Establishing an Evidence-Base for Erect Pelvis Radiography: Positioning, Radiation Dose and Image Quality

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Table of Contents

List of Tables

List of Figures

Publications, conferences papers and posters

NO	Title	Status
1	Optimum Positioning for Anteroposterior Pelvis Radiography: A Literature Review. ***Kholoud Alzyoud***, *Peter Hogg, Beverley Snaith, Kevin Flintham, Andrew England1* *https://doi.org/10.1016/j.jmir.2018.04.025*	Journal article **published** in Journal of Medical Imaging and Radiation Science (2018)
2	Impact of Body Part Thickness on AP Pelvis Radiographic Image Quality and Effective Dose. ***K. Alzyoud***, *P. Hogg, B. Snaith, K. Flintham, A. England.* *https://doi.org/10.1016/j.radi.2018.09.001*	Journal article **published** in the Radiography Journal (2018)
3	Video Rasterstereography of the Spine and Pelvis in Eight Erect Positions: A Reliability Study. ***K. Alzyoud***, *P. Hogg, B. Snaith, S. Preece, A. England.* *https://doi.org/10.1016/j.radi.2019.06.002*	Journal article **published** in the Radiography Journal (2019)
4	Impact of fat thickness on AP pelvis radiography image quality and effective dose. ***K. S. Alzyoud***, *A. England, B. Snaith, K. Flintham, P. Hogg.*	Conference poster **presented** at ECR (2018)
5	An evaluation of eight different standing positions for undertaking erect pelvis radiography using videorastereography. ***K. S. Alzyoud***, *P. Hogg, B. Snaith, S. preece, A. England*	Conference poster **presented** at ECR 2019
6	Impact on radiation dose and image quality - supine versus erect positioning in pelvic radiography. ***K. S. Alzyoud***, *P. Hogg, B. Snaith, K. Flintham, A. England*	Conference poster **presented** at ECR (2019)
7	Are we fatter when flatter? The SEPRAIDD Project *Kevin Flintham, Bev Snaith, Andrew England,* ***Kholoud Alzyoud,*** *Peter Hogg, Martine Harris*	Conference paper **presented** at UKCR (2018)
8	An investigation into the impact of aging on the performance of LCD 2.4 MP colour display monitor when visualising low contrast detail using a CDRAD phantom. *S. H. Al-Murshedi, P. Hogg,* ***K. Alzyoud***, *A. England*	Conference poster **presented** at ECR (2018)
9	Developing Evidence Based Practice: Experiences from The SEPPRAID Project. *Snaith B, Flintham K, Harris M,* ***Alzyoud K,*** *England A, Hogg P*	Conference paper **presented** at ISRRT 2018 Trinidad
10	Impact of changing body habitus on radiation dose and image quality. ***K. Alzyoud***	Radiography department seminar (presenter) 2018
11	Pelvic radiography and patient orientation: impact on body morphology, dose parameters and image quality. *Snaith B, Flintham K,* ***Alyzoud K***, *Hogg P, England A*	Conference paper **presented** at Australian Society of Medical Imaging and Radiation Therapy 2019

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List of abbreviation

AAPM	American Association of Physicists in Medicine
AC	Acetabular Cup
AD	Acetabular Dysplasia
AEC	Automatic Exposure Control
AI	Acetabular Index
AIS	Adolescent Idiopathic Scoliosis
Al	Aluminium
AP	Anteroposterior
AR	Acetabular Retroversion
a-Se	Amorphous Selenium
a-Si	Amorphous Silicon
ASIS	Anterior Superior Iliac Spine
AW	Anterior Wall
BMI	Body Mass Index
C-d	Contrast Details
CEA	Central Edge Angle
CEC	Commission of European Communities
cm	Centimetres
CNR	Contrast to Noise Ratio
COM	Centre of Mass
COS	Cross Over Sign
CP	Central Point
CR	Computed Radiography
CT	Computed tomography
DAP	Dose Area Product
DD	Dimple Distance
DDH	Developmental Dysplasia of the Hip
DDR	Direct Digital Radiography
DICOM	Digital Imaging and Communications in Medicine
DL	Dimple Left
DQE	Detector Quantum Efficiency
DR	Digital Radiography
DRL	Dose Reference Levels
E	Effective Dose
ER	Effective Risk
ESAK	Entrance Surface Air Kerma
ESD	Entrance Surface Dose
FAI	Femoroacetabular Impingement
FROC	Free-Response ROC
FS	Film-Screen

GSDF	Grey Scale Standard Display Function
GT	Greater Trochanter
Gy	Gray
HRA	Health Research Authority
HU	Hounsfield Unit
HVL	Halve Value Layer
IAEA	International Atomic Energy Agency
IC	Iliac Crests
ICC	Intra-Class Correlation Coefficients
IDR	Indirect Digital Radiography
ILS	Inflectional point of the curvature from Lumbar to Sacral Spine
INAK	Incident Air Kerma
IPEM	Institute of Physics and Engineering in Medicine's
IQ	Image Quality
IRMER	Ionising Radiation Medical Exposure Regulations
ITL	Inflectional point of the curvature from Thoracic to Lumbar spine
J kg	Joules per Kilogram
JAFROC	Jackknife Free-Response ROC
JSW	Joint Space Width
kVp	Tube Voltage Potential
LCEA	Lateral Central Edge Angle
LCM	Lower Costal Margin
LL	Lumbar Lordosis
LROC	Localisation ROC
mAs	milli Ampar second
MC	Monte Carlo
MESH	Medical Subject Headings
mm	millimetres
MOSFET	Metal Oxide Semiconductor-Field Effect Transistor
MP	Mega Pixel
MRI	Magnetic resonance imaging
MTF	Modulation Transfers Function
NCRP	National Council on Radiation Protection and Measurements
NDRL	National Diagnostic Reference Level
OA	Osteoarthritis
PA	Posteroanterior
PB	Pubic Bone
PACS	Picture Archiving and Communication System
PRIS	Prominent Ischial Spine Sign
PS	Pubic Symphysis
PSI	Pelvic Sagittal Inclination
PSIS	Posterior Superior Iliac Spine

PSL	Photostimulated Luminescence
PT	Pelvic Tilt
PTcor	Pelvic Tilt in coronal plan
PTor	Pelvic Torsion
PTsag	Pelvic Tilt in sagittal plan
PW	Posterior Wall
PWS	Posterior Wall Sign
QCT	Quantitative Computed Tomography
REC	Research Ethics Committees
ROC	Receiver Operating Characteristic
ROI	Regions of Interest
ROM	Range of Motion
SCJ	Sacrococcygeal Joint
SD	Standard Deviation
SID	Source-to-Image Distance
SNR	Signal to Noise Ratio
SOD	Source to Object Distance
SPS	Storage- Phosphor Screen
SSD	Source to Skin Distance
Sv	Sievert
SVA	Sagittal Vertical Axis
TFT	Thin-Film Transistor
THA	Total Hip Arthroplasty
THR	Total hip replacement
TK	Thoracic Kyphosis
TLD	Thermoluminescent Dosimeter
VGA	Visual Grading Analysis
VR	Video Rasterstereographic
WB	Weightbearing

Abstract

Purpose: Pelvic radiography using X-ray imaging has traditionally been used for the identification of hip joint changes, including the identification of pathologies such as osteoarthritis. For patients suffering from hip pain, the supine pelvis X-ray examination is one of the initial diagnostic steps. Despite this, many recent studies have recommended that the position should now be undertaken erect and not supine to reflect the functional appearances of the hip joint. This thesis aims to establish an evidence base for erect pelvis radiography, and it will include assessing radiographic positioning, radiation dose and image quality.

Methods: The experimental work described in this thesis was conducted in three phases. Each phase has its own methods with the purpose of achieving a specific set of aims.

Phase One was the evaluation of the postural effects of different erect (standing) positions in order to recommend an optimal one for erect pelvic radiography. Eight different erect positions were investigated. A sample group of 67 healthy people participated, and a range of spinal and pelvis measurements were acquired using a 3D video rasterography system (Diers) and an inclinometer.

Phase Two was a phantom study evaluating the potential changes to radiation dose and image quality when moving between supine and erect imaging. Phase two was undertaken using three experiments (experiment #1, experiment #2 and experiment #3). Experiment #1 evaluated the impact of increased patient size on the radiation dose and image quality. In this experiment, animal fat was positioned anteriorly on a pelvic anthropomorphic phantom and the thickness increased incrementally in 1cm steps from 1 to 15cm. Image quality was evaluated physically and visually. The effective dose was calculated using Monte Carlo simulation software (PCXMC). During experiment #2, the anterior thicknesses for 109 patients, with a range of BMIs, who were referred for pelvis radiography, was measured in the erect and supine position. Experiment #3 evaluated the potential differences between the positions (supine and erect) in terms of image quality and radiation dose by modelling patient thickness changes between positions using the data obtained in experiment #2. An anthropomorphic phantom was used and modified (by adding additional fat) to simulate tissue changes for both erect and supine X-ray positions. Visual grading analysis was used (VGA) to evaluate image quality. The effective dose and absorbed dose were calculated using PCXMC.

During ***Phase Three***, 60 patients were imaged in erect and supine positions. The paired pelvis X-ray images were then compared, taking into account radiation dose and image quality.

Results: ***Phase One*** demonstrated no statistical differences between the eight-different standing positions for pelvic and spine metrics (P>0.05). Results also demonstrated no significant postural differences between BMIs across all eight standing positions (P>0.05). Also, no differences (P>0.05) were identified in the pelvis and spinal metrics when comparing between males and females. Standing relaxed with feet internally rotated by 20° and the upper arms supported was a recommendation derived from this phase.

Results from ***Phase Two*** showed an increase in effective dose (E) as the fat thickness increased. Also, all physical and visual image quality metrics decreased as fat thickness increased. Physical and visual image quality measures also decreased for erect images when compared to supine images, and the E also increased. 90kVp, 130/145 SID, using both outer chambers, were the recommended exposure parameters settings for obtaining erect pelvis X-ray images.

Results from ***Phase Three*** showed that anterior patient thickness was 17% (P<0.001) higher in an erect position. The DAP and absorbed dose were 46% and 45% (P<0.001) greater in the erect position. Also, the effective dose was 67% (P<0.001) higher in the erect position when compared with supine. In regard to the image quality (IQ), that of the erect position decreased by 10% when compared with supine (P<0.001).

Conclusion: The eight proposed standing positions could theoretically be suitable for erect pelvis imaging. People in a relaxed standing position, with their feet internally rotated by 20° and their upper arms supported would be recommended. In terms of IQ and radiation dose for erect positions, this position decreases image quality (both physical and visual) and increased radiation dose. Changes were largely due to the effect of gravity on the anterior soft tissue distribution. These issues should be considered and optimised more fully when deciding if to move from supine to erect pelvis imaging.

Chapter 1: Introduction

In this chapter, a short introduction will be provided along with a summary of the main topics which will be outlined in this thesis. It will detail the structure of the various chapters, including the individual contributions made by each study to the overarching aim of the PhD thesis. The introduction will also include the rationale behind this thesis, and it is overall aim and objectives.

1.1 Introduction

Over the past two-decades, orthopaedic evaluations of hip pain have increased dramatically (Gerhardt et al., 2012; Herr & Titler, 2009). This is mainly due to the improved understanding of structural hip pathologies, including developmental dysplasia of the hip (DDH) and femoroacetabular impingement (FAI). Osteoarthritis (OA) is the fourth most common disability in the United Kingdom (UK) (Kaur, Hayward, & Wilkie, 2017; Kurien, Kerslake, Haywood, Pearson, & Scammell, 2016; NICE, 2014) and also a leading cause of hip pain. Early diagnosis of people who are suffering from hip pain is, therefore, important. If left untreated, it could lead to severe disability and the possibility of requiring joint replacement surgery. Within the scope of radiography, the assessment and monitoring of pain and symptoms following total hip replacement (THR) surgery also requires frequent radiological evaluation (Clohisy et al., 2008).

The development of medical imaging equipment, such as computed tomography (CT) and magnetic resonance imaging (MRI), provides three-dimensional images, which offer accurate diagnosis for hip joint pathologies. Despite these developments, conventional radiography remains critical in the evaluation and diagnosis of hip joint pathologies. Primary reasons behind this are that it is simple, accessible, low cost and that it has a relatively low radiation dose. Importantly, it also provides valuable clinical information (Clohisy et al., 2008; Tannast, Murphy, Langlotz, Anderson, & Siebenrock, 2006). Despite the aforementioned advantages, the precise evaluation of the hip joint still poses challenges to clinicians especially in cases of mild structural abnormality. With this in mind, clinicians are now requiring reliable and correct acquisition parameters to allow for the optimum assessment of the hip joint by projection radiography. The information obtained from such an examination can help with precise diagnosis, correct disease classification and with decisions regarding management (Steppacher, Anwander, Zurmühle, Tannast, & Siebenrock, 2015).

There are numerous radiographic measurements that can be used to describe hip joint disorders. These measurements, used by orthopaedic surgeons, are indicators of changes within the hip joint. For instance, two common metrics are the lateral centre-edge angle (LCEA) and acetabular index (AI), both of which have been used to demonstrate acetabular dysplasia (AD) (Wiberg, 1939). Head/neck offset and the alpha angle have been used to diagnose femoroacetabular impingement (FAI) (Clohisy et al., 2008). Pelvic tilt (PT) is considered to be one of the most important factors that affects the radiological outcome and relates to the position of the patient during imaging. As the PT increases, there is a significant increase in acetabular cup anteversion and vice versa. To illustrate, in a healthy population, if the pelvic X-ray image is acquired with more PT, it will then lead to more acetabulum retroversion. Increasing or decreasing cup tilt during surgery can lead to anterior or posterior dislocation and prosthesis wear along with loosening (D'Lima, Urquhart, Buehler, Walker, & Colwell, 2000; Kummer, Shah, Iyer, & DiCesare, 1999; Siebenrock, Kalbermatten, & Ganz, 2003; Wang et al., 2017; Yun et al., 2018). As such, insufficient attention to PT can lead to an incorrect diagnosis and thus the wrong treatment decision may also be made (Tannast et al., 2006; Yun et al., 2018, 2019). More detail about the importance of PT is described in section 3.3.1. To counteract this problem, pelvis radiography needs greater standardisation in order to accurately reflect a patient's normal/habitual anatomy in the erect position (Maratt et al., 2015; Pierrepont et al., 2017; Pytiak et al., 2016). In addition, image quality for this projection should be optimised. This will again help clinicians when making informed choices and selecting the correct equipment during surgery (Shon et al., 2008).

1.2 Rationale

Hip pain is evaluated by both historical and clinical examination. This is commonly accompanied by acquiring X-ray images of the pelvis and hips. Younger adults who are suffering from pain often have a condition called dysplasia which is characterised by symptoms of bony impingement (Tannast, Siebenrock, & Anderson, 2007). This pain plays an important role in evaluating and monitoring any progression to osteoarthritis (OA). By 2020, OA will be the fourth most common cause of the disability in the UK (Kaur et al., 2017; Kurien et al., 2016; NICE, 2014). As a result, OA accounts for a large number of non-traumatic referrals for pelvis and hip X-ray examinations. The incidence of OA increases with age and it affects millions of the people in Europe. Due to the aging of the population the incidence is set to increase (Felson & Hodgson, 2014; Iorio et al., 2008).

Joint replacement is almost the worst outcome from OA progression. It has been reported that 90% of hip replacements are due to OA and almost 101,651 hip replacements were performed in 2016 in England, Wales and Northern Ireland (National Joint registry, 2017). Costs resulting from treating OA have also increased and this has driven the need to continue to search for more appropriate methods for early diagnosis (McCarthy & Lee, 2004; Tanzer & Noiseux, 2004). The medical and social care of hip disorders costs the UK £2 billion per year. This figure is predicted to rise to £6 billion by 2036 (National Institute for Health and Clinical Excellence, 2011). Alongside this, it is also possible to predict that these cases will increase as national obesity levels rise and further exacerbate the incidence of hip problems. In 2015, 68% of men and 58% of women were overweight, and obesity accounted for 8.6% of disability (National Health Service, 2017).

Radiographic diagnosis for OA often depends on the identification of subtle changes to the joint. However, these changes could be obscured depending on the hip orientation, which is affected by patient positioning (Auleley et al., 1998; Troelsen, Rømer, Kring, Elmengaard, & Søballe, 2010) or by anatomical variations which may cause appearances of pelvic anteversion (anterior tilt) or retroversion (posterior tilt) (Van Der Bom, Groote, Vincken, Beek, & Bartels, 2011). Siebenrock et al., suggested limits for neutral radiographic PT to ensure image acceptability, but they did not acknowledge natural variations between people, they rather took imaging differences as a failure of radiographer positioning (Siebenrock et al., 2003).

Until very recently, X-ray images of the pelvis and hip would be taken with the patient supine. As body weight is carried by the hips, there is an effect on the radiological appearances of the hip joint. These relationships are critical in providing accurate diagnosis and treatment of musculoskeletal diseases. Weightbearing changes to the hip joint are further increased as the prevalence of obesity increases, which causes further changes to posture (Escalante, Lichtenstein, Dhanda, Cornell, & Hazuda, 1999; Gilleard & Smith, 2007; Maciałczyk-Paprocka et al., 2017; J. Paul, Sallé, & Frings-Dresen, 1996). Therefore, several studies (Fuchs-Winkelmann, Peterlein, Tibesku, & Weinstein, 2008; Jackson, Estess, & Adamson, 2016; Troelsen, Jacobsen, Rømer, & Søballe, 2008) have provided evidence that suggest erect X-rays of the pelvis offer better visualisation of functional anatomy. In these studies, there are significant changes in the appearances of the pelvis (PT/orientation) after repositioning from supine to erect (see chapter 3). Furthermore, hip pain tends to only be present during daily function, which is in the erect position (Lazennec et al., 2004; Tannast et al., 2006; Troelsen et al., 2008). Findings from these studies confirm that there is a change in pelvis orientation inter-related to posture. Therefore, this change might have implications for treatment, hip replacement outcome and the pain associated with HD, FAI or OA.

Recent research recommends [functional] erect pelvis radiography for people who suffer from conditions such as AD and FIA (Jackson et al., 2016; Pierrepont et al., 2017; Ross et al., 2014). Awareness of different body postures and pelvis changes is increasing (Jackson et al., 2016; Tannast et al., 2006). Therefore, there is a critical demand for correct (non-invasive) radiological methods to demonstrate, evaluate and diagnose hip pathologies which can then be used to plan more appropriate and accurate treatments. Research conducted so far has been undertaken using lateral pelvis X-ray images, inclinometry data and images reconstructed from CT datasets, and different positions. This makes the comparison between the publications/results difficult (see chapter 3).

In addition, research has generally been concentrated in specific patient groups (i.e. those with OA). These reports have considered the effect of repositioning on PT (Tannast et al., 2006; Troelsen et al., 2008), joint space width (JSW) (Auleley et al., 1998; Fuchs-Winkelmann et al., 2008; Terjesen & Gunderson, 2012) and the acetabular component (AC) (Ala Eddine et al., 2001; Jackson et al., 2016; Shon et al., 2008). Results from these studies were inconsistent and some of the research found no changes, while others found a decrease.

Moreover, no previous studies have considered radiation dose changes when repositioning from supine to erect. Many research studies previously identified were undertaken by orthopaedic surgeons, with a focus on clinical outcomes rather than the development of radiographic techniques. Consequently, existing publications show restricted and inconsistent results with no evidence base for radiographic positioning and technique for erect pelvis x ray. Research involving radiographers is also important to better understand the effects of moving from a supine to an erect position on radiation dose and image quality. As the posture changes, the radiation dose is likely to change too. This is because of the increase in overlying abdominal soft tissue resulting, and the position of the internal organs and anterior soft tissues from the natural effects of gravity.

1.3 Research questions

The thesis intended to answer the following question:

What is the optimal patient position for obtaining erect pelvis X-ray images, and what are the differences in terms of image quality and radiation dose when compared to supine radiography?

1.4 Aim and objectives

This thesis is divided into three main phases. During ***Phase One*** the optimal position was recommended for acquiring pelvis X-ray images in the erect position (which was then performed in ***Phase Three***). During ***Phase Two*** the acquisition optimum parameters were derived for the erect position in order to identify the methods that were to be used in ***Phase Three***. Finally, ***Phase Three*** acquired supine and erect images from a cohort of patients using the data obtained from ***Phase One*** and ***Two*** - see **Figure 1-1**.

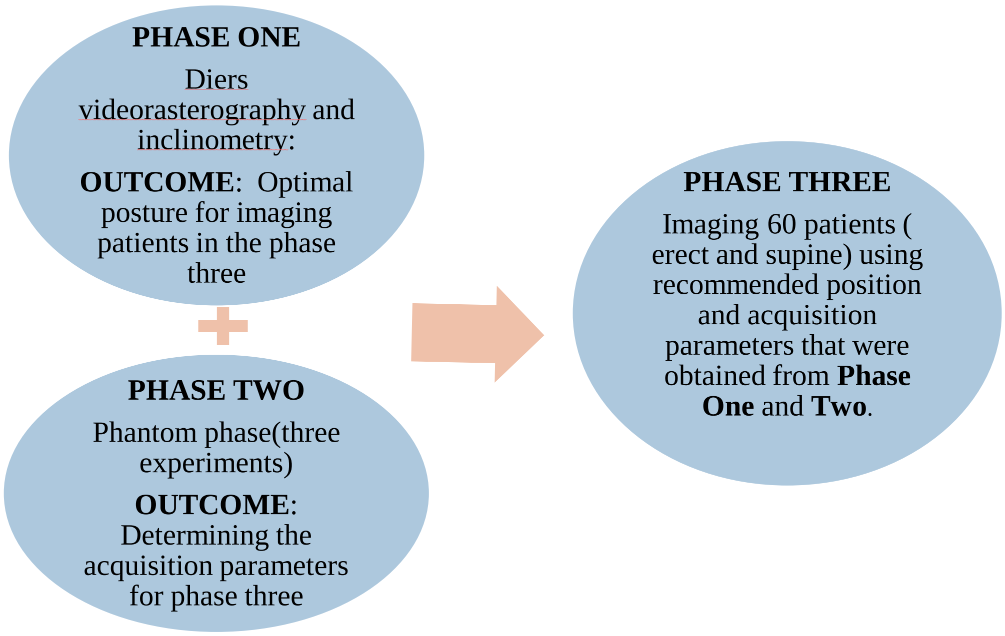


Figure 1-1: Illustrates the main research phases in this thesis and their relationship to each other.

