, the smallest number of participants (n=2) with similar bilateral and combined variability was found during *pre-swing* and *initial swing* which suggests that these two gait sub-phases present the least potential for interchangeability of left and right elbow data, thus highlighting the importance of body side during analysis, and the inappropriateness for the use of the total mean and/or data from a single body side for representing gait of individuals. For gait phases with similar bilateral variability but a higher combined variability, *pre-swing* was also the sole gait segment with only a single participant (P1), thus reinforcing the relevance of discriminating between body sides when analysing elbow flexion and extension.

Overall, participants present partial consistency in the similarity of intraindividual bilateral and combined variability throughout the gait cycle, a similar find also encountered in the shoulder joint. Participant P17 is the sole participant with similar bilateral and combined intraindividual variability throughout 60% of the gait cycle sub-phases (*heel strike, mid-stance, mid-swing,* and *terminal swing*), followed closely by P2 across half of the gait sub-phases (*heel strike, mid-stance, terminal stance* and *late mid-swing*). The participant with similar intraindividual variability (but different combined variability) across the highest proportion of the gait cycle (70% of sub-phases) was P12. Likewise, P18 presented similar bilateral variability without combined variability throughout 60% of the gait cycle sub-phases, but also combined variability during *initial swing* and *early mid-swing*; the majority of gait sub-phases correspond to those of P12, with the exception of *late mid-swing*. Since only 4 out of the 20 participants are consistent in at least bilateral variability throughout a maximum of 70% of the gait cycle, this may indicate that in general, flexion/extension movements in the elbow joint are asymmetrical.

Out of the 20 participants, only 2 exhibited intraindividual variability of one standard deviation or less for the elbow joint, as shown in Table 6.4, pg.133 (the participants were grouped in the same manner described for the shoulder joint (Section 6.2.2)). Only P5 and P18 presented a variability of one standard deviation in the right elbow during *loading response*, whilst for the left elbow joint, no participant presented low or negligible variability during any complete gait sub-phase. Short segments of one standard deviation variability were noted in P1 left elbow heel strike, P8 left elbow pre-swing, P9 right elbow mid-stance, and P17 right elbow mid-stance. Negligible variability (close to zero) were noted in P16 early mid-swing, and P18 late mid-swing. However, as noted throughout Section 6.3.1, these regions were too brief in a given gait sub-phase to be of use in claiming low variability throughout the entire sub-phase. As also previously stated in the discussion section of the shoulder joint (Section 6.2.2), short segments are of little use for observational gait analysis. Nevertheless, such high intraindividual variability in the elbow joint is indicative of the stylistic nature of upper limb movements during gait, inference also supported by the similar finds for the shoulder joint. However, as illustrated in Section 6.3, Figure 6.3, pg.122, the left elbow does not present a much larger variability than in the right elbow, thereby contrasting the results obtained by Bruening at colleagues (2015). Based on the obtained results, it cannot be concluded whether the elbow joint may be suitable for use in forensic gait analysis due to high intraindividual variability, given the two justifications previously presented in Section 6.2.2 (Shoulder Joint Discussion). Therefore, bilateral elbow joint intraindividual variability requires comparison not only with that of the shoulder joint but also with the intraindividual variabilities in the lower body joints, namely the hip, knee, and ankle (found in Chapter 7 – Intraindividual Body Region Variability (Research Question 2)). Likewise, the impact of the high elbow joint intraindividual variability on the potential for individualisation, and test the claim of uniqueness, further analysis was conducted (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

Table 6.4 – Gait Cycle Regions with Lowest Intraindividual Variability in the Bilateral Elbow Joint

		Participant Index									
Left Elbow Intraindividual Variability	**One Standard Deviation**										
	No Variability										
Right Elbow Intraindividual Variability	**One Standard Deviation**		P5 P18								
	No Variability										
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.4 summarises the gait cycle regions of the left and right elbow joint flexion/extension of all 20 participants which present with an intraindividual variability of one standard deviation or less. The majority of participants, as noted above, presented intraindividual variability higher than one unit. Also, none of the participants present with zero variability during any of the gait cycle phases. The light red and dark red coloured boxes indicate the magnitude of the intraindividual variability (**light red – one standard deviation**; **dark red – zero variability**).

The evaluation of this dataset also suggests that the flexion and extension movements of the elbow joint are highly variable within the same participant, with little evidence to indicate that either the left or the right body side may present low intraindividual variability. This find reinforces the conclusions drawn from Table 6.3, pg.131 which indicate that the data of the bilateral elbow cannot be utilised interchangeably, and that due to the high bilateral variability, the elbow joint may not be suited for identification. Also, as observed in the shoulder joint, many of the elbow joint angular data presented saccadic transitions across the gait events which translated into lack of smoothness, as illustrated throughout Section 6.3.1. However, the lack of smoothness of the angular waveforms did not constitute a detrimental effect upon interpretation of the results since the overall shape and range of values are also in accordance with previous publications (e.g. Romkes and Brach-Schweizer 2017).

In contrast to the shoulder joint, anomalies were found in a larger number of participants for the elbow joint regarding large differences in overall shape, as was depicted throughout Section 6.3.1. For instance, participants P18 presents the most erratic angular waveforms, with no definitive peak flexion events, whilst P5, P9, P16 and P19 exhibit a generally flat right elbow angular waveforms, with no distinctly larger peak flexion event. P8, on the other hand, exhibited an additional smaller peak flexion event during the swing phase whilst P11 presented with the largest difference between body sides with respect to position of peak flexion. However, the bilateral cycles of P11 were highly synchronised with one another, thus providing additional evidence for challenging the universality of flexion/extension movement symmetry during gait, particularly since the number of cycles analysed per body side was twelve, the largest number of cycles available for this study in a given joint. In contrast, P13 presented the highest degree of synchronicity of all participants, however, similarity in bilateral and/or combined variability was found in less than 40% of all gait events, none of which was below at least two standard deviations. This further reinforces the lack of bilateral elbow symmetry, considering that 7 cycles per body side were analysed. As a result, the aforementioned characteristics (with the exception of the saccadic transitions amongst gait events) are not likely to be anomalies, and may more likely result from individualistic style of arm swing, as stated in previous paragraphs of this section and based upon the same rationale discussed for the shoulder joint (Section 6.2.2), whereby these may constitute an additional variable related to intraindividuality. The assessment of this dataset therefore suggests that the flexion and extension movements of the elbow are not symmetric, thus emphasising that bilateral elbow data should not be utilised interchangeably, and that the total mean is not accurately representative of the intraindividual variability observed in both the left and right body sides.

Hence, the main outcomes of the bilateral elbow joint data analysis from all 20 participants are summarised are:

- *early mid-stance* may constitute the gait sub-phase with the highest potential for interchangeability in the elbow joint;
- *pre-swing* and *initial swing* represent the gait sub-phases with the least potential for interchangeability in the elbow joint;
- only a single participant (P17) presented with largely symmetric elbow joint movements;
- intraindividual variability in the elbow joint generally amounts to at least one unit regardless of body side or gait sub-phase, as also noted in the shoulder joint;
- degree of synchronicity of gait events in the elbow joint may constitute an additional, participant-dependent variable and should be independently considered in future studies;
- elbow joint gait cycles presented saccadic anomalies to a higher degree than the shoulder joint;
- given that the number of participants with similar bilateral and combined variability in the elbow joint does not constitute a majority, the utilisation of the total mean or unilateral elbow joint data in differentiating amongst individuals is inappropriate, thereby highlighting the importance of body side during analysis of elbow joint angular data in the sagittal plane.

6.4 Left and Right Hip

6.4.1 Results

The bilateral hip joint exhibits a more consistent shape, synchronicity, and value ranges in most participants across most gait events (Figure 6.4), in contrast to the shoulder (Figure 6.2, pg. 105) and elbow joints (Figure 6.3, pg.122). One common characteristic with the upper body joints is the inconsistency in the timing of maximum extension (i.e. maximum flexion equivalent of the upper body joints) which, in general, occurs earlier in the cycle for the left hip waveforms (~55-57% during pre-swing) and later for the right hip waveforms (~60-68% during initial swing). With respect to maximum extension values, these are more consistent than observed in the upper body joints across all waveforms, irrespective of body side (approximately +12 to -15 degrees), except one left hip waveform with a maximum extension value of -26 degrees (Figure 6.4A, red arrow) and one right hip waveform with a value of approximately -20 degrees (Figure 6.4A, blue arrow). At the start of the gait cycle, flexion values are generally clustered in a range of 24 to 40 degrees, a similar range of values also observed during swing.

As illustrated in Figure 6.4, the variability trends of the hip joint differ to those of the shoulder and elbow, whereby the lowest intraindividual variability range (1-4 units) across all participants was located during terminal stance and pre-swing (~45-59%), as highlighted by the red box. Conversely, the highest variability range was observed throughout the middle of the swing phase (~75-81%), largely caused by a single participant with an intraindividual variability of 19 standard deviations (P11, red arrow). Although this range decreases to approximately 10-12 standard deviations throughout the final 19% of the gait cycle, the swing phase generally presents a higher intraindividual variability range than the stance phase (0-54%), where the intraindividual variability does not exceed approximately 8 standard deviations in the majority of participants. Overall, the left hip variability is maintained lower (0-4 standard deviations) throughout the stance phase in comparison to the right hip variability. This characteristic changes throughout the swing phase where both body sides present with similarly large intraindividual variability range, although the left hip is greatly exceeded during mid-swing.

Figure 6.4 – Research Question 1: Summary of the Bilateral Hip Joint Data

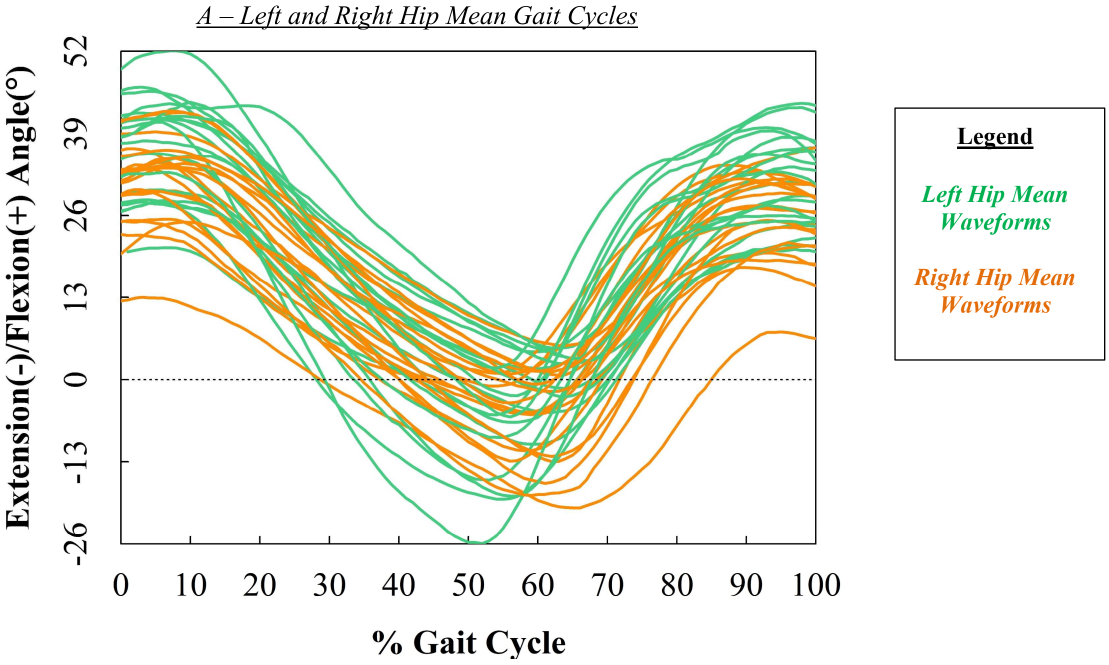


Figure 6.4A illustrates the mean gait cycle waveforms of the left and right hip joints of all 20 participants. Each one of the 20 participants is represented by one green line and one orange line corresponding to the mean gait cycle waveform for the left and right hip joints, respectively. The black horizontal dashed line represents a y axis value of zero.

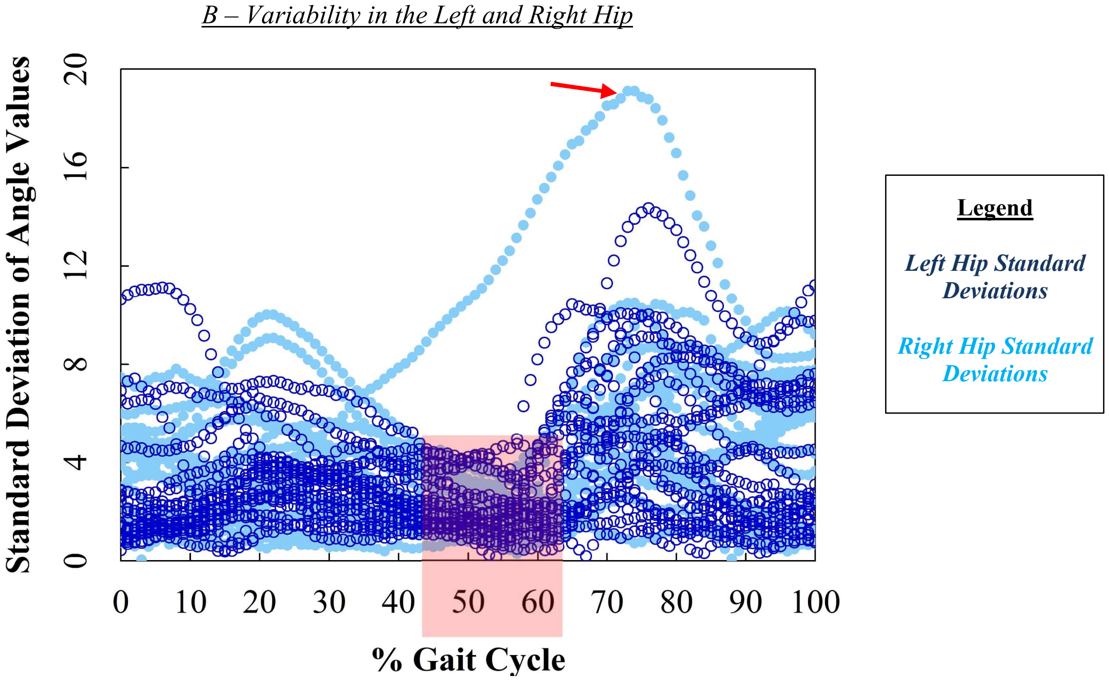


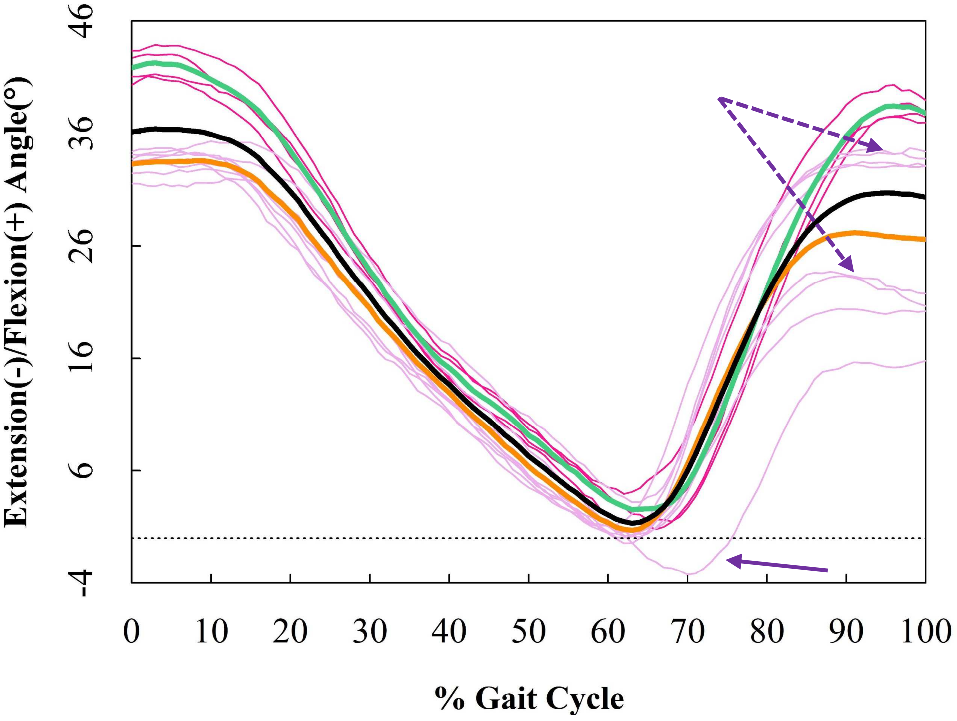
Figure 6.4B illustrates the standard deviations of the gait cycle values of each of the 20 participants. The dark blue circles and light blue circle represent the standard deviations of the left and right hip joints respectively, at every 1% of the gait cycle. The **red** arrow indicates the **largest** variability across all participants, found in the right hip (corresponding to P11). The red box highlights the gait cycle sub-phases with the lowest interval of intraindividual variability across all 20 participants.

One of the most congruent angular waveforms were found in Participant 9 (female, 25 years, 52 kilograms, 1.63 metres), a feature noted in most female participants and amongst male participants. As shown in Plot 6.9A, the shapes of the left and right hip mean waveforms of P9 are generally similar throughout all gait events, as is synchronicity, with only a single right hip cycle exhibiting a phase shift of approximately 8% (purple arrow). Also, the mean maximum extension values are just above zero, thereby showing that the hip is rather in a more neutral position rather than undergoing extension, as previously seen in Participants 2 and 6. The highest and most extensive differences in mean values were found during the first and final 20% of the gait cycle, where the differences reach a maximum of 10-12 degrees during terminal swing. At the start of the stance phase (~0-20%) the differences do not exceed 6-8 degrees, whilst during the remainder of the gait events until swing phase, the differences are negligible. Nevertheless, the left hip mean values exceed those of the right hip throughout all gait events.

Individually, the 8 right hip gait cycles are more variable throughout the swing phase than are the 4 left hip gait cycles throughout all gait events, particularly due to the separate grouping of half of the right hip cycles at a narrower interval and higher values than the other half (Plot 6.9A, dashed purple arrows), a previously unobserved feature in the right hip. For instance, the differences in flexion values across the 8 right hip cycles during terminal swing approach 18 degrees, whilst those of the left hip do not exceed 2-3 degrees, hence the larger right hip variability of 7-8 standard deviations (Plot 6.9B). Likewise, the combined variability is also higher than in both joints during early stance and late swing, not only due to the larger range of values of the right hip, but also because these are grouped at lower values than the left hip. The differences in variability are negligible during the stance phase, the highest being 2 standard deviations during late mid-stance (~29-32%); both joints present with similar ranges of values during stance and implicitly, the variability does not increase above 2 standard deviations. However, the differences in variability increase throughout the swing phase to a maximum of 7 units during terminal swing; hence, the total mean is least representative bilaterally during swing. The lowest variability of just under one standard deviation was found during left hip pre-swing (~52-59%).

Plot 6.9 – Variability in the Left and Right Hip (**Participant 9**)

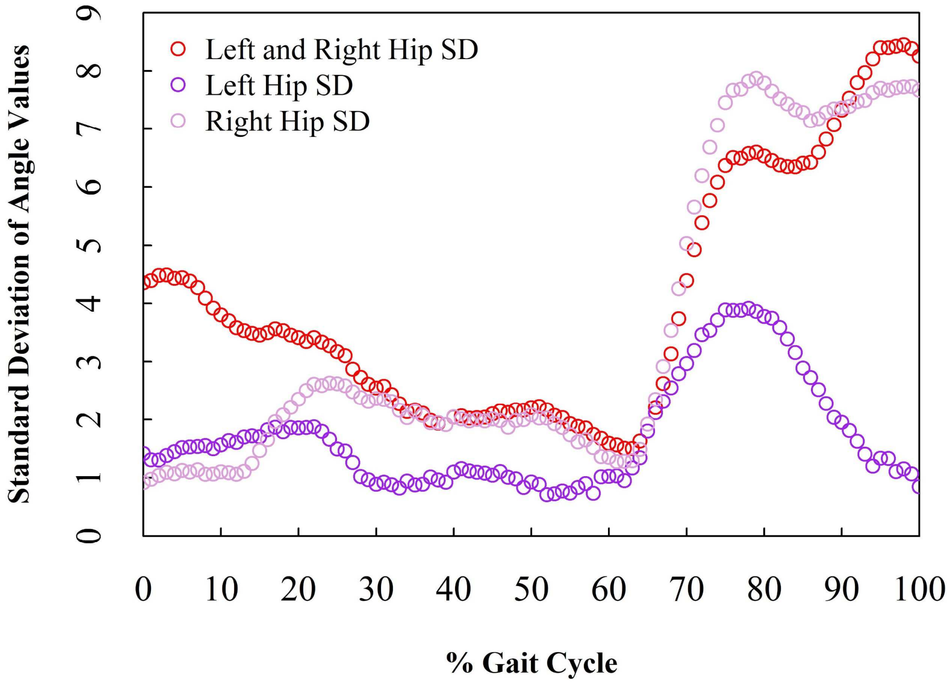
A – Gait Cycles of the Left and Right Hip of Participant 9



Left Hip (LH) Cycles; Right Hip (RH) Cycles; LH Mean; RH Mean; Total Mean

Plot 6.9A illustrates the gait cycles of the left (LH) and right hip (RH) joints of Participant 9, together with their respective means (green and orange respectively), as well as their combined mean (black). The LH joint (dark pink) is represented by a total of 4 cycles and the RH joint (light pink) by 8 cycles. The black horizontal dashed line represents a y axis value of zero. The purple arrow indicates the right hip cycle with the maximum extension phase shift, whilst the dashed purple arrows highlight the separate clustering of the 8 right hip cycles into two groups.

B – Standard Deviation Plot of Participant 9



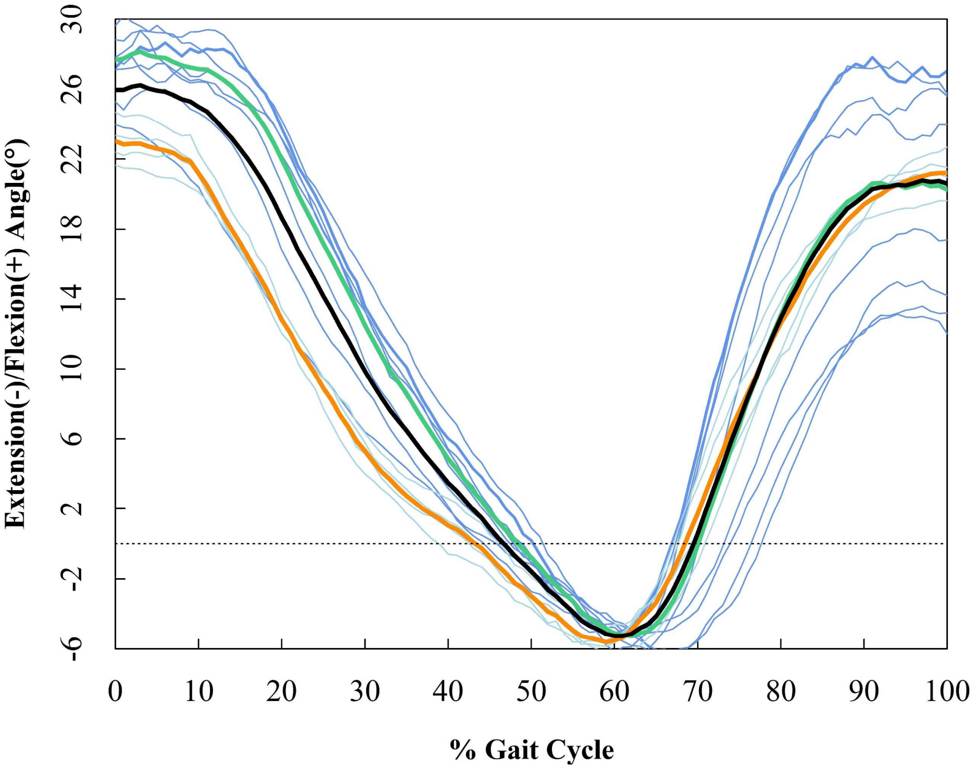
Plot 6.9B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 9 for the left and right hip joints (dark purple and light purple respectively) and the combined standard deviation for both joints (red).

Another example of high degree of gait cycle congruency was found in Participant 3 (male, 24 years, 74 kilograms, 1.92 metres). The mean values of the left hip are larger during the first half of the gait cycle (by approximately 8 degrees), and equal to/close to equal to those of the right hip during the latter half (Plot 6.10A). During the second half of the stance phase (~35-60%), the difference of 8 degrees is reduced gradually to approximately 2 degrees until the beginning of the swing phase (~61-62%) where the two means become negligible, remaining so until the end of the gait cycle. With respect to the maximum extension event, the left hip mean peak value occurs slightly later in the cycle (61%) than the right hip (~59%), but nevertheless, the difference is insignificant since all 12 cycles (8 left hip cycles, 4 right hip cycles) achieve maximum extension in similar locations. As a result, the differences in variability of peak extension are negligible, as shown in Plot 6.10B. Throughout the swing phase, the range of values for the 8 left hip gait cycles is high whereby half of the cycles are located in the 13-15 degree range and the other in the 23-27 degree range. Contrastingly, the right hip cycles (4 in total) are more clustered around similar values, hence the difference in variability of 6 standard deviations (Plot 6.10B). However, in contrast to previous participants, the degree of extension is greater whilst the degree of flexion is lower.

The differences in variability are low during the stance and early swing phase (~0-64%), not exceeding one standard deviation, whereas during the majority of the swing phase, the variability increases to 6 standard deviations. During heel strike (~0-10%) and throughout mid-stance, terminal stance, pre-swing, and initial swing the differences are negligible (~40-65%), but the combined variability is higher, thus highlighting differences in the location of the range of values. The variability of the right hip is approximately one standard deviation throughout most gait events, except during mid-swing where this increases to just over 2 standard deviations (~70-82%). Conversely, the variability of the left hip is small, not exceeding 3 standard deviations during stance phase, but increases steadily at the start of the swing phase to a maximum of 8 standard deviations during initial swing/start of mid-swing, after which it decreases to 7 standard deviations during terminal swing. Overall, the variability trends are similar, but different in value, particularly during the swing phase, thus highlighting that the total mean is not appropriate for use to characterise bilateral movement. The lowest variability of close to zero standard deviations, was noted during late pre-swing/early initial swing (58-62%) of the left hip.

Plot 6.10 – Variability in the Left and Right Hip (**Participant 3**)

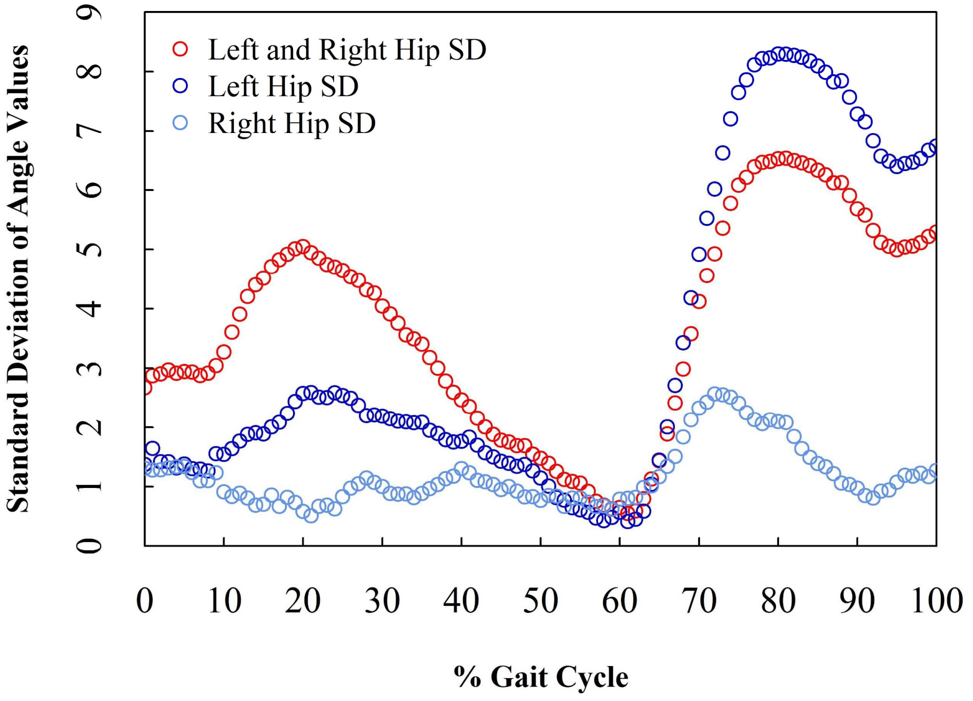
A – Gait Cycles of the Left and Right Hip of Participant 3



Left Hip (LH) Cycles; Right Hip (RH) Cycles; LH Mean; RH Mean; Total Mean

Plot 6.10A illustrates the gait cycles of the left (LH) and right hip (RH) joints of Participant 3, together with their respective means (green and orange respectively), as well as their combined mean (black). The LH joint (dark blue) is represented by a total of 8 cycles and the RH joint (light blue) by 4 cycles. The black horizontal dashed line represents a y axis value of zero.

B – Standard Deviation Plot of Participant 3



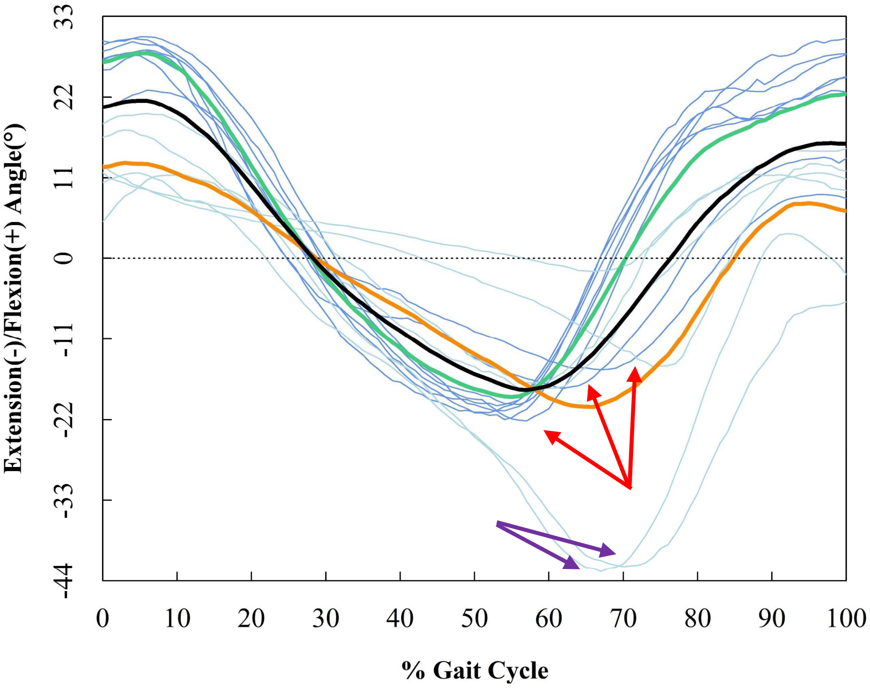
Plot 6.10B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 3 for the left and right hip joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

Conversely, Participant 11 (male, 44 years, 85 kilograms, 1.81 metres) presented the highest degree of incongruency out of all 20 participants, not only between body sides but also amongst individual cycles and their respective mean waveforms; some degree of asynchronicity was encountered in the majority of participants but to a lesser degree, whilst anomalies as observed in the elbow and shoulder were not encountered. In addition, as previously indicated in Figure 6.4A, pg.137 (red arrow), P11 also presented the highest degree of intraindividual variability. As illustrated in Plot 6.11A, the left and right hip mean waveforms and the associated individual cycles possess distinct characteristics, thereby resulting in an unrepresentative total mean. For example, only 5 out of the 8 left hip cycles are clustered around similar flexion and extension values during the stance phase, period during which the variability increases to a maximum of 5 standard deviations (Plot 6.11B). Thereafter however, the three aforementioned left hip cycles (Plot 6.11A, red arrows) present with phase shifts during maximum extension, as well as lower values during swing where the variability increases to a maximum of 9 standard deviations as a result of the clustering of 6 out of the 8 cycles at higher values than the remaining 2 cycles.