The aim of this thesis is to evaluate pelvis X-ray imaging in the erect position in terms of positioning and with a view to providing an evidence-based set of optimised acquisition parameters for use in routine clinical practice. In addition, this thesis also aims to determine if the patient position (erect versus supine) has an effect on radiation dose and image quality. Within this thesis, the following objectives were formulated:

1. To evaluate a range of erect postures in order to identify those which reflect the most appropriate habitual positions that can be used for undertaking erect pelvis radiography. Thus, the identified position can be used subsequently to evaluate people suffering from hip pain (***Phase One***)
2. To determine the optimum exposure factors (e.g. tube potential) and acquisition conditions (e.g. the use of additional filtration) for erect pelvis radiography. These should promote the low as reasonably practical (ALARP) principle (***Phase Two***)
3. To evaluate the differences in image quality and radiation dose between supine and erect pelvic radiography using clinical data (***Phase Three)***.

1.5 Overview and structure of the Thesis

This thesis is divided into eight chapters (see **Figure 1-2**). These chapters include:

Chapter One- the introduction chapter. This chapter introduces the key issues, the rationale for the work (which also introduces the research being conducted), the thesis aim and the objectives in general terms. The chapter concludes with an overview of the structures of this PhD thesis.

Chapter Two- the background chapter. This chapter includes background information about pelvis anatomy and imaging, and the main pelvic disorders that are reported in the literature and can be affected by repositioning from supine to erect. These disorders are acetabular retroversion, femoroacetabular impingement (FAI), hip dysplasia and osteoarthritis. The chapter will be concluded with a summary.

Chapter Three- the literature review chapter. This chapter provides a review of the literature regarding the effects of repositioning from supine to erect. In this chapter, all the studies that provide a comparison between the two positions, for the different pelvis metrics, will be presented. A critical evaluation of the literature and identification of the knowledge gap will be explored in this chapter. Also, the importance of pelvis tilt on the diagnosis of hip pathologies will be presented. Separate sections for providing information about the repositioning on other body parts and the effect of repositioning on image quality and radiation dose will also be provided in this chapter.

Chapter Four- this chapter will cover the first experimental phase in this thesis. The chapter starts with the aim and objective of this phase. Background information on the methods that will be used for posture evaluation will follow. The literature discussing the effect of different standing positions on pelvic tilt will be provided in order to help understand the methods discussed in this phase. Then, the methods, results and discussion will be given. Finally, the limitations and conclusion from this study will be provided.

Chapter Five- this chapter provides background information for **Chapters 6 and 7**. It gives an overview of the digital X-ray technology used in imaging departments. The radiographic acquisition parameters and their effect on image quality and radiation dose are discussed, as are the methods available for radiation dose assessment. Finally, the methods for evaluating digital radiographic image quality will be explained

Chapter Six- this chapter provides a description of the materials and methods used in Phase Two of this thesis. The aims and objectives for this phase will be provided. This chapter has three different experimental studies (Experiment #1, Experiment #2 and Experiment #3). For each one, the methods, results and discussion will be explored. The chapter will conclude with the limitations and conclusions.

Chapter Seven- this chapter provides the clinical data needed to evaluate the differences between erect and supine. The chapter has subsections including an aim and objectives, methods, results and a discussion.

Chapter Eight- this chapter provides an overall summary of the thesis, highlighting novelty and limitations as appropriate with some recommendations for future work.

Chapter 1 **Introduction**	•Introduction •Rationale, aim and objectives. •Thesis structure.
Chapter 2 **Background**	•Pelvic bone anatomy and imaging •Disorders which imaging apperences are affected by repostioning
Chapter 3 **Literature review**	•The impact of repostiong on PT •The impact of repostioning on the accceatbulum •The impact of repostioning on JSW and CEA •The impact of repostioning on other body part •The impact of repostioning on image quality and radiation dose
Chapter 4 **Evaluation of an optimum standing position for erect pelvis radiography** **(*Phase one*)**	•Aims and objectives •Methods for posture analysis •Effect of diffrent erect postions on PT •Piolt study •Methods •Results •Discussion, Limitations and conclustion
Chapter 5 **Image quality and radiation dose in digital radiography**	•Digital radiography •Radiographic acquestion parameters •Radiation dosemetry •Image qulaity assessment methods
Chapter 6 **Supine versus erect pelvis radiography technique: the effect on image quality and radiation dose using phantom (*phase two*)**	•Aims and objectives •Methods •Results •Discusstion, limitations and conclusion
Chapter 7 **Clinical impact of erect position on image quality and radiation dose** **(*phase three*)**	•Aim and objectives •Study methods •Study results •Discsstion, limitations and conclusion
Chapter 8 **Overall summary, conclusion, limitations and recommendations for future work**	•Overall summery of the thesis •Thesis novality •Limitaions •Recomendations for future work

Figure 1-2: Schematic diagram illustrating the main structure of this thesis

Chapter 2: Background

2.1 Chapter overview

In this chapter the relevant background information on the anatomy and disorders of the pelvis will be provided. The objective of the anatomy section included within this chapter is to provide an overview of the main anatomical components. This is important when considering the imaging challenges for the pelvis- particularly when moving from a supine to an erect technique. Anatomical appearances often change between positions. This may affect the resultant radiological appearances of the pelvis and potentially the diagnosis of pathology. It is, therefore, very important to have a thorough understanding of the anatomy of the hip joint, including the soft tissue structures. It is also important to understand the pelvic metrics used by the clinicians when making comparisons between the two positions. Furthermore, it is vital to draw attention to the hip disorders section in this thesis, which focuses on the pelvic diseases that may be affected by the pelvic positioning. A sound understanding of the standard radiographic techniques, normal anatomy, and patterns of disease that affect the pelvis can be helpful in understanding the effect of positioning on radiographic appearances.

The first section describes the pelvic anatomy and subsequent imaging appearances, along with details about the main pelvic components and how these appear on conventional radiography. This section will be divided into two subsections. The first explores the anatomy of the pelvis and provides some general details on the corresponding soft tissues, ligaments and muscles. The second provides details on pelvic radiography; the positioning, centring and overall technique. Also, within this section there will be an explanation as to how the anatomy mentioned in the previous subsection (**section 2.2.1**) will appear on the resultant radiographic image. An overview of common pelvic and hip disorders will be presented in the next section (**section 2.3**). The focus of this will be on the hip disorders that orthopaedic surgeons are interested in, including acetabular retroversion, FAI, AD and OA. These disorders were found to be the most affected by the different positions (erect vs supine) for diagnosis. In this section the appearances of the pathology on the radiographic images will be explained with the aim being to help provide an understanding of how the erect and supine imaging positions may affect the diagnosis of the different pathologies.

2.2 Pelvic bone anatomy and imaging appearances

2.2.1 Pelvic anatomy

The word pelvis is a Latin derivative meaning for basin. It is situated at the lower part of the abdomen. The pelvis facilitates the bony connections between the vertebral column and the lower extremity (Bontrager & Lampignano, 2013). While standing the weight of the body is transmitted from the spine to the lower limbs through the pelvis. The pelvis consists of four main bones- two hip bones (the ossa coxae, also called the innominate bones), one sacrum and one coccyx (Bontrager & Lampignano, 2013). The sacrum and coccyx are joined with the hip bone posteriorly by the sacroiliac joint, and anteriorly by the symphysis pubis. The pelvic bone contains three distinct fused bones, namely the ilium, ischium and pubis (see **Figure 2-1**) (Heylings et al., 2017).

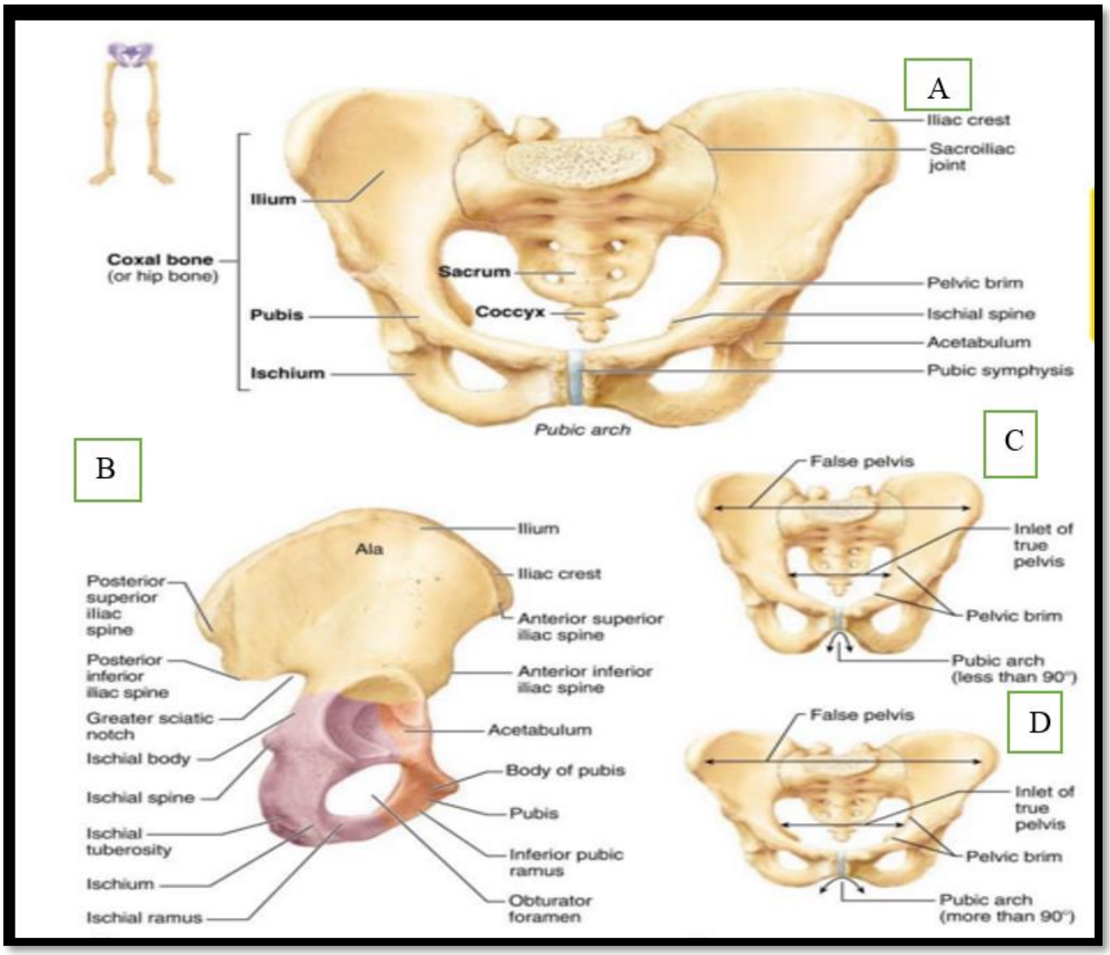


Figure 2-1: A diagram illustrating the anatomy of the pelvis. (A) right hip bone showing the fusion of the ilium, ishim and pubic symphysis (B) comparison between male (C) and female (D) pelvic anatomies (Marieb & Hoehn, 2015).

The ilium is the largest of the three pelvic bones and consists of a body and an ala, or wing. The iliac crest is the most superior part of the ala and it extends from anterior superior iliac spine (ASIS) to posterior superior iliac spine (PSIS). The ischium is the second hip bone, and is located inferiorly and posteriorly to the acetabulum. It consists of the body and ramus. The superior part of the body makes up the posteroinferior two fifths of the acetabulum. Anteriorly from the ischial tuberosity is the ramus of the ischium (Frank, Long, & Smith, 2012; Lewis, Laudicina, Khuu, & Loverro, 2017). The last of the three-main bones of the pelvis is the pubic bone. The two superior rami meet in the midline to form the pubic symphysis joint (Campbell, 2005). The foramen formed by the ramus and each ischial body is called the obturator foramen and it is the largest foramen in the human skeleton (Bontrager & Lampignano, 2013; Cook & Khan, 2008). When the bony pelvis is correctly orientated, the pelvis is tilted forwards. This means the ASIS and the pubic symphysis are at the same vertical plain. To illustrate, when the bony pelvis is positioned against a wall these landmarks would touch the wall (Heylings et al., 2017). The main functions of the pelvic bones mentioned above are to support and protect the organs which sit inside the pelvis and permit movement of the lower extremities.

Within the pelvic cavity there are several muscles that help and maintain movement. On the anterior side of the sacrum, as well as on both sides of it, are the piriformis muscles. The obturator internus muscles extend from the inner part of the hip bone. These two muscles are within the gluteal region and provide the lateral rotation of the hip joint. Muscles which form the floor of the pelvis are the levator ani and coccygeus muscles. The main function of these muscles is to secure the abdomen and pelvic organs inside the peritoneal cavity.

There are several fundamental differences between the male and female pelvis, and these helps to distinguish them on X-ray images. Firstly, the female pelvis is wider, with the ilia more flared and shallower from front to the back. In contrast, the male pelvis is slight, deeper and less flared. So, from a frontal point of view the pelvis has a general difference in shape. Secondly, the angle of the pubic arch, which is the angle immediately inferior to the pubic symphysis, is different for each gender. This angle for the female pelvis is more than 90°, whereas in men it is typically less. The third difference is the shape of the pelvic inlet. For females it is larger and likely to be round in shape; in contrast men have a narrower and oval or heart shaped pelvic inlet (Colbert, Ankney, Lee, Steggall, & Dingle, 2012; Kurki, 2011; Logan, McCarthy, & Parkin, 2007; Marieb & Hoehn, 2015). The shape of the pelvis also differs from one individual to another. This means that the pelvis of a slim female may appear similar to the pelvis of male. However, the differences between the genders are quite obvious, and thus easily distinguishable on pelvic X-ray images (see **Figure 2-2**) (Logan et al., 2007)

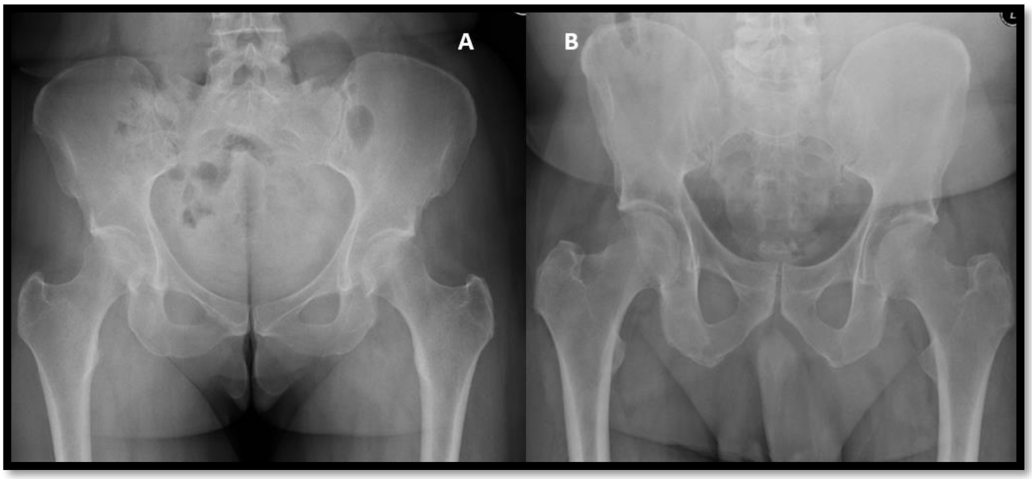


Figure 2-2: Illustrates the main differences between X-ray images of the female (A) and male (B) pelvis.

The hip joint is an extremely important part of the pelvis, providing the articulation between the upper part of the body and the lower limbs. It is vital to maintaining an upright position and a normal human gait. The hip joint supports most of a person's body weight, and the muscle that support this joint acts mainly at the centre of the joint (Cailliet, 2004). The hip joint consists of two main areas, namely the acetabulum (concave) and femoral head (convex) (see **Figure 2-3**). These two structures are symmetrical and have such a construction as to adapt to both standing and walking. The joint space is equal at all points, with minor deviations to allow for adequate lubrication. The acetabulum forms a cavity that permits the femoral head to rotate around a fixed axis. The acetabulum has a thick capsule which is horseshoe-shaped and coated with a cartilage (Cailliet, 2004; Molini, Precerutti, Gervasio, Draghi, & Bianchi, 2011; Noble, Dwyer, Gobba, & Harris, 2017).

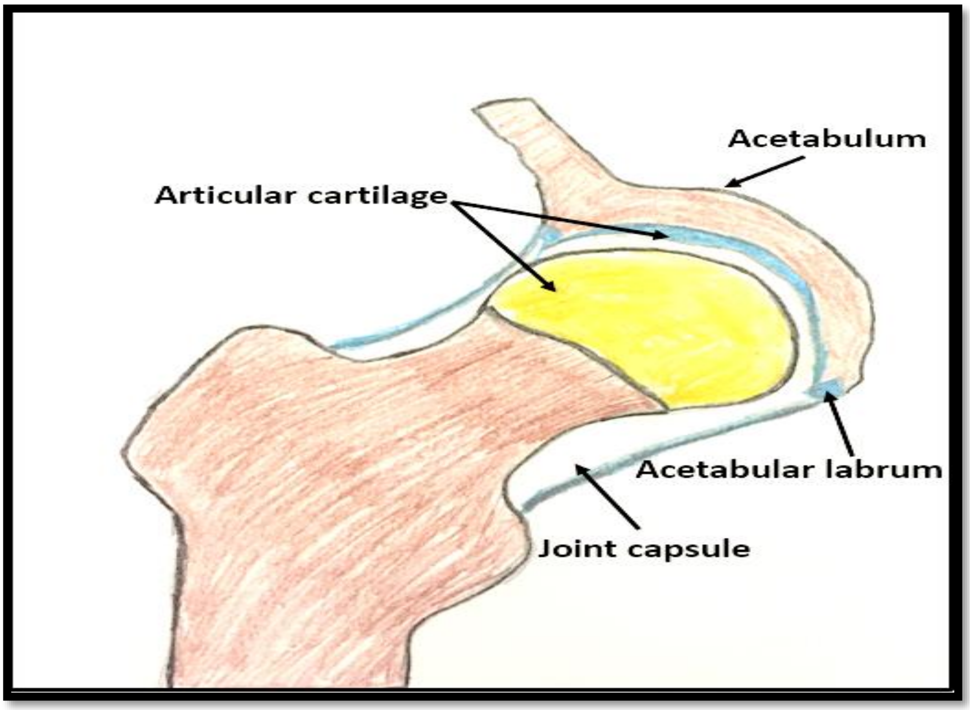


Figure 2-3: Illustrates the main parts of the hip joint, acetabulum, the main ligaments and the femoral head.

The proximal femur consists of four main parts- the head, neck and greater and lesser trochanters. The head is ball shaped and it articulates with the acetabulum. The femoral head is coated with cartilage which provides protection and lubrication for the joint. A normal articulation between the femur neck and acetabulum forms a 130° anteriorly (see **Figure 2-4**). The lesser trochanter is a pyramidal prominence that is located on the medial side of the femur. Finally, the greater trochanters form a great prominence on the lateral shaft of the femur (Bontrager & Lampignano, 2009; Frank et al., 2012; Whitley, Jefferson, Hoadley, & Sloane, 2005).

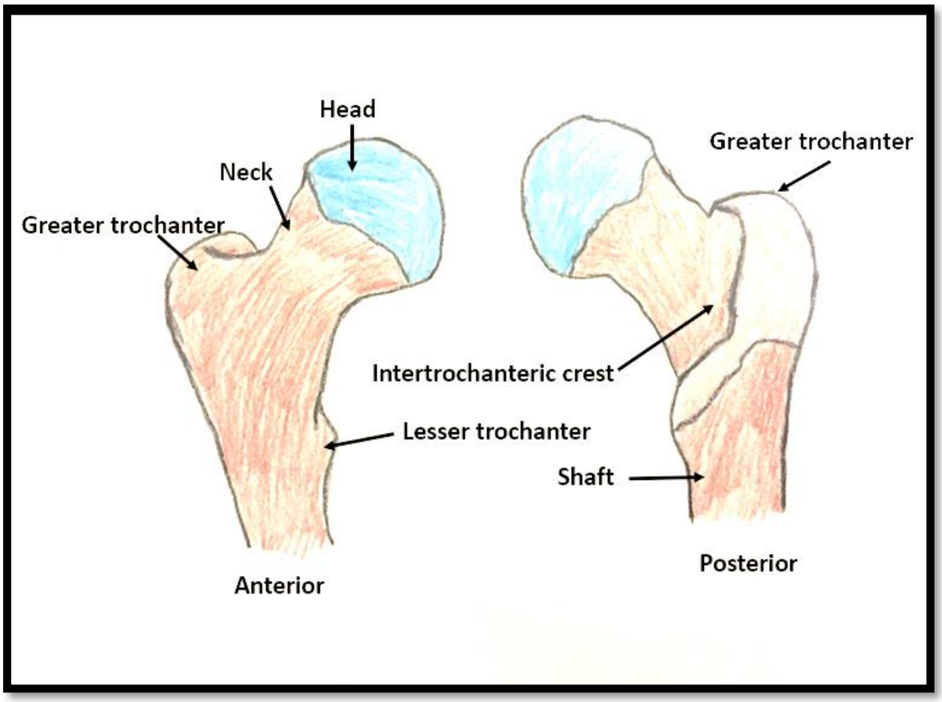


Figure 2-4: An illustration of the proximal femur and its main components.

The pelvis has many bony prominences that act as bony landmarks when undertaking pelvic X-ray imaging. Such landmarks are described as follows (Whitley et al., 2005):-

- The pubic symphysis (PS), which is located anterior to the bladder and is aligned with the coccyx
- The anterior superior iliac spines (ASIS), which are level with the second sacral segment
- The posterior superior iliac spines (PSIS), which are level with the sacroiliac joints
- The iliac crests (IC), which are located at the level of the disc space between lumbar vertebrae four and five.

2.2.2 Anteroposterior (AP) pelvic radiography

Traditionally, for conventional anteroposterior (AP) radiography of the pelvis, the patient must lie on his/her back (supine) symmetrically, which means the medial sagittal plane should be perpendicular to the table top. The midline of the patient must align with the central ray and the centre of the table receptor Bucky. To minimise rotation of the pelvis, the ASIS must be equidistant from the table top. When the femur is in its true anatomical position, the femoral neck is rotated by 15° to 20°, thus the neck appears short and the lesser trochanter is visible. To avoid this, the legs should be slightly abducted and rotated internally by 15° to 20°. Using this technique, the maximum length of the femoral neck is visualised, allowing the femoral neck and the image receptor to be in a parallel position. This, results in an adequate AP view of the proximal femur (Bontrager & Lampignano, 2013; Gold et al., 2016) . The radiographic centring point in the literature is at the mid-point of the distance between the pubic symphysis and the line connecting the ASIS (Albers et al., 2016; K. Alzyoud, Hogg, Snaith, Flintham, & England, 2019; Manning-Stanley, Ward, & England, 2012; Scheidt, Galia, Diesel, Rosito, & Macedo, 2014; Whitley et al., 2005; Yun et al., 2018) (see **Figure 2.5**). However, there are another centring points that have been used by researchers (Pierrepont et al., 2017; Tamura et al., 2015; Uemura et al., 2017) (see **Table 2-1**). A literature review concerning radiographic positioning, has demonstrated various techniques/centring points for supine AP pelvis examinations (see **Table 2-1**). While this examination is considered to be a basic projection for pelvic radiography, the available literature that is widely used in educational and clinical departments demonstrates a diversity of approaches for pelvic radiography (Snaith, Field, Lewis, & Flintham, 2019). Variations in the supine position itself are seen in the literature (see **chapter 3**). Moreover, these text books were reviewed to assess the availability of erect pelvis radiograph positioning along with any other valuable information about the radiation technique that possibly can be considered during this thesis. This was necessary, as the erect AP pelvis position has been used by the researchers in the literature.

Table 2-1: A review and summary of the textbooks describing the radiographic positioning and centring for supine pelvic radiography.

Title/author(s)	Year	CP	SID	Patient Position	Exp. Factors	Comment
Clark's Positioning in Radiography (Whitley et al., 2005)	2005	Midline midway between the upper border of the pubic symphysis and the anterior superior iliac spines (ASIS)	Not provided	The patient lies supine, limbs slightly abducted and internally rotated	Not provided	The internal rotation angle is not specified. There is no description of the upper arm position. The erect position is not described
Merrill's Atlas of Radiographic Positions & Radiologic Procedures (Ballinger & Frank, 1999)	2003	About 2 inches (5 cm) inferior to level of ASIS and 2 inches superior to pubic symphysis	48 inches	Patient supine and lower limbs rotate 15-20º. The heel should be 8-10 inches apart	70 kVp	There is no description of upper arm position. The erect position is not described
Textbook of Radiographic Positioning and Related	2014	2 inches (5 cm) inferior to level of ASIS	102 cm	Supine, with arms placed at their sides or across superior	80 to 85 kVp	May be performed erect with correction of lower limbs to rotate proximal

Anatomy(Bontrager & Lampignano, 2014)				chest. Separated legs and feet, which are internally rotated along the axes of feet and lower limbs by 15° to 20°		femora into anatomical position where no fracture is suspected. The erect position is not described
Diagnostic Radiography a Concise Practical Manual (Bryan, 1987)	1987	2.5cm above the pubic symphysis	Not provided	Feet separate slightly and medially rotated by 30º	100 kVp or more	The erect position is not described
Medical imaging Techniques, Reflection and Evaluation (Carver & Carver, 2012).	2012	Midline midway between the upper border of the pubic symphysis and ASIS	115 cm	Supine, arms raised to pillow level, with legs slightly internally rotated	Minimum 70kVp	When imaging large people using more than 115 cm SID is recommended. The erect position is not described
CP: centring point; SID: source to image distance						

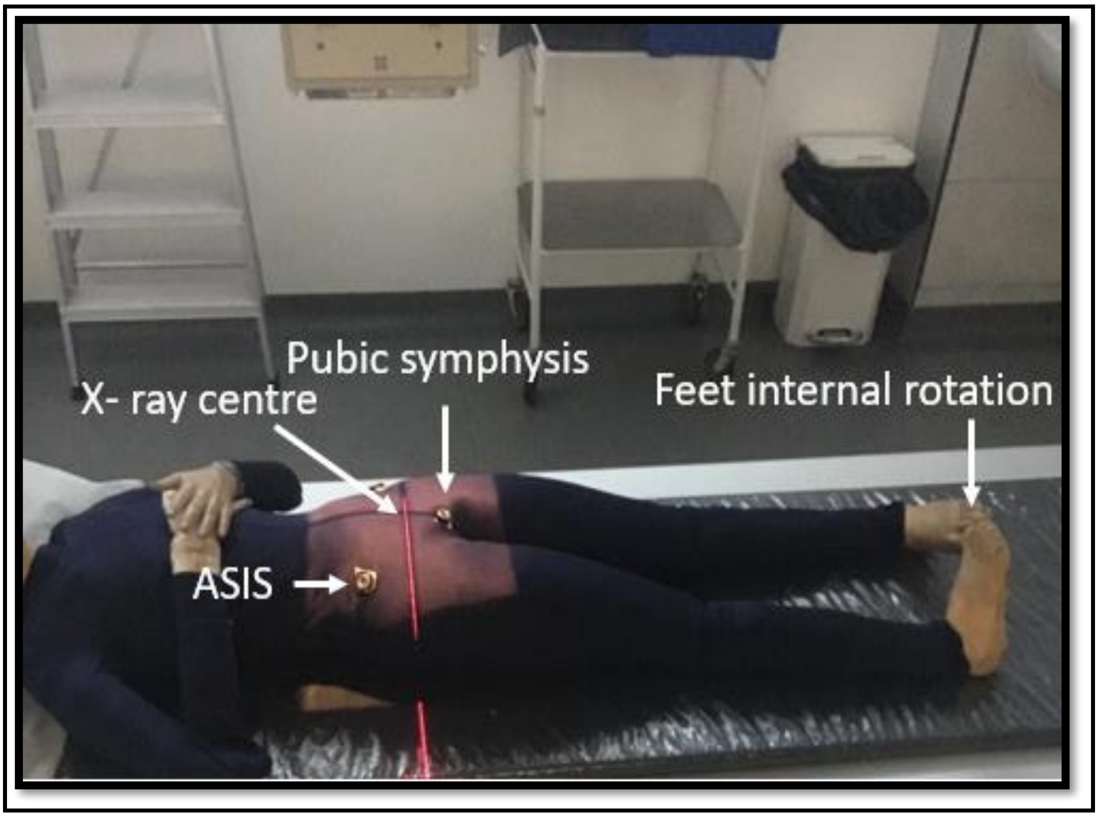


Figure 2-5: AP positioning for a supine pelvic X-ray image. The patient is lying down on their back with their feet internally rotated.

The essential radiographic anatomical characteristics of an AP pelvic X-ray image are illustrated in **Figure 2-6**. This figure includes both iliac crests, proximal femora, and the greater and lesser trochanter. The iliac bone should be equal in dimension and the obturator foramina must be symmetrical in size and shape. These features must be considered when imaging the pelvis and confirm the pelvis has been positioned with no rotation during imaging (Ballinger & Frank, 1999; Lim & Park, 2015; Whitley et al., 2005)

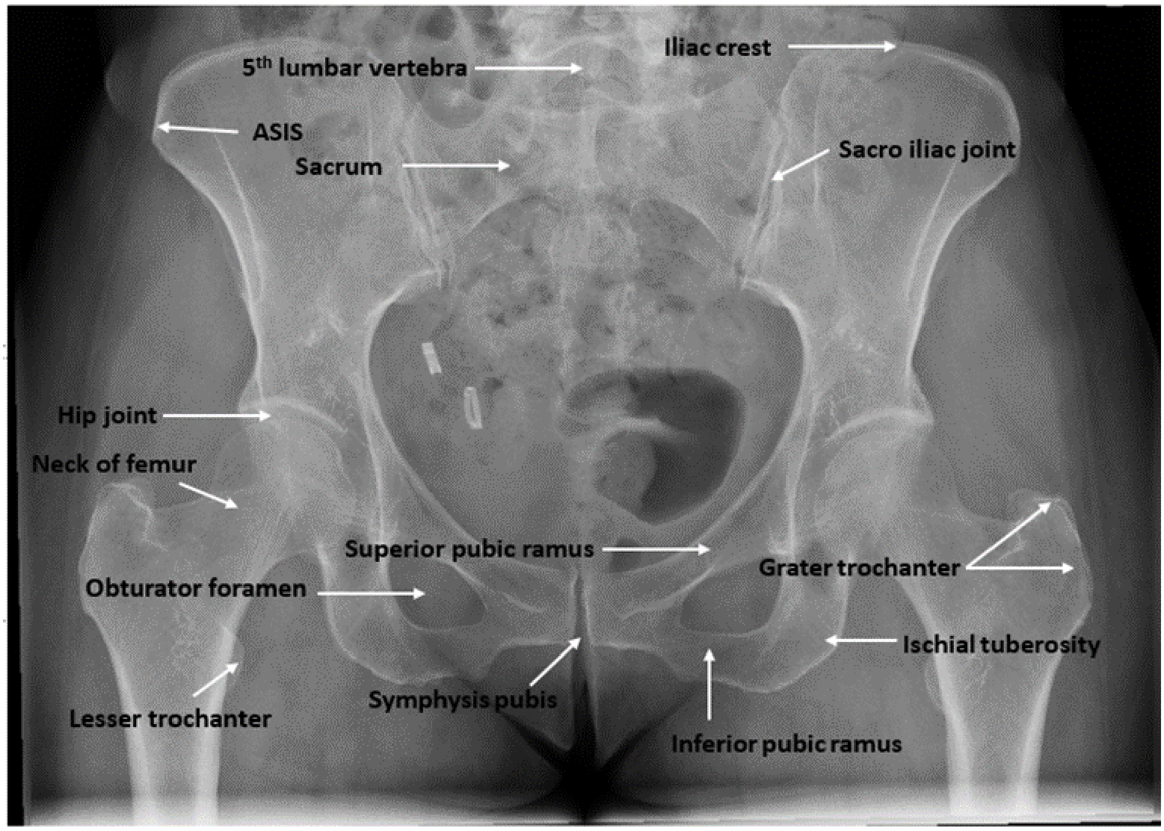


Figure 2-6: Radiological anatomy as seen on the AP pelvic X-ray image.

Different lower limb positions produce different radiological appearances on pelvic X-ray images (Whitley et al., 2005). For instance, an image acquired using a neutral rotation of the lower limb makes the femoral neck appear in an oblique position and the lesser trochanter is only “just visualised”. With internal rotation of the lower extremity, the femoral neck becomes enlarged and appears parallel to image receptors, and the lesser trochanter is obscured by the femur. For external rotation, the femoral neck is shortened, and the lesser trochanter appears more clearly (Bontrager & Lampignano, 2009; Whitley et al., 2005). These different radiographic appearances, that are associated with different feet positions, demonstrate of the importance of understanding the effect of feet positioning while imaging people for pelvis radiographs in the erect position. This is more important after the findings which have proven that the foot rotation is related to JSW measurements in the knee, and that the minimum joint space in the hip may be altered by modifying foot rotation (Buckland Wright, 1998; Lynch, Buckland-Wright, & Macfarlane, 1993).

There are several radiographic lines that are associated with pelvic radiography and imaging criteria, and these are often used by clinicians when assessing their patients (see **Figure 2-7**). Firstly, Shenton’s line, which is the line from the inferior border of the femoral neck to the lower border of the superior pubic ramus. In normal cases (without injury or OA) and good pelvis positioning, it should appear symmetrical on both sides. Secondly, the teardrop sign, which forms the floor of the acetabulum and consists of the medial portion of the acetabulum laterally and the antero- inferior of the quadrilateral plate medially (Waldt, Eiber, & Woertler, 2013). Thirdly, the ilio - pubic line, which forms the anterior margin of the acetabulum. Fourthly, the ilio- ischial line, which forms the posterior margin of the acetabulum.

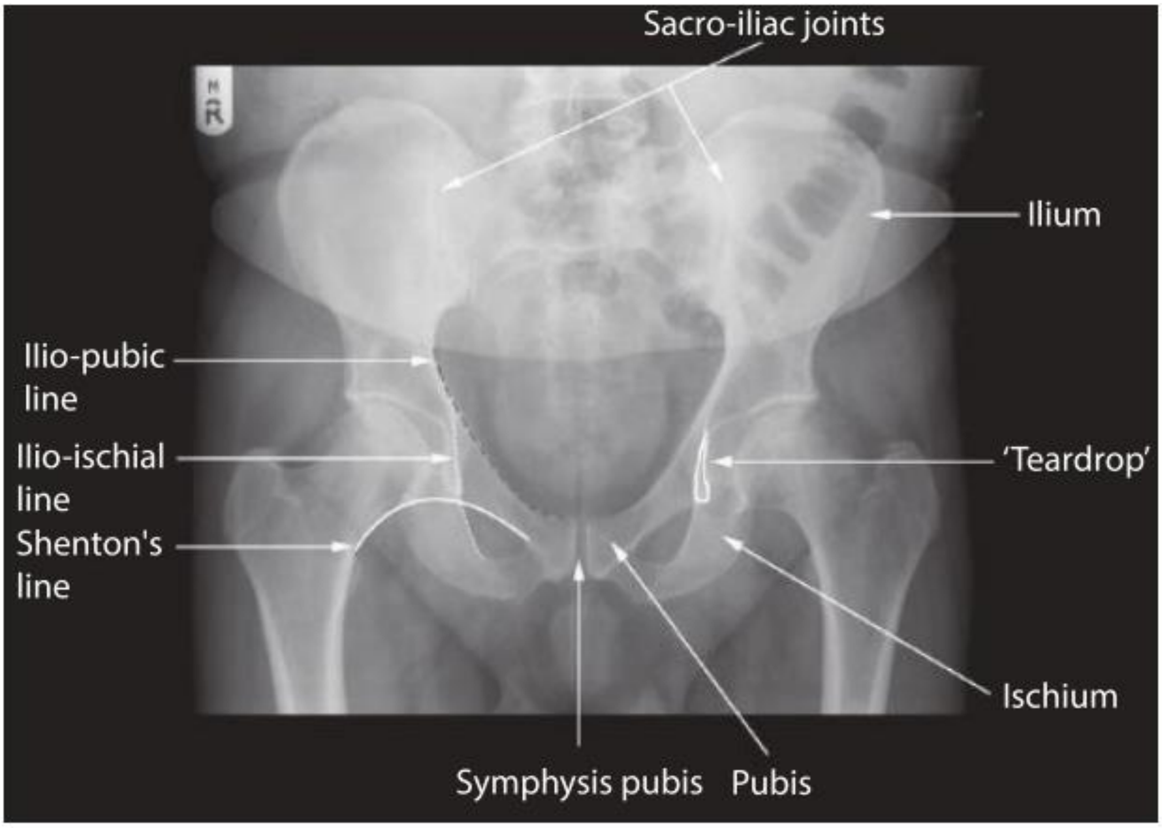


Figure 2-7: Schematic diagram of an AP pelvic X-ray image labelled with a series of radiographic landmark lines (Whitley et al., 2005).

2.2.2.1 Exposure factors and imaging conditions

Exposure factors should be carefully selected to reduce the radiation dose administered to the patient. Literature reports that the tube potential (kVp) of 80-85 kVp is recommended, along with 100 SID and no additional filtration (C. T. P. Chan & Fung, 2015; European Commission, 1996; Manning-Stanley et al., 2012; Seeram, Davidson, Bushong, & Swan, 2016). When combined with a low mAs, this helps maintain a lower radiation dose [national dose reference level NDRL: entrance surface dose 10 mGy, with a mean of 2.86] (Shandiz, Toossi, Farsi, & Yaghobi, 2014; Whitley et al., 2005). However, high kVp decreases the contrast, which is not ideal for patients who may have lost bone mass (Bontrager & Lampignano, 2013). Using high kVp increases the penetrating power of the X-ray photons and this in turn decreases the visibility of bony detail. The minimum collimation necessary to irradiate only the relevant parts under investigation should be used. The selection of exposure factors should follow the ALARP principle (as low as reasonably practicable) for obtaining a diagnostic image. It should be noted that the above expected DRL and ESD are for pelvis x-ray images that are acquired in a supine position as there was no available information in the literature, or in text books, documenting the recommended radiation dose for the erect position.

2.3 Disorders which imaging appearances are affected by repositioning from supine to erect

The aim of this section is to provide a background for the major pathologies which affect the pelvis and hip joint. The subtle diagnostic appearances on radiographic images and how changes in position (erect from supine) can affect the presence or absence of radiological features or signs are also included.

2.3.1 Acetabular retroversion (AR)

Acetabular morphology is an important prognostic indicator for hip pathologies (Fowkes, Petridou, Zagorski, Karuppiah, & Toms, 2011). In normal hips, the acetabular opening is anteverted in the sagittal plane. This allows impingement free motion, for example internal rotation, adduction and flexion (Kappe et al., 2011). For AR, the opening of the acetabulum is retroverted from the sagittal plane (there is a posterior orientation of the acetabular aperture) (see **Figure 2-8**). This leads to a reduction in clearings between the femoral head/neck junction and the anterior wall of the acetabulum during even small degrees of flexion and internal rotation. This produces lesions of the anterior labral cartilage (Reikeras, Bjerkreim, & Kolbenstvedt, 1983). AR is an early sign of the FAI (Siebenrock et al., 2003) and AD (Li & Ganz, 2003; Mast, Brunner, & Zebrack, 2004). Also, it has been reported as being able to provide a high contribution to the development of OA (Ganz et al., 2003; Giori & Trousdale, 2003; W. Kim, Hutchinson, Andrew, & Allen, 2006; Li & Ganz, 2003; Menke, Schmitz, Schild, & Köper, 2008; Reikeras et al., 1983; Reynolds, Lucas, & Klaue, 1999; Tönnis & Heinecke, 1999). Up to 48% of the population may be affected by AR (Werner et al., 2008).

Figure 2-8: CT scan of the hip. The acetabulum opening in a normal anteverted position with the sagittal plane (A), the acetabulum in retroverted opening (B). The image adapted from (Reynolds et al., 1999).

Conventional radiography is still the gold standard for diagnosing acetabular retroversion and the radiographic signs for this have been well described (Dandachli et al., 2009; Reynolds et al., 1999). However, the radiographic assessment of acetabular versions presents challenges, since the inadequate standardization of the radiographic technique can affect the diagnosis (Eckman et al., 2006; Nishihara, Sugano, Nishii, Ohzono, & Yoshikawa, 2003). For instance, pelvic tilt affects the presence or absence of the radiographic signs of AR. Furthermore, visualization of the presence of signs of AR is highly dependent on patient position and radiation beam orientation since malrotation of either the patient or the X-ray beam has been shown to have a high influence on the appearance of the AR signs on radiographs (Dandachli et al., 2009; Siebenrock et al., 2003). Therefore, judging acetabular retroversion requires a precise radiographic technique and a well understood procedure (Kappe et al., 2011). Reviewing the literature, different and inconsistent radiographic techniques were identified (see chapter 3).

Using CT can help in the diagnosis of acetabular retroversion and has been introduced as a supplementary method (Dandachli et al., 2009; Reynolds et al., 1999). However, CT scans are expensive and are not often used as a primary diagnostic tool, but instead are used alongside conventional methods. This has the potential to expose patients to a higher radiation dose. Moreover, as with conventional radiography, the effect of positioning may affect its reliability. Due to the nature of CT scans, the standard positioning of the pelvis cannot be evaluated because the imaging of the acetabulum is depicted within thin ‘slices’ (Jamali et al., 2007; Werner et al., 2010).

There are three main radiographic signs that have been used by clinicians to identify acetabular retroversion on conventional pelvic X-ray images. These include the cross-over sign (COS), posterior wall sign (PWS) and prominent ischial spine sign (PRIS) (Kalberer, Sierra, Madan, Ganz, & Leunig, 2008; Kappe et al., 2011; Siebenrock et al., 2003). These signs are easy to apply, even for inexperienced clinicians (Werner et al., 2010). Of these three, the COS and PWS indicate insufficient posterior femoral head coverage (Reynolds et al., 1999). The COS occurs when the most proximal anterior acetabulum rim appears lateral to the posterior rim, and appears as a figure of eight on pelvic radiography. It typically suggests acetabular retroversion (see **Figure 2-9**)(Jamali et al., 2007).

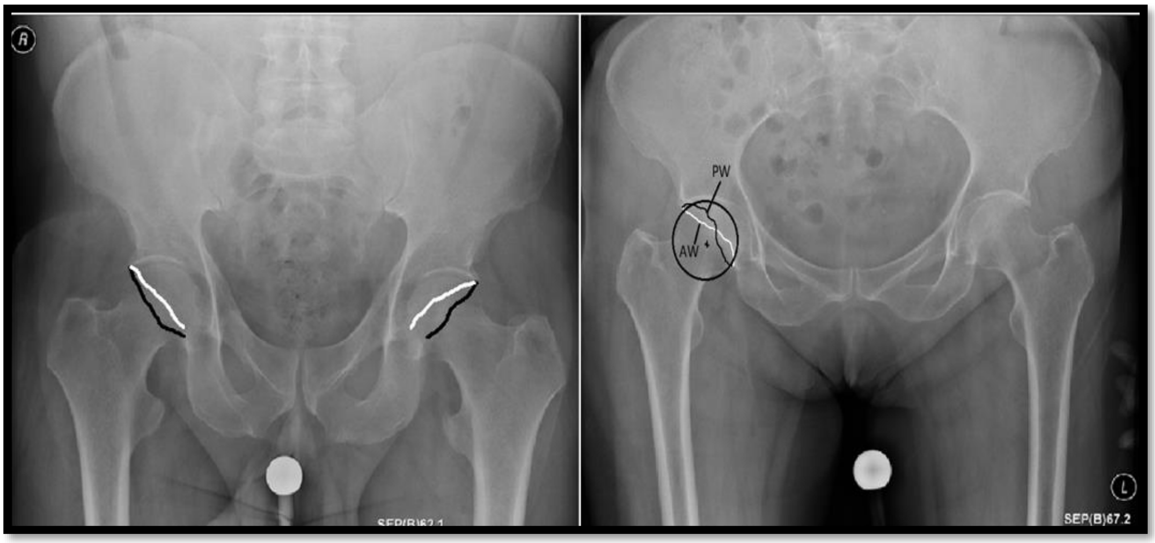


Figure 2-9: (A) normal hip without COS appearances (hip anteversion). (B) pelvic radiograph indicates COS (figure-of-eight sign) as the anterior wall [white (AW)] located medial to the posterior wall [black (PW)].