The 6 right hip cycles present even greater variation throughout all gait events, 2 of which display maximum extension values greater by approximately 32 degrees (Plot 6.11A, purple arrows) than the other 4 cycles, reflected in the approximately 20 standard deviations variability during mid-swing (Plot 6.11B); such a pronounced degree of extension is a previously unobserved find. Overall, peak extension of the right hip cycles occurs during late initial swing/early mid-swing (~69-72%), much later than for the majority of the left hip cycles (pre-swing, ~52-54%). In addition, the mean values of most of the left hip cycles are generally larger than those of the right hip, particularly during early stance and late swing where the location of the interval of values is also higher, thus the greater combined variability during these gait phases (Plot 6.11B). Mean values are equal at the end of mid-stance (~29%), and pre-swing (~55-58%), although the latter phase is misleading since the variability difference between the two joints is approximately 9 standard deviations; this stems from the aforementioned maximum extension phase shifts in the right hip. For a large part of the gait cycle (~42-85%), the variability differences do not decrease below 4 standard deviations, attributed to a much larger variability in the right hip. The smallest difference in variability is during early stance (negligible value), and during terminal swing (less than 2 units) whilst during shorter cycle segments (~18%, ~24%), the differences are null. The trends of the bilateral hip alternate during heel strike and resemble one another solely during mid-swing. Overall, the left hip heel strike (~5-10%) and initial swing (~59-61%) presented the lowest variability of just over 2 standard deviations.

Plot 6.11 – Variability in the Left and Right Hip (**Participant 11**)

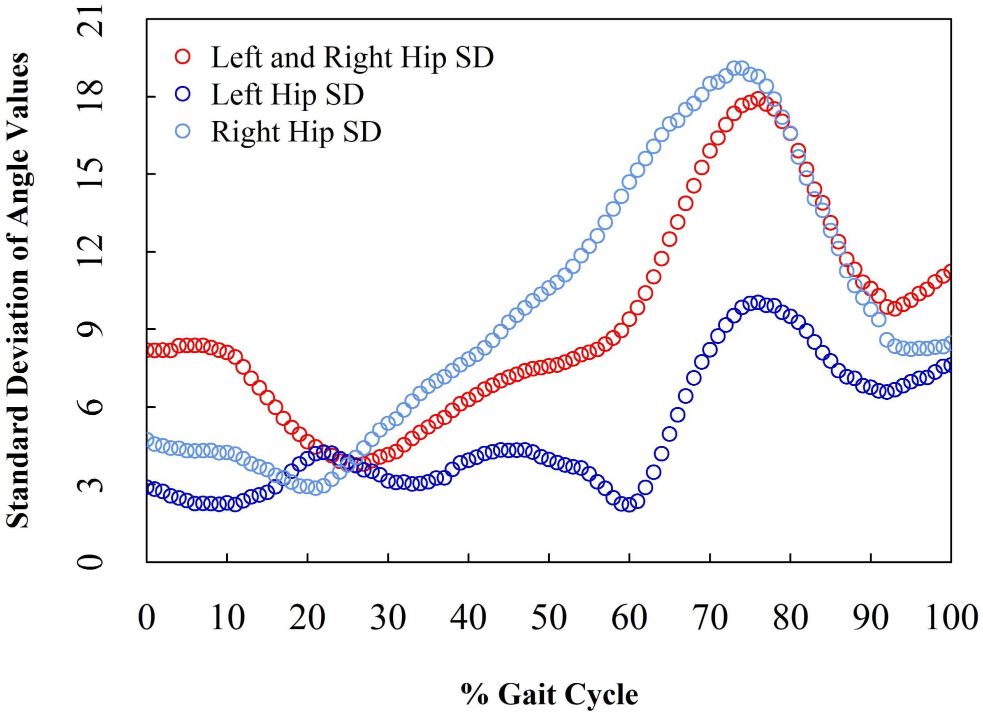
A – Gait Cycles of the Left and Right Hip of Participant 11



Left Hip (LH) Cycles; Right Hip (RH) Cycles; LH Mean; RH Mean; Total Mean

Plot 6.11A illustrates the gait cycles of the left (LH) and right hip (RH) joints of Participant 11, together with their respective means (green and orange respectively), as well as their combined mean (black). The LH joint (dark blue) is represented by a total of 8 cycles and the RH joint (light blue) by 6 cycles. The black horizontal dashed line represents a y axis value of zero. The red arrows indicate the 3 left hip cycles with maximum extension phase shifts and the purple arrows indicate the higher degree of extension in 2 of the right hip cycles.

B – Standard Deviation Plot of Participant 11



Plot 6.11B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 11 for the left and right hip joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

6.4.2 Discussion

In contrast to the shoulder and elbow joints, the intraindividual variability of the left hip joint is not similar to the intraindividual variability of the right hip joint in all 20 participants throughout all gait events (Research Question 1), based on the analysis of a total of 240 bilateral gait cycles. As shown in Table 6.5, pg.145, the participants were grouped according to whether they exhibit similar bilateral intraindividual variability or bilateral *and* combined intraindividual variability (given the rationale previously discussed in Sections 6.2.2 (shoulder joint) and 6.3.2 (elbow joint)). The *late mid-swing* sub-phase was the sole gait cycle region which did not present similarity in either bilateral or bilateral and combined variability in any of the 20 participants. Also, the combined variability was not similar to the bilateral variability during *heel strike* and *terminal swing*. In contrast, *late mid-stance* is the gait phase where the largest number of participants (n=5) presented with similar bilateral and combined variability, thus highlighting that both body sides of less than half of the participants also share a common range of values (dark orange).

Therefore, for the hip joint dataset analysed in this thesis, *late mid-stance* constitutes the gait segment with the highest potential for interchangeability, but due to the small number of participants exhibiting this feature, the conclusion of hip joint lack of symmetry remains valid even for this gait sub-phase. This aspect is further reinforced by the larger number of participants (n=8) with similar variability but different combined variability during *heel strike*; since the range of values between the two body sides differ in more than half of the participants, the analysis of this dataset suggests that the data from the bilateral hip joint is not interchangeable during any gait event and therefore, the use of the total mean to represent 'average' gait cycles of individuals may be unsuitable. Likewise, the use of a singular body side for the same purpose is not recommended. These conclusions reflect those previously drawn for the upper limb joints.

With respect to consistency of both bilateral and combined variability, P20 is the only participant for which bilateral and combined variability magnitudes were similar throughout 40% of the gait sub-phases. Hence, P20 remains the only individual with some degree of body symmetry during the gait cycle. In contrast, P5 is the sole participant with similar bilateral variability (but larger combined variability) throughout 60% of the gait cycle (i.e. throughout the entire stance phase). However, since the combined variability is higher than the bilateral variability, this find further highlights the differences in body symmetry resulting from different ranges of value for the two body sides. In addition, since only two participants presented this feature, it further indicates that flexion and extension movements in the hip joint are largely asymmetric across the gait cycle. Conversely, the intraindividual variabilities of participants P6, P12, and P18 were different throughout all gait events, and are therefore not found in Table 6.5; this contrast the finds from the upper limbs joints where all 20 participants were found to have similar bilateral and/or combined variability in at least one gait sub-phase.

Table 6.5 – Gait Cycle Regions with Similar Intraindividual Variability in the Bilateral Hip Joint

	Participant Index									
Right and Left Hip Intraindividual Variability	P2 P3 P4 P5 P7 P9 P13 P16	P4 P5 P9	P1 P2 P5 P4 P14	P1 P2 P3 P4 P5 P9 P14	P2 P3 P5 P8 P9 P17	P2 P3 P5 P8 P9 P17	P9	P13		P8 P11
Total Number of Participants	**8**	3	5	7	6	6	1	1		2
Right and Left Hip Intraindividual Variability + Combined Intraindividual Variability		P14 P19	P11 P15 P20	P1 P10 P15 P16 P20	P4 P13 P20	P4 P19 P20	P3 P5 P13	P17		
Total Number of Participants		2	3	**5**	3	3	3	1		
	Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
	Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.5 summarises the gait cycle regions of bilateral hip joint flexion/extension in all 20 participants where the intraindividual variability of the left and right body sides, as well as their combined intraindividual variability, are similar (i.e. difference of one standard deviation or less). Note that participants P6, P12, and P18 are not found in this table since these participants do not present similar variability in any gait event. The light and dark orange coloured boxes highlight the largest number of participants in a given category.

In contrast to the elbow joints, the hip joint does present absence of variability in both the left and right body sides, as shown in Table 6.6, pg.146 (the participants were placed into the appropriate category following the rationale presented in Section 6.2.2 (shoulder joint)). This feature was found in 10 out of 20 participants; however, for none of the 10 participants was the variability zero bilaterally during any gait sub-phase. In addition, the participants were dispersed throughout multiple gait events, with a maximum of two participants per gait sub-phase, namely P15 and 18 in *loading response* (left hip), P3 and P16 in *pre-swing* (left hip), and P2 and P4 in *terminal swing* (right hip); elsewhere, only one participant was found to present this zero-variability feature in a given gait sub-phase. Also, as highlighted throughout Section 6.4.1, the aforementioned regions with zero variability occur during very short gait segments of a given sub-phase, rather than throughout the entire sub-phase. This can be noted from the appearance of the same participant in both the 'one standard deviation' and 'no variability' categories. Other gait cycle sub-phases of the aforementioned participants during which this feature was present were right hip mid-swing (P3), right hip heel strike and mid-swing (P6), left hip loading response (P17), and left hip mid-swing

(P18). However, since these segments constituted less than a full gait sub-phase AND the variability of the remaining sub-phase was greater than one standard deviation, these were not included in Table 6.6. Likewise, P12 also presented zero variability during right hip mid-stance, but for a too short of a duration. For the ‘one standard deviation’ category, the same participants were noted, as well as P9, thereby bringing the total number of participants with low variability in the hip joint to eleven. From these 11 participants, only two participants (P3 and P8) presented with equal variability bilaterally but in different gait sub-phases (*pre-swing* and *terminal swing* respectively), and the maximum number of participants in a given gait subphase was three (left hip *pre-swing* and right hip *terminal swing*)). One-unit variability was also noted in the right hip pre-swing for P1, and P8, left hip pre-swing for P14 (not included in Table 6.6), and left hip loading response for P19 and P20 (not included in Table 6.6). However, as with the ‘no variability category’, the gait segments were too short to be incorporated in Table 6.6. These finds therefore emphasise the absence of universal body symmetry in the hip joint and implicitly, the lack of validity in utilising bilateral data interchangeably given that intraindividual variability is discrepantly low across gait sub-phases and between body sides.

Table 6.6 – Gait Cycle Regions with Lowest Intraindividual Variability in the Bilateral Hip Joint

		Participant Index									
Left Hip **Intraindividual Variability**	**One Standard Deviation**	P8	P15 P18		P9		P3 P9 P16	P17			P8
	No Variability	P8	P15 P18				P3 P16	P17		P15	P8
Right Hip **Intraindividual Variability**	**One Standard Deviation**	P2	P2 P3	P2 P4	P5		P3 P6				P2 P4 P8
	No Variability				P5		P6				P2 P4
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.6 summarises the gait cycle regions of the left and right hip joint flexion/extension of all 20 participants which present with an intraindividual variability of one standard deviation or less. Of note is that participants P1, P7, P10-P14, P19, and P20 present higher intraindividual variability and are therefore not found in this table. The light and dark red coloured boxes indicate the magnitude of the intraindividual variability (**light red – one standard deviation**; **dark red – zero variability**).

Overall, a larger number of participants presented with lower intraindividual variability in the left hip (n=8) than in the right hip (n=6). Nevertheless, the participants are generally distributed throughout similar sub-phases bilaterally, amounting to 50% of the gait cycle (Table 6.6), namely *heel strike*, *loading response*, *late mid-stance*, *pre-swing*, and *terminal swing*. For the left hip however, one additional participant was found during *late mid-swing* (P15), and another during *initial swing* (P17); hence, the left hip presents low variability throughout 70% of gait sub-phases. For the right hip, P2 and P4 were found during *early mid-swing*, thereby amounting to a total of 60% of the gait cycle for which the right hip exhibits low intraindividual variability. Also, 6 participants presented zero variability in the left hip, with only 4 in the right hip; only *pre-swing* and *terminal swing* constituted the gait sub-phases common to both body sides with respect to absence of variability. Furthermore, the left hip presented two gait sub-phases for which variability was zero in a given participant, namely *loading response* and *late mid-swing* for P15, and *heel strike* and *terminal swing* for P8. Therefore, these findings indicate that the left hip is less variable than the right hip, thereby constituting a potentially better option for analysing interindividual variation in comparison to the right hip for which variability is less stable. This further reinforces the conclusions drawn from Table 6.5, pg. 145 which suggest that the data of the bilateral hip cannot be utilised interchangeably. an empirical basis is also needed for concluding whether collectively, the upper body joints are more (or less) suitable for use in forensic gait analysis than the lower body joints. Therefore, bilateral hip joint intraindividual variability required comparison not only the intraindividual variability of the shoulder and elbow but also with the intraindividual variabilities of the other lower limb joints, namely the knee, and ankle joints (results and analyses found in Chapter 7 – Intraindividual Body Region Variability (Research Question 2)). Nevertheless, despite the much lower variability observed in the bilateral hip joint in comparison to the shoulder and elbow, it cannot be concluded that the hip joint is more suitable than either the shoulder, elbow or both, for forensic gait analysis. Likewise, the low intraindividual variability does not necessarily imply that the interindividual variability is greater, hence, the impact of hip intraindividual variability on the potential for individualisation and on the claim of uniqueness required further analysis (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

As opposed to the shoulder and elbow joints, the majority of the hip joint angular waveforms do not present specific and/or evident anomalies which may indicate anatomical, physiological, or mechanical origins. As described throughout Section 6.4.1, many of the participants exhibit some degree of asynchronicity across gait events, particularly during maximum extension, thus potentially resulting in an exacerbated intraindividual variation, particularly during the swing phase which was generally most affected by the delay in peak extension. This aspect has impacted the degree of variability in certain participants since its origin is not necessarily a difference in angle value or shape, but rather a difference in timing of the angle values, as highlighted throughout the participants plots in Section 6.4.1. However, as previously stated in the shoulder joint discussion (Section 6.2.2), the lack of synchronisation may also indicate that, for example, certain individuals achieve maximum extension in the hip joint during different gait events, hence this may constitute an additional intraindividuality variable with potentially impactful implication for forensic gait analysis. One example from the analysed dataset which strengthens this rationale, is that of P9 (Plot 6.9, pg.139) who displayed one the highest degrees of synchronicity in hip joint bilateral values; yet, as shown in Table 6.5, pg.145, the combined variability was not similar to the bilateral variability, thus evidencing that the range of values of the two body sides differ and implicitly, that the flexion/extension movements of the hip joint are not symmetrical with respect to values, thereby highlighting that asynchronicity may not necessarily exacerbate intraindividual variability in the absence of an 'actual' difference in values. Since the gait cycle extraction procedures were much less challenging for the hip joint, the asynchronicity features are less likely to have originated from an improper extraction of the cycles, in comparison to the shoulder and elbow joints. As previously recommended for the upper limb joints (Sections 6.2.2 and 6.3.2), additional research is required to test this rationale, including strengthened incentives for gait cycle sub-phase standardisation.

Nevertheless, the disparity in the number of left and right hip cycles should be considered. Since equal number of gait cycles could not be extracted bilaterally for each participant, the intraindividual variability of the hip may have been overestimated in participants with lower number of cycles and therefore incomparable with intraindividual variability obtained from a larger number of cycles, hence the smaller number of participants with similar bilateral and combined variability. However, the angular waveforms of all participants have been thoroughly examined throughout Section 6.4.1, and the majority indicate that the origin of most of the larger variability stems from a combination of differences in synchronicity as well as from differences in value. Irrespective of the origin of variability, the features of the dataset utilised in this thesis strongly suggest that the data of the bilateral hip joint cannot be interchanged to describe flexion and extension movements, thus highlighting that the use of a total mean irrespective of body side may result in an underrepresentation of intraindividual variability. Differences in value, combined with distinct periods of time of certain gait events indicate that hip joint movement should be discriminated according to body side.

In summary, the main conclusions that can be drawn from the analysis of the hip data are the following:

- the majority of gait sub-phases did not present similar bilateral and/or combined hip joint intraindividual variability, thereby suggesting that the hip joint does not present potential for bilateral data interchangeability;
- *late mid-swing* did not present similar bilateral and/or combined hip joint intraindividual variability in any participant;
- no participant presented symmetric movements for more than 40% of the gait cycle;
- left hip intraindividual variability is lower throughout a larger proportion of gait events;

- intraindividual variability in the hip joint is absent in half of the participants during short gait cycle segments;
- degree of synchronicity of gait events in the hip joint may constitute an additional, participant-dependent variable and should be independently considered in future studies;
- given that the number of participants with similar bilateral and combined variability does not constitute a majority, the utilisation of the total mean or unilateral hip joint data in differentiating amongst individuals is inappropriate, thereby highlighting the importance of body side during analysis of hip angular data in the sagittal plane, as also noted in the upper limb joints.

6.5 Left and Right Knee

6.5.1 Results

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 (Figure 6.5A). For example, maximum flexion (i.e. highest peak) synchronicity differs in some of the left knee waveforms, whereas for the right knee waveforms, the values differ to a greater extent, as does the degree of synchronicity. In contrast, the maximum extension values were more consistent across all 40 waveforms at the start of heel strike and during terminal swing. Also, the values of the right knee waveforms are generally lower than those of the left knee values throughout all gait events. Nevertheless, the overall shapes are highly similar, as also observed in the bilateral hip joint. The results of each one of the 20 are found in Appendix H4, Plots H4.1A-H4.20A.

As illustrated in Figure 6.5B, the lowest intraindividual variability range across most participants was found throughout mid-stance (1-6 units) in the regions of the plot where the highly darkened areas are found (~22-45%, red box); the final 10% of the gait cycle also presents lower variability of under 6 standard deviations, with the exception of the right knee in one of the participants (red arrow). This contrasts the end of the stance phase and most of the swing phase (~46-90%) where the intraindividual variability range is high across both body sides for all 20 participants, with no clearly discernible trend. For instance, during pre-swing (~50-60%), the variability approaches 19 standard deviations, and increases further to 21 units during mid-swing (~72-74%), after which it decreases to a general value of 15-16 standard deviations until the final 10% of the swing phase. Throughout late mid-swing, only a single participant presented with low variability in the left knee (green arrow). The results of each one of the 20 participants are found in Appendix H4, Plots H4.1B-H4.20B.

Figure 6.5 – Research Question 1: Summary of the Bilateral Knee Joint Data

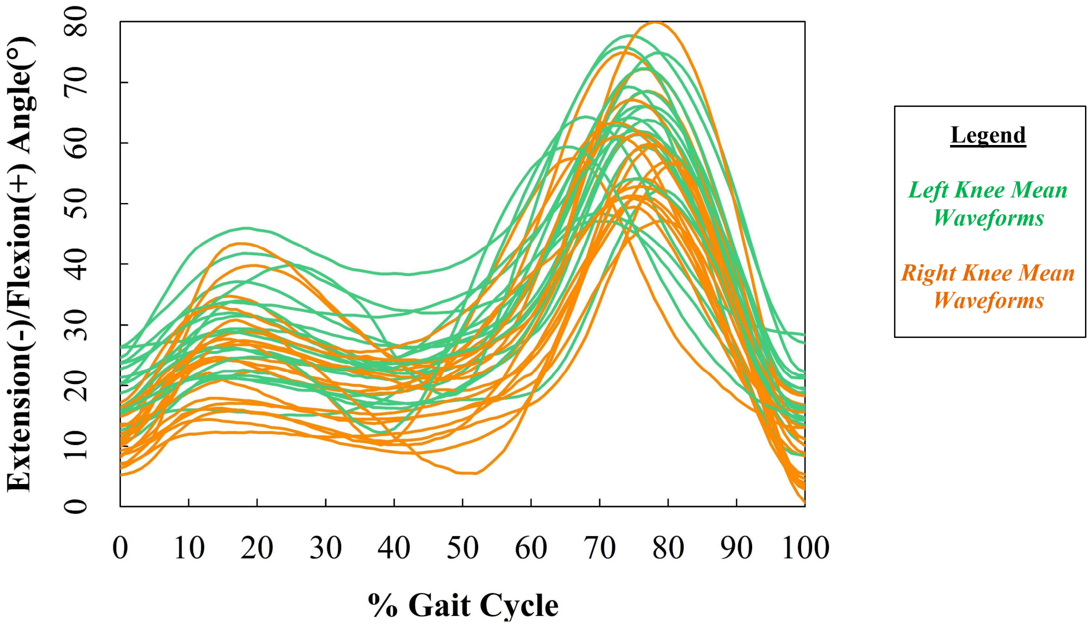

A – Left and Right Knee Mean Gait Cycles

Figure 6.5A illustrates the mean gait cycle waveforms of the left and right knee joints of all 20 participants. Each one of the 20 participants is represented by one green line and one orange line corresponding to the mean gait cycle waveform for the left and right knee joints, respectively.

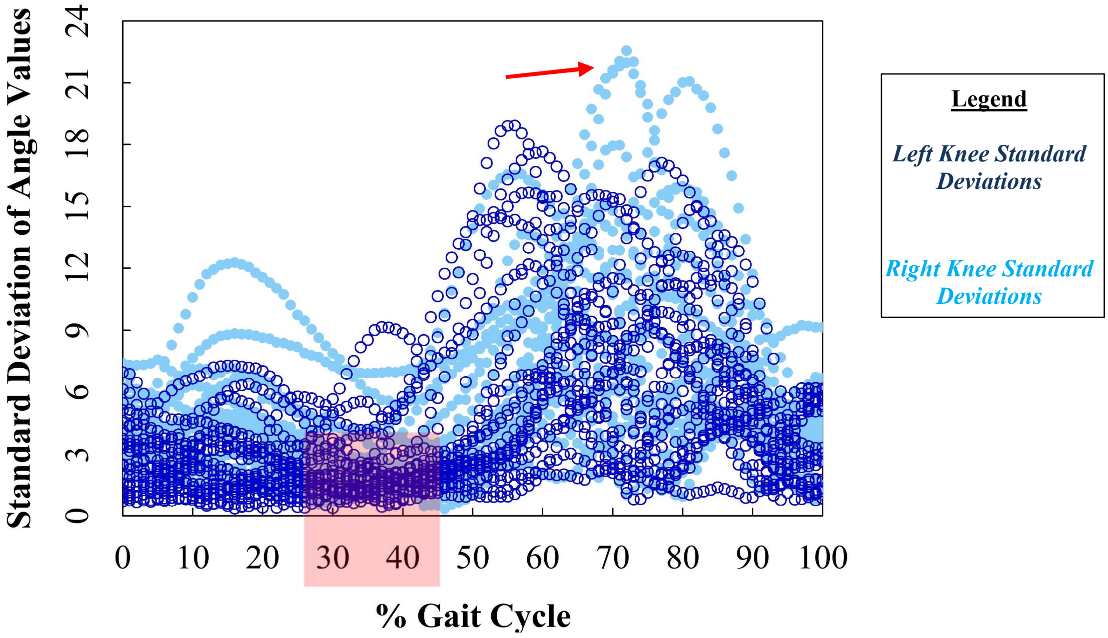

B – Variability in the Left and Right Knee

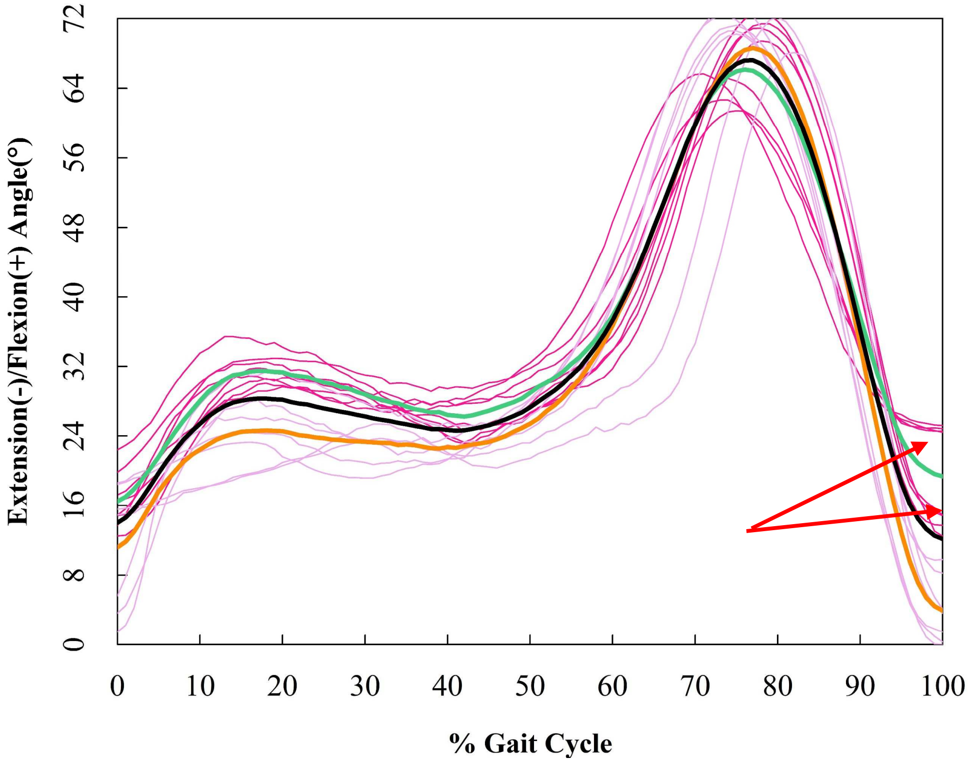
Figure 6.5B illustrates the standard deviations of the gait cycle values of each of the 20 participants. The dark blue circles and light blue circle represent the standard deviations of the left and right knee joints respectively, at every 1% of the gait cycle. The **red** arrow indicates the highest intraindividual variability in the right knee (corresponding to P8 and P9) and the red box indicates the region with the lowest intraindividual variability where the largest number of participants are concentrated.

One example of high degrees of bilateral synchronicity is Participant 6 (female, 23 years, 55 kilograms, 1.69 metres) who presents one of the most congruent mean waveforms and individual gait cycles from all 20 participants. As shown in Plot 6.12A, the mean waveforms as well as the individual cycles (8 left knee cycles, 7 right knee cycles) present a uniform and consistent appearance. The mean values of the left knee are generally larger than the values of the right knee, except for maximum flexion where the right knee peak value exceeds the left knee peak value by approximately 3-4 degrees. This difference in value is small, as is the difference in the timing of maximum flexion. The largest difference in mean value of 16 degrees occurs at the end of the cycle (99-100%), whereas elsewhere, the differences do not exceed 8 degrees. In comparison to previous participants, the degrees of both flexion and extension are the largest observed thus far.

Individually, the 8 left knee cycles are clustered at a higher range of values throughout the beginning of the stance phase (0-48%) than the 7 right knee cycles, with minimal overlap across the cycles from the opposing body side; nevertheless, the ranges of values are similar but located at different scales during most of stance, a feature reflected by the small differences in variability of less than 2 standard deviations, as well as the higher combined variability (Plot 6.12B). The overlap of the values of all 15 cycles increases towards the end of the stance phase/beginning of swing phase where the combined variability decreases to values within the bilateral variability interval. However, the range of values increases for the right knee, feature reflected in the approximately 15 standard deviations variability in this gait cycle region. The left knee variability also increases during mid-swing due to the difference in timing of maximum flexion (maximum of 9 standard deviations), whilst the variability of the right knee decreases, thus reflecting the lower degree of phase shifts during peak flexion. During terminal swing, the left knee cycles are clustered in two groups of four cycles (red arrows, Plot 6.12A), with an interval difference of approximately 9 degrees, hence the larger variability of just under 6 standard deviations. Overall, the variability trends of the two body sides are similar during the swing phase, but slightly out phase, mirroring the differences in location of the peak flexion phase shifts; considering these aspects, the total mean is not representative of the features of both body sides. The lowest variability of just over one standard deviation was found during left knee late mid-stance (~32-34%).

Plot 6.12 – Variability in the Left and Right Knee (**Participant 6**)

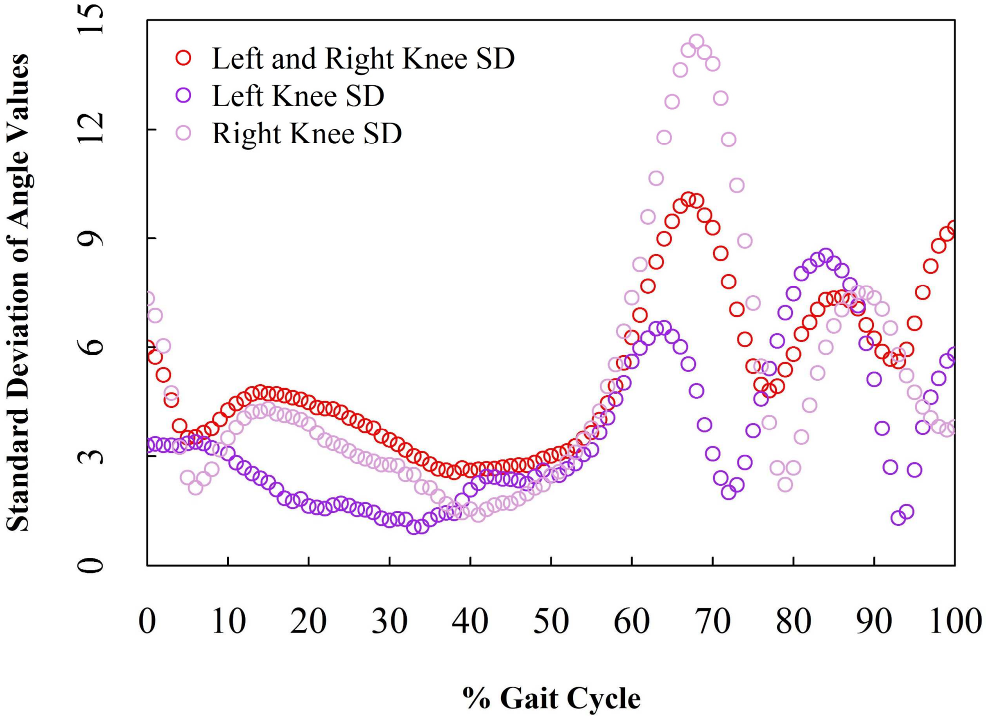
A – Gait Cycles of the Left and Right Knee of Participant 6



Left Knee (LK) Cycles*;* ***Right Knee (RK) Cycles****;* ***LK Mean****;* ***RK Mean****;* ***Total Mean***

Plot 6.12A illustrates the gait cycles of the left (LK) and right knee (RK) joints of Participant 6, together with their respective means (green and orange respectively), as well as their combined mean (black). The LK joint (dark pink) is represented by a total of 8 cycles and the RK joint (light pink) by 7 cycles. The red arrows indicate the grouping of the left knee cycles during terminal swing.