PWS was described by Reynolds et al. (1999) as the second sign. It accounts for the relation of the centre of the femoral head to the posterior wall of the acetabulum. In normal anteverted hips, the edge of the posterior wall travels through the centre or lateral of the femoral head. It is considered to be positive (the sign being present) on pelvic radiographs when the centre of the femoral head is positioned lateral to the posterior acetabular border (see **Figure 2-10**) (Reynolds et al., 1999**.**

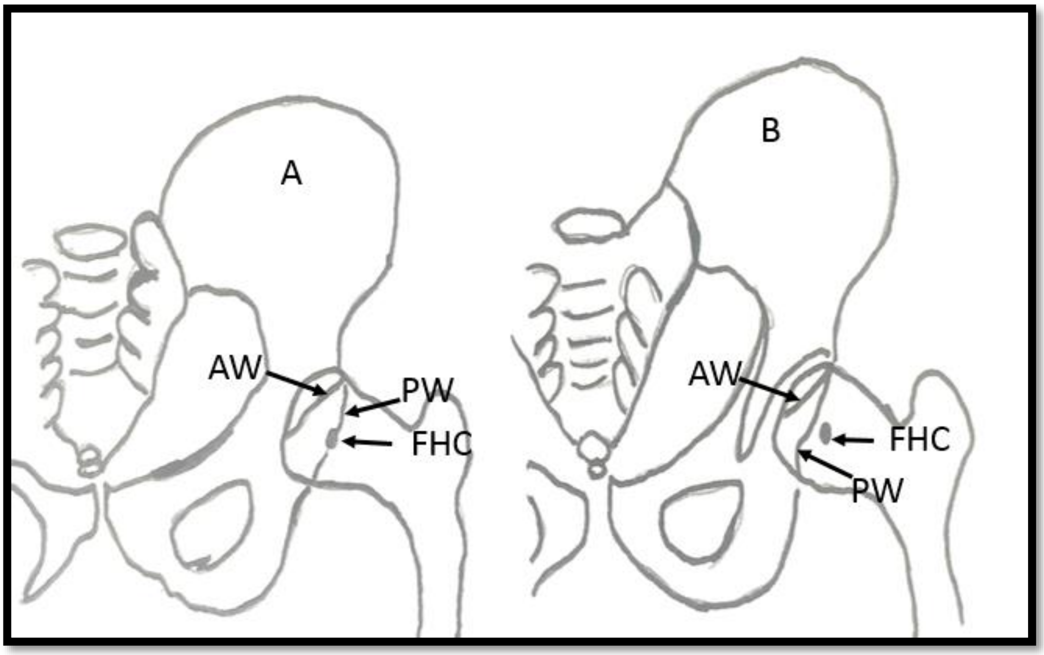


Figure 2-10: Illustrates the PWS. (A) normal hip with Posterior wall (PW) passes through the femoral head centre (FHC). In the hip with the PWS, the femoral head centre is lateral to the posterior wall.

Recently, the prominence of the ischial spine sign (PRIS) was introduced by Kalberer et al. (2008) to evaluate acetabular retroversion see (**Figure 2-11)**. In pelvic radiography, acetabular retroversion is considered to be positive when the medial prominence of the ischial spine is projected inside of the pelvic brim. This sign shows excellent sensitivity, reproducibility and reliability when identified by observers (Werner et al., 2010).

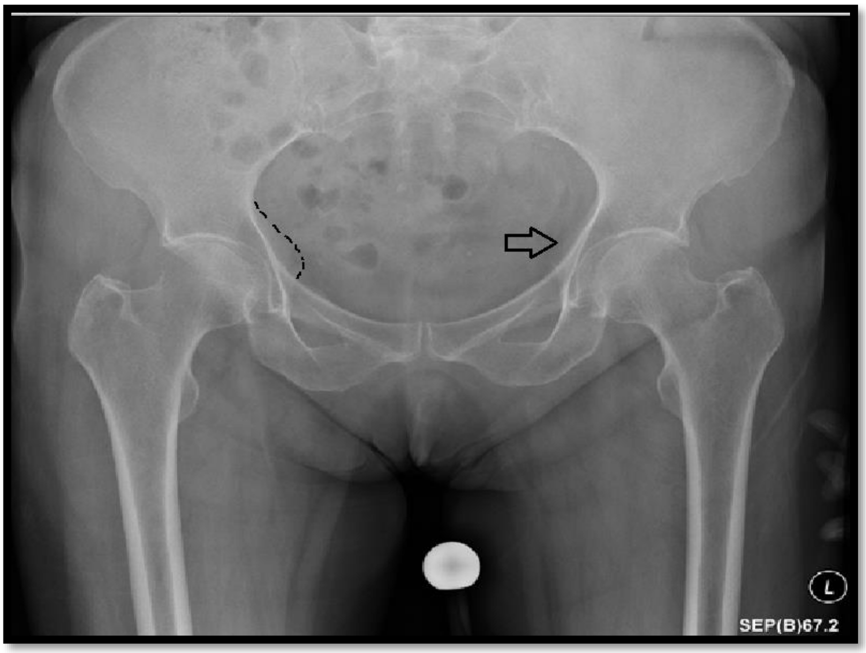


Figure 2-11: Pelvis radiograph of a patient presenting with positive PRISS at both sides (black dotted curve and arrow).

2.3.2 Femoroacetabular Impingement (FAI)

FAI is also known as "acetabular rim syndrome'' (Klaue, Durnin, & Ganz, 1991) or "cervicoacetabular impingement '' (Ganz, Bamert, Hausner, Isler, & Vrevc, 1991). In young and active individuals, it is the major cause of primary OA (Ganz et al., 2003; Jäger, Wild, Westhoff, & Krauspe, 2004; Murphy, Tannast, Kim, Buly, & Millis, 2004; Tanzer & Noiseux, 2004). It typically affects young people in their 20s and 40s (Beck et al., 2004; Ganz, Leunig, Leunig-Ganz, & Harris, 2008; Ganz et al., 2003; Leunig, Beaulé, & Ganz, 2009). In clinical examinations, the main symptoms of people who suffer with FAI is groin pain during hip rotation, whilst in the sitting position or during / after activity. Early detection of changes within the joint is vital and extremely important (Steppacher et al., 2015; Yun et al., 2018). It is better if the impingement is eliminated as early as possible, and for this reason surgical reconstruction of the hip joint is recommended promptly when early pain occurs (Beck et al., 2004; Murphy et al., 2004). Optimal radiographic positioning should be used for the early detection of FAI. Suboptimal or poor radiographic technique could lead to the underestimation of FAI or to an incorrect diagnosis (Tannast, Zheng, et al., 2005).

There are two main types of FAI- namely pincer impingement and cam impingement (Eijer & Hogervorst, 2017). Pincer impingent is linked to the anatomy of the acetabulum (see **Figure 2-12**). It may be primary and arise from acetabular retroversion, which is shown by COS on an AP pelvic X-ray image. It could also be secondary due to the excessive coverage of the femoral head by the acetabulum.

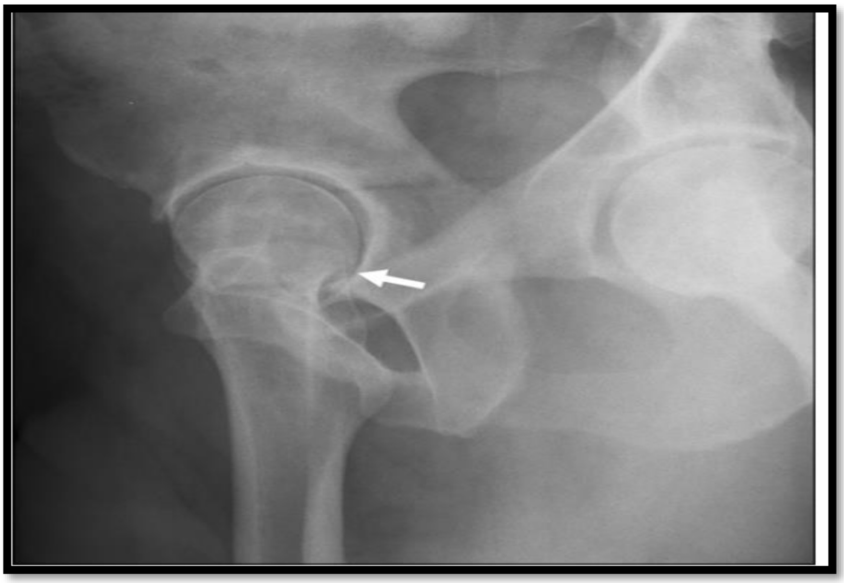


Figure 2-12: X-ray image demonstrating pincer impingement (Tannast et al., 2007).

Cam impingement describes the asphericity of the femoral head, and this leads to an abnormal contour of the femoral head junction (see **Figure 2-13**). Cam impingement is quantified by the alpha angle. This is acquired by drawing a line between the narrowest part of the femoral neck to the centre of the femoral head (the femoral head should be defined by a well-fitting circle). The alpha angle is the angle between the line passing through the femoral neck axis and the line connecting the centre of the head with the beginning of the asphericity of the head–neck contour. An X-ray image with an alpha angle exceeding 50° is considered to be an indicator for an abnormal shape of a head neck junction (Tannast et al., 2007).

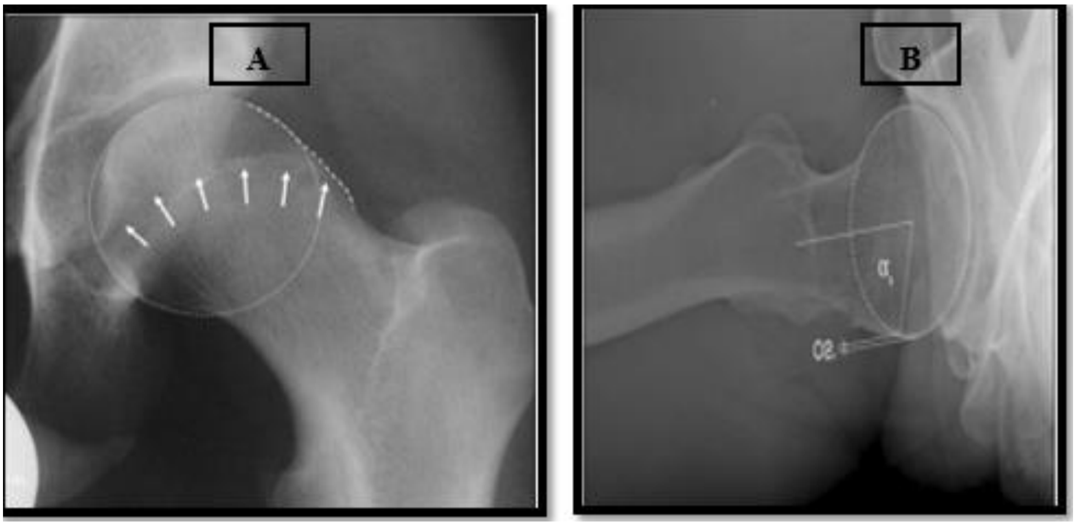


Figure 2-13: An example of a hip with cam impingement (A). (B) Alpha angle is more than 50º in cam impingement (Tannast et al., 2007).

Routinely for FAI, an AP pelvic projection and lateral view of the affected hip X-ray images are required (Philippon et al., 2007; Tannast et al., 2007). Morphological abnormalities and degenerative changes can be identified on these images. However, x- ray images must be of adequate quality for standardizing the various measurements. Evaluation of the images for quality and positioning of the patient is essential for the radiographic assessment of the hip. Moreover, quality radiographs are essential for obtaining the accurate measurements necessary for the comprehensive and quantitative assessment of a potential hip arthroscopy patient.

2.3.3 Hip (Acetabular) Dysplasia (AD)

AD is a type of anatomical abnormality in the hip. In AD there are specific changes in the morphology of the acetabulum. Klaue et al. (1991) reported that in AD the weight bearing surface of the acetabulum becomes shallow and steeply orientated. AD occurs as a consequence of childhood developmental hip dysplasia (DDH). It can also occur in adolescence or early adulthood in patients with no previous history of hip disease (Tonnis & Remus, 2004). The late stage of AD is the development of OA (more details about osteoarthritis will be provided in the next section).

In general, AP pelvis X-ray images provide the most diagnostic information about the acetabular morphology. Different projections provide different information about the structural anatomy of people who suffer from hip pain. So, image quality for each radiographic projection is highly technique-dependent. This means that variability in patient positioning can ultimately affect the accuracy of structural abnormality diagnosis (Clohisy et al., 2008). To illustrate, according to the studies of (Troelsen et al., 2008), there was an increase of 2cm in the distance between the pubic bone (PB) and the sacrococcygeal joint (SCJ) (this distance directly correlates to pelvic tilt) in the supine position compared with the erect position. Also, these changes are more pronounced in females than males, which, according to Tanest et al (2006), correlates with pelvic tilt changes. These were from 14° in females and 7° in males (Tannast et al., 2006) (see **Figure 2-14**).

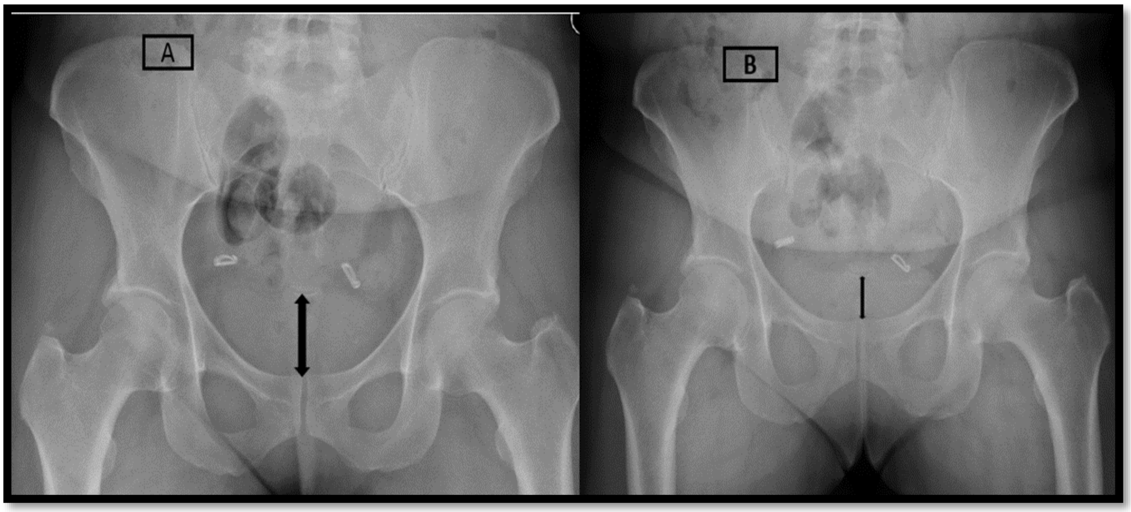


Figure 2-14: AP pelvic X-ray images for the same patient in (A) supine and (B) erect. The black arrow demonstrates the change in the distance between the sacrococcygeal joint and pubic symphysis.

There are three main radiographic measures on AP pelvic X-ray images that have been commonly used for screening and monitoring hip dysplasia. These include lateral central edge angle (CEA) (Wiberg, 1939), acetabular roof or acetabular index (AI), "Tönnis angle" (Tönnis, 1987) and Shenton's line (Shenton, 1911). The lateral CEA is the angle of the intersection between the horizontal line connecting the centre of the femoral heads to the lateral rim of the acetabulum, and the transvers pelvic axis (the line perpendicular to the vertical axis of the sacrum or line perpendicular to the line connecting the femoral head centres) (see **Figure 2-15**). A normal lateral CEA ranges from 25° to 35°, and an angle less than 20° is considered to provide evidence of AD in the hip (Wiberg, 1939).

The Tönnis angle is the angle formed by a parallel line directed to the transverse pelvic axis and a line connecting the most medial and lateral margins of the acetabulum. The normal range of the acetabulum roof angle is from 0° to 10°, while one with more than 10° is considered to be indicative of a dysplastic hip (Tönnis, 1987) (see **Figure 2-15**). Shenton's line in normal hips appears as a smooth contour from the superior obturator ring along the inferior surface of the femoral neck. Patients are diagnosed with a dysplastic hip if there is more than 5 mm of distraction in this line, indicating femoral head subluxation (Cooperman, Wallensten, & Stulberg, 1983).

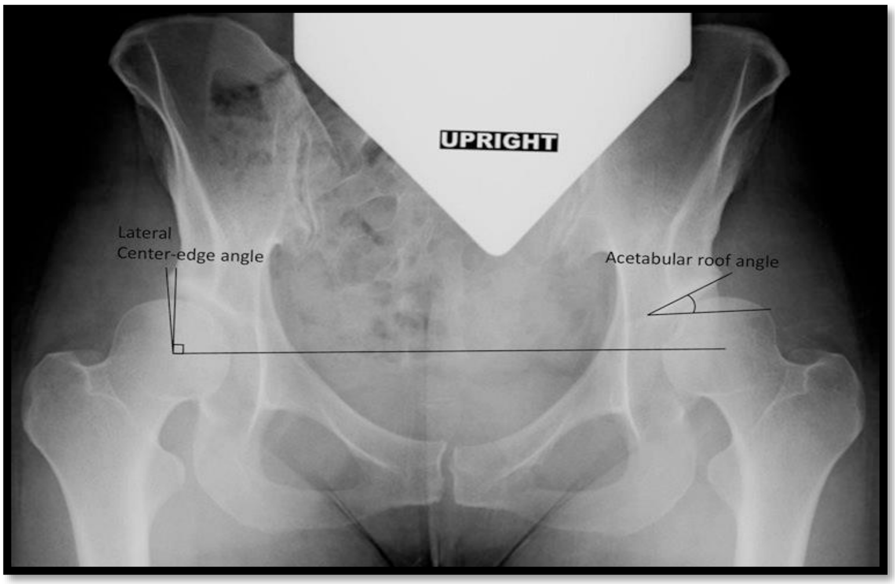


Figure 2-15: Erect pelvic radiography illustrating the methods for measuring lateral CE angle and Tönnis angle. In this patient, the lateral CE angle is small and the acetabular roof angle is shallow which indicates a dysplastic hip (C. B. Lee & Kim, 2017).

2.3.4 Osteoarthritis (OA)

When considering sources of pain associated with hip joint disease, osteoarthritis is an important source. It is also a major cause of disability and has a negative socioeconomic impact in middle aged and elderly people (Gerhardt et al., 2012; Glyn-Jones et al., 2015; Herr & Titler, 2009; Iorio et al., 2008; C. Kim et al., 2014; Skendzel et al., 2013). OA is a clinical condition in which different joints of the body, such as the knees and hips, become damaged. The cartilage that coats the articulating bony regions becomes roughened and thin.

Moreover, the bone underlying this cartilage becomes thicker and grows into the joint space, forming bony spurs which leads to a decrease in width of the joint. The inner layer of the joint capsule also becomes thicker and generates more fluid. This leads to joint swelling, in which the capsule and ligament around the joint become thickener and shrink (Arthritis Research, 2013).

The causes of OA are not fully understood, however there are many factors which could increase the risk of developing OA. Cartilage damage caused by unnecessary and repeated loading (such as in obesity) and stresses on the joint (such as injury) over time are the main causes of OA (D. Chen et al., 2017; Glyn-Jones et al., 2015). Another cause is related to genetic factors, which make some people more likely to develop OA than others (Zeggini et al., 2012). There are many other risk factors for OA, including age, gender and bone density (Arthritis Research, 2013; Blagojevic, Jinks, Jeffery, & Jordan, 2010; Conde et al., 2011; Glyn-Jones et al., 2015; Hochberg, Yerges-Armstrong, Yau, & Mitchell, 2013; Segal et al., 2010; Zhang et al., 2010).

The major factor making the hip joint one of the most common sites for OA is that the hips support body weight during standing and walking. This exposes the joint to physical stress over a person's life span. It can develop on one side or both sides, at the same time, or on each side at a different time. The pain that develops from hip OA decreases a person's quality of the life, and this could make walking and sleeping difficult. Variations in the changes to the joint structures produce different levels of pain. Small changes in the hip joints may result in intense pain, while modest changes may cause tolerable pain (Bedson & Croft, 2008; National Clinical Guideline Centre (UK)., 2014). Moreover, there is a lag between the physical symptoms and changes appearing on radiographic images. For instance, Miller et al. (2001) discovered that about half of knee OA cases have radiographic changes and significant symptoms (Miller, Rejeski, Messier, & Loeser, 2001). Thus, not all the people who have severe pain have radiographic changes (Richard & Loeser, 2010).

Narrowing joint space width (JSW) is the most sensitive parameter for detecting and diagnosing OA, as it measures the cartilage loss at the narrowest point on the X-ray image (R. D. Altman et al., 1987; Croft, Cooper, Wickham, & Coggon, 1990) (see **Figure 2-16)** . The narrowest point of JSW for a normal hip range from 2 to 5mm, and there were no differences between the right and left side. AP radiographs may be obtained either in supine or erect positions (Pessis et al., 1999), and the accurate measurement of JSW can be obtained in both. However, erect X-ray images may provide more precise information about cartilage thickness since this exposes the patient to the effect of loading (Marsh et al., 2013). In addition, it has been shown that JSW on erect X-ray images provides a more accurate evaluation in patients with dysplasia (K. Okano, Kawahara, Chiba, & Shindo, 2008). Gold et al., (2016) recently argued that foot rotation maps can support position reproducibility and should be used when undertaking standing views of the pelvis (Gold et al., 2016). This recommendation has been suggested previously by Auleley et al., (2001) when a special foot plate for improving reproducibility during radiography was developed (Auleley, Duche, Drape, Dougados, & Ravaud, 2001).

Figure 2-16: Pelvis radiograph illustrates JSW. Normal joint space (left) and joint space narrowed due to OA (right) (Lim & Park, 2015).

Using imaging can help in the early detection and diagnosis of OA (Gold et al., 2016). The acquisition methods and techniques include conventional radiography, MRI, CT and ultrasound (US). Conventional radiography is still the gold standard and traditional method for OA evaluation. This is due to many reasons including it is availability, cost, relatively low radiation dose, it is being easy to obtain, and that evaluating the findings from the X-ray images is relatively simple when compared with the other more complicated imaging modalities (Glyn-Jones et al., 2015; Gold et al., 2016; Tannast, Langlotz, et al., 2005; Tannast et al., 2006). Since radiography is a projection examination, standardisation of the position is critical during the acquisition. This is because JSW is highly influenced by joint positioning (Gold et al., 2016). Morphological alteration and magnification can add more difficulties to quantitative measurements. For example, it has been reported that variability in narrowing JSW can be introduced by variation in knee positioning and by variation in the beam height (Lynch et al., 1993; Ravaud et al., 1996). Therefore, the standardisation and reproducibility of the radiographic procedure are of great importance (Kinds Yz et al., 2012).

Erect X-ray images are considered as necessary for accurately assessing the narrowing in JSW in patients with known or suspected OA of the knee. Dieppe (1995) also reports that this should be the case when evaluating JSW in patients with OA of the hip joint. A study was undertaken to evaluate the possible changes in JSW between supine and erect position and between different radiographic procedures (pelvis vs hip) (Conrozier et al., 1997). The results show that the JSW does not vary in normal hips between the two positions. However, the JSW decreased in the erect position for OA hip joints. The authors argued that articular cartilage therefore has a nonlinear viscoelastic behavior when in compression. Also, that both fluid rearrangement within the matrix and fluid exudation are generated by cartilage compression. Moreover, the results have suggested that there is a possible benefit of taking X-ray images with a central ray on the hip, rather than using pelvis X-rays, in detecting understated hip joint space changes when bearing weight.