B – Standard Deviation Plot of Participant 6



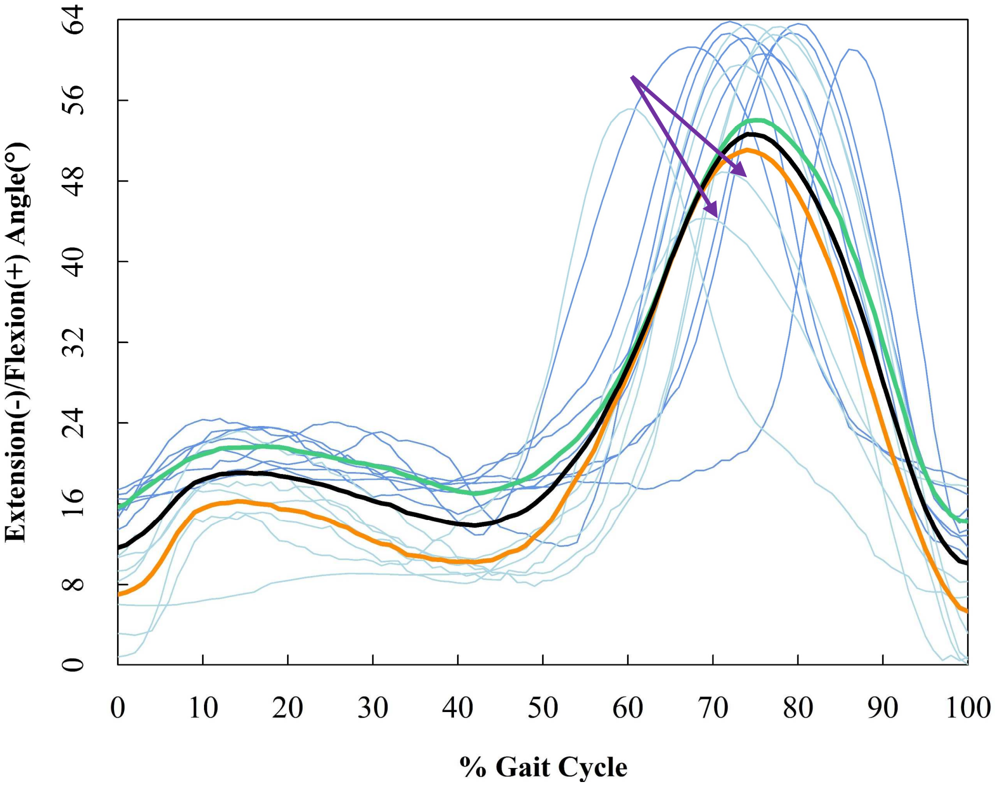
Plot 6.12B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 6 for the left and right knee joints (dark purple and light purple respectively) and the combined standard deviation for both joints (red).

Although the summary of the left and right knee mean waveforms of the 20 participants (Figure 6.5A, pg.151) present a high degree of congruency shape-wise, this aspect is somewhat misleading when examining each participant individually. One such example is Participant 19 (male, 33 years, 72 kilograms, 1.86 metres). As opposed to the majority of the participants, the individual gait cycles of the left and right knee of P19, present no specific trend with respect to synchronicity of gait events, despite the overall similarity of the respective mean waveforms, as shown in Plot 6.13A; hence, the total mean is largely representative of the characteristics of both body sides. The 8 left knee cycles present with a large dispersion of timing of flexion and extension events, despite similarity of mean peak values and of general shape. As a result, the variability is very high during the swing phase, reaching a maximum of just under 16 standard deviations (Plot 6.13B). However, as highlighted in many of the previous participants, the variabilities in cycles with substantial phase shifts do not represent the larger range of values during these regions, but rather the effects of the lack of synchronicity of these events.

A similar effect was also observed for the 7 right knee cycles. For example, 2 of the 7 cycles (purple arrows, Plot 6.13A) present with swing phase maximum flexion angles below 48 degrees, whilst the remaining 5 range between 50-63 degrees. Whereas the swing phase is highly variable for both body sides, the stance phase is, conversely, similar particularly during mid-stance. For instance, the variability of the left knee cycles during stance does not increase above 4 standard deviations whilst the maximum variability of the right knee is just under 6 standard deviations, both during early loading response (~10-14%). Another important feature to note is the combined variability which does not increase above the variability of the two body sides except during heel strike (0-8%), mid-stance/terminal stance (~27-45%); this denotes that during these gait cycle segments, the values of the left and right knee joints are clustered into distinct groups of values, rather than overlapping as in other gait regions, a noticeable aspect from Plot 6.13A. The lowest variability for Participant 19 was one standard deviation during left knee heel strike (~0-4%).

Plot 6.13 – Variability in the Left and Right Knee (**Participant 19**)

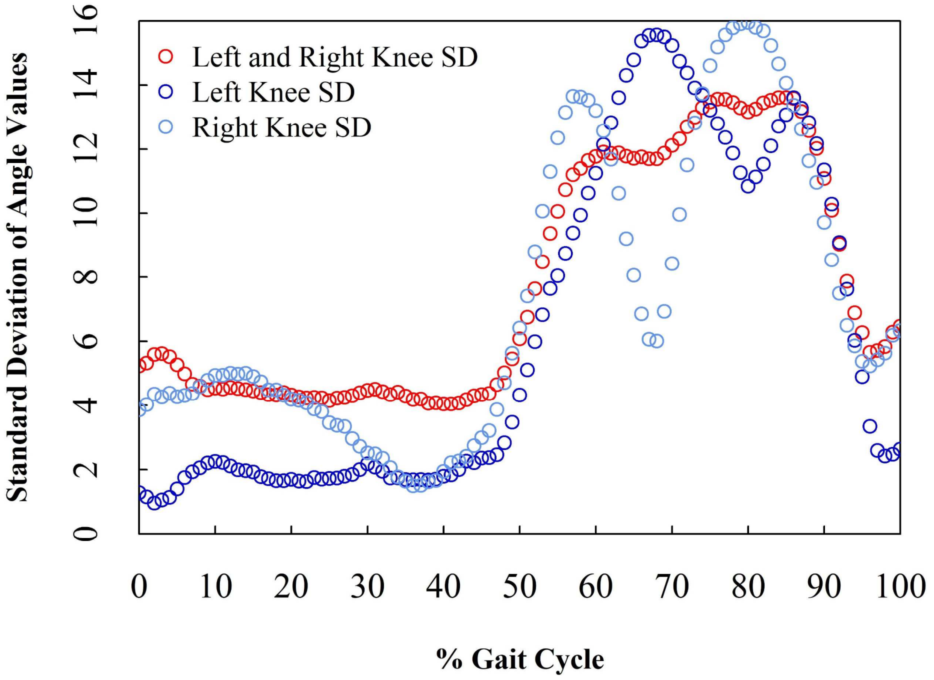
A – Gait Cycles of the Left and Right Knee of Participant 19



Left Knee (LK) Cycles; Right Knee (RK) Cycles; LK Mean; RK Mean; Total Mean

Plot 6.13A illustrates the gait cycles of the left (LK) and right knee (RK) joints of Participant 19, together with their respective means (green and orange respectively), as well as their combined mean (black). The LK joint (dark blue) is represented by a total of 8 cycles and the RK joint (light blue) by 7 cycles. The purple arrows indicate the right knee cycles with lower maximum flexion.

B – Standard Deviation Plot of Participant 19



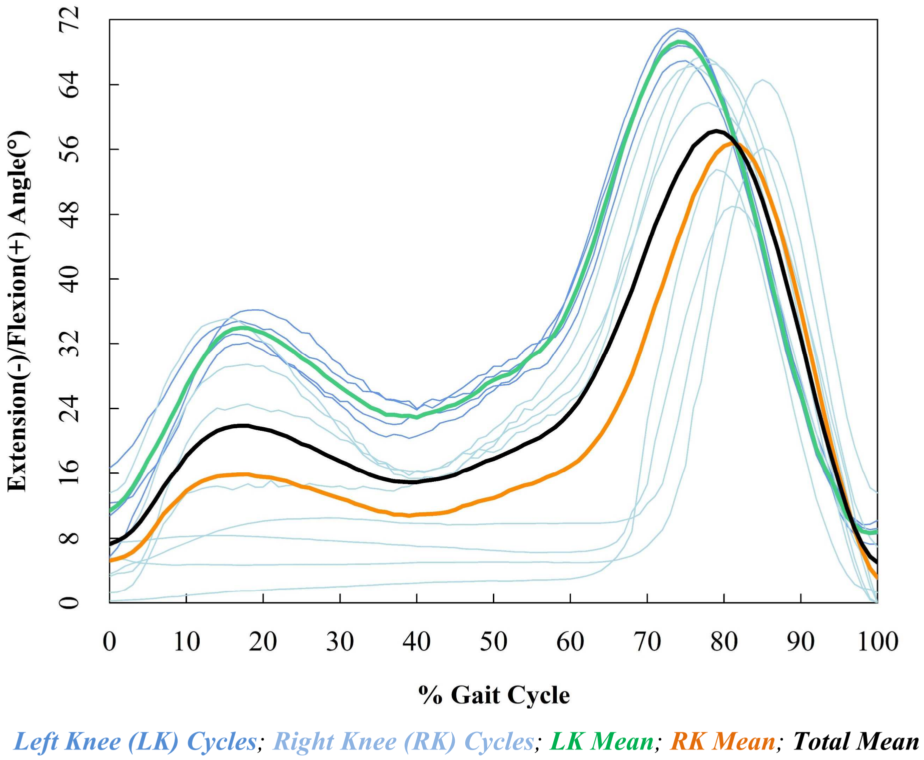
Plot 6.13B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 19 for the left and right knee joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

Anomalies were also noted for certain participants, an example being Participant 8 (male, 21 years, 85 kilograms, 1.70 metres),who did not present flexion peaks for 4 of the 8 gait cycles. In addition, P8 presented one of the highest intrandividual variability (indicated in Figure 6.5, pg.151, by the red arrow). As depicted in Plot 6.14A, the mean waveforms of P8 are also different throughout most of the gait cycle. The differences in mean value are large, not decreasing below 18-20 degrees except during heel strike and throughout the final 15% of the swing phase where they amount to approximately 4-5 degrees. The cycles of the right knee are not clustered into a narrow interval of values; rather, the range of values across the 8 cycles is large across the entire stance phase and initial swing, not decreasing below a 16-degree difference, thereby resulting in an unrepresentative total mean. In addition, the values of half of the cycles are consistently lower than the other half, with no distinct flexion event during stance; these also achieve swing phase maximum flexion later in the cycle (~85-89% rather than 78-81%). In contrast, the 4 left knee cycles are more consistent throughout all gait events, as is their timing of maximum flexion which occurs during mid-swing (72%) for all 4 cycles.

These discrepancies in bilateral characteristics is well reflected by the dissimilar variability trends presented in Plot 6.14B. The variability in the left knee is much more constant throughout all gait events, not exceeding 3 standard deviation except at the start of the heel strike where one of the 4 cycles present higher values than the other 3 cycles. For the right knee however, 3 standard deviations is the lowest variability, found solely during the first moments of heel strike. Overall, the combined variability values are found to be relatively analogous to the variability values of the right knee; despite a much larger range of values, all 8 cycles present distinctly lower values than the left knee. The largest difference in bilateral variability of approximately 19 standard deviations corresponds to mid-swing (~70-75%) where the variability in the right knee is largest as a result of the substantial differences in timing of maximum flexion as well as differences in maximum flexion values. The lowest variability of just under one standard deviation was found during the final 20% of the swing phase of the left knee.

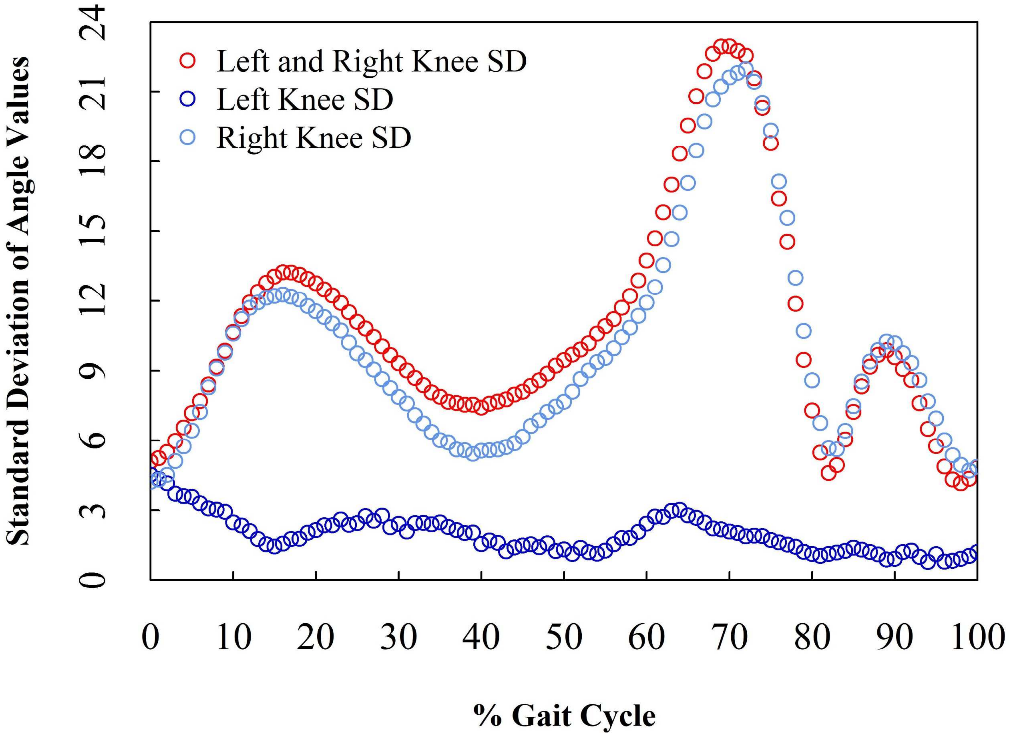
Plot 6.14 – Variability in the Left and Right Knee (**Participant 8**)

A – Gait Cycles of the Left and Right Knee of Participant 8



Plot 6.14A illustrates the gait cycles of the left (LK) and right knee (RK) joints of Participant 8, together with their respective means (green and orange respectively), as well as their combined mean (black). The LK joint (dark blue) is represented by a total of 4 cycles and the RK joint (light blue) by 8 cycles.

B – Standard Deviation Plot of Participant 8



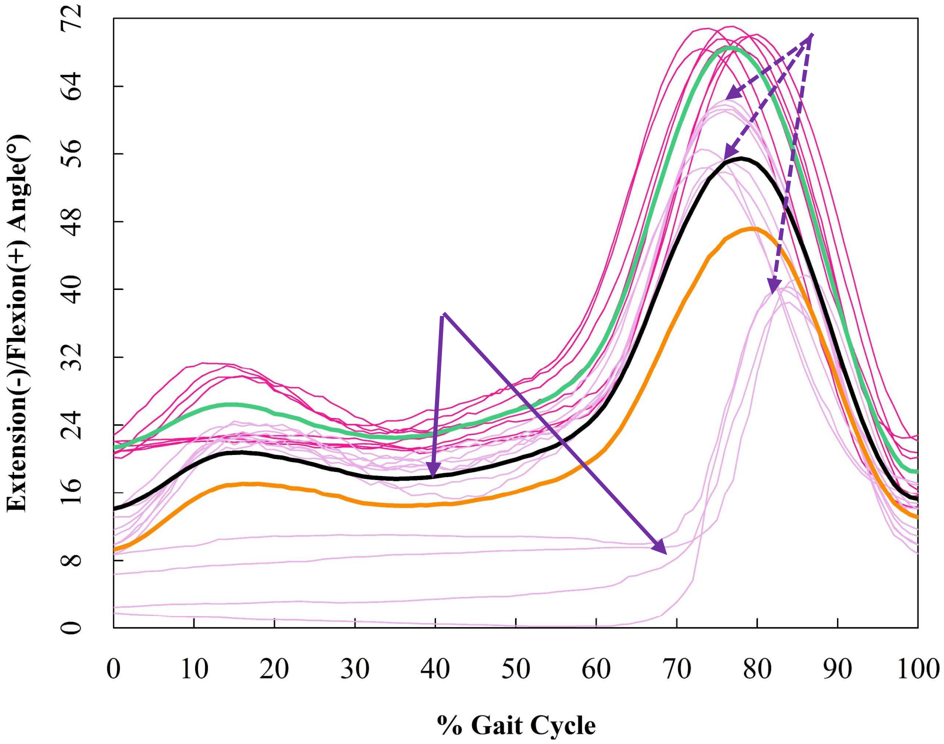
Plot 6.14B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 8 for the left and right knee joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

The second participant for which intraindividual variability was highest (Figure 6.5, pg.151, red arrow) was Participant 9 (female, 25 years, 52 kilograms, 1.63 metres) who shares similar characteristics with respect to shape, synchronicity and range of values to P8 (Plot 6.14) . This find therefore highlights similarities in gait cycle features between both males and females, emphasising that large variabilities may be found in both males and females. The mean waveforms of P9 are largely similar in shape and synchronicity, as illustrated in Plot 6.15A. However, the left knee mean values are maintained higher than the values of the right knee throughout all gait events, but to different degrees. For example, throughout the stance phase, the differences are generally constant at 13 degrees, increasing to 24 degrees during maximum flexion (77-80%); nevertheless, the difference in the timing of the peak is small (3%) between the two body sides. Throughout the final 20% of the swing phase, the differences decrease uniformly to the lowest value of 6-7 degrees at the end of terminal swing. Considering these characteristics, the total mean is therefore unrepresentative of both body sides.

Overall, the 8 left knee cycles are more consistent to one another with respect to shape, synchronicity (small phase shifts only) and values, particularly during the stance phase and mid-swing, hence the smaller overall variability illustrated in Plot 6.15B; however, half of the cycles present no discernible peak flexion during stance. In comparison, the 12 right knee cycles appear as separate clusters, each of which presents with different characteristics (Plot 6.15A, purple arrows). During stance and early swing, 4 out of the 12 right knee cycles present a greater range of values at a lower interval, also with no discernible peak flexion, whilst the other 8 cycles are highly synchronised and clustered around a narrower range of values at a higher interval. This latter group further sub-divides during swing phase maximum flexion, resulting in three groups of four cycles, two with higher maximum flexion values occurring slightly earlier than the other, and another with lower peak values (Plot 6.15A, dashed purple arrows). As a result, the right knee presents the highest variability of approximately 22 standard deviations during this gait event. As with Participant 8, the combined variability closely resembles the variability of the right knee due to the much larger range of values in comparison to the left knee for which the values are consistently higher. The exception is terminal swing where the right knee values are clustered around a narrower interval, similar to the left knee, but at slightly lower values, hence the reversal in the rapport between the two body sides. The lowest variability of one standard deviation was found in the left knee during heel strike (~0-3%) and mid-stance (~32-35%).

Plot 6.15 – Variability in the Left and Right Knee (**Participant 9**)

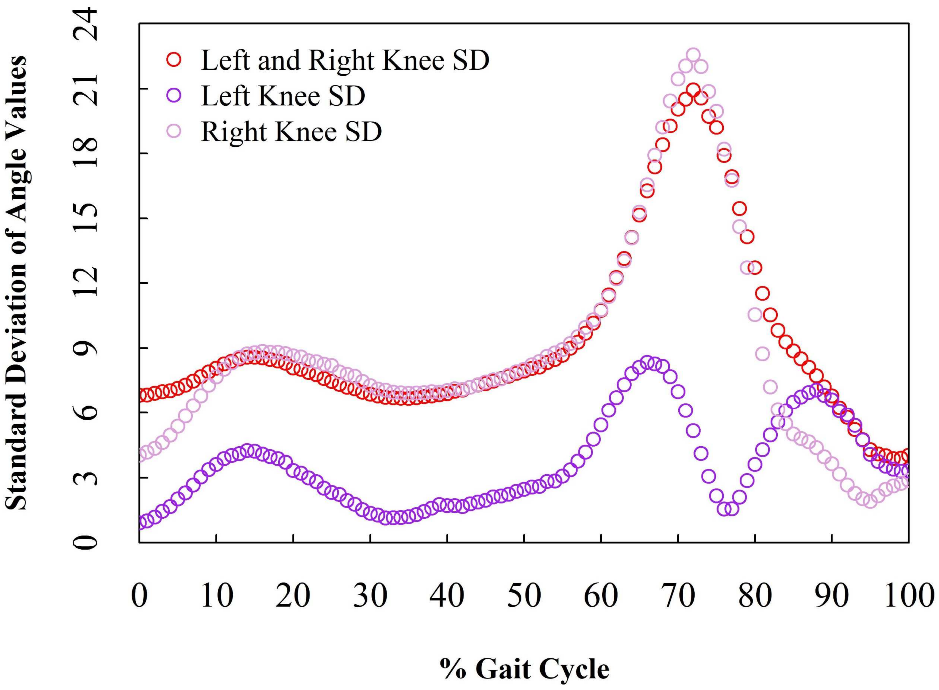
A – Gait Cycles of the Left and Right Knee of Participant 9



Left Knee (LK) Cycles**; **Right Knee (RK) Cycles**; **LK Mean**; **RK Mean**; **Total Mean

Plot 6.15A illustrates the gait cycles of the left (LK) and right knee (RK) joints of Participant 9, together with their respective means (green and orange respectively), as well as their combined mean (black). The LK joint (dark pink) is represented by a total of 8 cycles and the RK joint (light pink) by 12 cycles. The purple arrows indicate the right knee cycles groups, and the dashed purple arrows indicate the different right knee cycle groups with differing timing and values in swing phase maximum flexion.

B – Standard Deviation Plot of Participant 9



Plot 6.15B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 9 for the left and right knee joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

6.5.2 Discussion

As observed in the hip, the intraindividual variability of the knee joint is not similar bilaterally in all 20 participants throughout all gait events (Research Question 1), conclusion drawn based on a total of 305 bilateral gait cycles. As summarised in Table 6.7 below, the participants were grouped according to whether they exhibit similar bilateral intraindividual variability or bilateral *and* combined intraindividual variability (given the rationale previously discussed in Sections 6.2.2-6.4.2). *Early mid-swing* does not present similarity in neither bilateral nor combined variability in any of the 20 participants, whilst *pre-swing* is the gait phase where the largest number of participants (n=7) presented with similar bilateral and combined variability, thus highlighting that both body sides of less than half of the participants also share a common range of values (dark orange). Conversely, *heel strike,* and *initial swing* are two gait sub-phases with the least symmetry between the two body sides, evidenced by only one participant for each category, whilst *early mid-swing* presents no symmetry at all.

Table 6.7 – Gait Cycle Regions with Similar Intraindividual Variability in the Bilateral Knee Joint

	Participant Index									
Right and Left Knee Intraindividual Variability	P5 P10 P12 P13 P16 P20	P6 P7 P10 P14 P20	P3 P6 P7 P17 P18 P19	P5 P6 P7 P11 P18 P19	P5 P6 P7 P11 P19	P7 P13	P10 P20		P13	P5 P10 P12 P13 P14 P20
Total Number of Participants	**6**	5	**6**	**6**	5	2	2		1	**6**
Right and Left Knee Joints + Combined Intraindividual Variability	P17	P15 P16 P17 P18 P19	P14 P15 P16	P4 P12	P1 P4 P12 P18	P1 P4 P6 P7 P17 P18 P19	P11		P4 P19	P1 P16 P19
Total Number of Participants	1	5	3	2	4	**7**	1		2	3
	Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
	Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.7 summarises the gait cycle regions of bilateral knee joint flexion/extension in all 20 participants where the intraindividual variability of the left and right body sides, as well as their combined intraindividual variability, are similar (i.e. difference of ≤1 standard deviation). Note that participants P2, P8 and P9 are not found in this table due to the discrepancies in variability. The light and dark orange coloured boxes highlight the largest number of participants in a given category.

With respect to consistency of both bilateral and combined variability, P19 is the sole participant for which bilateral and combined variability was similar throughout 40% of gait sub-phases (*loading response*, *pre-swing*, *late mid-swing* and *terminal swing*), followed closely by P16-18 which presented with similar variability throughout 30% of the gait cycle; however, *loading response* is the only gait phase where all four participants are found whilst elsewhere, the participant indices are distinctly distributed, as shown in Table 6.7. High consistency in variability amongst half of the gait sub-phases was also noted in P7, although only in bilateral symmetry. Likewise, P5, P6, P10, P13, and P20 exhibited similar bilateral variability throughout 40% of sub-phases, most of which were found during stance. This find suggests that knee joint sagittal plane movements may be more symmetric during the stance phase. Contrastingly, participants 2, 8, and 9 did not present similar bilateral or combined variability during any gait sub-phase, a similar total number of participants as observed in the hip joint. Therefore, for this knee joint dataset, *pre-swing* constitutes the gait segment with the highest potential for interchangeability, but due to the small number of participants exhibiting this feature, the conclusion of knee joint lack of symmetry remains valid. This aspect combined with the small number of participants exhibiting similar bilateral and/or combined variability emphasises the need body side discrimination when analysing knee flexion/extension movements for gait analysis. This find remains consistent with the results obtained from the previous joints, whereby intraindividual variation is not similar bilaterally throughout all gait events.

Intraindividual variability in the knee joint is absent in less than half of the participants (n=6), as shown in Table 6.8, pg.162; the grouping of participants was conducted as previously described for the shoulder, elbow and hip joints (Discussion sections 6.2.2-6.4.2). However, the number of participants is higher than in the shoulder (n=3), but lower than in the hip (n=10) and does not constitute a majority. Furthermore, the 6 participants are dispersed differently across four gait sub-phases bilaterally, with the largest number of 3 participants during left knee *loading response* (P2, P3, P15). Participant 17 also presented zero variability during a brief *late mid-stance* period; however, the gait segment was too short for inclusion. Low variability (i.e. one unit), was also noted in Participants 4, 16, and 17 yet only in a single sub-phase for each participant (*early mid-stance* for the left knee in P4, and right knee in P16, and *loading response* for the left knee in P17). In contrast to the zero-variability category, a much larger number of participants presented short gait segments with one unit of variability, particularly during left knee *heel strike* (P4, P9, P18, P19); other gait phases include *mid-stance* of the right knee (P3, P16, P17) and left knee (P7, P9), left knee terminal stance (P1), right knee *terminal swing* (P4, P15), left knee *mid-swing* (P15), and right knee *mid-swing* (P14).

Table 6.8 – Gait Cycle Regions with Lowest Intraindividual Variability in the Bilateral Knee Joint

		Participant Index									
Left Knee Intraindividual Variability	**One Standard Deviation**	P3 P15	P2 P3 P17	P3 P4	P2 P15 P18					P8	P8
	No Variability		P2 P3 P15	P15	P18						
Right Knee Intraindividual Variability	**One Standard Deviation**			P16		P8 P13					
	No Variability					P8 P13					
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.8 summarises the gait cycle regions of the left and right knee joint flexion/extension of all 20 participants which present with an intraindividual variability of one standard deviation or less. Of note is that participants P1, P5-P7, P9-P12, P14, P19, and P20 present higher intraindividual variability and are therefore not found in this table. Also, none of the participants present zero variability in any of the gait segments. The light and dark red coloured boxes indicate the magnitude of the intraindividual variability (**light red – one standard deviation**; **dark red – zero variability**).

As observed in the hip, the largest proportion of gait sub-phases in the knee for which the intraindividual variability was low, was noted in the left body side. Low variability in the right knee was noted only during *early mid-stance* for a single participant (P16), and during *terminal stance* for two participants (P8, P13). For the left knee, low variability was noted during the first 40% of stance and final 20% of swing, although for the latter, only a single participant was noted (P8). The largest number of participants in a given sub-phase was three, during *loading* response and *late mid-stance*. Bilaterally however, no participant was noted during any gait sub-phase. Hence, the data presented herein further support the conclusions drawn from Table 6.7, pg.160 which highlight the importance of distinguishing between the left and right body sides in the knee joint when analysing movement in the sagittal plane. However, as discussed in Section 6.4.2 (Hip Joint), further analysis was required amongst other lower body joints as well as between upper and lower body joints, to build an empirical basis for intraindividual variability given body side. Therefore, bilateral knee joint intraindividual variability required comparison not only the intraindividual variability of the shoulder and elbow but also with the intraindividual variabilities of the other lower limb joints, namely the hip, and ankle joints (results and analyses found in Chapter 7 –

Intraindividual Body Region Variability (Research Question 2)). Nevertheless, despite lower variability than in the shoulder and elbow but greater overall variability than in the hip, it cannot be concluded that the knee joint may be more (or less) suitable for use in forensic gait analysis than any other joint previously examined. Likewise, the degree of intraindividual variability found does not necessarily imply that the interindividual variability is greater, hence the impact of knee intraindividual variability on the potential for individualisation and on the claim of uniqueness required further analysis (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

As with the hip, the majority of the knee joint angular waveforms do not present specific and/or evident anomalies which may indicate anatomical, physiological, or mechanical origins. As described throughout Section 6.5.1, most participants show lack of synchronicity across gait events, particularly during peak flexion events, thus resulting in a higher intraindividual variation. This is especially applicable for the swing phase which is generally most affected by a delay in peak flexion, as evidenced by the summarised data in Table 6.8, where low variability is found in only one participant during left knee *terminal swing*. However, since asynchronicity has been noted in the previous three joints, the data provide further evidence that differences in timing of gait events may constitute an additional variable, following the same justifications presented throughout Sections 6.2.1-6.4.1 of the shoulder, elbow and hip joints respectively. For instance, P7 presented the highest degree of bilateral synchronicity, yet the range of values are distinct throughout half of the gait sub-phases, as evidenced by the absence of this participant in the majority of the combined variability boxes of Table 6.7, pg. 160 and the variability does not decrease below 2 standard deviations except for a brief period during left knee *mid-stance*. These finds emphasise that a higher degree of synchronicity does not necessarily imply a higher similarity in bilateral and combined variability or a low overall variability. Therefore, the features of the dataset utilised in this thesis strongly suggest that the data of the bilateral knee joint cannot be interchanged to describe flexion and extension movements during gait, thus also implying that the use of the total mean to represent ‘average’ movement of an individual may not be appropriate. Differences in value, combined with distinct periods of time during which maximum peak flexion is achieved, indicate that knee joint movement should be discriminated according to body side.

In summary, the main findings obtained from the analysis of the bilateral knee joint data from all 20 participants are:

- the majority of gait sub-phases did not present similar bilateral and/or combined knee joint intraindividual variability;
- *early mid-swing* did not present similar bilateral and/or combined knee joint intraindividual variability in any participant;
- no participant presented symmetric movements for more than 40% of the gait cycle;
- the stance phase may be the most symmetric region of the gait cycle;

- intraindividual variability in the knee joint is absent in 6 out of the 20 participants;
- left knee intraindividual variability is lower throughout a larger proportion of gait events;
- degree of synchronicity of gait events in the knee may constitute an additional, participant-dependent variable and should be independently considered in future studies;
- given that the number of participants with similar bilateral and combined variability does not constitute a majority, the utilisation of the total mean or unilateral knee joint data in differentiating amongst individuals is inappropriate, thereby emphasising the importance of body side during analysis of knee angular data in the sagittal plane.

6.6 Left and Right Ankle

6.6.1 Results

In the ankle joint, the synchronicity of maximum dorsiflexion during stance and maximum plantarflexion during swing, differs between the two body sides during the swing phase, as shown in Figure 6.6A. The gait cycle region with the highest degree of bilateral similarity (shape and synchronicity-wise) is the first 35% stance, whilst elsewhere, the right ankle joint gait events generally occur later than those of the left ankle joint. Overall, both body sides present with similar interval of values across the stance phase, characteristic which changes during swing, where the right ankle values become clustered around a narrower interval. For instance, during maximum plantarflexion (~60-63%), the mean values of the left ankle approach -29 degrees, whilst those of the right ankle which occur during late initial swing/mid-swing (65-71%), do not exceed -16 degrees. 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. In addition, certain anomalies were present, such as flattened peak dorsiflexion (red arrow). The results of each one of the 20 participants are found in Appendix H5 Plots H5.1A-H5.20A.

As opposed to the intraindividual variability found in the shoulder, elbow, hip, and knee joints, the intraindividual variability of the ankle joint across the gait cycle is more narrowly clustered around lower values, particularly in the left ankle (Figure 6.6B). The first 45% of the stance phase presents with a variability which does not exceed 5 standard deviations for the left ankle whilst during the final 30% of the swing phase, the variability exceeds 8 units in only two participants (red arrows); the maximum variability of 31 standard deviations was found at the start of initial swing (~60-61%) in the right ankle. Whilst the variability was generally lower and more constant across most gait events for the left ankle, the variability of the right ankle fluctuates to a higher degree in some participants throughout all events. For example, the variability of two of the participants exceeds 5-6 standard deviations during stance, whilst during mid-swing (~70-85%), the variability is in excess of 10 standard deviations. During pre-swing/initial swing, the variability increases to a much greater degree than in the left knee, reaching 24-31 standard deviations in two of the participants. Overall, however, the variability of the ankle joint is lower during most gait events when compared to other joints (and to early swing) and is generally similar in both body sides for the majority of participants. The results of each one of the 20 participants are found in Appendix H5, Plots H5.1B-H5.20B.

Figure 6.6 – Research Question 1: Summary of the Bilateral Ankle Joint Data

A – Left and Right Knee Mean Gait Cycles

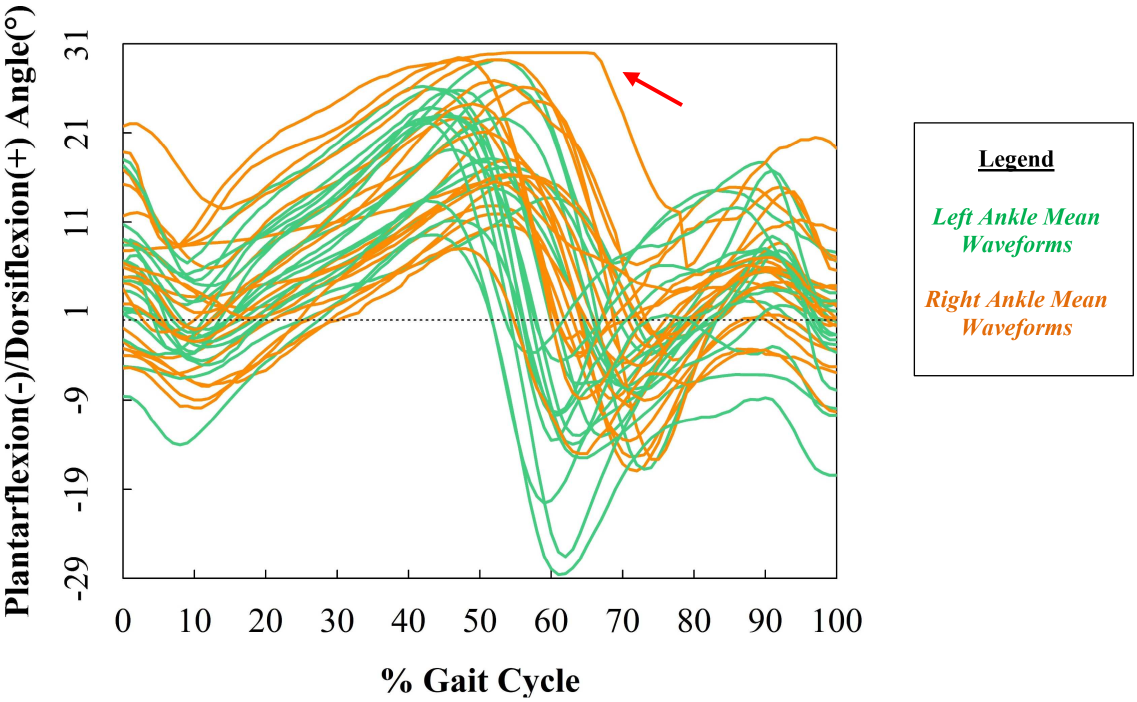


Figure 6.6A illustrates the mean gait cycle waveforms of the left and right ankle joints of all 20 participants. Each one of the 20 participants is represented by one green line and one orange line corresponding to the mean gait cycle waveform for the left and right ankle joints, respectively. The black horizontal dashed line represents a y axis value of zero. The **red** arrow indicates the right ankle waveform with the flattened peak dorsiflexion event, corresponding to P16.

B – Variability in the Left and Right Knee

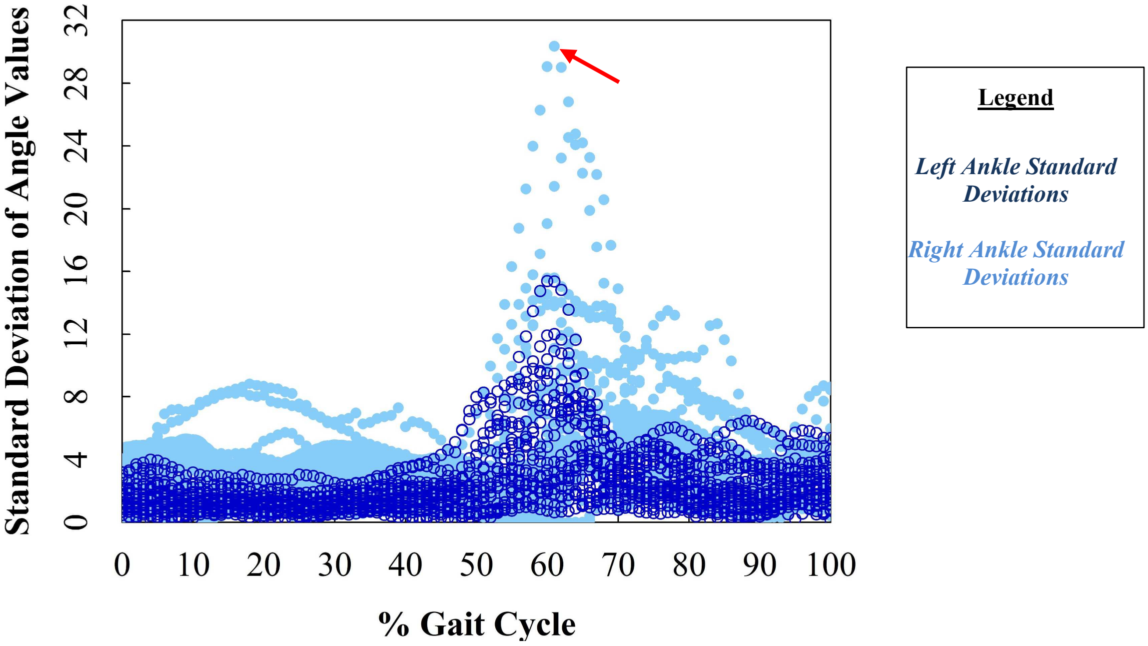


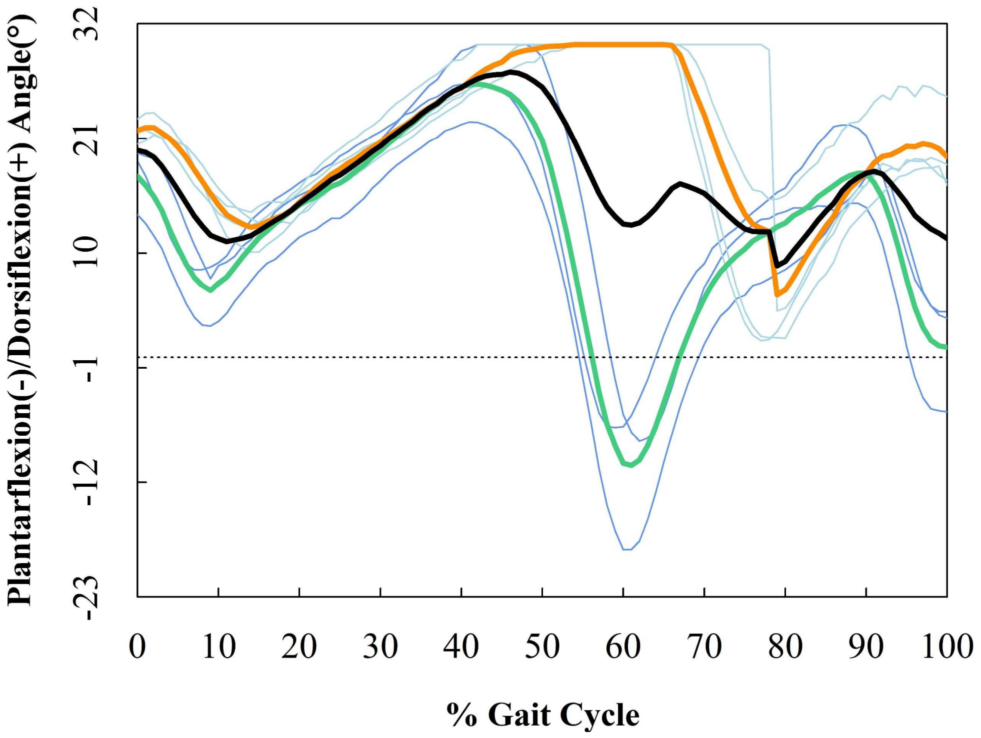
Figure 6.6B illustrates the standard deviations of the gait cycle values of each of the 20 participants. The dark blue circles and light blue circle represent the standard deviations of the left and right ankle joints respectively, at every 1% of the gait cycle. The **red** arrow indicate the highest intraindividual variability in the right ankle (P11).

Several anomalies were associated with the ankle joint data, one of which is a flattened dorsiflexion peak during late stance/early swing. Although this was present in multiple participants to greater or lesser extents, it appeared more evident for Participant 16 (male, 29 years, 65 kilograms, 1.88 metres), as indicated by the red arrow in Figure 6.6A. When examining the individual gait cycles of P16 in more detail, the left and right ankle mean waveforms are highly dissimilar during most gait phases, as shown in Plot 6.16A. The sole region where all ankle mean waveforms are congruent is a short segment of the stance phase (~14-42%), thus representing the sole gait segment for which the total mean is representative bilaterally. Substantial discrepancies are found in all peaks; for example, peak dorsiflexion occurs during a short segment of terminal stance (~40-41%) for the left ankle whilst for the right ankle, the peak is flattened, starting at the end of terminal stance and terminating during initial swing. This plateau effect was also observed in P14; due to the synchronicity of peak dorsiflexion, and its presence in all 3 cycles, this effect has been captured by the mean waveform in P16. As a result of this substantial phase shift, the end of right ankle dorsiflexion is met by the peak plantarflexion of the left ankle, resulting in the highest difference of approximately 42 degrees between the mean values. Loading response plantarflexion and swing phase dorsiflexion also occur later by 7-8% for the right ankle, whilst swing phase plantarflexion by 14%.

Throughout the first 40% of the stance phase, the variability of the 3 left ankle cycles is therefore low, remaining under 4 standard deviations, as illustrated in Plot 6.16B. Throughout terminal stance, the variability increases steadily to a maximum of approximately 10 standard deviations during pre-swing as a result of a larger range of values during maximum plantarflexion. Throughout the swing phase, the variability remains relatively constant, between 4-6 standard deviations as a result of differences in shape and implicitly, of values. As observed with P14, the maximum dorsiflexion plateau anomaly in the right ankle is also present in P16; however, since all 4 cycles are synchronised during this plateau, the dorsiflexion values are equal, hence the absence of variability during this gait segment (i.e. 48-60%); however, this zero variability is misleading in the absence of a peak value, largely an instrument error which will be discussed further in Section 6.6.2. As with the left ankle, the variability of the right ankle is also higher during the swing phase, reaching a maximum of 14 standard deviations during mid-swing, as a result of both differences in value and phase shifts. Overall, the trends are similar but out of phase, particularly during the swing phase; therefore, the largest variability difference is equal to the maximum variability of the left ankle. Also, the values of all 9 cycles are generally interspersed, with the exception of heel strike, pre-swing, initial swing, and terminal swing where the cycles of each body side is grouped into distinct ranges of value, thus reflecting the higher combined variability. Since the zero variability originates from the right ankle dorsiflexion anomaly and cannot be considered valid, the lowest variability of one standard deviation arising from genuine gait cycle values was noted during right ankle heel strike (~0-5%).

Plot 6.16 – Variability in the Left and Right Ankle (**Participant 16**)

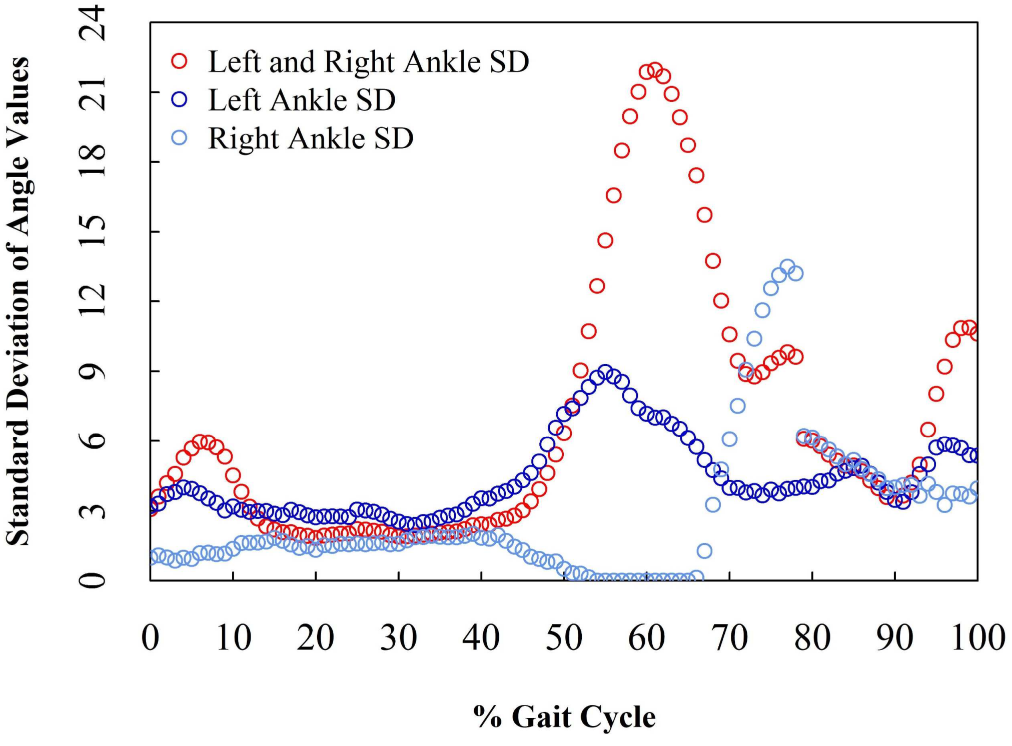
A – Gait Cycles of the Left and Right Ankle of Participant 16



Left Ankle (LA) Cycles**; **Right Ankle (RA) Cycles**; **LA Mean**; **RA Mean**; **Total Mean

Plot 6.16A illustrates the gait cycles of the left (LA) and right ankle (RA) joints of Participant 16, together with their respective means (green and orange respectively), as well as their combined mean (black). The LA joint (dark blue) is represented by a total of 3 cycles and the RA joint (light blue) by 4 cycles. The black horizontal dashed line represents a y axis value of zero.

B – Standard Deviation Plot of Participant 16



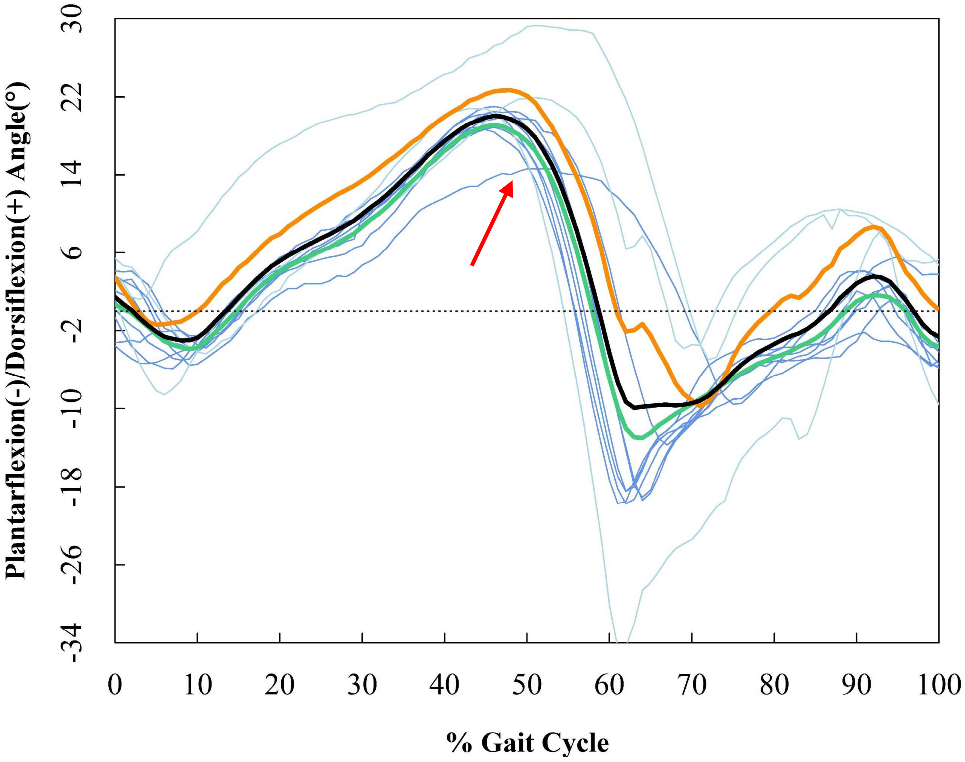
Plot 6.16B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 16 for the left and right ankle joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

Other anomalies also include saccadic transitions across gait events, as exemplified by the gait cycle data of Participant 11 (male, 44 years, 85 kilograms, 1.81 metres) presented in Plot 6.17A. The right ankle mean waveform is highly irregular in comparison to the left ankle mean waveform, lacking smooth transitions across the gait events of the swing phase, region where the total mean is least representative. Also, one of the right ankle cycles presents a larger peak plantarflexion value, exceeding the value observed in the previous participant. In addition, as indicated by the red arrow in Figure 6.6B, pg.166, P11 also presented the largest intraindividual variability. Overall, the right ankle values of P11 are larger than those of the left knee yet by a small amount, not exceeding 4 degrees during the stance phase. At the start of the swing phase, the differences increase to approximately 12 degrees during initial swing and remain relatively constant at 7-8 degrees throughout the final 20% of the swing phase. Maximum dorsiflexion occurs at the same time for both body sides, and the shapes of the mean waveforms are congruent throughout the entire stance phase.

As illustrated in Plot 6.17B, the right ankle variability is higher during early stance (8 standard deviations), corresponding to the higher range of values observed from Plot 6.17A. During pre-swing, the variability increases gradually to a maximum value of approximately 31 standard deviations during initial swing, as evidenced in Plot 6.17B. The reason for this abnormally high variability is not only the differences in values but also the lack of synchronicity across the 3 cycles. Throughout mid-swing, the variability does decrease to 12 standard deviations, whilst at the start of terminal swing, the variability is approximately one standard deviation due to the more constrained range of values; however, this increases again to 8 standard deviations at the end of terminal swing. Although the 8 left ankle cycles are more consistent across the majority of the gait events, the overall variability trend does resemble the variability of the right ankle, particularly throughout the latter half the gait cycle (~50-90%), albeit at a much lower quantity. With the exception of one of the left ankle cycles which is different in shape and in synchronicity (Plot 6.17A, red arrow), values are highly similar across all cycles, evidenced by the small variability of 1-2 standard deviations throughout the stance phase. This variability increases to a maximum of 10-11 standard deviations at the start of initial swing, largely as a result of that single out of phase cycle which enlarges the range of values during maximum plantarflexion (~61-63%). During the remainder of the swing phase, the variability is maintained under 4 standard deviations, also evidenced by the congruency of the cycle values in Plot 6.17A. Since all left ankle values are contained within the very large range of right ankle values, the combined variability remains within the upper and lower variability limits of the two body sides. The lowest variability of one standard deviation was found in the left ankle during loading response (~10-11%) and late mid-swing (80-85%), and right ankle terminal swing (~91-93%).

Plot 6.17 – Variability in the Left and Right Ankle (**Participant 11**)

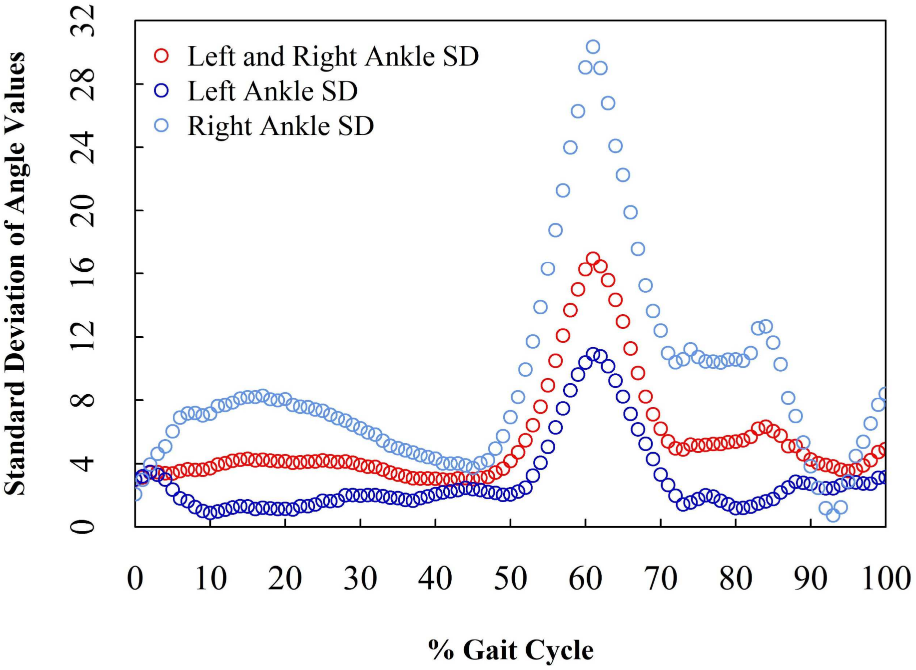
A – Gait Cycles of the Left and Right Ankle of Participant 11



Left Ankle (LA) Cycles; Right Ankle (RA) Cycles; LA Mean; RA Mean; Total Mean

Plot 6.17A illustrates the gait cycles of the left (LA) and right ankle (RA) joints of Participant 11, together with their respective means (green and orange respectively), as well as their combined mean (black). The LA joint (dark blue) is represented by a total of 8 cycles and the RA joint (light blue) by 3 cycles. The black horizontal dashed line represents a y axis value of zero. The red arrow indicates the left ankle gait cycle with the most prominent asynchronicity.

B – Standard Deviation Plot of Participant 11



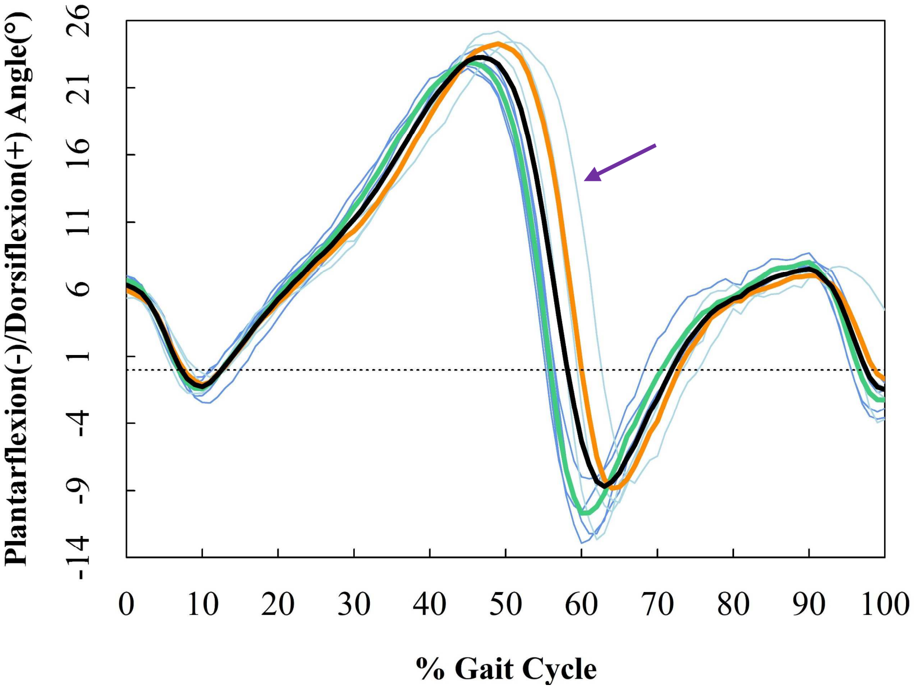
Plot 6.17B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 11 for the left and right ankle joint (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

Most participants, as opposed to the hip joint angular data, presented with prominent lack synchronicity, differences in values, and shape incongruency, irrespective of whether the participant was male or female. One of the few exceptions is Participant 18 (male, 26 years, 87 kilograms, 1.74 metres) who presented the highest degree of bilateral congruency. As depicted in Plot 6.18, In contrast to the majority of participants, the mean waveforms of P18 are highly synchronised (both with respect to the mean waveforms and to the individual cycles), follow the an almost identical shape, and the differences in mean values are negligible throughout all gait events, as depicted in Plot 6.18A. As observed in the previous participant, the peak events values are also in accordance with other participants. The exceptions to synchronicity were found during maximum dorsiflexion whereby the peak occurs earlier for the left ankle than for the right ankle and during swing phase, where a similar feature was noted; although these phase shifts largely constitute a common feature to the right ankle cycles, the differences in value remain lower than 4 degrees, hence negligible. As a result, the total mean waveform is highly representative of the characteristics of both body sides.

The similarity of the two mean waveforms is also substantiated by the congruency of their respective cycles, yet certain differences are noted between body sides. Although the 4 cycles of each body side are highly congruent to their respective means, the right ankle cycles are more varied than those of the left ankle, evidenced by the 9 standard deviations observed during initial swing, corresponding with the most notable phase shift observed in one of the right ankle cycles (Plot 6.18A, purple arrow). Elsewhere however, the variability does not exceed 2 standard deviations except at the end of terminal swing where it approaches 4 units, an effect exclusively due to a larger range of values (Plot 6.18B). The 4 left ankle cycles also reflect a similar general trend to the 4 right ankle cycles, except during initial swing, where the variability difference increases to approximately 7 standard deviations, given that the left ankle variability remains low (under 3 units) and the right ankle variability peaks to its maximum. Overall, the left and right ankle mean waveforms share a similar range of values, except during stance phase maximum dorsiflexion where the right ankle values are collectively higher than the values of the left ankle, and during early mid-swing. As a result, the combined variability is higher during this gait event. Negligible variability was found at the start of the loading response (~10-13%) for the right ankle, terminal stance of the left ankle (~40-45%), and during mid-swing (~80-90%) bilaterally.

Plot 6.18 – Variability in the Left and Right Ankle (**Participant 18**)

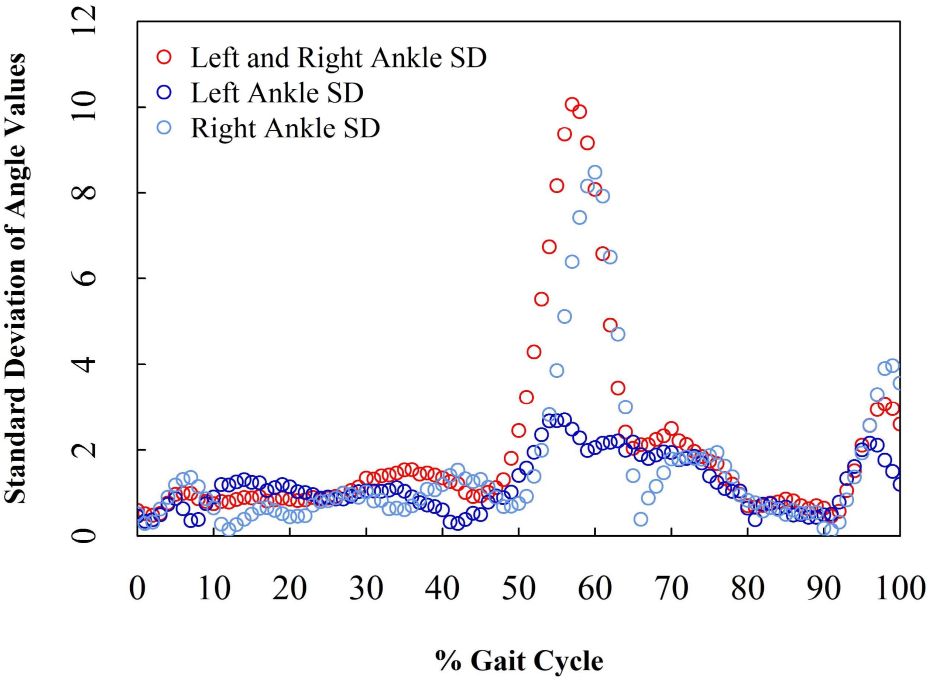
A – Gait Cycles of the Left and Right Ankle of Participant 18



Left Ankle (LA) Cycles**; **Right Ankle (RA) Cycles**; **LA Mean**; **RA Mean**; **Total Mean

Plot 6.18A illustrates the gait cycles of the left (LA) and right ankle (RA) joints of Participant 18, together with their respective means (green and orange respectively), as well as their combined mean (black). The LA joint (dark blue) is represented by a total of 4 cycles and the RA joint (light blue) also by 4 cycles. The black horizontal dashed line represents a y axis value of zero. The purple arrow indicates the right ankle cycle for which the most prominent phase shift was observed.

B – Standard Deviation Plot of Participant 18



Plot 6.18B illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 18 for the left and right ankle joints (dark blue and light blue respectively) and the combined standard deviation for both joints (red).

6.6.2 Discussion

Based on the analysis of a total of 242 bilateral gait cycles, the intraindividual variability of the left ankle joint is not similar to the intraindividual variability of the right ankle joint in all 20 participants as shown in Table 6.9, pg. 174 , a similar find observed in the knee, and hip. As stated throughout Sections 6.2.2-6.5.2, the data of the participants were grouped in Table 6.9 according to whether they exhibit similar bilateral intraindividual variability or bilateral *and* combined intraindividual variability (given the rationale previously discussed in the aforementioned sections). The maximum number of participants (n=9) with similar bilateral and combined variability was found to be during *late mid-stance* and *terminal stance*, whilst throughout the majority of the remaining gait sub-phases, the number of participants does not exceed n=5. For similar bilateral variability in the absence of combined variability, the maximum number of participants exhibiting this feature was n=7 during *heel strike* and *loading response*, thereby indicating that despite similarity in left and right ankle joint variability, the location of the range of values are different. This find, combined with a number of participants which does not constitute a majority, supports the previously observed trend in the shoulder, elbow, hip, and knee, of the absence of body movement symmetry. Hence, intraindividual variation is not similar bilaterally throughout all gait events and for neither of the five joints examines in this thesis (Research Question 1). Conversely *initial swing* presents no symmetry for any participants other than those which also presented similar combined variability (i.e. P3 and P4). Also, the majority of the gait sub-phases with similar bilateral variability but not combined variability contain only two participants per category, as shown in Table 6.9, pg.174; this aspect further highlights the differences in movement symmetry resulting from different clustering of values for the two body sides.