The effects of positioning and radiographic procedures were evaluated by a group of investigators (Auleley et al., 2001). The study consisted of two parts. The first part evaluated the effect of foot rotation on JSW. The patients were hereby in the supine position with their feet rotated by 15°, using a V shaped positioning frame. The patients were then imaged in 5° feet internal rotation using another V shaped tool. The second part evaluated the impact of a centring point on JSW diagnosis. The images were obtained with a centring of 2 cm above the superior aspect of the symphysis pubis. 5 min later, a modified radiograph was taken with the X-ray beam centred on the umbilicus. The finding indicated that 10° of foot rotation did not have an effect on JSW measurements. The authors argued that they cannot exclude the possibility that a greater difference in foot rotation could induce a significant difference in JSW measurements. In contrast, there were increases in JSW on radiographs achieved with the X-ray beam centred on the umbilicus, compared with the images centred on 2 cm above the superior aspect of the symphysis pubis. From the above, it is clear that the criteria used to define or classify OA changes between positions might be changed if the imaging technique was not standardised.

2.3.4.1 Management and treatment

Lifestyle modifications, pharmaceutical drugs and surgery are the most therapeutic strategies for OA. THR is used at the last stage. The number of THRs has increased during the last two decades due to OA (Maradit Kremers et al., 2015; Patel, Pavlou, Mújica-Mota, & Toms, 2015). This increase suggests that good results can be obtained from hip replacement surgery; hence the upward trend. However, this also indicates that there are problems with the nonsurgical treatment and a failure to avoid the progression of the disease. There are currently no treatments which have been shown to delay structural progression (Felson & Hodgson, 2014). The major reason behind these treatments failing to prevent THR are that the treatment is initiated too late to have an effect. Therefore, the rationale for focusing on early OA is that irreversible structural changes may not yet have been established (Felson & Hodgson, 2014). This is the main focus of this thesis. Erect pelvic radiography could help in the early detection of structural changes in the hip joint, which would in turn help with early OA diagnosis and may facilitate effective non-surgical treatment. That is why radiography should be obtained under standardised conditions and the effect of this position on image quality and radiation dose should be investigated (Maruyama, Tensho, Wakabayashi, & Hisa, 2014; Polkowski, Nunley, Ruh, Williams, & Barrack, 2012). The differences between the supine and standing position was studied after THR by Maruyama et al. (2014). The results showed that the supine position may result in a maximum of 20% underestimation in joint wear (see **Figure 2-17**).

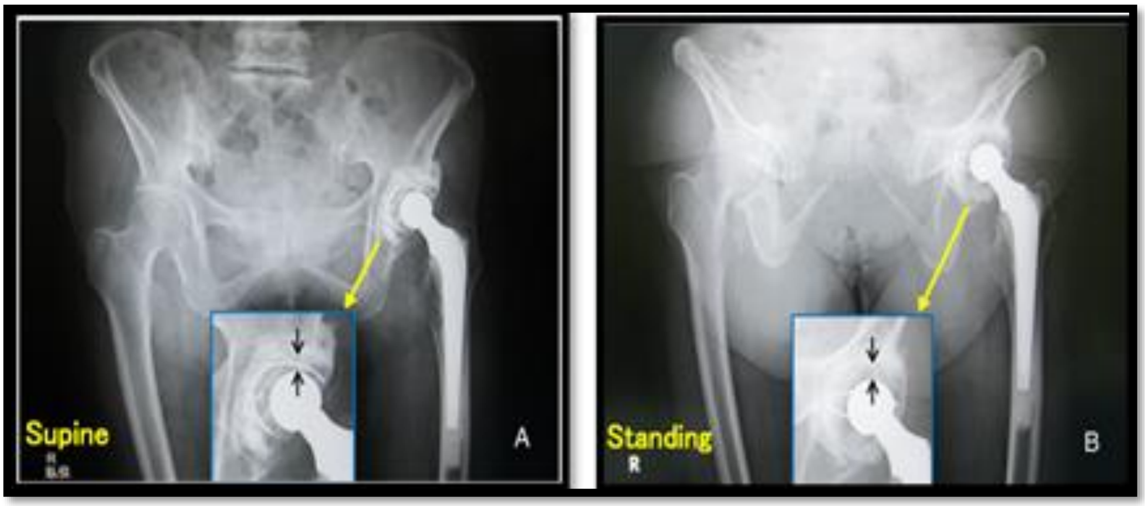


Figure 2-17: Pelvic X-ray image of a 60-year-old female patient postoperative in supine position (A). (B) Pelvic X- ray image of the same patient in standing position. The black arrows indicate joint wear. In standing position the pelvis tilts posteriorly which makes a diffrence between the two postions(Maruyama et al., 2014).

A further study determined whether adopting a standing position could change the standard measurements of the acetabular component positioning after THR (Polkowski et al., 2012).

Two X-ray images were obtained in a supine position using CT scans and in a standing position using the EOS X-ray imaging system. The results showed that 52% of patients who underwent THR had a difference of greater than 5° anteversion in their standing versus supine position (see **Figure 2-18**). Despite the differences identified in the previous study, it should be noted that the comparison was made using different image modalities (EOS and CT). This draws attention to non-standardised methods that were reported in the literature when comparing supine and erect positions (more detail in **chapter 3**).

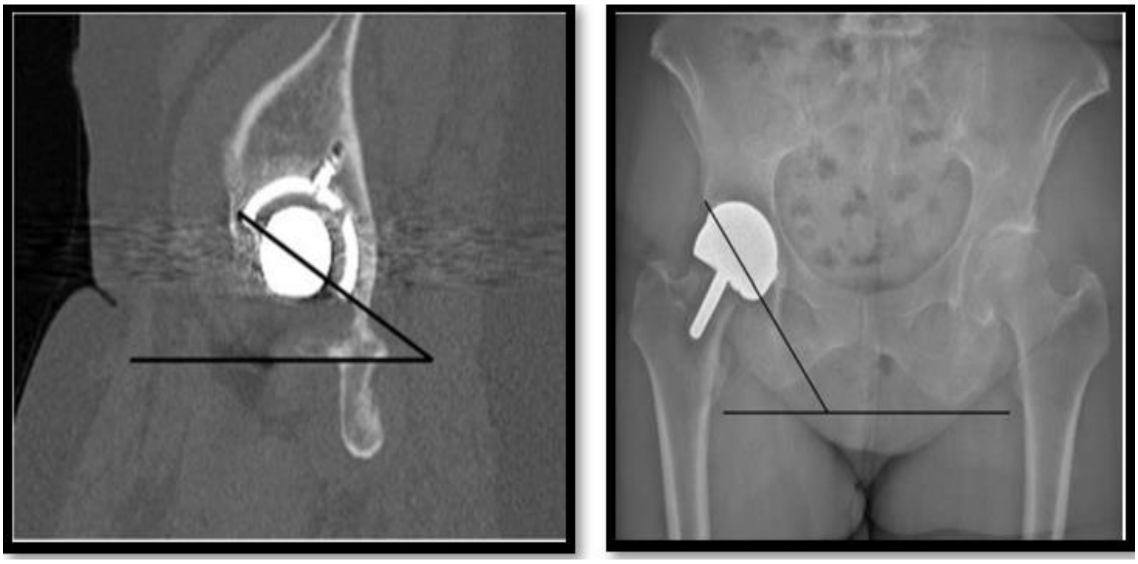


Figure 2-18: Reconstructed CT image in supine position shows acetabular component anteversion of 42° (Left). Pelvic X ray images for the same patient in standing position shows an acetabular inclination of 54° (Right) (Polkowski et al., 2012).

2.4 Chapter summary

In this chapter the necessary background information was provided. This background is important to help in understanding the literature review chapter (chapter three), and how the erect position could affect the diagnosis of the pelvis and hip disorders diagnosis. The general bony pelvis anatomy was presented in order to understand the different evaluation criteria used in methods sections during this thesis. Also, this helps in understanding the different pelvic metrics that are used when evaluating hip pain. The routine supine imaging and it is radiological appearances were also provided. In the last section (**section 2.3**) details about different pelvis and hip disorders were explained. These disorders were found to most affect diagnosis when moving from the supine to erect position. These disorders are AR, FAI, HD and OA, and represent cases wherein erect AP pelvis imaging would be required. In this chapter the evidence for standardising pelvis radiography was explored.

Chapter 3: Literature Review

3.1 Overview of the chapter

In this chapter, the results of a literature search on the history of erect pelvic radiography and the main differences between the supine and erect positions, in terms of clinical appearances, image quality and radiation dose, will be presented. A focus will be placed on the different metrics orthopaedic surgeons use for evaluating the hip joints (please see the metrics that have been illustrated in the **section 2.3**). Within the literature review no significant information was found to support a comparison between the supine and erect positions, in terms of image quality and radiation dose for pelvis radiography. As a result, the effects of different positions (projections) of other body parts on image quality and radiation dose, were investigated instead. Furthermore, the review will also consider potential recommendations for radiographic techniques when performing erect pelvic projections. The gap in the literature for erect pelvic radiography, which leads to the rationale for subsequent studies, will be identified.

This chapter will be divided into five main sections. The first section will discuss the impact of repositioning on PT, the importance it holds in the diagnosis of pelvic pathologies and other pelvic measurements. The second section will focus on the impact of repositioning on the acetabular component of joint replacement prosthesis. The third section will consider the impact of repositioning on JSW. The fourth and fifth sections will consider the impact of repositioning on other body parts and the effect of different positions (orientations) on image quality and radiation dose, respectively. Metrics considered in the first three sections (3.3, 3.4, 3.5) were selected since they are the most common measurements used to evaluate anatomical changes between the two positions (erect and supine). The areas concerning clinical differences between the two positions, and the critique of these studies, were published as a literature review article in the Journal of Medical Imaging and Radiation Science (Kholoud Alzyoud, Hogg, Snaith, Flintham, & England, 2018). This directly resulted from work within this thesis.

3.2 Search strategy

In order to find relevant literature, a comprehensive search was conducted using online scientific databases. Peer-reviewed literature was selected from four medical databases: Science Direct, Web of Science, PubMed and Medline. These were used to acquire scientific literature regarding the differences between the supine and erect position and for the identification of the optimal erect position. Search terms included Medical Subject Headings (MESH) and keywords such as hip, pelvis radiography, erect and supine pelvis, erect pelvis, weightbearing, total hip replacement, osteoarthritis, dysplasia, femoroacetabular impingement and developmental dysplasia of hip. Only articles written in English were considered. There were no time limitations placed on the search; this was to ensure that all significant and important studies were identified. The search used Boolean operators (AND, OR & NOT) to further narrow the results. To guarantee the information contained within this literature review chapter is quality assured, only submissions from peer-reviewed journals were selected. Furthermore, publications with unrestricted accessibility to their full-text were considered eligible for inclusion. An example of this would be wherein an abstract has been provided, but full access to the article itself has been not provided. Additionally, texts only associated with erect and supine positions were used. Articles that did not involve projection radiography, such as MRI and ultrasound were excluded. However, articles focusing on the differences between the two positions, but using other imaging modalities, were included if deemed to be relevant. Moreover, the articles that used the two positions (erect and supine) for other body parts were included. For the last section in this chapter, the key words used were positioning, dose reduction, image quality and radiation dose, using the same databases as for the previous four sections.

The sections below discuss the most important findings regarding the impact of repositioning from supine to erect for pelvis radiography, and the value of the erect pelvic X-ray image. Key aspects of the articles are summarised in **Table 1,** in Appendix 1. The impact of repositioning on the different radiographic appearances is also considered. Moreover, this section highlights the different positions and imaging techniques that were used to obtain pelvic X-ray images (both supine and erect) in the reviewed literature. If the position or technique is not described, then the authors did not provide technical details on how images were obtained.

3.3 The impact of repositioning on PT

3.3.1 PT and its effect on pelvic metric appearances

The PT is defined by the angle between the line that connects the ASIS and PSIS, and a horizontal line (Sprigle, Flinn, Wootten, & McCorry, 2003)(see **Figure 3-1**). Anterior PT is the forward rotation of the pelvis, and it is determined by muscular and ligamentous forces that act between the pelvis and adjacent segments (such as the lumbar and sacrum spine segments). It is well-known that some disorders, such as low back pain and cruciate ligament deficiency, are linked to an anterior PT (Hertel, Dorfman, & Braham, 2004; Loudon, Jenkins, & Loudon, 1996). This is because anterior PT increases the lumbar lordosis (LL) (Levine & Whittle, 1996), which in turn increases the load on the lumbar spine (Preece et al., 2008).

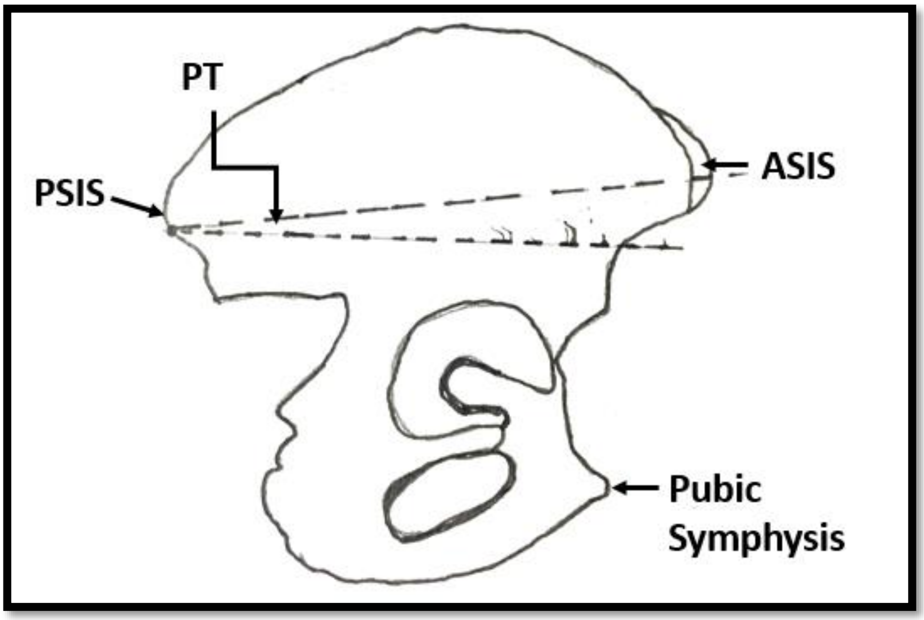


Figure 3-1: Diagram illustrates the PT which is the angle between the line connecting the ASIS and PSIS and a horizontal line.

PT has a significant effect on the radiographic appearance of the pelvis and is likely to affect orthopaedic metrics, which could in turn affect the diagnosis and treatment of hip joint pathologies. Acetabulum retroversion is one of the early signs of hip OA and it varies with PT (more details about acetabulum retroversion in **section 2.3.1**). PT influences the presence or absence of retroversion signs. Moreover, it influences femoral coverage as well. Consequently, as PT increases the COS also increases (Siebenrock et al., 2003), which has an effect on the identification of the early signs of OA.

For a patient who has to undergo THR, the increased PT (rotation around the transverse axis) results in a significant decrease in cup anteversion and vice versa (Ala Eddine et al., 2001). These variations have a significant effect on the precision of acetabular cup positioning, which can lead to instabilities, wear and osteolysis (Yun et al., 2019). Moreover, even in normal people without abnormality, if pelvic X-ray images are obtained with excessive PT it can lead to the false diagnosis of acetabulum retroversion (Anda, Svenningsen, Grontvedt, & Benum, 1990). This has many disadvantages, such as influencing the correct diagnosis of FAI, and affecting the recommendation for surgical treatment.

Complications that can occur following THR surgery are wear and dislocation (Ochi et al., 2016). The rate of dislocation during the postoperative period varies from 0.6% to 11% (Sato, Nakashima, Matsushita, Fujii, & Iwamoto, 2013). To overcome this, many studies have sought to determine the safe zone (optimum orientation of the acetabulum component during total hip replacement) for implementation. They used some of the pelvic parameters to precisely determine acetabulum cup orientation, such as cup inclination. Cup inclination must be between 30° and 50°, and cup anteversion between 0° and 10° (Lewinnek, From, Tarr, & Compere, 1978). Despite these efforts to optimize cup implementation parameters, consideration should be given to PT, and cup implementation must be planned based upon PT (Lembeck, Mueller, Reize, & Wuelker, 2005). Lembeck et al. (2005) reported that there is a 0.7° change in cup anteversion for each 1° of PT. Another study reported that for each 1° of PT, the anteversion and inclination changed by 0.8° and 0.3°, respectively. Therefore, if PT changed by 10° it would lead to a 7° or 8° cup anteversion, which cannot be ignored after THR (Inaba et al., 2016).

Clinically, patients who undergo THR are traditionally evaluated by supine imaging. However, as they move into an erect position their pelvis tilts backwards, therefore, cup inclination and anteversion can become markedly deviated from the safe zone (Bhaskar, Rajpura, & Board, 2017; Scheerlinck, 2014). It has been reported that, for a patient with marked anterior PT, the mean cup retroversion was 10° after one-year post-THR. Recently, the fluctuation of PT on cup implementation angles as the posture changes has received more attention from researchers. Attention is paid especially to people with PT changes along with posture, or after THR (Inaba et al., 2016). Shon et al. (2014) presented a case that had recurrent dislocation of the hip due to excessive PT. The patient was a 69-year-old female THR candidate, with recurrent dislocation of the hip. The study results show that impingement is possible even when the cup implementation is performed within the safe zone. It was proposed that the poor outcome of surgery was because the optimum orientation for the cup position was based on supine position measurements, rather than erect. However, the dislocation mainly happened in functional positions (i.e. erect) during daily living activities (Shon et al., 2014). After surgery, increased anterior PT can lead to posterior impingement and anterior dislocation. Furthermore, posterior PT can cause anterior impingement and posterior dislocation (Inaba et al., 2016; McCollum DE, 1990).

The aim of the study undertaken by Henebry & Gaskill (2013) was to evaluate the effect of PT on acetabular coverage of the femoral head. This coverage was estimated by measuring lateral CEA. The results confirmed that small changes in PT create significant changes in the lateral CEA ($P<0.001$). This is a critical point for X-ray images that are obtained for evaluating hip disease. This represents precise bony characteristics and thus inadequate imaging could lead to the misdiagnosis of acetabular coverage. Henebry & Gaskill (2013) argued that the supine radiographic position should not be obtained, as there is a variation in PT between patients. They concluded that the supine position does not represent the erect (functional weight-bearing) characteristics of the acetabulum and the femoral head. Henebry & Gaskill recommended erect X-ray images when evaluating acetabular coverage and for suspected FAI. It can be concluded from the above literature that PT plays an important role in diagnosis as well as the treatment of hip joint pathologies. This importance has attracted attention from many researchers who have concentrated on examining the differences between supine and erect positioning on PT (Ala Eddine et al., 2001; Babisch, Layher, & Amiot, 2008; Pierrepont et al., 2017; Troelsen et al., 2008). The results from these appear to be contradictory, as some authors found differences between erect and supine, whilst others did not.

Troelsen et al. (2008) recommended the erect pelvic position for people suffering from DDH. Their study was conducted on 31 DDH patients and two images were acquired one supine and one erect. Supine images were acquired with the lower extremities parallel to each other and the feet internally rotated 15° to 20°. Erect images were acquired with the legs parallel to each other and with enough internal rotation for both feet to touch. PT, JSW, CEA and AI were all measured. Study findings indicated that there was a change in the PT between positions for both genders. In the erect position, PT was greater in females (13° to 14°) when compared to males (6°to 7°), however; this was not statistically significant ($p=0.14$ to 0.70). Additionally, there was a statistically significant change in CEA from 1.3° to 1.6° ($P<0.006$) and AI increased from 1.6 to 2.3 ($P<0.003$), however; JSW was not affected (P=0.16). Extension to the pelvis was noted in the erect position, as identified by the reduction in the distance between the sacro-coccygeal joint and the symphysis pubis (SC-S) (P<0.005). Images demonstrated that the COS reduced from 11 in supine to 4 in the erect position. It should be noted that the methods used to evaluate the differences between supine and erect do not only differ between the studies, rather they can differ within the same study, such as in the study by Troelsen et al. In this study, the researchers used different detention for the internal rotation of the feet.

A further study by Ala Eddine et al. (2001) was undertaken using 24 patients to investigate if pelvises were individual for everyone, and whether morphological changes exist between the supine and erect position. Lateral pelvic X-ray images were acquired in the erect and supine position for a healthy group of volunteers. The results demonstrated a number of important pelvic differences when repositioning. For example, 22 patients demonstrated acetabular retroversion and two patients showed anteversion when moving from supine to erect. The authors concluded that one of the reasons for the displacement of prostheses is due to differences in pelvic measurement methods. These often depend on a CT scan alone for evaluating the hip joints. Since the CT scan is performed supine, it is unlikely to take into account these changes when people are erect and may potentially increase the error in arthroplasty location during surgery. Moreover, it is important to acknowledge that CT acquisitions will demonstrate pelvic geometry differently than to projection radiography.

Findings from Ala Eddine et al. (2001) concurred with a recent study by Pierrepont et al. (2017) who evaluated the effect of three positions on PT in 1517 patients. X-ray images were acquired in the supine, erect and in sitting positions. PT was obtained using a supine CT scan and measured from lateral X-ray images in both erect and sitting positions. The mean supine, erect and sitting PT were 4.2°, -1.3° and 0.6°, respectively. Moving from supine to erect, the pelvis was observed to rotate posteriorly by ≥13°, increasing the risk of acetabular anteversion. These results highlight the increased risk of anterior loading and instability for people undergoing THR. Accordingly, the authors discussed the importance of surgical planning and the determination of the acetabular cup orientation when relying on supine imaging. They concluded that supine imaging may lead to the suboptimal orientation of the acetabulum in functional positions (erect, sitting). In addition, assessment by function, using erect/load bearing pelvic imaging, was recommended as an essential step for patients undergoing total hip replacement. Attention should be drawn to the methods that are used in this study for evaluating the positions (CT and lateral X-ray images). Using different imaging techniques could affect the results of the study. Moreover, it is accepted that there would be a role for lateral pelvic radiography in certain clinical manifestations. However, there would be dose implications when incorporating this projection.

Babisch et al. (2008) reported the effect of repositioning on PT and acetabular cup inclination. 40 patients were imaged supine and erect and the results showed a significant difference in PT between the positions ($P<0.001$). Within this work, the mean PT was -10.4° and -5° for erect and supine positions, respectively, with a change of 5.4°. Konishi & Mieno (1993) reported significant differences between erect and supine positions in PT. In their study they evaluated 54 healthy volunteers using AP and lateral pelvic X-ray images. Study findings demonstrated an increase in PT by 5° ($P=0.0001$) between positions.

A study undertaken by Miki et al. (2012) evaluated whether the supine position is still suitable for people who have a large pelvic tilt when erect, 91 patients were imaged in the two positions. PT ranged from -21° to 5° in the supine and erect positions, respectively, and there was a strong correlation between the two positions ($R=0.88$). Another study by Dhakal et al. (2015) was conducted to evaluate the differences between the two positions using lateral X-ray images. Twenty-three patients were imaged, and the results showed no significant differences in lumbar and pelvic measurements between positions. Similar findings were found by the last two studies, they found not significant differences between the erect and supine positions. However, the comparison is difficult to make, as different projections were used (AP and lateral), and there was no clarification about how the positions were obtained.
Evaluating PT using other techniques is well established. For example, using an inclinometer is a widely accepted test for measuring PT(Gajdosik, Simpson, Smith, & DonTigny, 1985; Preece et al., 2008; Salian, Gupta, & Yardi, 2015; Sprigle et al., 2003). Anda et al. (1990) measured PT in 40 healthy young adults using an inclinometer for erect and supine positions. No significant differences were reported between the erect and supine positions based on this non-radiological test. Similar results were found by Nashihara et al. (2003) when studying 101 THR patients.

Previous studies (Ala Eddine et al., 2001; Babisch et al., 2008; Troelsen et al., 2008) have demonstrated statistically significant differences between the two positions, however; comparisons must be taken into account cautiously since the research used different radiographic projections (AP and lateral). Furthermore, they also used different groups of participants (healthy volunteers, DDH patients and patients with hip replacements). There were also differences in the imaging modality used, including radiography and reconstructed CT images generated to mimic AP X-ray images. A clear description of the erect position was not included in several of the studies and, as such, the effects of the differences in positioning could not be evaluated. However, there is evidence that PT, and hence the CEA and the acetabulum, are affected when moving from supine to erect in both healthy and symptomatic patient groups. It should be recommended that erect radiography be considered when people are suffering from hip pain, and early diagnosis is paramount.

3.3.2 Using pelvic sagittal inclination (PSI) to evaluate PT changes

Several authors have used measures of PSI (pelvic position on the sagittal plane) to evaluate the impact of PT changes. Tamura et al. (2014) assessed 163 patients in a study to determine the different spinal factors affecting PSI, in both erect and supine positions. AP pelvic images were acquired in the erect position with the beam centred over the superior margin of the pubic symphysis. Patients were asked to stand ‘relaxed’, with their hands positioned on a support bar to remove them from the primary radiation field. Supine measurements were obtained using pre-operative CT scans. In 25% of the patients the PSI changed by >10° after moving from supine to erect. For the other 75%, the change was -6.9° ($P<0.001$) (Tamura, Takao, Sakai, Nishii, & Sugano, 2014).

A further study was conducted by Tamura et al. (2017) to investigate the longitudinal differences between the two positions on PSI. Patients were imaged in supine and erect positions 1, 5 and 10 years after THR. Pre-operative supine images were obtained from CT scans and, for erect imaging, the patients were asked to stand in a comfortable position. In the later, the X-ray beam was centred over the superior margin of the pubic symphysis. Ten years post-THR, there was more than a 10° increase in the PSI posteriorly when moving from erect to supine, however; this was not felt to cause late dislocation. Therefore, the authors concluded that supine positioning is still valid for acetabular cup diagnosis. The same findings were obtained recently in a study by Uemura et al. (2019). Uemura and colleagues found that pelvic positions in supine and standing postures are reproducible and the PSI can be measured from a single radiograph. For erect position, the authors recommended the patients stand in relaxed position with their hands crossed in front of their chest. This position is comparable with a relaxed position and has a minimum effect on PSI (Uemura et al., 2019).

3.3.3 PT and Acetabular cup orientation

A group of investigators studied the effect of PT on acetabular cup (Ala Eddine et al., 2001; Khan, Beckingsale, Marsh, & Holland, 2016; Lazennec, Boyer, Gorin, Catonné, & Rousseau, 2011; Lembeck et al., 2005; Nishihara et al., 2003). Lembeck et al. (2005) measured PT on 30 volunteers using inclinometer. The average PT was -4° and -8° in supine and erect positions, respectively. For every 1° of pelvic reclination there was 0.7° of cup anteversion. The authors concluded that clinicians must take particular care of increasing the risk of arthroplasty dislocation due to an incorrectly located acetabular cup, when pelvic measurements are taken in the supine position. Lembeck reported that, in the supine position, -4° of PT gives 2.8° of cup retroversion, which is unlikely to affect surgical outcomes. However, they also stated that when patients change to the erect position, the anterior PT shifts to 8° which generates 5.6° more anteversion than implanted. This is a particularly critical value. These findings were also in line with Ala Eddine et al. (2001), who found an increasing error of cup anteversion when depending on supine CT images alone.

Nishihara et.al (2003) used AP pelvis X-ray images acquired in supine, erect and sitting positions for 101 patients who had undergone THA. The purpose of the study was to determine the acetabular component position and the safe zone in different pelvic locations. For imaging, the source-to-image distance (SID) was 150 cm, centred over the superior margin of the symphysis pubis. Supine images were obtained using CT scans. 90% of the patients had 10° or less difference in pelvic flexion angle (tilt) between erect and supine, and 20° between erect and sitting ($R=0.84$; $P<0.0001$). Based on their results, the authors concluded that the supine position is as practical as the functional erect position and considered a suitable reference frame when evaluating acetabular component orientation. Also, the pelvic flexion angle can be predicted for erect and sitting positions from the supine position. However, for the remaining 10% of cases they needed more extensive evaluation wherein the acetabular component position needed to be determined (Nishihara et al., 2003).

A further study was conducted by Khan et al. (2016) investigating the effect of repositioning on the acetabular cup orientation. Fourteen patients with bilateral THR were included in the study, with AP pelvic images acquired in both positions. The cup anteversion was measured using software which enables orientation of the cup to be accurately assessed with less than 1° of error. This was based on two dimensional images. There were statistically significant differences in the mean cup anteversion angle 1.84° ($P=0.02$), greater in the erect position than supine. Cup orientation is highly affected by PT and orientation. As anteversion increases, the cup pressure, contact and lubricating loss will also increase. This will lead to greater wear of the THA and a potential for hip dislocation (Khan et al., 2016). Similar findings were obtained by Lazennec et al. (2011) when comparing the acetabular cup orientation between different positions. AP pelvic X-ray images were obtained in erect and sitting positions while supine positions were acquired using CT scans. Acetabular anteversion changed from 24.2º in supine to 31.7º and 38.8º in erect and sitting positions, respectively ($P<0.001$). The authors concluded that supine positions, using CT data acquired before THR, introduces bias and therefore consideration should be taken when evaluating the functional positions (Lazennec et al., 2011).

Au et al. (2014) found a significant increase in the acetabular inclination and anteversion in the erect position when they conducted a study to evaluate whether the cup remained within the safe zone when moving from supine to erect (Au, Perriman, Neeman, & Smith, 2014). During this study, 30 patients were imaged with AP and lateral images in both positions. The results showed that PT, inclination and anteversion increased significantly when people stand ($P<0.0001$), and importantly, they are likely not to be in the same safe zone as when in supine ($P<0.0001$). A recent study by Tiberi et al. (2015) also determined the changes on the acetabular cup between erect and supine positions. One hundred and thirteen THR patients were imaged on the same day in the two positions. Supine images were obtained using conventional radiography and erect images using EOS. The results showed that the mean changes in the acetabular cup inclination and version were 4.6° in supine, and 5.9° in erect ($P<0.0001$). Changes were more than 5° in 43% and 53% of hip inclination and version, respectively. The authors recommended that an erect position should be considered when planning for THA and when determining the optimal acetabular orientation.

3.4 The impact of repositioning on the acetabulum

A number of studies (Jackson et al., 2016; Polkowski et al., 2012; Ross et al., 2015) were conducted to evaluate acetabular morphology. Acetabular morphology has an important role in clinical decision making with regards to choosing the most appropriate treatment option. Differences between the erect and supine position were assessed on pincer-FIA patients. 46 patients complaining of hip pain were hereby evaluated (Jackson et al., 2016). Measures indicative of PT and AD were evaluated, including the distance between the symphysis and coccyx tip (T-S), the SC-S, retroversion signs, CEA and PT. The erect and supine images were taken with the lower extremities 15°internally rotated. When moving from supine to erect, the T-S distance decreased from 19 mm to 6 mm (P≤0.001), and the SC-S distance decreased from 47 mm to 32 mm (P≤0.001). These distances are related to PT, which means PT is less in the erect position than for supine. Findings regarding the crossover sign demonstrated that it decreased from 18 (supine) to 9 (erect) (23% to 13%; P≤0.001). The CEA did not change (P=0.64), but the inclination angle significantly increased between the positions (P=0.002). The authors concluded that AP pelvic imaging in the erect position must be standardised when evaluating hip abnormalities, and that caution must be exercised by clinicians if they are to use images acquired in the supine position when evaluating FAI (Jackson et al., 2016).

The effect of supine and erect pelvic positions on acetabular version (the orientation of the opening of the acetabulum) was studied by Ross et al. (2015) . Results were obtained from 50 FAI patients by taking an erect pelvic X-ray image and reconstructing supine images using pre-operative CT data. Patients were positioned for the supine examination with their legs abducted and patellae orientated anteriorly. This position was considered to provide a neutral supine PT. Study finding showed that the acetabular orientation differed between the two positions, and the authors proposed that positioning must be taken into account when diagnosing and treating FAI patients. Cranial acetabular version increased by 2º (P<0.001) when moving from supine to erect as a result of increased posterior PT. During erect positioning, there was an increase in hip flexion by 3º and an increase in internal rotation and abduction by 3º (P<0.001). Regarding the signs of acetabular retroversion, study findings showed no significant changes between the two positions (P=0.21, P=0.31, P=0.60 for the crossover, posterior wall and ischial spine signs, respectively). However, in 27% of participants the change in acetabular orientation resulted in a loss of the crossover sign in the erect position. This in turn may lead to an inaccurate diagnosis and an increase in the risk of ineffective treatment (Ross et al., 2015).

Differences between erect and supine were significant in the study by Polkowski et al. (2012), which was undertaken to determine whether the acetabular measurements change as a results. Erect images were obtained using the EOS system, a slit beam digital radiography system designed to enable three-dimensional low dose imaging, and supine images obtained from CT scans. Results showed that acetabular inclination and version changed in the erect position (P<0.0001 for cup anteversion and P=0.017 for inclination). Appropriate attention needs to be given when comparing the EOS system with images rendered from CT data.

Differences between positions could be attributed to differences in image acquisition techniques between the two systems. With an absence of validation data, caution must be exercised when interpreting differences between modalities.

3.5 Impact of repositioning on JSW and CEA

A comparison of erect and supine pelvic radiography was conducted in 2008 by Fuchs-Winkelmann and colleagues to determine whether there was a difference in the demonstration of OA signs. Measurements of AI, JSW and CEA were acquired using erect and supine X-ray images in patients with DDH. The results illustrated variations between supine and erect including that AI values were greater, those of CEA were smaller and the JSW was reduced in the erect position ($P<0.001$ all metrics) (Fuchs-Winkelmann et al., 2008). Okano et al. (2008) found significant differences in JSW in 162 OA hip patients when imaging people in supine and erect positions. In erect positions, patients were asked to stand in a comfortable position and distribute their weight equally on both feet, rotating their feet inwards by 15º±5º. The X-ray beam was centred on the pubic symphysis using an SID of 110 cm and the images were obtained using fluoroscopy. Supine images obtained using the same parameters resulted in the JSW being greater for supine positions ($P<0.0001$). Moreover, there were a number of patients with a JSW greater than 1 mm in the supine position, that also decreased by more than 1 mm in erect. The authors therefore recommended using the erect position when evaluating hip pain.

Findings obtained from another study by Terjesen & Gunderson (2012) did not vary significantly from the previously reported study. The aim of this study was to evaluate the reliability of AP pelvis X-ray images for DDH patients and compare the hip parameters between erect and supine. Patients were positioned with their legs parallel and the imaging technique used a 120 cm SID and a central ray positioned 3 cm above the symphysis pubis. Mean differences between the supine and erect positions for CEA ranged from -1.1º to 0.0º and a JSW of less than 0.1 mm. Neither of these differences were considered to be clinically significant. Accordingly, the authors continued to use supine imaging for evaluating hip problems.

A further study by Evison et al. (1987) which examined measurement differences between erect and supine images for 21 patients, also found no statistically significant differences. In this case, the authors provided technical details for imaging including a 100 cm SID, 70-75 kVp and 50-100 mAs. In 95% of their cases there were JSW differences of less than 1 mm between the positions. However, the authors recommended using the erect position for some patient groups, such as pre- and post-operative patients, but not for routine clinical practice.

3.6 The impact of repositioning on the other body parts

The value for erect positioning was also investigated by many researchers considering other body parts, such as the knee and spine. Erect X-ray imaging, rather than supine imaging, has been the preferred imaging method to detect joint space narrowing, which indicates structural damage to the articular cartilage of the knee and OA (Duncan et al., 2015). Skou and Egund (2017) assessed the differences in the detection of medial and lateral patellofemoral (PF) OA in supine and erect positions. Knee X-ray images in both positions were obtained for 35 women and 23 men. The results showed that when moving from supine to standing the patella moved medially, and that the medial JSW and lateral patellar tilt angle decreased. 14 knees were diagnosed with medial PF OA in a standing position compared with just three knees in the supine position. The authors recommended conducting knee X-ray images in a standing position in order to evaluate medial PF OA.

A further study was performed to evaluate whether elective knee X-ray images should be requested by general practitioners and whether they should be performed whilst erect [weight-bearing (WB)] (A. Chen, Balogun-Lynch, Aggarwal, Dick, & Gupte, 2014). The WB radiographs showed severe joint space narrowing compared with non-WB. The authors propose that all referrals for suspected OA should be performed WB- a strategy that is in widespread clinical use. This was reported as having the ability to decrease patient radiation dose by not needing to repeat the X- ray image in WB and therefore wasting patient/clinician time (A. Chen et al., 2014).

The effect of positioning the knee for OA detection is not totally based on repositioning from supine to standing. Instead, the sensitivity to detect joint changes between *different* standing positions was evaluated. A study performed by Wismayer and Zarb (2016) to compare knee X-ray images in the posteroanterior (PA), partial flexion (45°) or AP fully extended standing projection were evaluated. Knee X-ray images of 32 patients in both projections were obtained. The results showed that the PA projection was significantly ($p<0.05$) better for the visualization of JSW and tibial spines. Moreover, the authors pointed out a number of valuable recommendations which could minimize variations in radiographic positioning technique. These could be achieved by a positioning frame which would facilitate consistent, comparable and reliable images. These variations in patient positioning technique could influence the appearance of the anatomical criteria under evaluation. Such variations may have been caused by changes in positioning and differences in technique by the performing radiographers (Wismayer & Zarb, 2016).

Babatunde et al. (2016) found the same results when comparing a PA with knee in flexion and an AP projection. The results indicated that the PA projection is an effective tool which gives more information on painful knees than an AP projection alone. The same findings were concluded from a study which compared the sensitivity of AP and PA flexion views in detecting articular cartilage wear (Dervin, Feibel, Rody, & Grabowski, 2001). The results from this study demonstrated the superiority of the flexion projection in detecting lateral compartment wear, but that is offers no advantages for the medial side. The authors suggest that this projection should be considered when evaluating knee OA.

There are several studies evaluating the effect of repositioning (supine to erect) when imaging the lumbar spine. Vavruch & Tropp (2016) evaluated the differences in the Cobb angle (the angle used for spine scoliosis diagnosis) between the erect and supine positions (supine images obtained from a CT scout view) for 128 patients. The results showed that there was an 11º (SD 5º) decrease in Cobb angle in the supine position. Also, they found a strong correlation in the angle between the two positions. Dhakal et al. (2015) evaluated the differences between the standing and supine positions of the lumbosacral region in patients with spondylolisthesis (slippage or displacement of one vertebra compared to another). Images in both standing and supine for 23 patients were acquired. The results showed significant differences in percentage slips (36.9% in standing and 27.4%) and lumbar lordosis (37.7%, 31.0% in standing and supine, respectively). The authors concluded that, as the standing position has effectively demonstrated the increase in slip percentage, it can have a significant effect on the classifying of slip which can in turn impact on the treatment strategy (Dhakal, Biswas, Rathinavelu, Patel, & Basu, 2015). Benditz and colleagues (2017) evaluated the lumbar lordosis angle (LL) in the standing and supine positions. Standing lateral X-ray images of 63 patients were obtained, and the supine images were acquired by MRI. The LL was 45.0° in the standing position and 47.9° in the supine MRI images. 2.9° was the difference in the LL angle between the two positions, and this was statistically significant (Benditz et al., 2017).

3.7 The impact of repositioning on image quality and radiation dose

Whilst a growing number of studies have investigated the changes in pelvic measurements resulting from moving between erect and supine positions, there were no studies evaluating the effect of repositioning on image quality and radiation dose. This is an area which needs further evaluation, as there have been many studies that have demonstrated the effect of repositioning on image quality and radiation dose for other body parts, such as the knee and spine (Alukic, Skrk, & Mekis, 2018; Ben-Shlomo et al., 2016; Chaparian, Kanani, & Baghbanian, 2014; Davey & England, 2015; Davis & Hopkins, 2013; Mc Entee & Kinsella, 2010; Mekiš, Mc Entee, & Stegnar, 2010). This research proves that moving from one position to another can affect the radiation dose and image quality. This is the case when moving from AP to PA, which was found to decrease in radiation dose without affecting image quality. A comprehensive literature review was undertaken to identify the effect of repositioning from supine to erect during pelvic radiography on image quality and radiation dose. However, the literature solely concentrated on the effect of repositioning in terms of radiographic features rather than it is effect on image quality and radiation dose. This adds to the gap in the literature regarding erect pelvic radiography and indicates the need for further research. Therefore, this section will focus on the effect of repositioning on image quality and radiation dose for other body parts such as knee, lumbar spine, clavicle, pelvis (other positions) and thoracic spine. This review will explain the reason behind the need to study the effect of erect pelvic X-ray on image quality and radiation dose.

Lumbar spine radiography carries a relatively high radiation dose (Mekiš, Zontar, & Skrk, 2013). In order to reduce the patient radiation dose, the PA projection has been used by many researchers, instead of AP. Recently, Alukic et al. (2018) studied the differences in image quality and radiation dose between AP and PA projections of the lumbar spine. The study was undertaken by imaging a phantom and 100 patients. The results from the phantom were not significant between the two projections in terms of dose area product (DAP) and image quality, while the E was 25% lower (P=0.008) in PA compared with AP. In the patients' results, it was shown that for PA projections the E reduced by 53% ($P<10^3$), the thickness of the abdomen was 10% ($P<10^3$) lower than in the AP position, and the DAP was 27% (P=0.009) lower (Alukic et al., 2018). Recently, the same findings were found by Green and colleges when studied the effect of PA position compared with AP on radiation dose and image quality for lumbar radiograph. Eighty patients were imaged in both positions. The effective dose was reduced by 41% for PA without affecting image quality (Green, Karnati, Thomson, & Subramanian, 2019)

Dose reduction was noted in female patients in a study by Brennan and Madigan (1998) when using PA projections of the lumbar spine. They concluded that tissue displacement was the main cause of a reduction in entrance surface dose (ESD) of 38.6% in PA projection. E was decreased by 19.8% for lumbar spine radiography in the study by Davey and England (2015). An anthropomorphic phantom was used, and the image quality was less in the PA projection. However, this reduction was not statistically significant. These results draw attention to the differences in anterior thickness between the erect and supine positions when imaging the pelvis. Gravity also has an effect on the redistribution of the anterior abdominal soft tissue, which could affect image quality and radiation dose.

The same dose reduction was found in the abdomen, clavicle, sacroiliac joint and pelvic radiographs when using PA projections (Farrugia Wismayer & Zarb, 2016; Mc Entee & Kinsella, 2010; Mekiš et al., 2010; Nic An Ghearr & Brennan, 1998). 68% and 50% dose reductions were found for the ovaries and uterus, respectively, for PA abdomen X-ray images when compared with AP (Nic An Ghearr & Brennan, 1998). A further study was performed by McEntee and Kinsella (2010) using a cadaver to compare the AP and PA projections for clavicle radiography. The results demonstrated dose reductions in the PA projection of 56.1% and 62.3% for breast tissue and thyroid, respectively. Another study's findings indicated that testicular dose could be reduced by 93.1% using PA projection for sacroiliac joint radiography in anthropomorphic phantoms (Mekiš et al., 2010), and this reduction came with no significant reduction on image quality. The comparison in image quality between AP and PA projections was performed in knee radiography (Farrugia Wismayer & Zarb, 2016). 32 patients were imaged in both projections. Image quality scores were higher for the PA projection, but variation between the two projections was not significant. However, the PA projection significantly improved two image criteria, including JSW and the visualisation of the tibial spine. A further study found reductions in E of 50% to 57% in PA projection for abdomen, pelvis and lumbar spine (Chaparian et al., 2014).

It should be noted that the research was not limited to evaluating the effect of repositioning on image quality and radiation dose. Some researchers also considered the effect of tube orientation on the patient dose. A study was conducted by Davis and Hopkins (2013) to evaluate the impact of a horizontal and vertical beam on DAP values in lateral lumbar spine radiography. The DAP value for vertical beam with the patient lying on their side was 1.3 $Gycm^2$, while for a horizontal beam it was 2.7 $Gycm^2$. Moreover, the results showed an increase in tissue thickness of between 2-9cm when rotating the patients from their side to their back. The authors concluded that the UK's recommended NDRL of 2.5 $Gycm^2$ for the lateral lumbar spine resulted from data wherein the distinction was not made between horizontal and vertical beam techniques. The authors recommend separate local DLR for the two techniques.

3.8 Chapter summary

There are limitations to the assessment of JSW, as the location of the measures has not been consistently reported. Some confirm the smallest measure, whilst others suggest the middle of the superior joint space. In addition, different positions, SID, centring points and acquisition parameters were identified. No consistent position for erect and supine acquisitions were used, and some studies obtained the images with internal rotation of the feet while others maintained a parallel feet position.

While a growing number of studies have investigated changes in pelvic measurements resulting from moving between erect and supine positions, there have been no investigations of any changes in radiation dose resulting from the different positions. It has been proven by many researchers that different positions have an effect on image quality and radiation dose for other body parts, such as lumbar and knee X-ray imaging. Further studies are warranted that should investigate optimum radiographic acquisition factors for erect pelvic radiography. Within the reviewed literature there was an absence of detail regarding the precise positioning of patients for both supine and erect pelvic radiography. Some authors did attempt to standardise techniques, but the effectiveness of this was not discussed. Further research is required in order to understand how variations in radiographic technique can affect pelvic measurements and potentially diagnostic and procedural outcomes.