With respect to consistency of both bilateral and combined intraindividual variability, P18 is the sole participant which presented this feature throughout the majority of the gait sub-phases (i.e. 70% of the gait cycle), followed closely by P3, and P5 at 60% of gait sub-phases. P13 also presented this characteristic yet in two out of the seven gait sub-phases (i.e. *heel strike* and *loading response*), only bilateral variability was similar. The participant with similar intraindividual variability but different combined variability across the highest proportion of gait sub-phases (50%) was P9; of note is that this participant does not present similar combined variability during any gait sub-phase, an expected find given that the values of the left body side were distinctly clustered from the values of the right body side. Given that only 5 out of 20 participants presented at least similar bilateral variability in a maximum of 70% of the gait cycle, this may suggest that ankle movement in the sagittal is generally asymmetrical across the gait cycle and thus further emphasises that body symmetry is not universally encountered for all participants in a given gait phase (i.e. stance or swing) or throughout the entire gait cycle.

Table 6.9 – Gait Cycle Regions with Similar Intraindividual Variability in the Bilateral Ankle Joint

	Participant Index									
Right and Left Ankle Intraindividual Variability	P2 P4 P6 P9 P10 P12 P13	P2 P6 P7 P9 P12 P13 P15	P2 P4 P6 P7 P12 P15	P4 P18	P4 P14	P10		P7 P9	P9 P19	P9 P16
Total Number of Participants	**7**	**7**	6	2	2	1		2	2	2
Right and Left Ankle Joints + Combined Intraindividual Variability	P17 P18	P3 P5 P10 P16 P18	P3 P5 P10 P13 P16 P18	P2 P3 P5 P6 P7 P8 P10 P12 P13	P2 P3 P5 P6 P10 P12 P13 P17 P18	P2 P3 P4 P8 P13	P3 P4	P17 P18	P2 P5 P8 P16 P18	P5 P7 P8 P13 P15 P17 P18
Total Number of Participants	2	5	6	**9**	**9**	5	2	2	5	7
	Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
	Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.9 summarises the gait cycle regions of bilateral ankle joint flexion/extension in all 20 participants where the intraindividual variability of the left and right body sides, as well as their combined intraindividual variability, are similar (i.e. one standard deviation or less). Note that participants P1, P11, P20 are not found in this table due to the discrepancies in variability. The light and dark orange coloured boxes highlight the largest number of participants in a given category.

Low variability in the ankle joint was found in the largest number of participant (n=17) and is widespread throughout a larger proportion of gait cycle sub-phases bilaterally than in any of the previous joints, as illustrated in Table 6.10, pg.175. Out of the 17 participants, 12 present zero variability largely during the *stance phase,* with the largest number of participants (i.e. n=3) concentrated during *heel strike, early mid-stance,* and *late mid-swing* of the left ankle. However, only one participant (P18) presented zero variability bilaterally, solely during *late mid-swing.* For the ‘one standard deviation category’, the largest number of participants (n=8) was noted during *early mid-stance* in the left ankle; the second largest cluster of participants (n=7) was also noted during left ankle *loading response.* In contrast, the right ankle presented only a maximum of four participants throughout *mid-stance*, and an overall smaller proportion of gait sub-phases for which variability was low, thus suggesting that the left ankle may be most stable with respect to intraindividual variability.

Table 6.10 – Gait Cycle Regions with Lowest Intraindividual Variability in the Bilateral Ankle Joint

		Participant Index									
Left Ankle Intraindividual Variability	**One Standard Deviation**	P1 P9 P10 P18	P2 P8 P9 P10 P11 P15 P19	P2 P8 P9 P10 P12 P15 P18 P20	P8 P10 P12 P15 P17 P18	P5 P8 P17 P18	P5		P12 P15	P1 P17	
	No Variability	P1 P8 P18		P10 P14 P20	P12	P15 P18				P1 P17 P18	
Right Ankle Intraindividual Variability	**One Standard Deviation**	P2 P3	P2 P15 P18	P3 P5 P7 P18	P3 P5 P7 P18	P3 P5 P7					P3
	No Variability	P3	P15 P18	P3 P5		P7				P18	
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 6.10 summarises the gait cycle regions of the left and right ankle joint flexion/extension of all 20 participants which present with an intraindividual variability of one standard deviation or less. Of note is that participant P4, P6, P13, P16 presents higher intraindividual variability and is therefore not found in this table. The light and dark red coloured boxes indicate the magnitude of the intraindividual variability. (**light red – one standard deviation**; **dark red – zero variability**).

Nevertheless, one standard deviation variability was more frequently encountered bilaterally than in any other joint, namely, during *loading response* for P2 and P15, *mid-stance* for P18, and *terminal stance* for P5, finds which may suggest that stance phase movements (as observed in the knee joint) may be more symmetrical in the sagittal plane. However, since the data do not constitute a majority, the data presented herein further supports the conclusions drawn from Table 6.9, pg.174 which highlight the importance of distinguishing between the left and right body sides in the ankle joint when analysing movement, particularly during the swing phase. As discussed throughout Sections 6.4.2 (Hip Joint) and 6.5.2 (Knee Joint), an empirical basis regarding similarities and differences between body regions is needed, considering the paucity in research of this nature. Therefore, to provide evidence regarding intraindividual variability in the upper and lower body joints, bilateral ankle required comparison across all previously examined joints (results and analyses found in Chapter 7 – Intraindividual Body Region Variability (Research Question 2)). Nevertheless, despite the lowest intraindividual variability observed, it cannot be concluded that the ankle joint may be more suitable for use in forensic gait analysis than any other joint previously examined since this does not necessarily imply that the interindividual variability is greater, hence the impact of ankle intraindividual variability on the potential for individualisation and on the claim of uniqueness required further analysis (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

As exemplified in section 6.6.1, certain participants presented anomalous ankle joint angular waveforms, in contrast to the hip and knee joints. For example, participants P7, P11, P13, P14 and P16 presented abnormally flattened maximum peak flexion events (Plot 6.16, pg.168), whilst P20 presented the greater degree of saccadic transitions across gait sub-phases during the stance as well as highly asynchronous gait cycles; the abnormal transitions most likely originated from exaggerated movement of the body suit sensors sliding from their original position, their improper placement, or other similar technical issues regarding appropriate signal capture. For the abnormally flattened peak flexion events, an additional reason for their occurrence may also be represented by the reconstruction of the 3D data points into angle values. The remaining participants presented similar features to those observed in previous joints such as lack of synchronicity across gait events, particularly during peak events, thus resulting in a higher intraindividual variation, as evidenced by the summarised data in Table 6.9, pg. 174).

As observed in all of the previous joints, the ankle data also presented substantial asynchronicity across all major gait events, thereby also provide further evidence that differences in timing of gait events may constitute an additional variable, following the same justification discussed throughout the aforementioned sections. For example, P10 displayed a generally synchronised series of gait cycles for each body side, however, peak flexion events are not synchronised, thus resulting in large variability difference between the two body sides. Nevertheless, as highlighted throughout Section 6.6.1, the differences are not solely due to lack of synchronicity but also due to differences in values, an aspect further emphasised by the small number of participants with similar bilateral and combined variability throughout most gait events, as highlighted in Table 6.9, pg.174. Conversely, participants P8 and P18 (Plot 6.18, pg.172) present a high degree of synchronicity in the bilateral cycles, yet the variability remains above one standard deviations for most of the gait events, as shown in Table 6.10, pg. 175. These finds therefore indicate that a higher degree of synchronicity does not necessarily imply a higher similarity in bilateral and combined variability or a low overall variability. Therefore, the features of the dataset utilised in this thesis strongly suggest that the data of the bilateral ankle joint cannot be interchanged to describe flexion and extension movements during gait, and that the use of the total mean to describe average gait cycles of individuals may introduce further error for identification. Differences in value, combined with distinct periods of time for peak gait events, indicate that ankle joint movement should be discriminated according to body side.

The main findings obtained from the analysis of the bilateral ankle angular data from all 20 participants are summarised below:

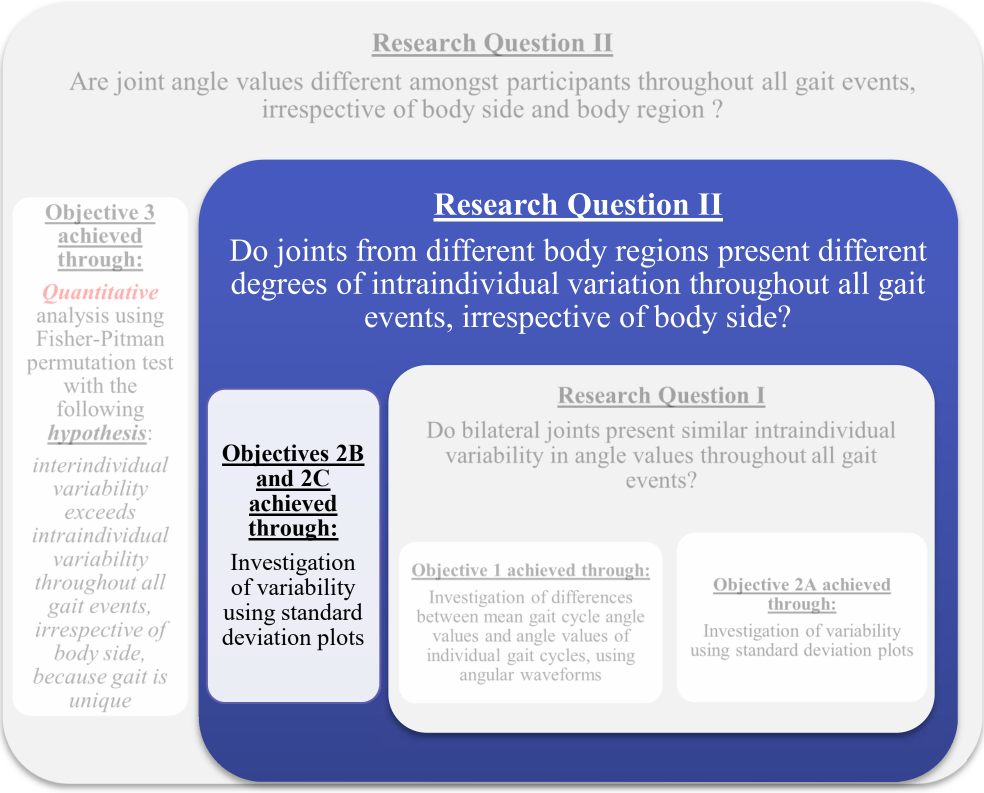
- *late mid-stance* and *terminal stance* constitute the gait sub-phases with the highest potential for interchangeability in the ankle joint;
- low variability was found in the majority of participants (n=17);
- left ankle intraindividual variability is lower across a greater gait cycle proportion;
- degree of synchronicity of gait events in the ankle joint may constitute an additional, participant-dependent variable and should be independently considered in future studies;
- ankle joint gait cycles do present some anomalous angular waveforms, including flat peak-like effects and saccadic transitions across gait sub-phases;
- given that the number of participants with similar bilateral and combined variability does not constitute a majority and that the left ankle presented lower variability, the utilisation of the total mean or unilateral ankle joint data in differentiating amongst individuals is inappropriate, highlighting the importance of body side during analysis of ankle angular data in the sagittal plane.

Chapter 7 – Intraindividual Body Region Variability (Research Question 2)

7.1 Overview

Chapter 7 describes and critically evaluates the findings of Research Question 2, as illustrated below in Figure 7.1. Section 7.2 presents the results of the left and right body sides in the form of multi-panel standard deviation plots which illustrate the variability of all 20 participants for all five joints. For each body side, an example of two participants is provided to illustrate differences amongst the five joints and between body sides in more detail, with the remainder of the standard deviation plots located in Appendix I. The results for Research Question 2 are presented separately for each body side given the results obtained from Research Question 1 which have highlighted bilateral discrepancies. In Section 7.3, the results of all participants are compared and contrasted, also taking into consideration the findings presented in Chapter 6 which answered Research Question 1.

Figure 7.1 – Thesis Investigation Approach (Research Question 2)



7.2 Results

As discussed throughout Chapter 6, the 20 participants presented different degrees of intraindividual variability for each one of the five joints of interest. Figure 7.2 illustrates this aspect through a comparative approach of the left shoulder, elbow, hip, knee, and ankle. Overall, the shoulder and ankle joints presented the lowest degree of intraindividual variability in most participants, evidenced by standard deviations which did not generally exceed 5-6 units. For the left shoulder joint, the exceptions included the middle period of the stance phase and for the left ankle joint, the end of stance/beginning of the swing phase. In contrast, the left knee joint was more variable in a larger number of participants, particularly during the end of the stance phase and throughout most of the swing phase. Likewise, the left elbow also presented a large range of variability, common to all gait events. For the left hip, the lowest variability range was encountered during the latter half of the stance phase, the standard deviation not exceeding 5 units. Similarities amongst the variability values of all five joints can be noted, particularly during early stance. However, the extent to which this feature is present throughout the rest of the gait cycle is low, particularly with respect to the knee joint.

The greatest degree of similarity can be noted between the shoulder and ankle during the first 50% of the stance phase and final 20% of the swing phase. In addition, the shoulder joint presented the lowest range of variability overall, with a maximum value of approximately 12 units noted solely during terminal stance (~40-42%). The left ankle presented the lowest variability values for the greatest proportion of gait events (~0-45%, 70-100%), although the maximum variability was found to be in excess of 15 standard deviations at the start of the swing phase. Conversely, the knee joint presented the highest degree of variability oscillation for the greatest proportion of gait sub-phases (~50-90%), ranging from approximately one standard deviation to approximately 19 standard deviations during early swing. To provide further detail regarding the variability relationships amongst different joints, examples of two participants are provided in Plots 7.1 and 7.2, pgs. 181 and 182, respectively. The results of all 20 participants are found in Appendix I1.

Figure 7.2 – Research Question 2: Summary of Variability in the Left Upper and Lower Body Joints

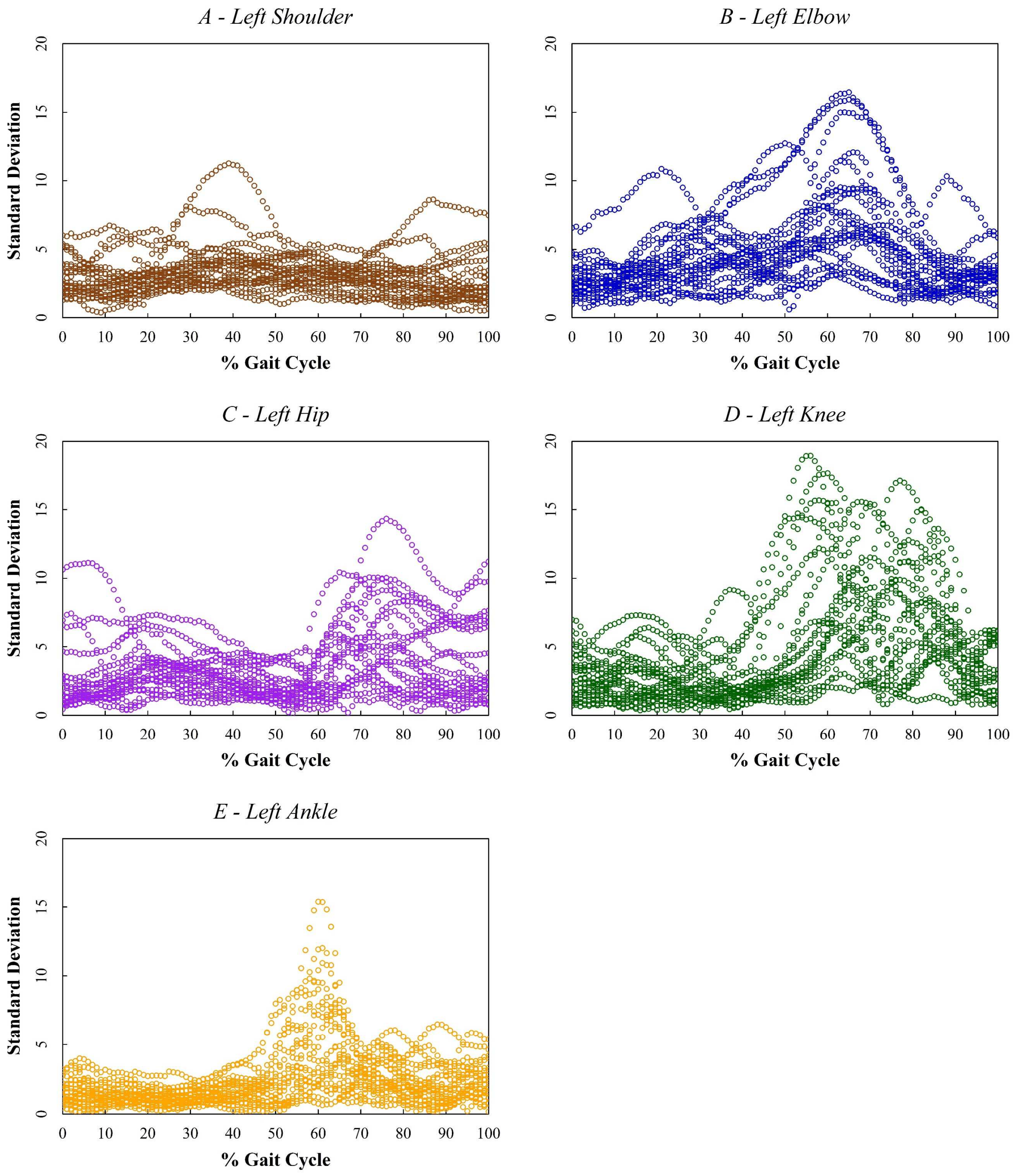
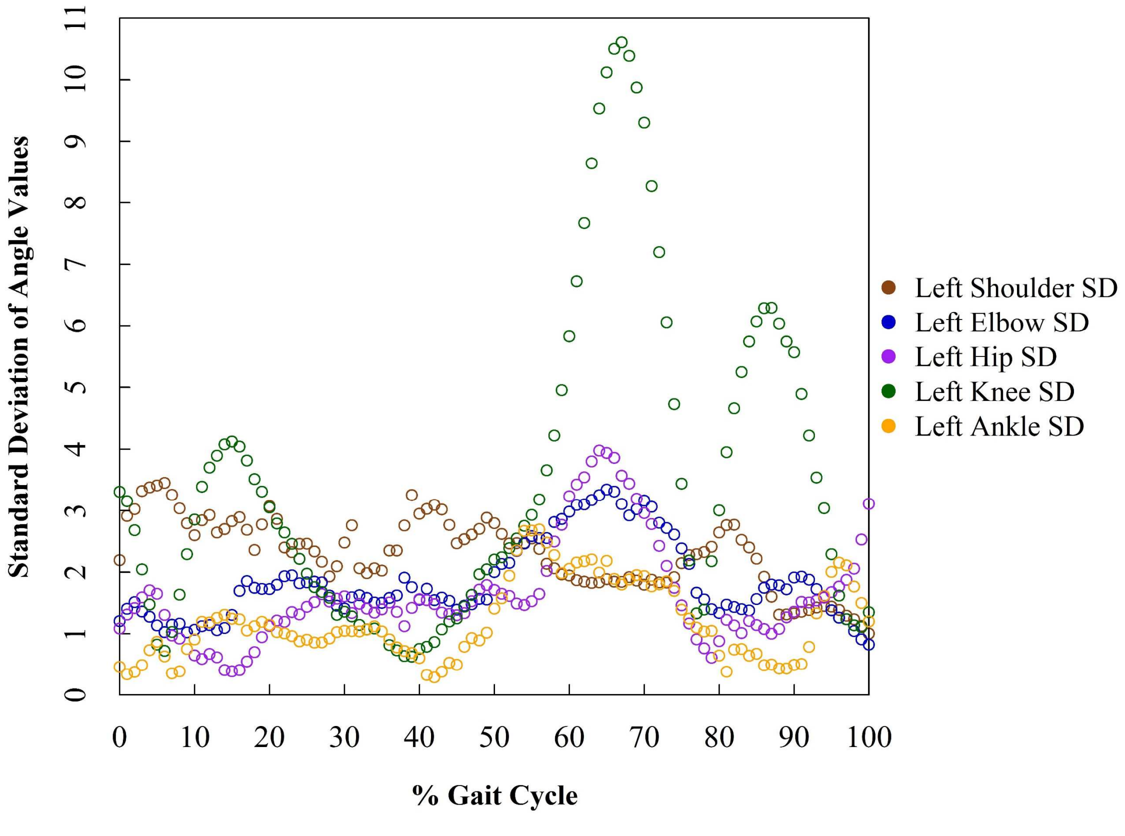


Figure 7.2 illustrates the standard deviation of each one of the 20 participants for each one of the five joints for the left body side.

One of the greatest similarities amongst upper and lower body joints was found in Participant 18 (male, 26 years, 87 kilograms, 1.74 metres). With the exception of the magnitude of the knee variability, P18 presents some of the lowest variabilities in at least four of the five joints. Participant 18 presents small differences in variability between the five joints during the stance phase, oscillating between just over zero variability to a maximum of just over 3 standard deviations, as shown in Plot 7.1. The most congruent variability amongst all joints was therefore noted during mid-stance and during pre-swing. However, the left elbow and hip presented similar variabilities across the largest percentage of gait events, the exception being the final 5% of the gait cycle. Other similarities amongst body regions were noted between shoulder and ankle during initial swing and early mid-swing, between elbow, hip, and ankle during mid-stance, and between hip, ankle and elbow during mid-swing. During the swing phase, the differences in variability across the five joints was more accentuated as a result of the much higher variability in the knee, reaching just over 10 units during initial swing and 6 units during late mid-swing; however, the variability similarities remained for all but the shoulder joint. The left ankle presented the lowest variability throughout most gait events, whilst the shoulder was the most consistent (2-3). For the upper body joints, the greatest degree of similarity was observed during most gait events, as also observed for the hip and ankle.

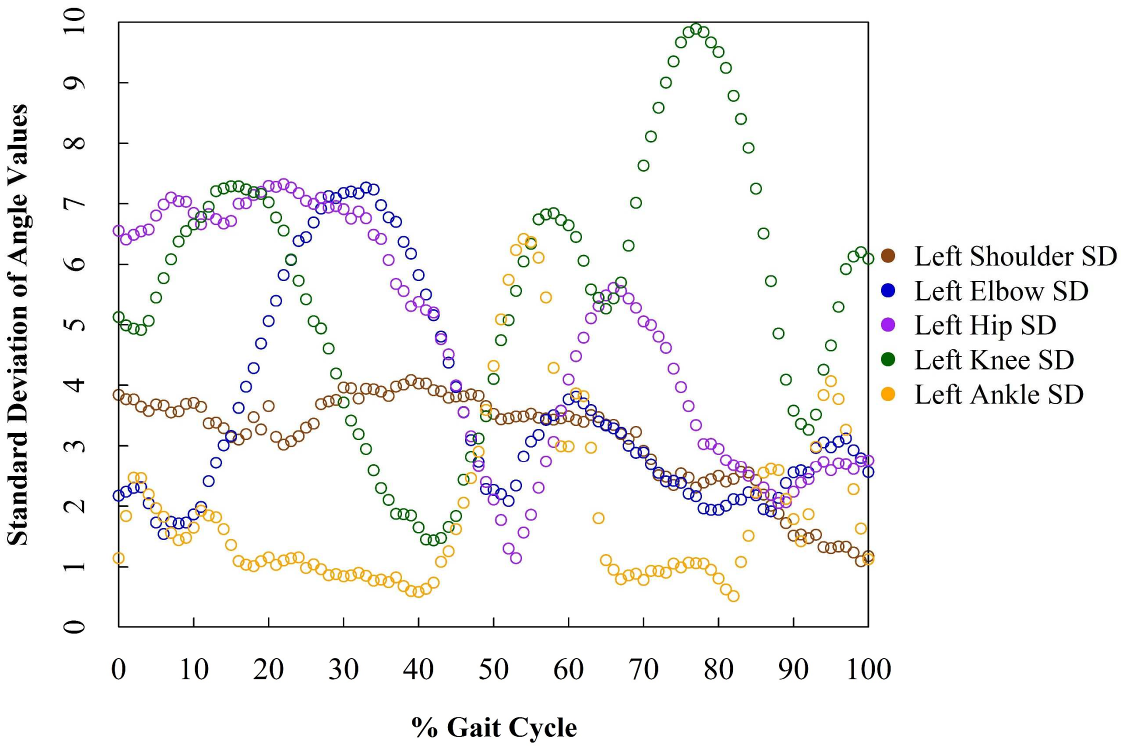
Plot 7.1 – Variability in the Left Upper and Lower Body Joints (**Participant 18**)



Plot 7.1 illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 18 for the left shoulder (brown), elbow (blue), hip (purple), knee (green) and ankle (yellow) joints.

In contrast to the intraindividual variability congruency observed in P8, Participant 12 (male, 24 years, 80 kilograms, 1.88 metres) presents one of the largest oscillations in variability observed across all five joints, as illustrated below in Plot 7.2; this aspect was also noted in P14 (male), P15 (female), and P17 (female), thereby highlighting that discrepancies in variability were found in both males and females. For P12, the most consistent magnitude in variability was observed in the left shoulder, remaining constant at approximately 4 standard deviations, a feature also noted in most of the previous participants. The variability of the left shoulder only resembles that of the elbow during the swing phase. The same feature was also noted in the lower body joints where similarities are few. For example, the variability of the hip and knee are similar solely during loading response, and those of the ankle and knee solely during terminal stance and pre-swing. Nevertheless, the lowest variability was found in the ankle during most of stance (~0-44%), and mid-swing, as observed in most of the previous participants, whilst the highest variability was found in knee during mid-swing (10 standard deviations). For this participant, the following sub-phases presented similar variability across different combinations of upper and lower body joints: during heel strike for the left elbow and ankle (0-10%), during late mid-stance, terminal stance, pre-swing, and final 20% of swing for the left elbow and hip, and during late mid-swing for the left shoulder, elbow, hip, and ankle (80-90%).

Plot 7.2 – Variability in the Left Upper and Lower Body Joints (**Participant 12**)



Plot 7.2 illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 12 for the left shoulder (brown), elbow (blue), hip (purple), knee (green) and ankle (yellow) joints.

In comparison to the left body side, both similarities and differences in overall characteristics emerge for the right body side, as expected from the analyses conducted in Chapter 6, as illustrated in Figure 7.3. illustrates this aspect through a comparative approach of the left shoulder, elbow, hip, knee, and ankle. As opposed to the left body side, only the shoulder joint presented the lowest degree of variability across most gait events on the right body side. The ankle joint presented a higher range of intraindividual variability across all gait events, in comparison to the left body side; the lowest variability range was found during most of the stance phase, where the majority participants were found to be concentrated. In addition, the maximum variability value was substantially higher than previously observed for the contralateral body side, and higher than observed in any of the other four joints, irrespective of body side. For the right shoulder joint, the variability did not exceed 8 standard deviations for most participants (a similar range for the left body side), except for a single participant during the swing phase, therefore remaining the most stable joint with respect to variability amongst a majority of participants bilaterally. The right knee joint was also more variable in a larger number of participants than the left knee joint, particularly during loading response (~10-20%), pre-swing (~50-60%) and throughout most of the swing phase. The right elbow also differs from the left elbow, particularly during the stance phase where the overall variability of 8-10 standard deviations was lower in the right body side (in excess of 12 standard deviations).

With respect to the hip joint, both body sides presented similar overall variability, with the lowest range of 0-5 standard deviations encountered during pre-swing for both body sides (excepting for one participant which presented a variability of just under 20 units. Similarities amongst the variability values of all five joints are nevertheless also present for the right body side, especially at the start of the stance phase. However, as also observed for the left body side, the extent to which this feature is present throughout the remainder of the gait events is low, feature also stemming from the right knee joint. The greatest degree of intraindividual variability similarity for most participants on the right body side was also found between the shoulder and ankle during stance (as observed contralaterally), as well as between the shoulder and elbow during early stance and late swing. Likewise, the right shoulder joint presented the lowest range of variability overall, with a maximum value of approximately 11 units noted solely during swing in only a single participant. Furthermore, as observed in the left body side, the right knee joint was most variability for the greatest proportion of gait sub-phases. To provide further detail regarding the variability relationships amongst different joints, examples of two participants are provided in Plots 7.3 and 7.3, pgs.185 and 186, respectively. The results of all 20 participants are found in Appendix I2.