In conclusion, from the literature it is clear that there are changes to the pelvis that occur when repositioning people from supine to erect. There is inconsistency in the literature, which is exacerbated by the different methods and techniques that have been used when evaluating the changes in position. These differences made the comparison between the studies very difficult, and study populations showed both intra- and inter-study heterogeneity. In addition, research has generally concentrated on specific patient / pathological groups (i.e. OA or FAI), limiting the generalisability of the research. Moreover, no studies have considered the radiation dose and overall image quality while repositioning from supine to erect position. Trends within the publications hereby analysed suggest that there are statistically significant differences in PT, CEA, PSI and JSW between different positions. For instance, many symptoms of hip pathologies are only present when assuming weight-bearing positions, and there are growing arguments supporting imaging in this position. It is likely that both supine and erect pelvic radiography, using standardised techniques, provide the opportunity for accurate evaluation of the hip joints. However, erect radiography provides a greater opportunity to evaluate the effects of force on the hip joint as well as the postural orientation of the pelvis. Such information can allow the identification of more subtle cases of pathology or provide more robust information for treatment planning. Ultimately, understanding that there can be differences in the measurements between techniques is important, and both supine and erect pelvic radiography will have a role in the investigation and management of hip disease.

Descriptions of radiographic techniques for erect radiography are limited. None of the publications discussed within this report have provided any evidence of validation on whether their approach to imaging is optimum. Additionally, some studies utilise non-standardised imaging such as reconstructed CT data or standing lateral spine X-ray images. Equally, no research has been conducted into optimising erect pelvic radiography, either from an image quality or dosimetry perspective. This represents a major gap in the literature and should be the focus of future research studies. The movement of abdominal and pelvic tissue is likely to be different between positions (e.g. erect versus supine), and is likely to have an effect on radiation dose and image quality. This would need to be considered when defining technical parameters, as it is important to be able to optimise the examination and provide maximum diagnostic information. Therefore, the aim of this thesis will be to evaluate pelvic X-ray images in the erect position in terms of positioning, with a view to providing an evidence-based set of optimised acquisition parameters for use in routine clinical practice.

Chapter 4: Evaluation of an optimum standing position for erect pelvis radiography (Phase one)

4.1 Chapter overview

This chapter describes the first experimental study in this thesis and to achieve the aims, a set of research objectives have been formulated. The output from this chapter will help inform the methods for the main clinical chapter in this thesis (phase three, chapter 7). The chapter starts with a summary of the literature informing the methods that have been used for posture evaluation (section 4.3). This literature discusses the advantages and disadvantages for each method, which helps to justify the methods section used in this chapter. An explanation of the effect of different standing positions on PT will be provided in order to help the reader understand the origin and reasons behind evaluating different positions during this phase of the thesis (section 4.4). Further details are provided in subsection 3.3.1 which show the effect of PT on hip radiographic parameters. These clarify the reasons behind choosing PT as a principle metric for monitoring the selection of positions for erect pelvic radiography. A pilot study which was conducted in order to evaluate the feasibility of the method and to make any changes that might be needed before starting the main study will be discussed (section 4.5). Section 4.6 of the chapter focuses on the details of the methods that were used to achieve the aim and objectives. The results section outlines the main findings from this phase of the thesis (section 4.7). The chapter then concludes with a discussion (section 4.8), the limitations (section 4.9) and a conclusion (section 4.10).

4.2 Aims and objectives of the study

The primary aim of this study was to evaluate the effect of different erect positions on pelvic and spinal postural measurements. The secondary aim was to recommend a reliable and repeatable erect position which could be used in the clinical phase (phase three; chapter 7) of this thesis. This aim was achieved by using video rasterstereography and manual inclinometry methods in order to evaluate PT in the coronal and sagittal plane. To achieve the aims of the study, the following objectives were established:

- To evaluate the differences in spine and pelvic metrics in eight different standing positions using a non-radiation method
- To evaluate the reliability for each position

- To compare seven erect positions, using position one which is considered the normal (neutral) standing position to evaluate any deviation from normality
- To evaluate the effect of different positions of the feet and arms on spinal and pelvic posture
- To compare the differences in the positional postures between different BMIs and genders. This is to evaluate if each BMI or gender needs a particular recommended position when performing erect pelvic radiography

4.3 Methods for posture analysis

In the last few decades a wide range of methods have been used for postural evaluation. The development of several technologies has provided reliable and easy to use methods, such as radiography (Beningfiel et al., 2003; Brink, Louw, & Grimmer-Somers, 2011; Wunderlich et al., 2011) and computerised photographic systems (Ferreira, Duarte, Maldonado, Burke, & Marques, 2010). Postural assessment methods can be divided into five main groups, namely radiography (Vedantam, Lenke, Keeney, & Bridwell, 1998), three dimensional motion analysis (Grimmer-Somers, Milanese, & Louw, 2008; Uritani, 2013), rasterstereography (McEvoy & Grimmer, 2005), photographic posture analysis (Nam, Son, Kwon, & Lee, 2013; Shaheen & Basuodan, 2012; Watson & Mac Donncha, 2000) and manual or observational methods. The latter involves many different methods, such as manual and electronic goniometry or inclinometer (Edmondston, Henne, Loh, & Østvold, 2005; Engh, Fall, Hennig, & Söderlund, 2003), observational methods that use gravity lines and fixable or curvature rulers (flexicurve) (Hazar, Karabicak, & Tiftikci, 2015).

X-Ray imaging is considered to be the most reliable and standardised method used for postural evaluation, as reported in the literature (Hazar et al., 2015). However, it is not favoured as it carries risks from its use of ionising radiation. This restricts its widespread use in research studies (Perry, Smith, Straker, Coleman, & O'Sullivan, 2008). Three-dimensional (3D) motion analysis is another method for postural analysis, and it has been proven to be valid and reliable (Sprigle, Wootten, Bresler, & Flinn, 2002), however this is expensive and requires specialist equipment (Lissoni, Caimmi, Rossini, & Terenghi, 2001). Such equipment may also have a limited number of sensors which restricts the potential for multi-angle measurements. Furthermore, 3D motion analysis requires specialist laboratory conditions. Setting up the equipment and managing the resultant data is also time-consuming (Perry et al., 2008).

Rasterstereography analysis uses a multidirectional video recording of the back surface and permits the production of a high-resolution 3D computer reconstruction image (Puglisi et al., 2014). This allows for the automatic calculation of measurements of spinal curvature, and is free from the use of ionising radiation. The reliability of this system has been widely described in both healthy and diseased populations (Betsch, Wild, et al., 2011; Drerup & Hierholzer, 1987b; Furian, Rapp, Eckert, Wild, & Betsch, 2013; Goh & Price, 1999; Guidetti et al., 2013). The results from these studies have shown high intra- and inter-day reliability (Guidetti et al., 2013; Mohokum et al., 2010; Schroeder, Reer, & Braumann, 2014). It is validity also has been widely examined in previous research studies (Betsch, Wild, et al., 2011; Knott et al., 2016; Mohokum, Schülein, & Skwara, 2015; Tabard-Fougère et al., 2017). Validity was established by comparing the spine and the pelvic measurements with that X -ray imaging (Hackenberg, Hierholzer, Pötzl, Götze, & Liljenqvist, 2003; Padulo & Ardigò, 2014). Correlation coefficients ranged from 0.22 to 0.87 (Knott et al., 2016), and in another study from 0.5 to 0.97 (Tabard-Fougère et al., 2017). The authors concluded that rasterstereography has a good validity compared to radiography and overall excellent intra- and inter-rater reliability. This method has the disadvantage of requiring the entire torso to be uncovered, which is not acceptable for some people - in particular for adolescents (Perry et al., 2008).

The next method in postural evaluation is photography posture analysis. This method is simple and one of the many observational methods available. It is convenient and readily accessible. It relies on calculations of the angles depending on the anatomical reference points (Fortin, Feldman, Cheriet, & Labelle, 2011). In addition, it is portable, relatively cheap and the only requirements are a camera, adhesive tape and a marker (Perry et al., 2008). The reliability of this method has previously been evaluated (Ferreira et al., 2010; McEvoy & Grimmer, 2005; Watson & Mac Donncha, 2000) and the results demonstrated good inter- and intra-reliability. Validity was established by a comparison with the results from an inclinometer (O'Sullivan, Mitchell, Bulich, Waller, & Holte, 2006), however; it was moderate to poor when ranked against radiography (Johnson, 1998) and only reasonable with 3D imaging systems (J. A. Paul & Douwes, 1993). With this method the researcher measures the angle manually by drawing the lines between the reference points. A photogrammetric method is another kind of photography method. It has the same basic principles as the photography method, but instead of using manual angular calculations the computer system utilises these calculations after the photo has been captured (Veqar, 2014).

The last method for postural analysis is the manual method. This includes several methods such as visual observation (Veqar, 2014), use of a goniometer or inclinometer (Sprigle et al., 2003), plumb line methods and flexicurve. These methods have also displayed good validity and reliability (Engh et al., 2003; Hickey, Rondeau, Corrente, Abysalh, & Seymour, 2000). However, these kinds of methods may be only suitable for a single angle measure, while it is considered to be time consuming if multi-angle measurements are performed (Perry et al., 2008). The only advantage of observational methods and the use of a plumb line is that they do not require any expensive equipment. However, they have displayed poor inter-rater agreement (Iunes, Bevilaqua-Grossi, Oliveira, Castro, & Salgado, 2009). A goniometer and inclinometer are used in physiotherapy practice for measuring range of motion (ROM). They are also used for angular measurement and postural assessment (Sacco et al., 2007). In addition, the goniometer and inclinometer have been used widely in research studies for measuring PT (Beardsley, Egerton, & Skinner, 2016; Gnat, Saulicz, Biały, & Kłaptocz, 2009; Herrington, 2011; Reis & Macedo, 2015). There are many reasons as for why the inclinometer is the most common tool used by clinicians for measuring PT. For example, they generally express good reliability in measuring PT (Crowell, Cummings, Walker, & Tillman, 1994; Gnat et al., 2009; Hagins et al., 1998; Heino, Godges, & Carter, 1990; Herrington, 2011; Krawiec, Denegar, Hertel, Salvaterra, & Buckley, 2003; Petrone et al., 2003; M. Walker, Rothstein, Finucane, & Lamb, 1987). The intra-class correlation coefficient was reported as good in one study (Herrington, 2011), and excellent in another (Gnat et al., 2009). Moreover, the validity of this method was proven when compared to radiography (Crowell et al., 1994; Petrone et al., 2003). Furthermore, these devices offer more advantages to clinical practice, such as being quick and easy to use, small, portable, inexpensive compared with other devices and relatively safe when compared to X-ray imaging. Using this kind of device allows for measuring both sides of the pelvis, which is important when identifying differences between both sides (Preece et al., 2008).

4.4 The effect of different erect positions on PT

The aim of this section is to provide an overview of the erect positions used in the literature for other body parts and recognise the effect of these different positions on PT. This helps understand the origin of the positions that were used during the methods section in this chapter. Section 3.3.1 provided more details on the effect of PT on hip radiographic parameters which account for PT important in the selection of positions for erect pelvic radiography in this thesis.

In one study, a 3D motion analysis camera was used to assess the effect of 18 different foot positions (positions ranging from 15° eversion to 15° inversion, and from 40° internal rotation to 40° external rotation) while standing erect on a rigid platform. These results showed that there is no effect from over-supination or pronation of the feet on PT. However, PT is rotated anteriorly with internal rotation of the leg and posteriorly with leg external rotation (Duval, Lam, & Sanderson, 2010). Bagwell et al. (2016) also reported similar results when performing a study of four different hip flexions with maximum anterior and posterior PT. Constant pelvic motion across all hip flexion angles was found. 1.2° to 1.6° of internal rotation of the femur resulted from every 5° of anterior PT, and the opposite was true for posterior PT (Bagwell, Fukuda, & Powers, 2016).

Studies were undertaken to find the best positioning for the arms during lateral spine radiography (Faro, Marks, Pawelek, & Newton, 2004; Marks, Stanford, & Newton, 2009; Vedantam, Lenke, Bridwell, Linville, & Blanke, 2000). The study was conducted in 2004 and sought to evaluate the functional position on patients with adolescent idiopathic scoliosis (AIS). Erect lateral X-ray images of the spine were obtained in two different positions with the arms 45° forward and with the elbow fully extended, and elbow fully flexed with fists rested on the clavicle (see **Figure 4-1**). The position with fists on the clavicle had less of a negative effect on the sagittal vertical axis (SVA: horizontal distance from the posterior superior corner of the sacrum to the plumb line dropped from the center of the body of the C7 vertebra), and less compensation of the posterior rotation of the pelvis. The authors concluded that this position represents more of the patient's functional balance, and that it also represents a suitable method for imaging the spine (Faro et al., 2004).

Figure 4-1: Illustrates two arm positions. Fully extended arms (left) and arms touching the clavicle (right).

In contrast, four erect postures were studied in relaxed erect positions, with the arms by the sides (control), shoulders flexed with fully extended elbows (active), elbows extended and hands on a support (passive) and standing with the arms (fists) on the clavicles (see **Figure 4-2**). The positions were evaluated by eight cameras with an infrared motion capture system. The passive position was felt to be optimum for moving the arms away from the spine during lateral radiography. This position also has the least effects on total sagittal balance (Marks et al., 2009).

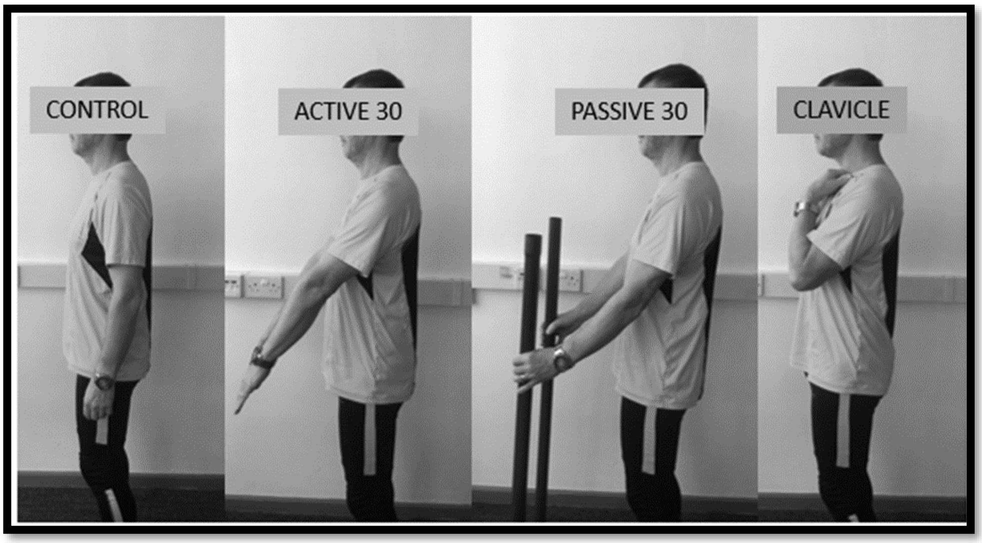


Figure 4-2: An example on four different erect positions examined in order to select an optimum position for erect lumbar spine radiography.

A study was conducted by Vedantam et al. (2000) to measure the negative shift of SVA for different lateral erect spine radiography positions. The X-ray images were obtained with 90° angles at the shoulders and arms forward, and with hands resting on supports. SVA was negatively shifted in the two arm positions, but less so in the position with hands on the support. The lumbar lordosis/sacral inclination was not affected. The author explained that the decrease in the negative shift of SVA was due to using the hand supports, which compensated for the weight bearing of the arms. The hand resting on support position was recommended by the author as a standard position during full lateral erect spine imaging (Vedantam et al., 2000).

The negative SVA shift was also evaluated by Marks et al. (2003). The study was performed using a motion capture system at the same time as lateral radiography acquisitions. Different erect positions were assessed, including relaxed erect with arms at sides, shoulders flexed 45° with elbow extended, arms at sides with knees flexed 30°, and shoulders and knees flexed. The results show negative SVA shift due to shoulder flexion during lateral erect radiography, relative to the relaxed erect position. In addition, 3° of posterior rotation of the pelvis was reported as a result of this. This rotation is explained as a compensatory response to prevent the centre of mass (COM) moving posteriorly and causing a loss of balance. Moreover, there were no differences in SVA while the knee was flexed or in a relaxed erect position. (Marks, Stanford, Mahar, & Newton, 2003).

A study by Aota et al. (2011) was undertaken to evaluate which arm position is optimal for radiographic visualisation of spinal and pelvic sagittal morphology, as the arms are interference on the radiograph during the relaxed standing position. Arms were positioned in five different positions: arms by the sides, flexed 45°, elbows fully flexed and fists resting on the clavicle, arms across the chest, and arms relaxed in front with hands loosely clasped (see **Figure 4-3**). The results showed that having the arms in front with hands loosely clasped provided the lowest negative SVA when compared with other arms positions which are considered to be the optimal positions for SVA measurements.

Figure 4-3: Different arm positions for lateral spinopelvic radiography. From left to the right: arms by sides, arms flexed 45°, elbows fully flexed and fists resting on the clavicle, arms across the chest, and arms relaxed in front with hands loosely clasped.

In 2013, a study was undertaken to evaluate the reduction in back pain achieved by standing erect on sloped surfaces. Flattening of the lumbar spine and posterior PT was reported when standing erect on sloped (declining) surfaces. On the other hand, standing erect on an inclined surface resulted in an increase in lumbar lordosis and anterior PT (Gallagher, Wong, & Callaghan, 2013). A study was performed to evaluate the differences in lumbar posture between two groups- those with and without lumbar pain. It also studied the effect of two erect aids on lumbar posture. Sagittal X-ray images were taken on level ground in the normal erect, erect on a declining slope, fully extended and using elevated surfaces. The results showed significant differences between a normal erect position and full extension in the lumber lordosis measurements. Moreover, lumbosacral flexion was found on elevated surfaces, and the changes were most noted in the lower region, but not on the total lumber lordosis. These findings may highlight the importance of the posterior PT on hip biomechanics (Gallagher, Sehl, & Callaghan, 2016).

4.5 Pilot study

4.5.1 Introduction and methods

A pilot study is a small portion of a main study, and is always conducted using a smaller sample size with the same inclusion and exclusion recruitment criteria of the main study (Doody & Doody, 2015). The pilot study in question was conducted to provide an opportunity to practice and evaluate collecting positional data. In addition, it helped to detect any problems which may affect the workflow of the data collection methods, and also to assess the validity and reliability of the data acquisition tools. Finally and most importantly, the pilot study was conducted to determine the effect size that would be utilized for sample size calculations within the main study (Gardner, Gardner, MacLellan, & Osborne, 2003; Teijlingen, Edwin & Hundley, 2001). During the pilot study, the reliability of the Diers system and inclinometer were assessed. Following University of Salford ethical approval (HSR1617-142) (Appendix 2), twelve (6 male and 6 female) healthy participants were recruited for the pilot study using the same inclusion and exclusion criteria as would be used for the main study (see section 4.6.4). The study was conducted in the Human Physiology Laboratory in the Mary Seacole Building, University of Salford, Manchester. Volunteers were made up of from university staff and students. Volunteers performed eight different standing positions, as described in section 4.6.6. The researcher did not use any reflective markers placed on the participants, as this can sometimes be used to help the system detect surface landmarks. This decision was made based on previous research that assured the ability of the system to detect landmarks automatically. The results from this body of literature recommended letting the system detect the anatomical landmarks automatically (Knott, Mardjetko, Tager, Hund, & Thompson, 2012; Mohokum et al., 2010). Also, in the system manual, it reports that in 90% of cases will detect the landmarks correctly (Diers international, n.d.).

The data collected from the pilot study showed a large variation in several postural measurements, especially in the pelvic tilt and pelvic torsion (coefficient of variation values were greater than 40%). Following data analysis from the pilot study, a number of modifications to the study protocol were made. These included, using reflective markers instead of letting the system detect anatomical landmarks automatically. This decision was made to overcome variations as the participant performed the eight different standing positions, and these positions (except position 1) were considered not the usual position for the system. No special instructions were given to the participants that may have affected the positioning. However, the participants were asked not to move during the acquisition and to keep their eyes looking forward at a fixed point. In view of the changes to the method, the pilot study was repeated for further evaluation.

In order to evaluate the reliability of the Diers system and the manual inclinometer, measurements for each position were repeated three times and the duration for each trial was set at a maximum of 15 minutes. Within this window the evaluation of the intra-participant variability could be obtained. The reliability study was performed on same day for Diers and inclinometer measurements. The Diers was used to evaluate the PT in the coronal plane, as well as the pelvic torsion (PTor), dimple distance (DD), thoracic kyphosis (TK) and lumbar lordosis (LL). The inclinometer was used to evaluate the PT in the sagittal plan. To distinguish between PT in the coronal and the sagittal planes, throughout this thesis the abbreviation PT_{cor} was used for the coronal pelvic tilt which was obtained by Diers and PT_{sag} was used for the sagittal pelvic tilt obtained by the use of the inclinometer. The evaluation of PT in the two planes is essential because pelvis pathologies are usually evaluated by coronal and sagittal radiographs (Ghostine et al., 2017). Participants were asked to perform the procedure after one hour on the same day and one week after the first trial. The aim of repeating the procedure after one hour and one week was to evaluate the reliability of the researcher in positioning the reflective markers. The inclinometer angles were read by an assistant researcher and the main researcher was blinded from these readings. The assistant researcher was an expert in physiotherapy and had experience in using inclinometers.

4.5.2 Pilot study results

The results from the Diers system pilot phase are reported as mean, standard deviations and the standard error of measurements. **Table 4-1** presents the demographic data for the pilot study sample and **Table 4-2** shows the mean (SD) for the three repeated measures for each position (Schroeder et al., 2014) and SEM. Intra-class correlation coefficients (ICC) were calculated for the reliability of the system **Table 4-3**, and for the inclinometer measurements. The ICC can range from -1 to 1. ICC values less than 0.5 are indicative of poor reliability; values between 0.5 and 0.75 indicate moderate reliability; values between 0.75 and 0.9 indicate good reliability; and values greater than 0.90 indicate excellent reliability (Koo & Li, 2016; Portney & Watkins, 1993). ICC values were **c**alculated using the SPSS software and standard error of measurements (SEM) were calculated using the equation below. **Table 4-4** demonstrates the results for the inclinometer on the same day and after one week.

SEM= $SD\sqrt{1 - ICC}$ (Denegar & Ball, 1993)

Table 4-1*:* Demographic data for the pilot study, separated for males and females (means ± standard deviation).

	Age (years)	Height (m)	Weight (kg)	BMI (kg/m^2)
Total (n=12)	29.8± 3.2	1.7± 0.07	70.1± 7.9	23.5± 2.3
Female (n=6)	28.4± 2.2	1.7± 0.07	65.5± 4.9	22.9± 2.3
Male (n=6)	30.8± 3.5	1.8± 0.05	74.3± 7.2	23.8± 2.2

Table 4-2: Descriptive (mean ± SD) intra-individual variability expressed as SEM.