Figure 7.3 – Research Question 2: Summary of Variability in the Right Upper and Lower Body Joints

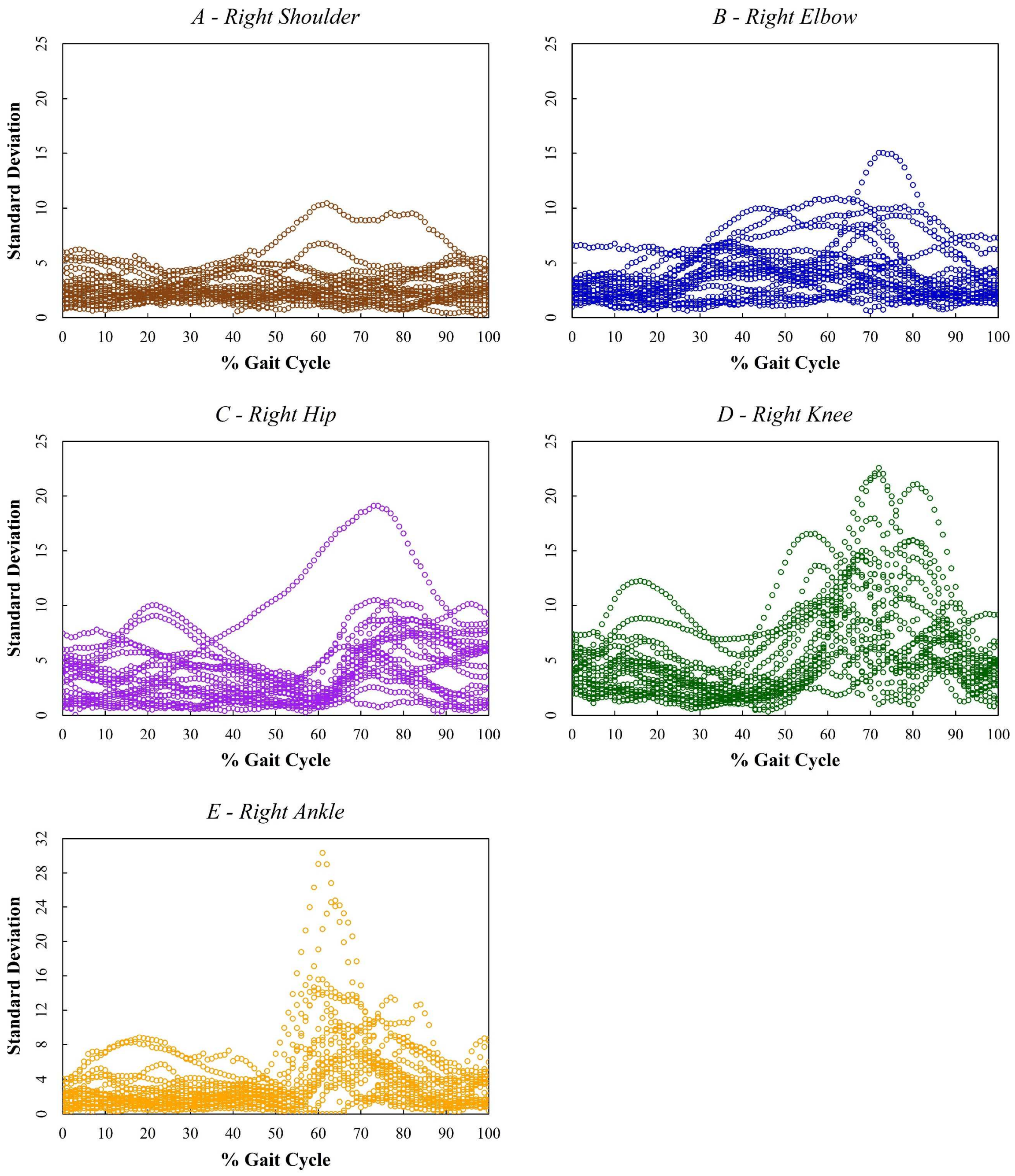
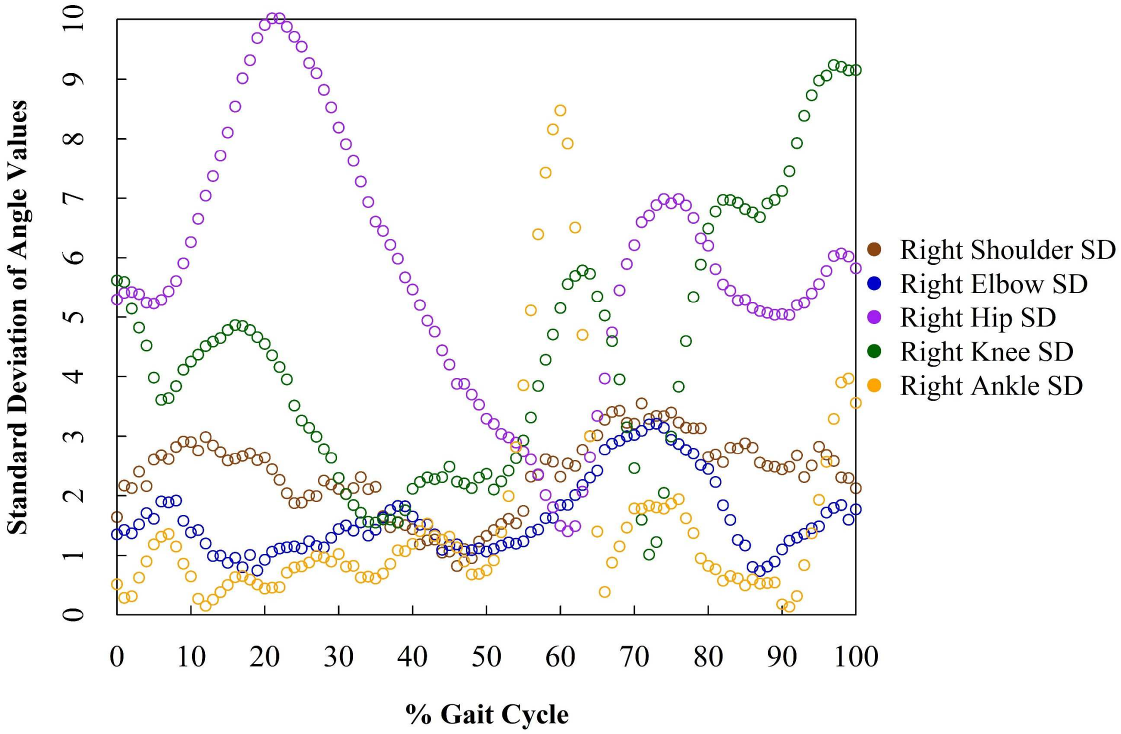


Figure 7.3 illustrates the standard deviation of each one of the 20 participants for each one of the five joints for the right body side.

In contrast to the left body side, P18 presents substantial differences in the five joints of the right body side across all gait events, with the hip presenting the largest variability during stance, followed closely by the knee during late swing and the ankle just before initial swing. This aspect was common amongst all participants to a greater degree than in the left body side. As shown in Plot 7.3, the variability trends are similar throughout a larger proportion of gait events solely for the elbow and ankle (0-52%), and for the shoulder and elbow (0-10%, 30-80%). Similarities amongst all three lower body joints were not found. However, contrast to other participants, the lowest variability for the largest proportion of gait events was found in the ankle, whilst the most consistent variability was found in the shoulder, and in the elbow joint; for the elbow joint, variability consistency was encountered in only one other participant (P19).

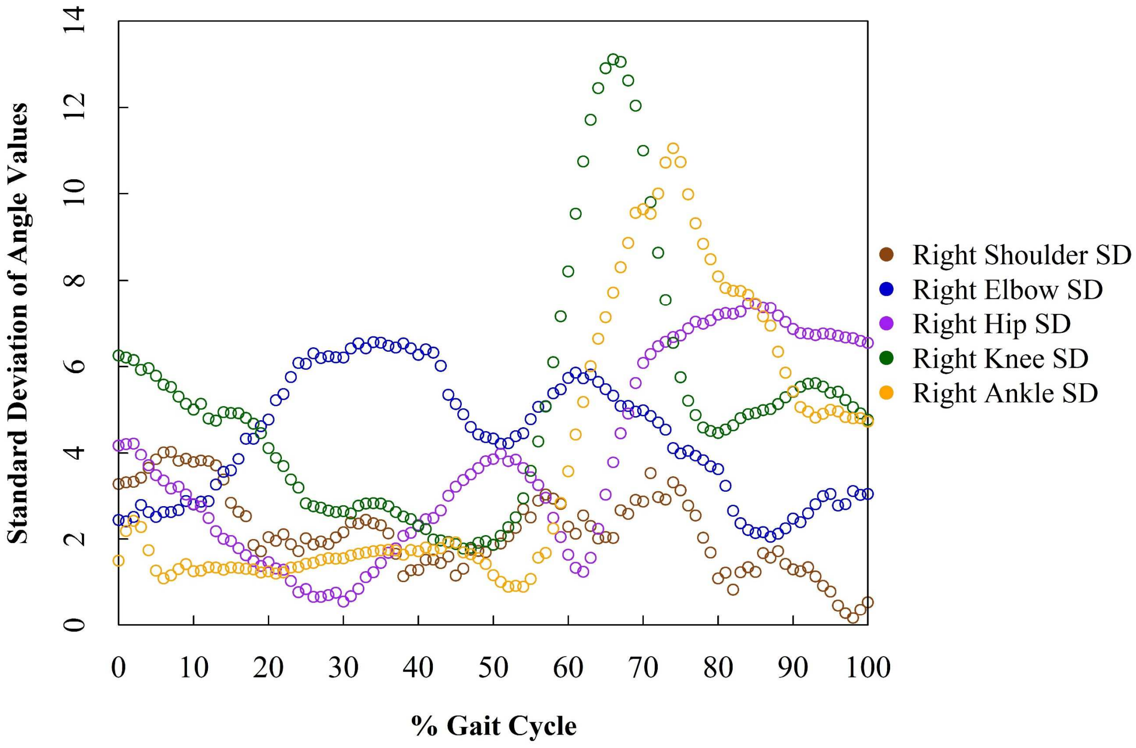
Plot 7.3 – Variability in the Right Upper and Lower Body Joints (**Participant 18**)



Plot 7.3 illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 18 for the right shoulder (brown), elbow (blue), hip (purple), knee (green) and ankle (yellow) joints.

As illustrated below in Plot 7.4, variability differences within body regions generally exceed 2 standard deviations, which lower differences largely found during short gait segments within sub-phases for P12. Similar features were also observed in the left body side, although not to the same extent, whereby some similarities were also noted within body regions. Exceptions include the elbow and shoulder during late mid-swing, hip and ankle during mid-stance, and ankle and knee during terminal swing. Larger gait segments with similar variabilities were rather found between body regions such as between the shoulder and hip during the first 20% of the gait cycle, and the shoulder and knee during the latter half of the stance phase. As with other participants, the largest variability of 13 units was found during initial swing in the right knee. However, the lowest variability fluctuates depending on gait sub-phase, with the lowest observed in the hip during early mid-stance and in the shoulder joint during terminal swing. This contrasts the left body side for which the lowest variability largely found in the ankle joint. The shoulder joint remains the most consistent throughout all gait events, not exceeding 4 standard deviations.

Plot 7.4 – Variability in the Right Upper and Lower Body Joints (**Participant 12**)



Plot 7.4 illustrates the standard deviations (SD) at each 1% of all of the gait cycles of Participant 12 for the right shoulder (brown), elbow (blue), hip (purple), knee (green) and ankle (yellow) joints

7.3 Discussion

As highlighted through Figures 7.2 and 7.3 and exemplified in Plots 7.1-7.4, similarities in intraindividual variability between the upper limb joints (shoulder and elbow) were more commonly encountered amongst participants than similarities amongst the lower body joints (hip, knee, and ankle). Table 7.1 below collates all 20 participants and presents the proportion of participants presenting intraindividual variability similarities throughout each gait sub-phase. The upper limb joints (shoulder and elbow) present the largest percentage of participants for which the intraindividual variability was similar (i.e. one standard deviation or less), as opposed to the lower body joints for which no majority was encountered during any gait event. Therefore, joints from different body regions present different degrees of intraindividual variation, irrespective of body side, yet also depending on gait sub-phase (Research Question 2).

Table 7.1 – Similarities in Intraindividual Variability of Upper and Lower Body Joints

		Percentage of Participants (%)									
Upper Body Joints	***Left Body Side***	60%	60%	55%	30%	20%	25%	15%	25%	55%	60%
	Right Body Side	**65%**	60%	60%	35%	40%	35%	35%	40%	40%	45%
Lower Body Joints	***Left Body Side***	35%	35%	15%	25%	40%	**5%**		15%	10%	15%
	Right Body Side	10%	10%	10%	20%	15%					
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 7.1 summarises the percentage of participants for which upper or lower body joints present similar intraindividual variability (i.e. difference of ≤1 standard deviation). The boxes marked in **red** represent the gait cycle regions where a *majority number of participants* presented with similar intraindividual variability and the boxes marked in **yellow** represent the gait cycle regions where the *lowest number of participants* presented with similar intraindividual variability. The empty boxes represent gait events during which no similarity was noted.

For the upper body joints, the largest percentage of participants for which the shoulder and elbow joint variabilities were found to be similar, was encountered during *heel strike* for the right body side (65% of participants). This feature was not present to the same extent in the contralateral upper body side where a maximum percentage of 60% was found (i.e. one less participant). The only sub-phase for which the proportion was identical bilaterally was *loading response*. For the right body side, *early mid-stance* also presented with similarities across 60% of participants; contralaterally however, the percentage was smaller by one participant (i.e. 55%). For the left body side, *terminal swing* was also found to present a majority of participant with similar variability (60%) but contralaterally, this percentage was lower (only 45%). Overall, the percentage of participants for the right body side is higher for all gait events, amounting to at least 35% of participants. This contrasts the left body side for which percentages were generally between 15-30%. This find may therefore suggest that the right body side of the upper body joints is more passive than the left body side, meaning that some of the participants in this dataset may have begun the arm swinging movement in the left side. Therefore, the right body side served as support for the movement intentionally initialised by the left body side, resulting in a right body side movement which was less consciously controlled than the movement of the left body side. This evaluation may also explain the discrepancy in the total percentage between the two body sides. Interestingly, a greater degree of intraindividual variability similarity was observed at the start and end of the gait cycle for both body sides, possibly indicating that from a physiological and psychological viewpoint, arm swing represents a greater necessity to initialise and desist motion. Hence, the lower percentages throughout the middle regions of the gait cycle may indicate the degree to which each participant individualises their motion according to their personal, physiological needs. These findings therefore suggest that the influence of the intraindividual variability on interindividual variability may be least similar for both joints during the middle of the gait cycle and more similar for both joints during first 30% of stance, irrespective of body side. In addition, given that intraindividual variability was found to be high in the majority of participants and that intraindividual variability was not found to be equally similar bilaterally (as discussed throughout Chapter 6) it is nevertheless possible that interindividual variability may be negatively impacted by this aspect and influenced by body side. To obtain empirical evidence for these claims, further analysis was required (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

The data from the upper body joints contrasts the data found in the three lower body joints (hip, knee, and ankle), as evidenced by the data in Table 7.1. For the latter, no majority percentage was found during any gait event; the largest proportion of participants was 40%, encountered solely during *terminal stance* for the left body side whilst during *initial swing*, none of the 20 participants presented with similarities across all three bilateral joints. Despite the absence of a majority number of participants, overall, the left body side presented a larger number of participants, and a larger number of gait events for which at least one participant was noted with similar intraindividual variability, as opposed to the right body side for which the largest percentage of 20% was found during *late mid-stance*. Whereas the three joints from the left body side presented similar variability in all but one gait phase (*initial swing*), the variability of right body side joints were congruent solely during 50% of the stance phase. Based on these findings, an analogous reasoning may be applied to the lower body joints as discussed earlier for the upper body joints, whereby the lower percentages may be explained by the inconsistency in the dominant leg which was employed by the participants to initialise the movement. With respect to similarity in variability trends between the hip, knee and ankle, discrepancies were expected since, as detailed throughout Chapter 3, different joints perform specific functions to allow for efficient locomotion; also, some degree of asymmetry is to be expected. The findings suggest that although the right body side presents the least congruency amongst lower body joints, the stance phase may represent the gait cycle region with the most similar intraindividual variability in all lower body joints irrespective of body side. This may therefore indicate that the influence of the intraindividual variability on interindividual variability may be similar for all three joints during stance, irrespective of body side. However, since a larger proportion of participants were found to present similar intraindividual variability in the left body side across all three joints (Table 7.1), it is also possible that interindividual variability will be affected by body side. This premise is also substantiated by the findings from Chapter 6 which have shown that there are different degrees of movement symmetry and differing degrees of low intraindividual variability given body side, in the hip (Section 6.4.2), knee (Section 6.5.2), and ankle (Section 6.6.2). To resolve these conflicting premises, further analysis was required (found in Chapter 8 – Interindividual Variation Across Joints (Research Question 3)).

Considering the paucity of data on the impact of the assumption of body symmetry and discriminatory power of different body regions, an investigation into any potential similarities between the upper and lower body joints was also necessary to evaluate whether either of the two upper body joints (or both) present similarities in variability with the lower body joints. Hence, in Table 7.2, pg. 190, the participants were grouped according to different combinations of upper AND lower body joints to evaluate the degree to which the shoulder and/or elbow joints are similar to the hip, knee, or ankle (i.e. difference in intraindividual variability of one standard deviation or less). To emphasise this aspect, the participants which presented similar intraindividual variability in both shoulder and elbow were not included in the single upper body category; therefore, a clear separation of the number of participants which presented similar intraindividual variability only in one of the two upper body joints was achieved. As summarised in Table 7.2, pg. 190 (and detailed in Appendix I), no majority percentage of participants was found during any gait event for any of the nine combinations of joints. The largest percentage of participants (45%) was found during *early mid-stance* of the right shoulder and ankle, whilst only 40% of participants presented similar intraindividual variability amongst joints from different body regions (i.e. left shoulder, left elbow, and one of the lower body joints (i.e. the left hip) during *loading response*)). Despite the absence of a majority, these finds may indicate that during the aforementioned gait sub-phases, the influence of intraindividual variability on interindividual variability may be similar between shoulder and ankle, and amongst the shoulder, elbow, and hip; since these percentages were found only unilaterally, it is likely that interindividual variability will be affected by body side (this aspect is further investigated in Chapter 8). In addition, no participants presented similarity between the upper body joints and any of the three lower body joints during *initial swing*, whilst the percentages were generally low amongst all nine joint combinations.

Table 7.2 – Similarities in Intraindividual Variability Between Upper and Lower Body Joints

		Percentage of Participants (%)									
Shoulder and Hip	**Left**	20%	25%	30%	30%	35%	35%	15%	25%	10%	15%
	Right	25%	20%	20%	25%	25%	25%	**5%**	15%	10%	15%
Shoulder and Knee	**Left**	20%	25%	30%	30%	35%	20%	15%	10%	10%	**5%**
	Right	**5%**	**5%**	**5%**	30%	15%	10%				15%
Shoulder and Ankle	**Left**	15%	30%	10%	**5%**	25%	15%	25%	15%	35%	20%
	Right	25%	25%	**45%**	35%	25%	10%	**5%**	**5%**	15%	10%
Elbow and Hip	**Left**	10%	10%	25%	20%	30%	15%	**5%**	10%	15%	30%
	Right	25%	10%	25%	15%	15%	15%		10%	15%	25%
Elbow and Knee	**Left**	25%	10%	20%	10%	20%	10%	**5%**	10%	20%	30%
	Right	15%	20%	15%	20%	10%	10%		**5%**		10%
Elbow and Ankle	**Left**	20%	10%	10%	15%	20%	15%		20%	10%	40%
	Right	25%	30%	15%	20%	10%	**5%**		15%	25%	25%
Shoulder, Elbow and Hip	**Left**	25%	40%	20%	15%				**5%**	15%	10%
	Right	10%	20%	10%	10%	15%	10%		**5%**		**5%**
Shoulder, Elbow and Knee	**Left**	10%	25%	**5%**			**5%**				15%
	Right	10%	15%	15%	20%	10%					
Shoulder, Elbow and Ankle	**Left**	20%	25%	20%	15%		**5%**		**5%**	10%	20%
	Right	10%	25%	20%	**5%**	15%	**5%**			**5%**	**5%**
		Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
		Stance Phase (0-60%)						***Swing Phase (60-100%)***			

Table 7.2 summarises the percentage of participants which present with similarity in intraindividual variability amongst upper and lower body joints (i.e. difference of ≤1 standard deviation). The boxes marked in **red** represent the gait cycle regions where the *largest percentage of participants* presented with similar intraindividual variability in a given category. The boxes marked in **yellow** represent the gait cycle regions where the *lowest percentage of participants* presented with similar intraindividual variability. The empty boxes represent gait events during which no similarity was noted.

As previously mentioned in this section, these finds may also suggest a somewhat universal regulatory feature of the musculoskeletal system to initialise and finalise movement, whilst during the middle of the gait cycle where the general trend was 5%, the degree of movement is adapted to individualistic needs. These data therefore indicate that the effect of intraindividual variability of the upper and lower body joints will not be similar on interindividual variability during the middle region of the gait cycle. Of note is that bilateral similarity across joints from different body regions was infrequent across gait phases; the largest proportion of gait events for which at least two joints from different body regions were noted with similar bilateral variability was found in the elbow and hip category during *loading response, early mid-stance*, *pre-swing, early mid-swing* and *late mid-swing* (Table 7.2). This find further emphasises the premise that the discriminatory power of the upper and lower body regions is distinct, thereby requiring separate evaluation with respect to interindividual variability.

The analysis and evaluation angular data from movements in the sagittal plane of the left and right shoulder, elbow, hip, knee, and ankle joints have therefore yielded the following main findings:

- upper body intraindividual variability was similar throughout all gait events in at least three participants (15%), albeit in different participants to different extents, and depending on body side and gait sub-phase:
    - *highest* participant percentage (65%) was found during right body side *heel strike*;
    - *lowest* participant percentage (15%) was found during left body side *initial swing*;
    - a higher number of minimum participants for which intraindividual variability was similar, was found for the right body side (35%), than the left body side (15%);
    - a majority percentage of participants (60-65%) for which intraindividual variability was similar, was found during early *stance* bilaterally, and left *terminal swing*;
- lower body intraindividual variability was not similar bilaterally during any gait event depending on body side and did not present a majority percentage:
    - the left body side did not present similar intraindividual variability during *initial swing*;
    - the right body side did not present similar intraindividual variability during *pre-swing* and throughout the entire *swing phase*;
    - *highest* participant percentage (40%) was found during left body side *terminal stance*;
    - *lowest* participant percentage (5%) was found during left body side *pre-swing;*
- upper and lower body joints intraindividual variability was dissimilar in most participants:
    - largest participant percentage (45%) was found during *early mid-stance* for the left shoulder, and ankle;
    - no similarity amongst participants for all five upper and lower body joints were noted during *initial swing*;

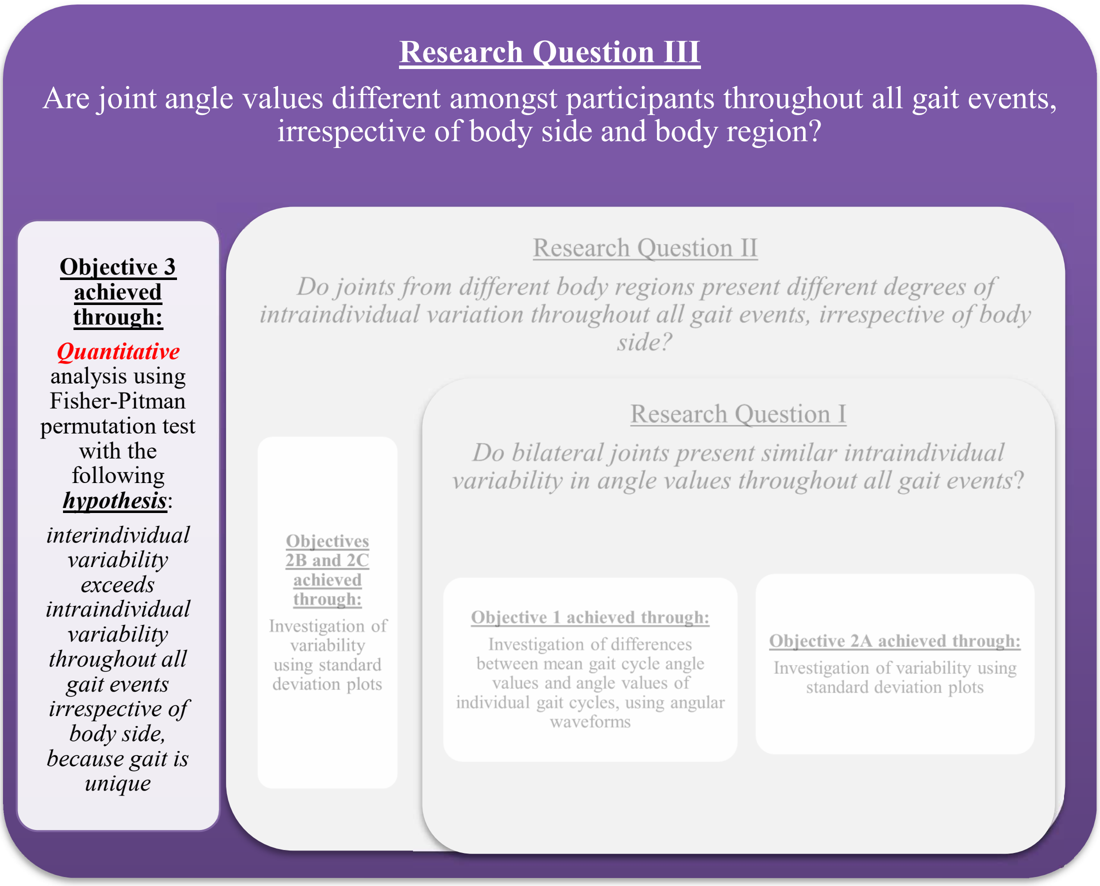
- based upon the conducted analyses, joints from different body regions present different degrees of intraindividual variation that are dependent on body side and gait event (Research Question 2), thus providing further evidence for the findings from Chapter 6 (Research Question 1) which highlighted the importance of body side during analysis, as is the utilisation of mean values to represent the gait of individuals in the absence of body side differentiation.

Chapter 8 – Interindividual Variation Across Joints (Research Question 3)

8.1 Overview

Chapter 8 describes and critically evaluates the findings of Research Question 3, as depicted in Figure 8.1. To quantitatively evaluate this research question, the following hypothesis was developed: *interindividual variability exceeds intraindividual variability throughout all gait events, irrespective of body side, because gait is unique*. Section 8.2 presents the interindividual variability results for the upper body joints (8.2.1) and for the lower body joints (8.2.2) in the form of complete gait cycle plots of the (A) left, (B) right, (C) left and right, and (D) left versus right body sides. Each plot depicts the regions of the gait cycles where statistically significant and non-significant p-values were obtained using the Fisher-Pitman permutation tests applied as described in Chapter 5, Section 5.4.3. For the analyses presented in Plots A-C, *statistically significant* results indicate differences amongst participants, whereby differences amongst joints angle values of the 20 participants (interindividual variability) are exceeded by differences within joint angle values of the same participant (intraindividual variability). However, since the hypothesis assumes that this interindividual variability is *not* dependent on body side, additional analysis of the role of body side was required (Plot D). Therefore, *statistically significant* results obtained from Plot D analyses lead to hypothesis *rejection* because these indicate interindividual variability is dependent on body side. Section 8.3 evaluates these findings in light of the results discussed in Chapters 6 and 7.

Figure 8.1 – Thesis Investigation Approach (Research Question 3)

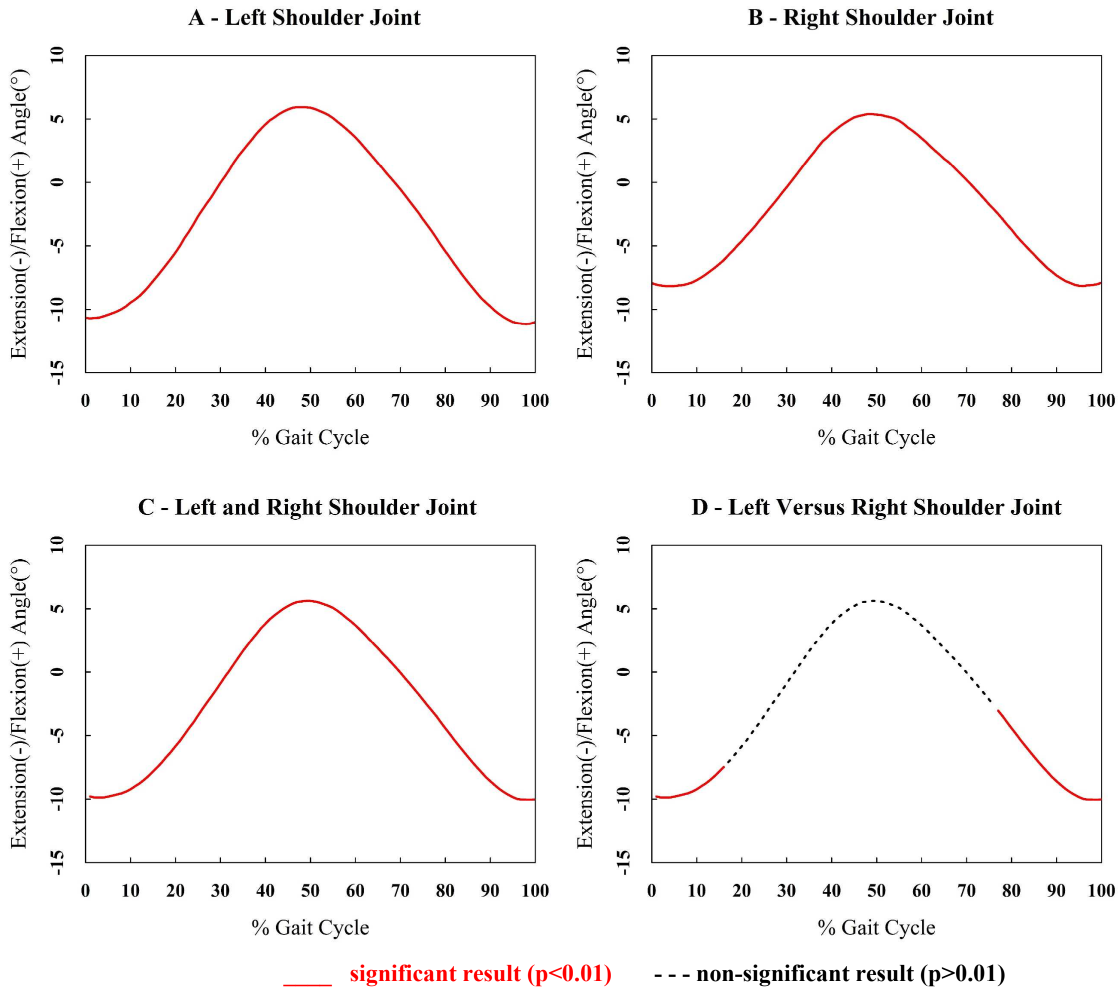


8.2 Results

8.2.1 Upper Body Joints: Shoulder and Elbow

The Fisher-Pitman permutation tests on the data of the shoulder yielded *statistically significant* results ($p<0.01$) in all gait cycle regions for three out of the four conditions (left shoulder, right shoulder, and combined left and right shoulder joints). As illustrated below in Plot 8.1A and 8.1B, interindividual variation exceeds the observed intraindividual variation in Chapters 6 and 7, for each body side separately. Similarly, if the data are tested irrespective of body side (Plot 8.1C), interindividual variability remains *statistically significant* for all gait events. In contrast, the results for the tests that discriminate between the left and right body sides of the shoulder (Plot 8.1D), are *statistically significant* throughout early stance and late swing (~0-16%, 77-100%). Since at least one gait sub-phase presents statistically significant results, the hypothesis of interindividual variability exceeding intraindividual variability throughout all gait events irrespective of body side, is therefore *rejected* for the shoulder joint. The full set of p-value results per gait cycle percentage is found in Appendix J1, Table J1.

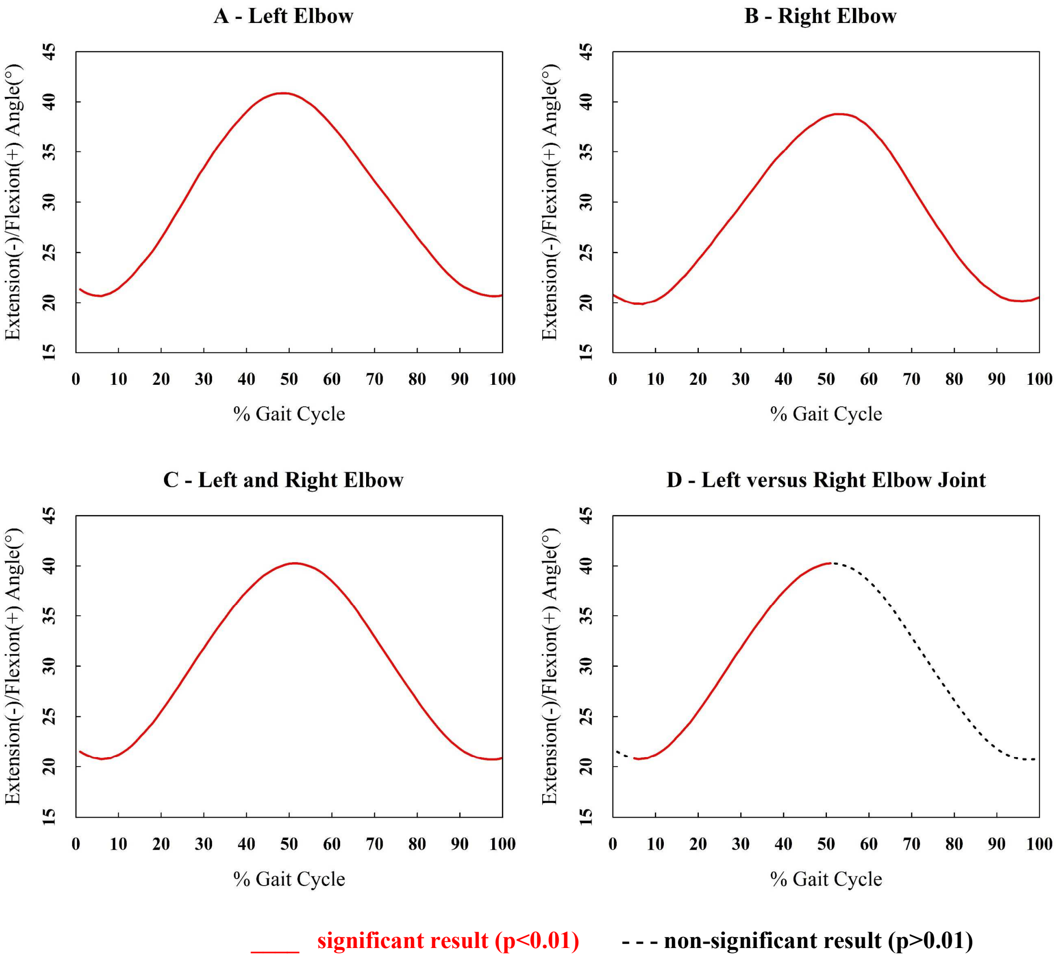
Plot 8.1 – Regions of the Shoulder Gait Cycles Exhibiting Interindividual Differences



Plot 8.1 depicts the regions of the gait cycle of the shoulder joint where interindividual differences were found to be statistically significant ($p<0.01$).

For the elbow joint, the Fisher-Pitman permutation tests also yielded *statistically significant* results ($p<0.01$) in all gait cycle regions for the same three conditions (left elbow, right elbow, and combined left and right elbow joints). As depicted in Plot 8.2A and 8.2B, interindividual variation exceeds the observed intraindividual variation obtained from the previous two research questions for each body side separately. Likewise, if the data are tested irrespective of body side (Plot 8.2C), the interindividual variability is also *statistically significant* throughout all gait events. As with the shoulder joint, the results for the tests that discriminate between the left and right body sides (Plot 8.2D), are *statistically significant* for approximately half of the gait sub-phases (~4-51%). As a result, the hypothesis of interindividual variability exceeding intraindividual variability throughout all gait events irrespective of body side, is *rejected* for the elbow joint. In addition, the *statistically significant* gait cycle regions are not identical to those of the shoulder joint. Whereas *heel strike*, part of *loading response* and the final 13% of the swing phase were *statistically significant* for the shoulder joint, part of *heel strike* and the full *swing phase* were *statistically insignificant* for the elbow. 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%). The full set of p-value results per gait cycle percentage for the elbow is found in Appendix J2, Table J2.

Plot 8.2 – Regions of the Elbow Gait Cycles Exhibiting Interindividual Differences

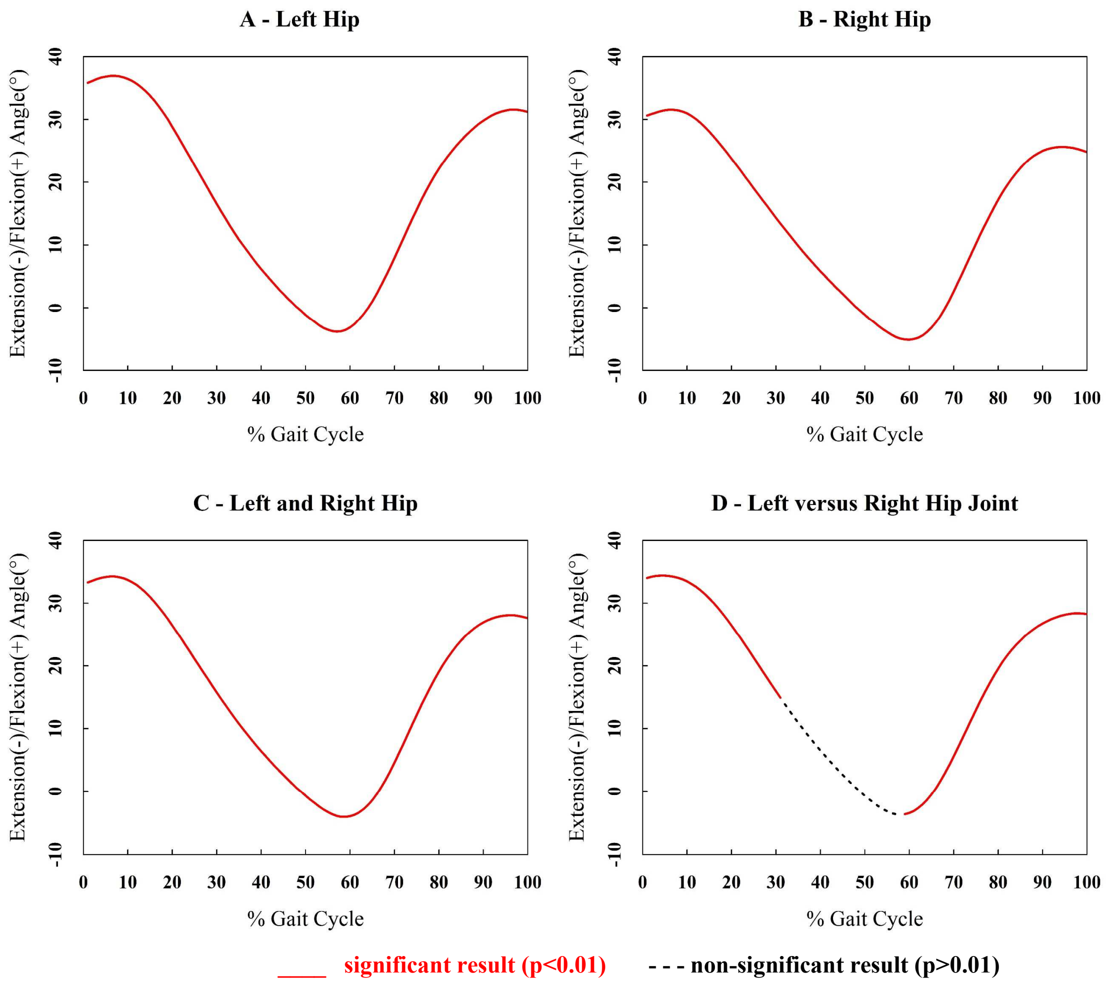


Plot 8.2 illustrates regions of the gait cycle of the elbow joint where interindividual differences were found to be statistically significant ($p<0.01$).

8.2.2 Lower Body Joints: Hip, Knee, and Ankle

In the hip joint, the Fisher-Pitman permutation tests likewise yielded statistically significant results ($p<0.01$) in all gait cycle regions for the same three conditions as observed in the upper body joints (left hip, right hip, and combined left and right hip joints). Interindividual variation exceeds the observed intraindividual variation obtained from the previous two research questions for each body side separately (Plot 8.3A,B). Furthermore, if the data from both body sides are not accounted for in the analysis (Plot 8.3C), the interindividual variability is also statistically significant throughout all gait events. In contrast to the upper body joints however, the results for the tests that discriminate between the left and right body sides (Plot 8.3D), are *statistically significant* for the majority of gait sub-phases (0-31%, 59-100%) in the hip joint. Hence, the hypothesis of interindividual variability exceeding intraindividual variability throughout all gait events irrespective of body side, is strongly *rejected* for the hip joint. 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%). The full set of p-value results per gait cycle percentage for the hip joint is found in Appendix J3, Table J3.

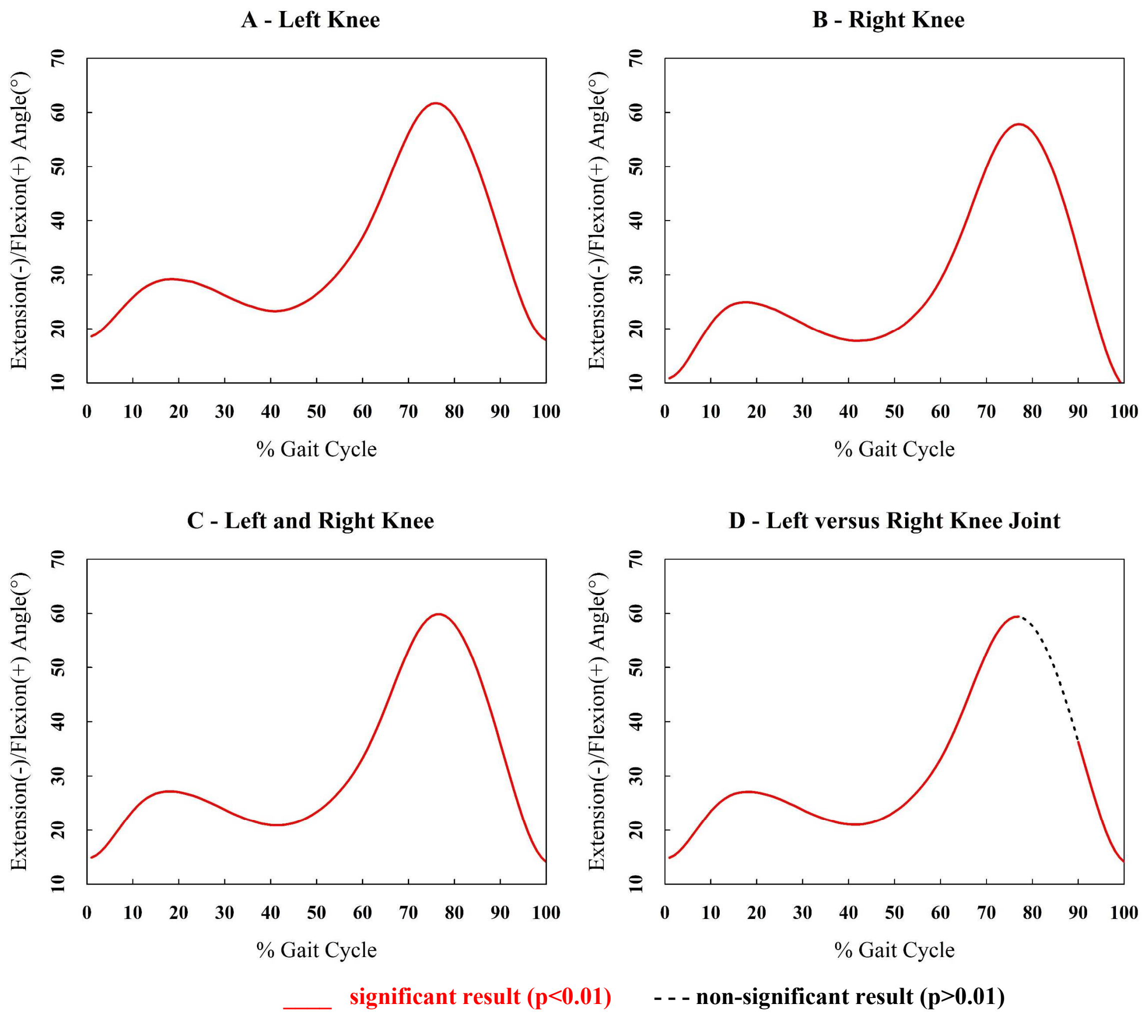
Plot 8.3 – Regions of the Hip Gait Cycles Exhibiting Interindividual Differences



Plot 8.3 illustrates regions of the gait cycle of the hip joint where interindividual differences were found to be statistically significant ($p<0.01$).

For the knee joint, the Fisher-Pitman permutation tests yielded statistically significant results ($p<0.01$) in all gait cycle regions for the same three conditions as observed in the upper body joints and in the hip. Interindividual variation also exceeds the observed intraindividual variation obtained from the previous two research questions for each body side separately (Plot 8.4A,B). Also, if the data from both body sides is undiscriminated (Plot 8.4C), the interindividual variability is also *statistically significant* throughout all gait events. 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%, Plot 8.4D). Hence, the hypothesis of interindividual variability exceeding intraindividual variability throughout all gait events irrespective of body side, is strongly *rejected* for the knee joint. 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%). The full set of p-value results per gait cycle percentage is found in Appendix J4, Table J4.

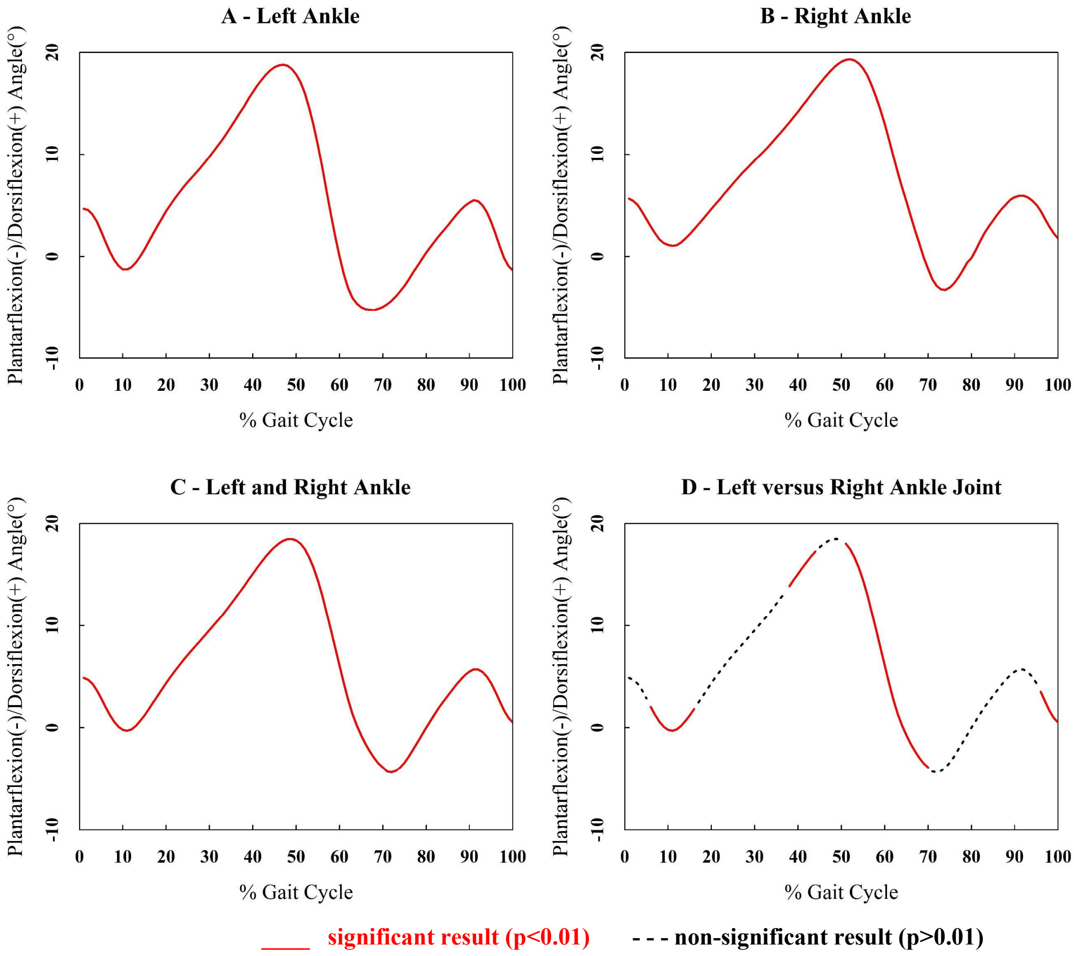
Plot 8.4 – Regions of the Knee Gait Cycles Exhibiting Interindividual Differences



Plot 8.4 illustrates regions of the gait cycle of the knee joint where interindividual differences were found to be statistically significant ($p<0.01$).

Lastly, the Fisher-Pitman permutation tests for the ankle joint yielded statistically significant results (p<0.01) in all gait cycle regions for the same three conditions as observed in the upper body joints, hip, and knee. Interindividual variation also exceeds the observed intraindividual variation obtained from the previous two research questions for each body side separately (Plot 8.5A,B). Also, if the data from both body sides is combined (Plot 8.5C), the interindividual variability is also *statistically significant* throughout all gait events. However, when analysing the results given body side, the ankle joint presents the smallest proportion of the gait cycle with *statistically significant* results (~6-16%, 38-45%, 51-70%, 96-100%, Plot 8.5D) in comparison to all of the previous joints. Nevertheless, since at least one gait sub-phase presents with statistically significant results, the hypothesis of interindividual variability exceeding intraindividual variability throughout all gait events irrespective of body side, is therefore *rejected* for the ankle joint. Overall, the ankle joint presents 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%). The full set of results of p-value results per gait cycle percentage is found in Appendix J5, Table J5.

Plot 8.5 – Regions of the Ankle Gait Cycles Exhibiting Interindividual Differences

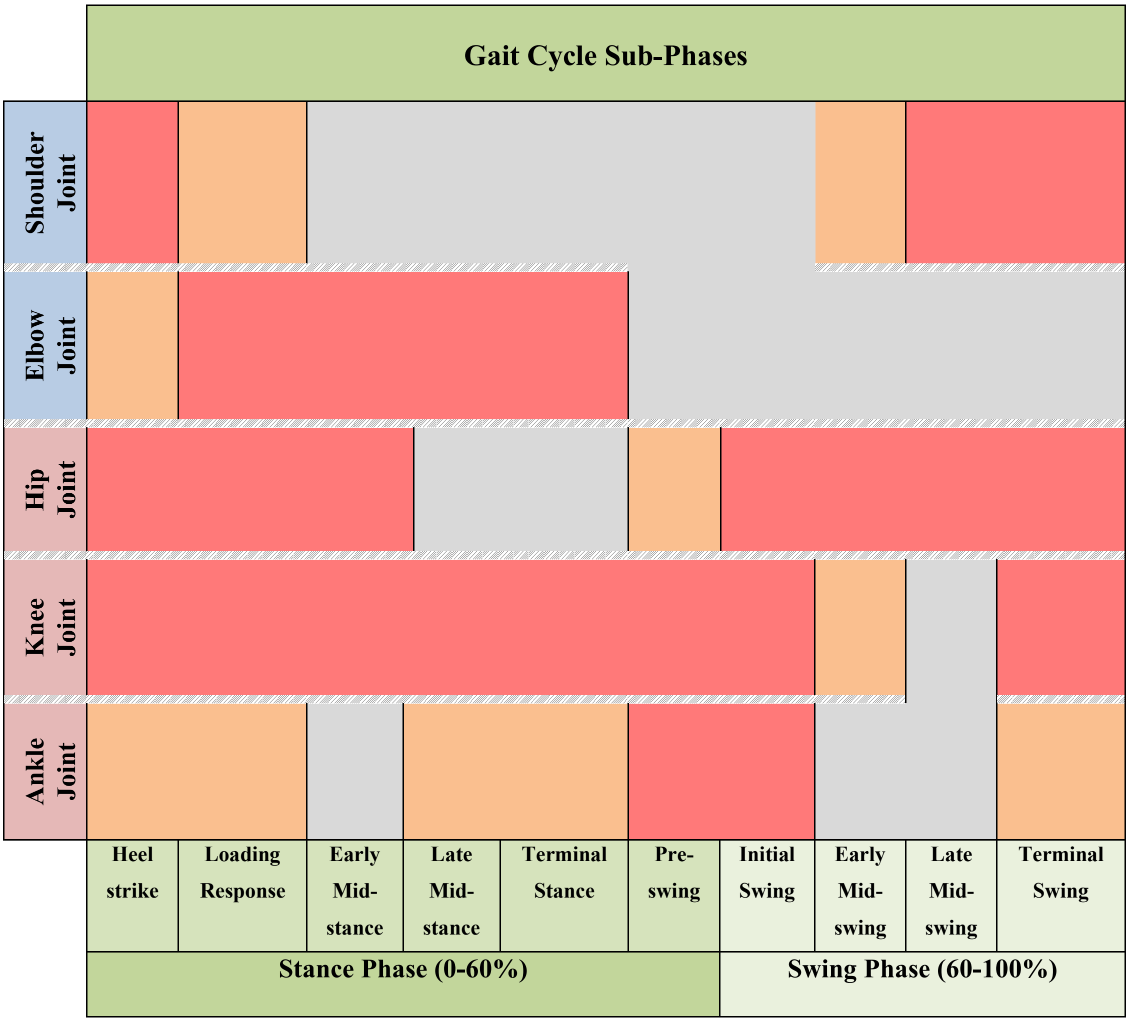


Plot 8.5 illustrates regions of the gait cycle of the ankle joint where interindividual differences were found to be statistically significant (p<0.01).

8.3 Discussion

As summarised in Table 8.1 below, and described throughout Sections 8.2.1 and 8.2.2, the statistically significant gait cycle regions for interindividual variability in the upper and lower body joints differ, when considering body side as a potential influence. The differences not only lie in which gait sub-phases body side plays a role, but also in whether body side plays a role throughout the entire sub-phases; this aspect is highlighted by evidencing fully statistically significant regions in red, and partially statistically significant regions in orange in Table 8.1 below. Based on the collected data, joint angle values are different amongst participants throughout all gait events irrespective of body region, yet body side plays a distinctive role throughout different gait sub-phases depending on the joint in question (Research Question 3). As a result, the hypothesis of interindividual variability exceeding intraindividual variability throughout all gait events, irrespective of body side, is rejected.

Table 8.1 – Statistically Significant Gait Cycle Regions in Upper and Lower Joints Given Body Side



	Gait Cycle Sub-Phases									
Shoulder Joint	🟥	🟧	⬜	⬜	⬜	⬜	⬜	🟧	🟥	🟥
Elbow Joint	🟧	🟥	🟥	🟥	🟥	⬜	⬜	⬜	⬜	⬜
Hip Joint	🟥	🟥	🟥	⬜	⬜	🟧	🟥	🟥	🟥	🟥
Knee Joint	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	⬜	🟥
Ankle Joint	🟧	🟧	⬜	🟧	🟧	🟥	🟥	⬜	⬜	🟧
	Heel strike	**Loading Response**	**Early Mid-stance**	**Late Mid-stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Early Mid-swing**	**Late Mid-swing**	**Terminal Swing**
	Stance Phase (0-60%)						**Swing Phase (60-100%)**			

Table 8.1 summarises the results from Plots 8.1D-8.5D, displaying the gait cycle sub-phases with statistically significant results in all five joints given body side. The **red** boxes indicate that the significance is found during the entire gait sub-phase whilst the **orange** boxes indicate significance during part of the gait sub-phase. The boxes in grey indicate statistically insignificant results.

As illustrated in Table 8.1, the shoulder joint presents one of the lowest gait cycle proportion for which interindividual variability is *statistically significant*. These results suggest that shoulder-based individualisation is less affected by body side than other joints. As discussed in Chapter 6, Section 6.2.2, and illustrated in Table 6.1, pg.115, *initial swing* presented the largest number of participants (n=8) with similar bilateral and combined variability and only three additional participants with similar bilateral variability, thus suggesting that the *statistical insignificance* of this sub-phase with respect to body side, stems from a 'true' lack of difference in the means between the two body sides rather than potentially due to an effect created by the generally high intraindividual variability observed in the shoulder joint (as shown in Section 6.2.2, Table 6.2, pg. 117). Conversely, *heel strike,* part of *loading response,* and *terminal swing*, which are gait phases with the lowest number of participants (n=2-4) with similar bilateral and combined variability, presented *statistically significant* results. Of note is that these sub-phases also presented with at least six participants with similar bilateral (but not combined) variability. Since a combined variability that is higher than the intraindividual variabilities of the left and right body sides highlights differences in the grouping of cycles at higher or lower mean values (as stated throughout Chapter 5, Section 5.4, and throughout Chapter 6), the *statistically significant* results originate from a 'true' difference in means, rather than from differences in variability. However, *late mid-swing* which presented a larger number of participants with similar bilateral and combined variability (n=7) also presented *statistically significant* results. Given that five additional participants also presented similar bilateral intraindividual variability, the statistically significant results most likely originate from genuine differences in the mean.

Of importance is that these results have an opposite effect on the evaluation of the discriminatory power of the shoulder joint, whereby a statistically significant result when discriminating against body (i.e. body side is important) indicates movement asymmetry. However, when considering whether intraindividuality affects interindividuality in unilateral or combined bilateral joint data, the results indicate that interindividuality is *not* affected by the substantial intraindividual variability observed throughout Chapters 6 and 7. Separately and combined, all gait regions in the bilateral shoulder are statistically significant according to the rationale outlined throughout this section (Plot 8.1A-C, pg.194). However, when considering whether body symmetry may have a role in influencing interindividual variability, the shoulder joint presents a small proportion of the gait cycle for which this statement holds true (Plot 8.1D, pg.194); therefore, early stance and most of the swing phase of the shoulder joint are the least recommended gait regions for identification because interindividual variability is affected by body side. This find may stem from the regulation of starting and ending a walking motion which is more restrictive from a physiological standpoint for each individual given their personal characteristics (such as dominant arm/leg (e.g. Schwartz *et al* 2014). Conversely, movement during the middle of the gait cycle is more flexible, serving to balance the body, thus requiring a more equal, bilateral contribution of the arms, hence statistically insignificant results with respect to body side.

As also observed in the shoulder, the elbow joint does not present *statistically significant* results for the majority of gait sub-phases. In addition, these were found solely during the stance phase, with partially significant results during *heel strike*, as shown in Table 8.1, pg.199. As discussed in Chapter 6, Section 6.3.2, and illustrated in Table 6.4, pg.133, the elbow joint also presented intraindividual variability greater than one unit in all but two participants and solely during *loading response*. Despite the high variability, interindividual variation was present throughout all gait events for separate and combined (but undiscriminated) bilateral data (Plot 8.2A-C, pg.195). However, when introducing body side into the analyses, bilateral differences do emerge for the elbow joint to a greater extent than in the shoulder joint; also, gait cycle regions with statistically significant results differ. As discussed in Chapter 7, Section 7.3, such differences of the impact of intraindividual variability on interindividual variability were expected, given that the shoulder and elbow joint intraindividual variabilities were least similar during the middle of the cycle, and most similar during the first 30% of stance, irrespective of body side; these aspects are therefore confirmed by the results presented in Table 8.1. As shown in Chapter 6, Section 6.3.2, Table 6.3, pg.131, *early mid-stance* presented the largest number of participants for which bilateral and combined variabilities were similar in the elbow joint (n=9), corresponding to one of the gait sub-phases for which *statistically significant* results were found during stance (Plot 8.2D, pg.195). Given that five additional participants also presented similar bilateral variability, the *statistically significant* results likely stem from a genuine difference in the means. In contrast, gait sub-phases with the smallest number of participants with similar bilateral and combined variability (e.g. initial swing, n=2, (Table 6.3, pg.131)) yielded *statistically insignificant* results (Plot 8.2D, pg.195). This find indicates that the *statistically insignificant* results may originate from a true absence of a difference in means since at least five additional participants also displayed similar bilateral variability. Conversely, sub-phases throughout the *swing phase* which presented a larger number of participants with similar combined and bilateral variability also yielded *statistically insignificant* results, thereby further highlighting that there is a genuine lack of differences between the means for the statistically insignificant regions in the elbow. Considering these findings, the elbow joint may be most suitable for identification during the swing phase rather than during stance, throughout which body side may influence interindividual variation.

For the hip joint, the results are largely *statistically significant*, indicating that throughout most gait events, body side does affect interindividual variation. This find contrasts those observed in the shoulder and elbow joints yet, since few similarities were noted amongst the upper body joints and the hip throughout Chapter 7, such differences were expected. Although the elbow and hip did present bilateral similarities during both stance and swing (Section 7.3, Table 7.2, pg. 190), the percentage of participants with this feature did not constitute a majority; also, the greatest degrees of similarity amongst body regions were found unilaterally rather than bilaterally (e.g. left shoulder, elbow, and hip in 40% of participants). As a result, the findings obtained from the current chapter as well as Chapter 7, emphasise the differences between body regions. As shown in Table 8.1, pg.

199, the sole regions for which body side did not present statistically significant results in the hip joint were part of *pre-swing,* and *late mid-stance* and *terminal stance*, also found in the shoulder joint. Of note is that the number of participants with similar combined and bilateral in the hip joint was found to be low during these gait segments, amounting to n=5 during *late mid-stance* and to n=3 during *terminal stance* (Table 6.5, pg.145); since combined variability is an indication of differences in the location of ranges of values, the *statistically insignificant* result for these sub-phases suggest a true absence of differences in the mean between the two body sides. In addition, the hip joint presents a much larger number of participants (n=11) and proportion of gait regions (60%) for which intraindividual variability was found to be low (Table 6.6, Section 6.4.2, pg.146), in contrast to the shoulder and elbow. Nevertheless, this low variability did not appear to have a greater impact on the interindividual variability unilaterally or in the combined left and right data since, despite the much larger variability in the shoulder and elbow, these also presented *statistically significant* differences throughout all gait events as also observed in the hip joint (Plot 8.3A-C, pg.196). This finding suggest that, despite the degree of intraindividual variability, interindividual variability remains higher. However, when considering differences between body sides, the intraindividual variability of the left hip joint was generally lower for a larger number of participants than the right hip joint, thereby further emphasising the lack of symmetry in hip joint movement. These data, combined with the *statistically significant* data from the separate and combined body sides in the previous sub-section of this chapter (Plot 8.3A-C, pg.196), and the data from Chapter 6, support the indication of body side influence on interindividual variability noted in Table 8.1, pg. 199. Hence, identification from the hip joint should largely be conducted taking into consideration body side.

In comparison to the upper body joints and the hip, the knee joint presents the largest proportion of gait sub-phases for which the results are *statistically significant* (Table 8.1, pg. 199), suggesting that body side is predominantly important to consider for individualisation. Discrepancies amongst the knee, and shoulder and elbow were expected, since, as detailed throughout Chapter 7, Section 7.3, bilateral similarities were only encountered amongst these joints during *heel strike,* but only for 10% of participants (Table 7.2, pg. 190); similarities were also found between the shoulder and knee during *late mid-stance* and elbow and knee during *pre-swing*, however, for less than 35% of participants. Moreover, similarities encountered unilaterally to different extents such as between the left elbow and knee during late swing phase (10-30% of participants), the right elbow and knee during early stance (20% of participants), and shoulder and knee during late stance (30-35% of participants). As a result, the findings obtained from the current chapter as well as Chapter 7, further underline the general differences between body regions. For instance, in contrast to the hip joint, the sole sub-phases with *statistically insignificant* results were part of *early mid-swing* and the entire *late mid-swing*, also encountered in the elbow joint. In addition, as summarised in Section 6.5.2, Table 6.7, pg.160, only two participants present with similar bilateral and/or combined variability in the knee joint during *late mid-swing*, an interesting find since Table 6.7 would suggest a clear difference in body side; this is further emphasised by the presence of a single participant with low variability in Table 6.8, pg.162 in the same section. However, since the results are *statistically insignificant* during this gait sub-phase, this may indicate that despite the differences in bilateral variability in the majority of participants, no difference in means of the left and right knee was found using the permutations tests. In contrast, the differences during the *stance phase* were more evident, particularly from Section 6.5.2, Table 6.8, pg.162, which emphasises the larger number of participants with low variability in the left knee, as well as from Section 6.5.2, Table 6.7, pg.160, which shows that less than 7 participants present similar bilateral and/or combined variability during most gait events. Nevertheless, the data obtained from the analysis of intraindividual variation unilaterally and in combined left and right data (Plot 8.4A-C, pg.197) highlight that, despite differences in intraindividual variability between body sides, statistically significant results were obtained in all three conditions (left, right, left AND right). These data therefore suggest that the *statistically significant* regions are largely due to genuine differences between the means, and that the knee joint may be suitable for identification only given body side since intraindividual variability influences interindividuality assessment.

Finally, the ankle joint presents a similarly low proportion of *statistically significant* results to the shoulder joint. However, these results differ substantially to the shoulder with respect to gait sub-phases. In the ankle, the *statistically significant* results were encountered largely during short gait segments, with the exception of *pre-swing* and *initial swing* (Table 8.1, pg.199). Both sub-phases coincided only with the knee joint, whilst *initial swing* also coincided with the hip joint; as illustrated throughout Chapter 7, Section 7.2, the ankle joint variability presented more similarities to the knee joint than to the hip joint. Partial statistical significance was also noted during *heel strike* a similar find to the elbow joint, and during *loading response*, similarly to the shoulder joint. This find is substantiated by the analyses conducted in Chapter 7, Section 7.3, and presented Table 7.2, pg.190, which show that there are some similarities (albeit small) to the shoulder and ankle, as well as to the elbow and ankle, particularly unilaterally, thereby emphasising the *statistically significant* regions given body side common to the upper limb and ankle. However, as shown in Table 7.1, pg. 187, the similarities amongst the ankle, knee, and hip are slight, with no similarities found amongst all three joints during *initial swing,* despite this sub-phase being *statistically significant* in all three joints. However, all three joints (hip, knee, and ankle), presented lower variability in the left body side (albeit to differing degrees), with the ankle joint presenting the largest number of participants with this feature (n=17, Table 6.10, pg.175). This is an interesting find which suggests that, despite differing degrees of intraindividual variability, the potential of individualisation of all three joints during this gait sub-phase remains dependent on body side whilst interindividual variability remains statistically significant for each one of the three joints unilaterally and when combining left and right body side data; this parallels the results of the upper body joints whereby, despite the much higher intraindividual variability than in the lower body joints, all gait events presented statistically significant results for unilateral and combined left and right data. As evidenced in Table 6.9, Section

6.5.2, pg.174, the ankle, as observed in all of the joints, does not present with a majority number of participants for which bilateral and combined variability are similar, the largest being n=9 during *late mid-stance* and *terminal stance*; hence, the partially *statistically insignificant* results may indicate a true absence of differences between the means rather than differences in variability, particularly since the results for *early mid-stance* and *early* and *late mid-swing* are also *statistically insignificant*, despite the smaller number of participants indicated in Table 6.9, pg.174. Therefore, identification for the ankle joint is generally body-side dependent, and the discriminatory process should be conducted mindful of the differences in bilateral variability, as in all of the previously examined joints, regardless of body region.

Based upon the analyses undertaken in this chapter, and those presented in Chapters 6 and 7, the following conclusions can be drawn regarding the *current* utility of gait as a biological characteristic in forensic investigations:

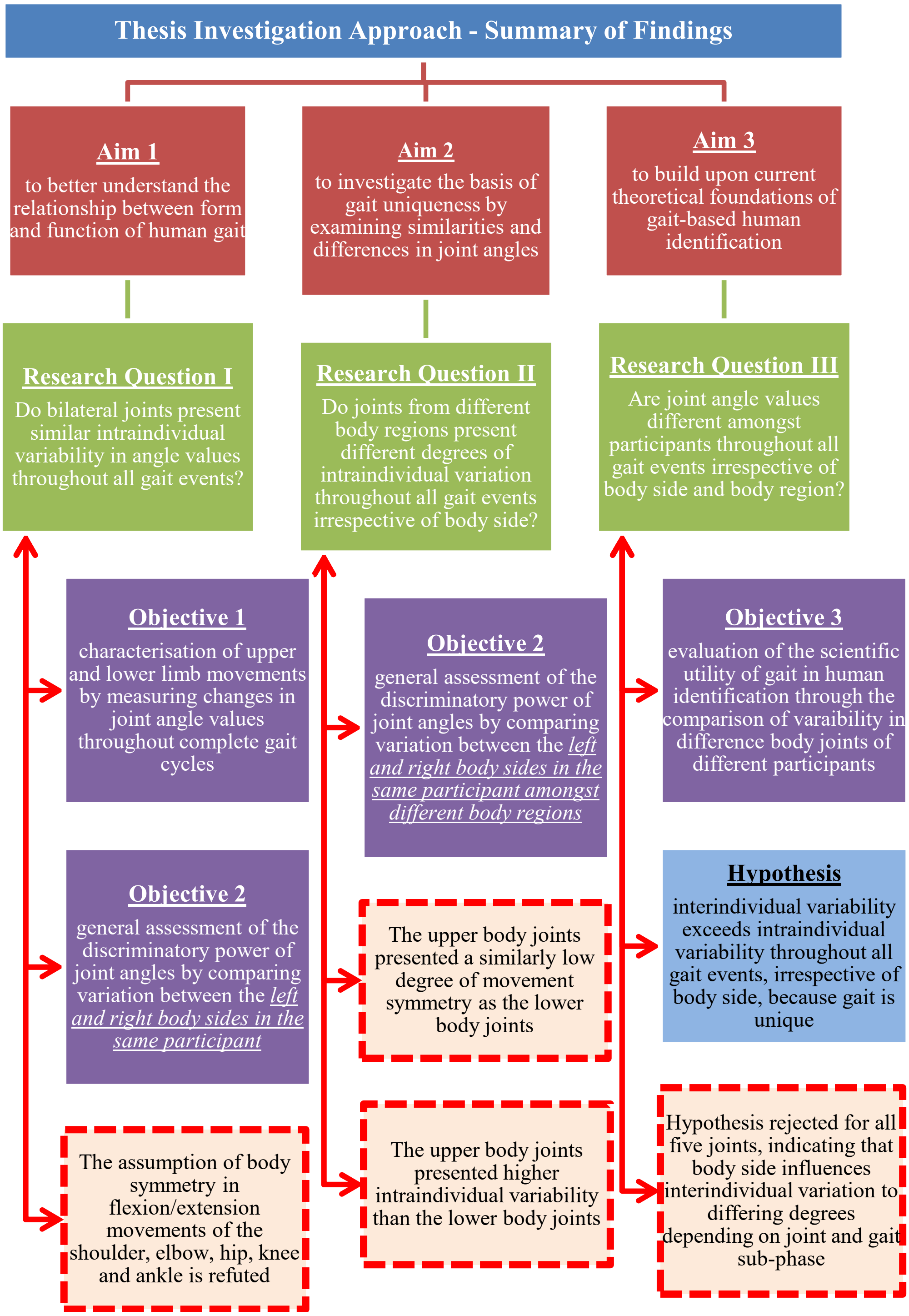
- all gait events present statistically significant interindividual variability in all joints when considering *body side singularly* and when *not* discriminating against this variable in the sagittal plane, thereby providing evidence for the claim of gait uniqueness;
- when factoring body side into analyses, interindividual variability of sagittal plane angular data of each joint (shoulder, elbow, hip, knee, and ankle) is influenced to different degrees and throughout different gait sub-phases, thereby rendering the claim of gait uniqueness and the potential for individualisation *dependent* on movement symmetry;
- interindividual variability is *least* affected by body side in the shoulder and ankle joints, potentially representing the most optimal body region selections in the sagittal plane for differentiating between individuals in conditions where video footage containing movement from the same body side cannot be obtained;
- interindividual variability is *most* affected by body side in the knee joint, potentially representing the least optimal body region selection in the sagittal plane for differentiating between individuals in conditions where video footage containing movement from the same body side cannot be obtained;
- *heel strike* and *loading response* gait sub-phases in the sagittal plane are affected by body side in all five joints (albeit at different levels) and therefore constitute the least recommended gait cycle regions for individualisation.

Chapter 9 – Emerging Trends and Future Research

9.1 Impact of Intraindividual Variation on Identification from Gait

The analysis of the dataset of 20 participants executing a simple walking motion on flat ground at self-selected speed, has highlighted several trends of interest for forensic gait analysis, as discussed throughout Section III and summarised below in Figure 9.1.

Figure 9.1 – Summary of Findings



Thesis Investigation Approach - Summary of Findings

Aim 1
to better understand the relationship between form and function of human gait

Aim 2
to investigate the basis of gait uniqueness by examining similarities and differences in joint angles

Aim 3
to build upon current theoretical foundations of gait-based human identification

Research Question I
Do bilateral joints present similar intraindividual variability in angle values throughout all gait events?

Research Question II
Do joints from different body regions present different degrees of intraindividual variation throughout all gait events irrespective of body side?

Research Question III
Are joint angle values different amongst participants throughout all gait events irrespective of body side and body region?

Objective 1
characterisation of upper and lower limb movements by measuring changes in joint angle values throughout complete gait cycles

Objective 2
general assessment of the discriminatory power of joint angles by comparing variation between the *left and right body sides in the same participant*

The assumption of body symmetry in flexion/extension movements of the shoulder, elbow, hip, knee and ankle is refuted

Objective 2
general assessment of the discriminatory power of joint angles by comparing variation between the *left and right body sides in the same participant amongst different body regions*

The upper body joints presented a similarly low degree of movement symmetry as the lower body joints

The upper body joints presented higher intraindividual variability than the lower body joints

Objective 3
evaluation of the scientific utility of gait in human identification through the comparison of varaibility in difference body joints of different participants

Hypothesis
interindividual variability exceeds intraindividual variability throughout all gait events, irrespective of body side, because gait is unique

Hypothesis rejected for all five joints, indicating that body side influences interindividual variation to differing degrees depending on joint and gait sub-phase

Based on the data obtained from over 100 angular waveform plots corresponding to five bilateral joints (shoulder, elbow, hip, knee, and ankle), the symmetry of flexion/extension movements in the sagittal plane is not only dependent on body side but also on specific gait cycle sub-phases. The investigation of similarity in intraindividual variability in angle values of bilateral joints (Research Question 1, Chapter 6), has therefore fulfilled the first thesis aim which is *to better understand the relationship between form (anatomy) and function (physiology) of human gait*. The characterisation of upper and lower limb joint movements throughout complete gait cycles using angular waveforms and standard deviation plots for each one of the 20 participants (Objectives 1 and Objective 2a, Figure 9.1) has illustrated the differences in movement symmetry in all five bilateral joints, thus challenging previous literature in which left and right gait cycles are utilised interchangeably and highlighting an additional aspect to consider in identification from gait. In addition, characterising gait of individuals using mean gait cycles may also be unsuitable in forensic contexts.

The shoulder, elbow, hip, knee, and ankle have also been examined to evaluate whether different body regions present discrepant degrees of intraindividual variation irrespective of body side (Research Question 2, Chapter 7), thus fulfilling the second thesis aim which is to *investigate the biomechanical basis of gait uniqueness by examining similarities and differences in joint angles* (Figure 9.1). Overall, the upper body joints (shoulder and elbow) presented a similarly low degree of movement symmetry as the lower body (hip, knee, ankle) joints, although the lowest was found in the hip. Therefore, the concomitant evaluation of intraindividual variability in all five joints in the form of standard deviation plots for each body side (Objectives 2b and 2c) has further strengthened the findings obtained from Research Question 1 (Figure 9.1). In addition, it has provided some evidence which indicates that the upper body joints may not be more discriminatory than the lower body joints, as suggested in previous forensic gait analysis studies (e.g. Birch *et al* 2013a, pg. 340) since body movement symmetry is not found throughout most gait events and therefore, the identification process is potentially dependent on the side from which the analysis is conducted. Since the aforementioned study does not report which body side was utilised in the analysis, a valid comparison cannot be conducted with the data obtained in this thesis, thus constituting a novel find.

The impact of movement asymmetry findings evaluated through Research Questions 1 and 2 was also reflected in the examination of interindividual variability across the 20 participants which, albeit to a different extent for each joint, suggests that body side is an important factor to consider when distinguishing individuals from one another. To investigate whether joint angle values differ amongst participants throughout the entire gait cycle irrespective of body side and body region (Research Question 3, Chapter 8), a series of Fisher-Pitman permutation tests were conducted, thus fulling the third thesis aim which is *to build upon current theoretical foundations of gait-based human identification* (Figure 9.1). The evaluation of the scientific utility of gait in human identification through the comparison of variability in the same participants and different participants in upper and lower body joints (Objective 3) has therefore shown that identification using flexion/extension joints angles of the shoulder, elbow, hip, knee and ankle joints is generally dependent on body side. However, body region and gait sub-phase are also important and related components to this finding, since each one of the joints presented different gait cycle regions for which body side was statistically significant. The shoulder and ankle joints presented the largest proportion of gait cycle sub-phases with statistically insignificant results, suggesting that they are least affected by body side variability. Conversely, the knee joint results were largely statistically significant, thus indicating that it is most influenced by body side.

Given the findings obtained from the KIT dataset for sagittal plane movements (flexion/extension) of the bilateral shoulder, elbow, knee, hip, and ankle, there are several recommendations which have emerged for the further development of forensic gait analysis. Firstly, its afferent definition provided in the code of practice as *the analysis, comparison and evaluation of features of gait to assist the investigation of crime* (Forensic Science Regulator, 2019, pg.4), should be further reconsidered in order to provide a more explicit scope for this field of study. Although the *features of gait* would be dependent on the nature and circumstances of the investigation, specificity can nevertheless be implemented, particularly since the code of practice is focused on observational, video analysis of gait, rather than on other features of gait which may be also submitted as evidence, such as footprint or footwear analysis from which gait characteristics can be extrapolated. Due to the vague and large scope and role of forensic gait analysis as defined in the code of practice, the definition does not explicitly state that forensic gait analysis is largely observational in nature, what the nature of the *features* is, or whether some degree of quantitative analysis is involved. Since gait itself is described as a 'person's manner of walking' within the code of practice, it is also imperative for the official definition to include this aspect to avoid unclarities regarding, for instance, speed.

Likewise, for observational gait analysis, certain camera angles may be unsuitable for analysis, as may be lighting conditions, distance from camera, clothing, shoes, body proportions visible, and, given the data from this thesis, body side as well. Finally, the definition also omits that the features of gait are generally analysed from video footage, and that certain body movements cannot be clearly visualised. Therefore, a potentially revised definition considering the current state of the field of study and considering the intent of the code of practice to focus on video-based gait analysis, would be as follows: *forensic gait analysis is the qualitative video analysis, comparison and evaluation of unilateral (bilateral if available) lower and/or upper body movements in the sagittal plane corresponding to a person's manner of walking, to assist the investigation of crime.* Although this proposed definition does not include aspects such as walking speed and walking surface, the essential scope should nevertheless remain as succinct as possible to avoid ambiguity which may induce erroneous perception in court. This is particularly relevant since, as the code of practice states, footprint/footwear marks can also be submitted as evidence; given that such features are exclusive to the foot, future amendments to the code of practice should consider the reclassification of these features under the remit of 'forensic podiatry' (i.e. field of study which specialises in analyses of the lower limb) rather than specifically under the remit of forensic gait analysis. This would allow the narrowing of the role and scope to reduce confusion.

Some of the limitations of forensic gait analysis are also presented in the code of practice (Forensic Science Regulator 2019, pg.6), however, the list is not exhaustive. Whilst this may not be possible due to case-specificity, there are several aspects which, although already mentioned in several previous publications, have not been included. For instance, 'normal walking' is not explicitly defined, and it is not stated that forensic gait analysis may not be applicable to certain conditions such as very fast walking, running, jogging or other such activities which may include a gait component. Walking surface is also omitted; since 'normal walking' can also be achieved through locomotory activity across an incline (such as a hill), stairs, etc., unclarities such as these allow the scope of practice to be extended in a limitless manner, which may lead to an erroneous application of current techniques. These aspects coupled with the data obtained from this thesis therefore require further amendments for the code of practice. For instance, the *Limitations of Services* section of the code of practice (Forensic Science Regulator 2019, pg. 6) should also include more information about the nature of the knowledge basis of the field of study, not necessarily from forensic science, particularly since forensic gait analysis is largely based on clinical methodologies; this is not stated in the code of practice. Although body asymmetry is a long-known aspect in anatomy and physiology, it has not been previously tested in forensic gait analysis and the code of practice does not state this limitation, nor does it address or mention video characteristics which would allow for a most accurate assessment of video footage.

Given that this thesis has provided novel empirical data of the impact of body side of on interindividual variation, the code of practice should consider including this aspect in the section presenting afferent limitations, not as an established fact, but rather as an additional confounding factor which may limit the scope of practice. Also, since the *features of gait* are not explicitly presented, consideration should also be given to including which body regions are most stable with respect to intraindividual variation. As highlighted throughout Section III of this thesis, interindividual variability in sagittal movements of the shoulder and ankle (given this dataset) is least affected by body side, and therefore, may widen the scope of practice, as opposed to lower body joints (i.e. knee and hip) for which interindividual variability is largely body side-dependent. Finally, the code of practice does not refer to the concept of a 'gait cycle'. Whilst such aspects may be considered too detailed for a generalised code of practice, it is important to note that the current definition implies that any type of gait feature under any circumstance, and as small as possible, can be utilised for evaluation. As highlighted throughout chapters 6,7 and 8, certain gait cycle sub-phases present higher intraindividual variation than others, for shorter or longer gait segments and/or sub-phases, with or without influencing interindividual variation with respect to body side. Despite the findings that interindividual variation is presented throughout all gait events when analysing unilateral sagittal movements or combined bilateral movements without discriminated against body side, the following distinctions should not only be clearly noted in the code of practice, but also further evaluated in more extensive empirical studies:

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.

iv. Sagittal plane movements should be favoured over coronal and transverse plane movements because these are more readily observed given the observational nature of forensic gait analysis;

v. Synchronicity of gait events for the shoulder, elbow, hip, knee, and ankle movements in the sagittal plane may constitute an additional intraindividuality variable to consider when making decisions regarding whether quantity of video footage is sufficient for accurate evaluation;

vi. Given current knowledge and the empirical findings of this thesis, forensic gait analysis is currently limited with respect to scientific foundations and additional variables which may have been empirically overlooked thus far, and may negatively impact the analysis of evidence in court; therefore, the use of forensic gait analysis information as evidence should only be considered under exceptional circumstances and only by highly experienced forensic gait analysts, given an explicit scope of practice accompanied by a presentation of all current limitations to the judiciary.

9.2 Challenges and Limitations of the KIT Dataset: Future Recommendations

As mentioned throughout Sections II and III, there are several limitations to consider concomitant with the evaluation of the impact of the findings of this thesis discussed herein. The main shortcoming of the data obtained in this thesis is the manual extraction of the gait cycles; since the angular data was not accompanied by annotated documents which would indicate the start and end of each gait cycle within the trial, these were approximated. To improve accuracy, this approximation was conducted through both visual means (i.e. plotting) and by examining the angle values at the given timepoints based on data from the literature. However, since the subsequent angular waveforms were also standardised using linear interpolation, the impact on the validity of the results is minimal, considering that annotation through, for example floor sensors, are also approximations which also require processing; also, data were repeatedly revised. Despite this, the lack of synchronicity of gait events across gait cycles posed challenges to the manipulation and interpretation of the data, as described throughout Chapter 6. Since repeated revision of the data was conducted and the relevant literature was consulted, it is likely that asynchronicity may constitute an additional variable related to intraindividuality, particularly for the upper limb. This is of importance to consider in future research since, in many of the participants irrespective of joint type, the bilateral ranges of values also differed, resulting in higher combined variability, thus further emphasising that joint motion is not necessarily symmetrical with respect to values. Hence, asynchronicity in isolation may not necessarily exacerbate intraindividual variability in the absence of an ‘actual’ difference in values, as discussed throughout Chapter 6. Therefore, additional research is required to test this rationale. The inequality of cycles obtained from the four trials, coupled with differing number of cycles for each joint and body side and lack of synchronicity, may have nevertheless introduced bias into the obtained results, particularly for Research Question 2 where the intraindividual variability in some joints may have been exacerbated; since gait also has a behavioural component, the cycles and their accompanying variability may not be truly representative of the normal gait of a given participant. Implicitly, this aspect is also of relevance to forensic gait analysis, thus bringing into question the number of gait cycles required to develop comparative profiles for different individuals that satisfy the concept of ‘persistence’ in order to develop a more solid scientific basis for gait uniqueness and its potential for individualisation.

An additional limitation of this dataset is the small number of gait cycles available from each of the twenty participants. Given that the purpose of this thesis was to evaluate the assumptions of gait symmetry and gait uniqueness through the analysis of intraindividual variation, the total number of participants is appropriate; as previously stated, the core of the thesis was founded the investigation of the assumption of gait symmetry and uniqueness, and the examination of interindividual variation in Chapter 8 served to emphasise the potential impact of intraindividual variability on the identification process. As a result, the number of gait cycles per participant, per joint and body side is more relevant as a limitation. Nevertheless, a larger dataset could have provided additional insight into the potential effects of sex, height, weight, and age on both intraindividual and interindividual variability. As shown in Appendix G, the number of gait cycles for each participant, body side and joint ranged from a minimum of 3 cycles to a maximum of 12 cycles. Despite the availability of data from four trials for each participant, the number of cycles per trial was also small; some were unextractable due to the anomalous overall appearance and/or values of the angular waveforms. These data errors most likely stem from soft tissue artefacts caused by the inappropriate placement of the sensors which resulted in abnormal raw data; this error was then ‘transferred’ along the model processing stages, thus producing angular waveforms which do not conform to normality. Furthermore, as exemplified throughout Chapter 6, angular data from many of the participants presented different anomalous characteristics. One example is the saccadic transitions of angle values across gait events within gait cycles, the origin of which can be multi-fold, ranging from a participant-specific type of gait, to lack of appropriate calibration of the equipment, to inaccurate reconstruction of the 3D data points into joint angle values. This is particularly relevant to the data of the shoulder and elbow joints. For example, the shoulder joint represents an anatomical region that is difficult to quantify, particularly using body worn sensors, and as a result, the anomalous nature of the angular waveforms may likely be due to soft tissue artefacts produced by the body-worn sensors sliding over the skin during the recording of the trials (Barré *et al* 2015), and therefore interfering with the captured signals and resulting in lack of smoothness in the afferent angular waveforms. A related anomaly is the plateau-effect peak dorsiflexion in the ankle joint which is also mechanical in origin (i.e. soft tissue artefact); the ankle joint also represents an anatomical region for which angular motion is difficult to quantify. Some participants also presented with flattened angular waveforms in the shoulder and elbow joints, likely a result of decreased arm movement during walking. Similarly, additional flexion peaks during swing were also noted in the shoulder joint data of several participants. Both of these characteristics are likely to constitute stylistic features of certain individuals, given that, as previously discussed throughout Chapter 3, arm movement is less regulated than lower limb movement due to the lower degree of dependency for efficient locomotion. This is further evidenced by the lower degree of anomalous features present in the lower body joints. Hence, stylistic features of arm movement during gait require further research in order to establish the frequency with which they occur. For instance, some individuals may swing both or a single arm in an obvious manner, whilst other may exhibit little arm swing. The latter can also be of interest in crime prevention where individuals may attempt to dissimulate an action or conceal an object; in this context medial/lateral rotation and circumduction can also be of importance.

Other alternatives to the data analysis approach employed were also considered. Rather than analysing differences in angle values at every 1% of the gait cycle, overall pattern analysis of the shape of the angular waveforms could have been employed to determine whether there are differences in the gait ‘signatures’ between and within individuals. Given that the aims of the thesis focused on the physiological underpinnings of gait as currently utilised in forensic gait analysis, the evaluation of the discriminatory power of joint angle values was deemed to be more suitable for direct application to the present knowledge basis. As described throughout Chapter 2, Section 2.3, the methodological nature of forensic gait analysis is observational, whereby the gait features usually observed from video are largely described in the form of limb positions (e.g. flexed knee, abducted hip, etc.). Since these methods are founded upon biomechanical principles, the use of the KIT dataset directly translates to the methodological approaches currently employed. As a result, the relevance of overall gait patterns is more applicable to biometric gait recognition rather than to forensic gait analysis. Furthermore, the utilisation of joint angle values to evaluate the utility of gait was preferred over other approaches to gait analysis (e.g. kinetic analysis (i.e. bodily forces exerted during walking), and spatio-temporal parameters (e.g. number of steps per minute, distance between left and right foot during walking)) also for methodologically-related reasons. For instance, analysis of spatio-temporal parameters is highly dependent on the camera position, requiring a validated quantitative approach in practice. Given that forensic gait analysis is largely based on qualitative descriptions of joint motion, such approaches would not have fulfilled the thesis aims which focus on the scientific basis of predominant methods in current use.

To improve upon the findings of the research proposed in this thesis to investigate the scientific basis of gait in criminal investigations, several aspects have to be considered. For example, equal number of trials should be obtained from all 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. This would also serve to confirm the persistence of more specific physiological characteristics which may have potential utility in circumventing, at least in part, certain behavioural components which may confound overall gait patterns. 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. Rather, cycles from the middle region of the trials should be extracted, to provide sufficient time for the participant to engage in as natural a gait as possible. These data could then be compared with cycles at the start and end of the trials since it may allow for inferences to be made regarding confounding variables in a real-world scenario where it might be that the suspect is not walking “unconsciously”, but rather fleeing and/or moving in a manner which is dictated by some stressful condition. As previously stated, this could not be conducted using the dataset for this thesis due to the small number of cycles. This limitation may have also introduced bias with respect to the location of the gait cycle within the trial, meaning that an individual may have adopt a slightly different gait at the start and end of a trial in comparison to a cycle during the middle of a trial. Additionally, coordination amongst upper and lower body regions should also 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. For instance, the lack of similarity between body sides may have also originated in the assumption employed in the methodology, whereby the degree of bilateral joint motion coordination was not considered due to the small number of available cycles per participant. However, despite this limitation, the results remain valid; in a forensic setting, the sets of video footage available for comparison will rarely contain the person of interest from identical angles and be of sufficient length to allow a thorough investigation. As a result, this thesis 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 into the decision-making process if data are not obtained from the same body side. 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.

It might also be of importance to consider future collaboration between computer vision experts who conduct research in biometrics and forensic gait experts, in order to widen the role and scope of gait in forensic investigation. For example, concepts from both fields are of relevance to one other whereby forensic gait analysts are knowledgeable in the biomechanics of human movement, the forensic scene and the quality of footage to be expected in such circumstances, whilst gait recognition experts are well-versed in algorithm design, latest technological advancement, and can potentially provide innovative solutions for challenges related to, for example, the CCTV system layout. Such an interdisciplinary collaboration can have potential benefits not only by providing out-of-the-box perspectives on current issues but can sustain and develop gait into a more robust field of study. For example, the rapid technological advancements of smart phones can be of use in developing methods for extracting spatio-temporal gait parameters. This would also allow for more realistic data to be obtained, given that participants could be asked to consent to data collection whilst undertaking their daily activities rather than conducting specific walking activities in the laboratory. To allow for baselines to be developed regarding the scientific basis for gait individualisation and uniqueness, participants could also be asked to contribute data from their daily activities as well as in participating in laboratory-based data collection. Through such an approach, differences regarding the constraints of laboratory conditions and real-life conditions can be compared. Interdisciplinary collaborations should also be considered given logistical issues associated with operator-camera ratios and the small number of qualified, hence the strong incentive for automatization. Related application could include human trafficking where gait can be used for tracking missing person(s) and tracing criminals based on demographics, and surveillance and monitoring for understanding criminal behaviour, thereby potentially contributing to crime prevention. Given that the background in the logistic limitations of an outdoor video system has already been extensively conducted in the field of gait recognition, collaborations amongst experts from different fields present numerous possibility in the study of crime, not solely for the purpose of identification ‘after the fact’ but rather in contributing to a safer society through deterrence.

9.3 Concluding Remarks

The findings of the three research questions evaluated in this thesis indicate that intraindividual variability is present in differing degrees amongst the 20 participants in the shoulder, elbow, hip, knee, and ankle. This indicates that the representation of the gait of an individual through an ‘average’ approach may not be appropriate, particularly for forensic purposes. Bilateral movement asymmetry was also noted and predominated the gait events of all five joints, albeit to differing degrees; this outcome further emphasises not only that mean cycle waveforms are generally unrepresentative, but that obtaining mean cycle waveforms by combining data from both body sides may lead to erroneous interpretation of gait. The impact of this asymmetry is less pronounced in the shoulder and ankle and presents a lesser effect on these two joints, as evidenced by the larger proportion of statistically insignificant results throughout the gait cycle sub-phases in comparison to the other joints, when examining interindividual variability given body side. Nevertheless, the importance of body side fluctuates depending on gait cycle sub-phase, and differences in statistically significant versus non-significant regions were found not only between upper and lower body joints but also amongst joints of the same body regions.

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). The impact of these novel finds (considering limitations) therefore warrants further research on a larger and more diverse dataset, not limited to adult gait. Although juvenile gait has not been a subject of discussion in forensic gait analysis or recognition, it is one of a high importance, considering that juveniles, even in the presence of clear, unobscured, or unconcealed facial features, can be easily disguised. Whether for missing persons or juvenile delinquency application, forensic gait analysis can play an important role in surveillance and tracking. Nevertheless, a more robust empirical basis and framework for conducting identification from gait is required, to not only extend the remit of the field but more importantly, to ensure that the methodology is valid for forensic purposes. Amendments for the current code of practice should be considered, and the notion of forensic gait analysis as an identification technique solely due to the premise of universal gait uniqueness, should be rendered obsolete. 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.

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List of Appendices

The appendices contain the complete R code utilised to process and analyse the data, as well as the complete dataset detailing the number of trials per joint per participant, and the complete set of results for Research Questions 2 and 3; all are attached in a single, separate document. To facilitate browsing, each appendix within the document has been alphabetised, and is provided with a separate table of contents and page numbers. The appendices document therefore contains the following, according to hyperlinked sub-headings:

Appendix A – R Code for Processing of Angular Data from each Joint

A1 Right Shoulder (RS)
A2 Left Shoulder (LS)
A3 Right Elbow (RE)
A4 Left Elbow (LE)
A5 Right Hip (RH)
A6 Left Hip (LH)
A7 Right Knee (RK)
A8 Left Knee (LK)
A9 Right Ankle (RA)
A10 Left Ankle (LA)

Appendix B – R Code for Summary Plots (Research Question 1)

B1 Shoulder
B2 Elbow
B3 Hip
B4 Knee
B5 Ankle

Appendix C – R Code for Angular Waveform Plots (Research Question 1)

C1 Shoulder
C2 Elbow
C3 Hip
C4 Knee
C5 Ankle

Appendix D – R Code for Standard Deviation Plots (Research Question 1)

D1 Shoulder
D2 Elbow
D3 Hip
D4 Knee
D5 Ankle

Appendix E – R Code for Standard Deviation Plots of All Joints (Research Question 2)

E1 Left Body Side
E2 Right Body Side

Appendix F – R Code for Fisher-Pitman Permutation Tests (Research Question 3)

F1 Shoulder
F2 Elbow
F3 Hip
F4 Knee
F5 Ankle

Appendix G – Complete Dataset of Number of Trials Per Joint Per Participant

Table G – Number of Cycles Extracted from the Four Trials of Each Joint

Appendix H – Complete Set of Results for Research Question 1

H1 Bilateral Shoulder
H2 Bilateral Elbow
H3 Bilateral Hip
H4 Bilateral Knee
H5 Bilateral Ankle

Appendix I – Complete Set of Results for Research Question 2

I1 Left Body Side
I2 Right Body Side
Table I1 – Similarities in Variability Patterns of the Bilateral Upper and Lower Body Joints
Table I2 – Similarities in Variability Patterns Between the Upper and Lower Body Joints

Appendix J – Complete Set of Results for Research Question 3

J1 Bilateral Shoulder
J2 Bilateral Elbow
J3 Bilateral Hip
J4 Bilateral Knee
J5 Bilateral Ankle