	MEAN (SD)						SEM					
METRIC /POSITION	**DD[1]**	**PTor[2]**	**PT_{cor}[3]**	**TK[4]**	**LL[5]**	**PT_{sag}[6]**	**DD**	**PTor**	**PT_{cor}**	**TK**	**LL**	**PT_{sag}**
1	90.9 (0.4)	0.54 (1.07)	-0.51 (0.90)	51.2 (1.72)	37.35 (1.45)	3.72(4.34)	0.01	0.2	0.2	0.2	0.08	0.05
2	89.06 (0.3)	-0.14 (1.02)	-1.05 (0.90)	51.04 (1.48)	39.01 (1.50)	3.81(2.47)	0.01	0.4	0.2	0.2	0.08	0.07
3	88.9 (0.51)	-0.79 (0.79)	-0.76 (0.64)	51.3 (1.9)	39.85 (1.82)	3.89(4.61)	0.03	0.2	0.2	0.1	0.2	0.07
4	89.1 (0.45)	0.19 (0.94)	-0.61 (0.89)	52.13 (1.84)	37.70 (1.22)	3.67(4.42)	0.01	0.2	0.2	0.3	0.2	0.09
5	89.8 (0.24)	0.23 (0.88)	-0.62 (0.79)	52.04 (1.58)	38.64 (1.18)	3.94(4.52)	0.04	0.2	0.3	0.3	0.1	0.08
6	89.7 (0.33)	0.36 (0.87)	-0.46 (0.37)	51.85 (1.52)	41.25(1.19)	3.94(4.61)	0	0.2	0.06	0.2	0.1	0.08
7	89.7 (0.28)	-0.78 (0.92)	-0.43 (0.43)	51.26 (1.24)	41.60 (1.01)	3.89(4.75)	0.01	0.2	0.07	0.2	0.1	0.07
8	89.9 (0.40)	0.50 (1.11)	-0.33 (0.43)	51.9 (1.63)	39.60 (1.46)	4.11(4.56)	0	0.2	0.05	0.2	0.1	0.06

1: Dimple Distance; 2: Pelvis Torsion; 3: coronal Pelvis Tilt; 4: Thoracic Kyphosis; 5: Lumber Lordosis; 6: sagittal Pelvic Tilt

Table 4-3: Reliability coefficients (ICC± CI 95%) for the eight standing positions.

METRIC /POSITION	ICC (95%CI)					
	DD[1]	PTor[2]	PT_{cor}[3]	TK[4]	LL[5]	PT_{sag}[6]
1	1.00*** (0.999-1)	0.95** (0.859-0.983)	0.93** (0.825-0.979)	0.98*** (0.941-0.993)	0.99*** (0.960-0.995)	0.961*** (0.88-0.998)
2	1.00*** (0.999-1)	0.94 (0.836-981)	0.95* (0.872-0.985)	0.98*** (0.957-0.995)	0.98*** (0.940-0.993)	0.917*** (0.741-0.973)
3	0.99*** (0.999-0.996)	0.95*** (0.875-0.985)	0.85** (0.609-0.954)	0.98*** (0.937-0.993)	0.96*** (0.901-0.988)	0.937*** (0.803-0.980)
4	0.99*** (0.999-1)	0.95 (0.854-0.983)	0.91* (0.758-0.971)	0.97*** (0.942-0.991)	0.99*** (0.980-0.998)	0.918*** (0.743-0.974)
5	1.00*** (0.998-1)	0.96 (0.903-0.989)	0.9* (0.734-0.969)	0.98*** (0.946-0.994)	0.99*** (0.977-0.997)	0.952*** (0.851-0.985)
6	1.00*** (0.999-1)	0.953* (0.876-985)	0.961*** (0.898-0.988)	0.981*** (0.949-0.994)	0.991*** (0.976-0.997)	0.96*** (0.876-0.987)
7	1*** (0.999-1)	0.97 (0.913-0.990)	0.98** (0.934-0.992)	0.986*** (0.962-0.996)	0.994*** (0.984-0.998)	0.968*** (0.900-0.990)
8	1*** (0.999-1)	0.93 0.839-0.981)	0.98* (0.954-0.995)	0.976*** (0.936-0.992)	0.986*** (0.964-0.996)	0.953*** (0.853-0.985)

Levels of significance * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$.
1: Dimple Distance; 2: Pelvis Torsion; 3: coronel Pelvis Tilt; 4: Thoracic Kyphosis; 5: Lumber Lordosis; 6: sagittal Pelvic Tilt.

Table 4-4: Intra-class Correlation Coefficients (ICC± CI 95%) for PT_{sag} on the same day and after one week for all different positions using the inclinometer.

METRIC /POSITION	Same day	One week
1	0.961 (0.880-0.988)	0.790 (0.51-0.985)
2	0.917 (0.741-0.973)	0.837 (0.186-0.967)
3	0.937 (0.803-0.980)	0.903 (0.516-0.981)
4	0.918 (0.743-0.974	0.875 (0.376-0.975)
5	0.952 (0.851-0.985)	0.893 (0.467-0.979)
6	0.960 (0.876-0.987)	0.842 (0.212-0.968)
7	0.968 (0.900-0.990)	0.900 (0.503-0.980)
8	0.953 (0.853-0.985)	0.777 (0.114-0.995)

The Diers system showed that the ICC ranged from 0.90 to 1.00 for measurements performed on the same day, indicating excellent reliability. The data from the inclinometer indicated excellent reliability again on the same day and good reliability after one week. These results are in line with previous research studies that have examined the reliability of the Diers system and the inclinometer (Beardsley et al., 2016; Betsch et al., 2015; Betsch, Wild, et al., 2011; Guidetti et al., 2013; Mohokum et al., 2015; Reis & Macedo, 2015; Romero-Franco, Montaño-Munuera, & Jiménez-Reyes, 2017; Schroeder et al., 2014; Tabard-Fougère et al., 2017).

4.6 Main study methods

4.6.1 Study site

This phase of experimental work was undertaken in the Human Physiology Laboratory of the Mary Seacole Building, University of Salford, Manchester, since the Diers system, which was used to collect the data, was located in this area.

4.6.2 Equipment and instrumentation

The data was obtained with two different instruments namely a manual inclinometer and a videorastereography (Diers) system. The rationale for using the two instruments was that the assessment of pelvic and hip pathology is usually undertaken with coronal and sagittal X-ray images (Ghostine et al., 2017). Therefore, the decision was made to measure pelvic tilt in these two different planes. The inclinometer was used to measure pelvic tilt in the sagittal plane, while the Diers system was used to obtain pelvic tilt measurements in the coronal plane.

4.6.2.1 Inclinometer

An inclinometer palm-palpitation meter (US. Patent 5327907) (see **Figure 4-4**) was used to measure anterior and posterior PT in the sagittal plane for each participant. The palm meter has a calliper which measures the inclination between 0° to 30°. The inclinometer has two arms (plastic strips). One of these was placed on the surface of the participant at the location of the ASIS, and the other was placed on the PSIS (these are essentially two bony landmarks on the front and back of the pelvis). Between these two arms there was a protractor which provided an indication of PT. During the procedure, two anatomical landmarks (ASIS and PSIS) were palpitated by the researcher on the participant's pelvis. Following this the researcher marked them with temporary (high visibility) markers, and the angle of the pelvic tilt was recorded. The methods used to obtain the pelvic tilt measurements used during this research thesis have been well described in previous studies (Gajdosik et al., 1985; Preece et al., 2008; Salian et al., 2015; Sprigle et al., 2003)(see **Figure 4-5**). Also, the validity and reliability of the inclinometer for measuring pelvic tilt has been widely reported (Beardsley et al., 2016; Gnat et al., 2009).

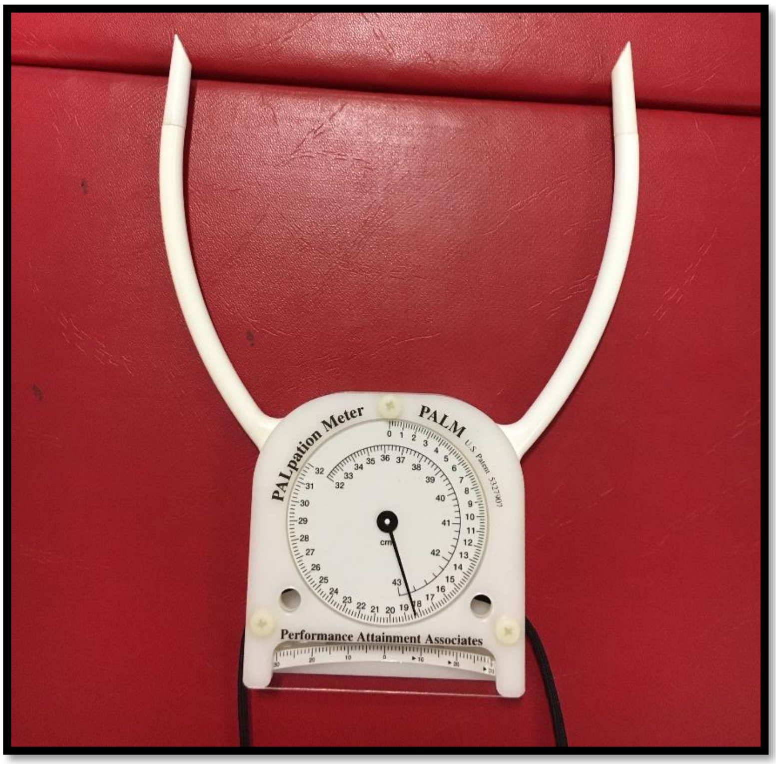


Figure 4-4: Inclinometer and it is main components (Palm meter).

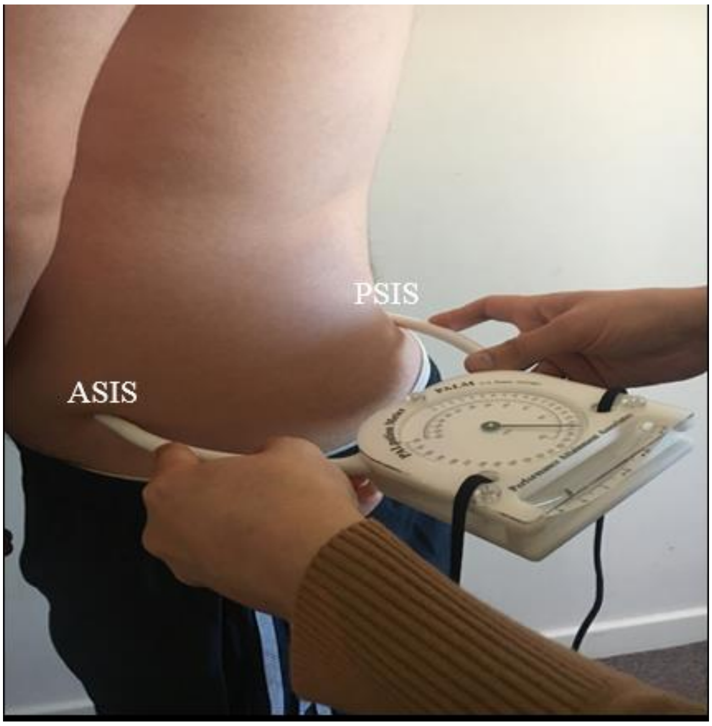


Figure 4-5: Pelvis landmarks and positioning the palmer inclinometer callipers for measuring PT_{sag}.

4.6.2.2 Diers system

Surface topography data was collected using the formatic dynamic modelling system developed by Diers (Diers International GmbH, Schlangenbad, Germany). The Diers system was chosen because it is absent of ionising radiation. The reliability of this system has been widely described in both healthy and diseased populations (Betsch, Wild, et al., 2011; Drerup & Hierholzer, 1987b; Furian et al., 2013; Goh & Price, 1999; Guidetti et al., 2013). The results from these studies showed high intra- and inter-day reliability when examining healthy volunteers and AIS (K. Alzyoud, Hogg, Snaith, Preece, & England, 2019; Frerich, Hertzler, Knott, & Mardjetko, 2012; Guidetti et al., 2013; Mohokum et al., 2010; Schroeder et al., 2014; Schülein, Mendoza, Malzkorn, Harms, & Skwara, 2013). The validly was also widely examined by previous research (Betsch, Wild, et al., 2011; Hackenberg et al., 2003; Knott et al., 2016; Mohokum et al., 2015; Padulo & Ardigò, 2014; Tabard-Fougère et al., 2017). The basic principle of this instrument is to measure the triangulation of dimensional points. During the procedure, a white light source is used and the surface area of the participant (their 'back') is illuminated. The scattered light from the participant is then registered by a camera and an image and biomechanical measurements are obtained (see **Figure 4-6**). During this study a 3D examination was used, and the examination parameters were as follows: a duration of 6 seconds, 12 images taken, and an acquisition frequency of 2 per second. During the acquisition, the system took 12 images of the same area after which the system took the average of them (see **Figure 4-7**). This improves the reproducibility for the same person due to certain images being rejected when involuntary movement, such as breathing, has occurred.

Figure 4-6: Diers system. This consists of a recording camera and light projector. The uneven back surface alters the straight projected light. The camera detects this distorted light from different angles of view and undertakes measurements.

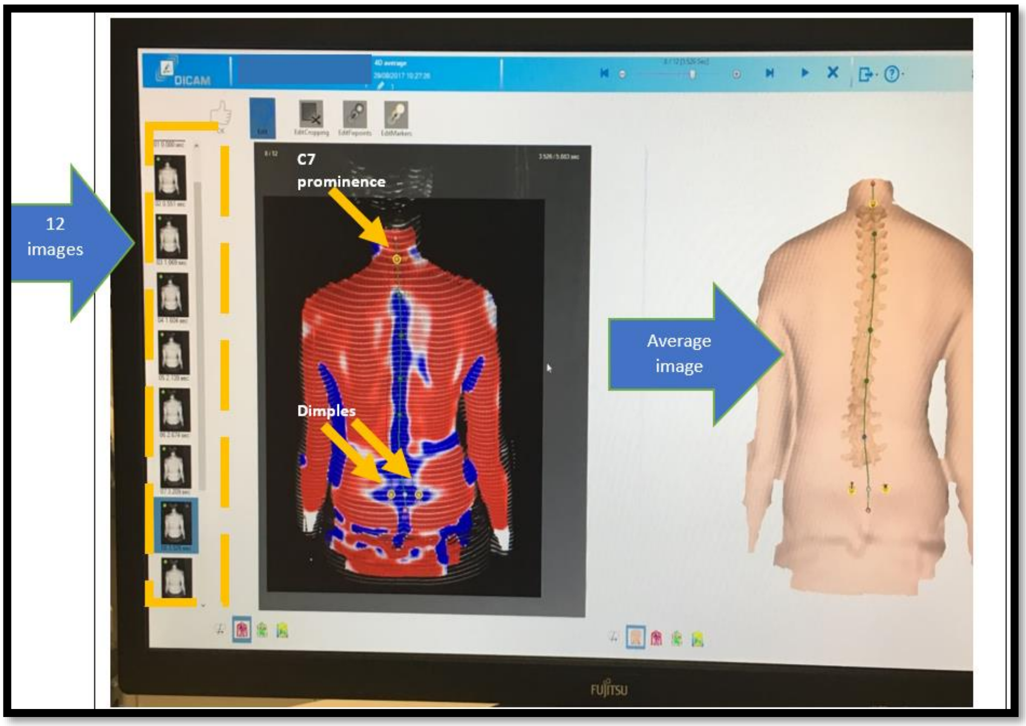


Figure 4-7: 3D images of the spine and pelvis were obtained using the Diers formetic 3D imaging system. The back-surface reconstruction is illustrated with red areas highlighting the convex curvature and blue areas for the concave curvature. Yellow dot within each image demonstrate the axis for the coordinate system. The left and right lumbar dimples are at the bottom of the image (DL, DR) and the vertebra prominens (VP) of the top.

Before starting the Diers data collection, quality control and maintenance was performed by the system engineers. This procedure included checking the position of the system, and adjustments were herein made when needed. Also, the position of the patient, which allows for the raster image to be projected in the sharpest possible way, was checked. Furthermore, the systems projected lines were adjusted, the lenses were cleaned, and the light bulb was changed. This is because as the bulb becomes hot, the glass on the inside starts to get darker (burned). The darker the glass, the less light the bulb will produce. As such, it needed to be changed (normally once per year) to ensure we had an optimal projection of the grid on the back of the patient.

4.6.3 Sample size

G power is a computer software programme used to calculate sample size. It has been shown to have excellent accuracy (Faul, Erdfelder, Buchner, & Lang, 2009). Repeated measures factor analysis of variance (ANOVA) have been run on the pilot study data in G power with an alpha set to 0.05 and a power set to 0.85. Theses showed that 20 participants were needed to conduct this study. This study aimed to assess the impact of different body habitus on PT. As body weight increases, it is influence on the pelvis and lumbar spine could differ.

Therefore, the sample size included three different groups according to BMI. Based on World Health Organisation report (World Health Organisation (WHO), 2005) the underweight (BMI<18.5) and normal weight (BMI 18.5 - 24.99) were one group, whereas overweight BMI≥25 and obese BMI ≥30 were made up groups two and three. A total of 20 participants were recruited for each group. One extra participant in each group was recruited to account for if participants possibly choose to leave the study or not attend subsequent data collections.

4.6.4 Inclusion and exclusion criteria

The inclusion and exclusion criteria were summarised in the **Table 4-5**:

Table 4-5: Summarise the inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
1. Healthy volunteers with a healthy skeletal system (no known conditions of the spine and pelvis/hip, and being presently pain and symptom free)	1. A history of pelvic or spinal abnormalities, fractures, serious trauma, previous pelvic surgery
2. Not have been injured or have had previous spinal or pelvic surgery (in the past six months)	2. Secondary degenerative arthritis changes in the spine and hip and with accompanying anatomical deformity of the hip
3. Free of any known neurological problems, pathological findings in the hip/pelvis (including congenital) and with no abnormality in their gait	3. Participants undergoing bilateral or revision THR
4. No known discrepancies in leg length	4. Had tattoos, physical disabilities or mental impairment, operations on their back, and scarring on their back
5. Ability to independently maintain an erect position for 6 to 10 seconds	5. Suffering from scoliosis or ankylosing spondylitis, experiencing back pain, fractures, pregnant or had given birth within the last 12 months.

4.6.5 Ethical considerations

The study received ethical approval from the University of Salford School of Health and Society Ethics Committee (Appendix 2). During this study, there was minimal risk for participants and the researcher since the Diers system is safe and does not use ionising radiation. Participants were asked to change in a private changing room and wear a gown to cover the anterior part of their body. The palpation for bony landmarks was performed just once. After marking these landmarks there was no need to touch participants again. Furthermore, sample Diers images were available to participants prior to gaining their consent to ensure that they understood the type of data being collected by the imaging system. Numerical data were only collected during the study, and imaging data were not captured. Participants had the option of seeing the collected data and could withdraw their consent for a period of up to 3 months following data collection. Confidentiality was preserved by coding any gathered data using unique coding numbers for every participant which would maintain their anonymity. Dignity and embarrassment issues were addressed by a clear participant information sheet.

4.6.6 Recruitment process

Participants were invited to take part in this study by email and through poster advertisement. The poster was displayed on the University notice boards, allowing for staff members and students to consider participating (Appendix 11). The information provided included the aims and the rationale of the study, and the inclusion and exclusion criteria were provided to any interested participants. Participant information and data collection sheets (Appendix 7 and 8) were sent to participants who agreed to take part before they attended the Diers and inclinometer measurements. These provided potential participants with more time to think and consider the different issues that would be raised in the study prior to them making an informed choice.

4.6.7 Procedures

On the day of the experiment each participant attended one session which lasted approximately 60 minutes. During this visit, they read and signed the consent form (Appendix 6). The researcher helped participants to complete a data collection sheet (i.e. noting down their age, weight and height). Before starting the experiment, participants were asked if they understood what was to happen and whether they had any questions. Participant were then asked to change her/his clothes in a private changing room. This included taking off the upper part of their clothes and wearing a special gown (revealing their posterior surface only). The gown was to cover the frontal part of their body while their back was undressed to facilitate the acquisition of the back measurements. The researcher marked the pelvic bony landmarks using a temporary marker (a sticker), so that the researcher did not need to palpate these landmarks more than once. Following this, participants were instructed to stand at a certain point with his/her back in front of the Diers system. Participants were then asked to stand in a relaxed state with their head facing forward. They were then invited to perform eight different erect positions. Four of these positions were performed with the feet shoulder width apart and parallel; and four positions were performed with the feet shoulder width apart and internally rotated. For the upper extremity, each of the two sets of four positions were performed with different arm positions (arms by the sides, arms crossed over the chest, arms flexed and touching the medial end of the clavicle, and arms flexed with the hands holding a support (see **Figure 4-8).**

Figure 4-8: The eight different standing positions that were examined in this research project. The first four were with parallel feet and different arms positions (A); the second four set with feet internally rotated and the same arms positions as in the same first set (B).

For each position listed above, the inclinometer was placed by the researcher against the markers, and the measurements of anterior or posterior PT were recorded. Then, participants were ready for the second part of the measurements which were obtained using the Diers system. This continued for all eight positions (postures). The eight positions were then coded for practical data collection and the data analysed follows in **Table 4-6.**

Table 4-6: Descriptions of the eight different erect positions with usual standing as well as different arm and feet positions.

Position	Feet position	Arms
1	Neutral	By sides
2	Neutral	Crossed over chest
3	Neutral	Arms flexed, fists touching the medial end of the clavicle
4	Neutral	Arms extended, hands on supports
5	Internally rotated	By sides
6	Internally rotated	Crossed over chest
7	Internally rotated	Arms flexed fists touching the medial end of the clavicle
8	Internally rotated	Arms extended, hands on supports

Measurements were performed in each of the eight standing positions. Between each position participants were allowed a short break and to move around the room. Once all eight positions were evaluated this process was then repeated twice during the same session. This gave a total of 24 measures for each pelvic/spinal parameter. Following image acquisition, the Diers system automatically generated different measurements of the spine and pelvis, such as: coronal pelvic tilt (PT_{cor}), pelvic torsion (PTor), thoracic kyphosis (TK), lumbar lordosis (LL) and dimple distance (DD). To understand the measurements of the Diers system it is necessary to define the parameters measured by the device. These are described as follows (see **Figure 4-9): -**

- Pelvic tilt angle (°) (PTcor) the angle between a vertical plumb line and the tangent on the lumbar dimples (DL and DR) in the frontal plane
- Pelvic torsion angle (°) (PTor) the torsion between the left and right side of the pelvis bones and the rotation of the surface of the two lumbar dimples (DL and DR)
- Dimple distance (mm) (DD) the distance between the two pelvic dimples (DL and DR)
- Thoracic Kyphotic angle (°) (TK) the maximum thoracic angle calculated from ICT (inflectional point of the curvature from cervical to thoracic spine) and ITL (inflectional point of the curvature from thoracic to lumbar spine)
- Lumbar Lordosis angle (°) (LL) the maximum lumbar angle calculated from ITL and ILS (inflectional point of the curvature from lumbar to sacral spine).

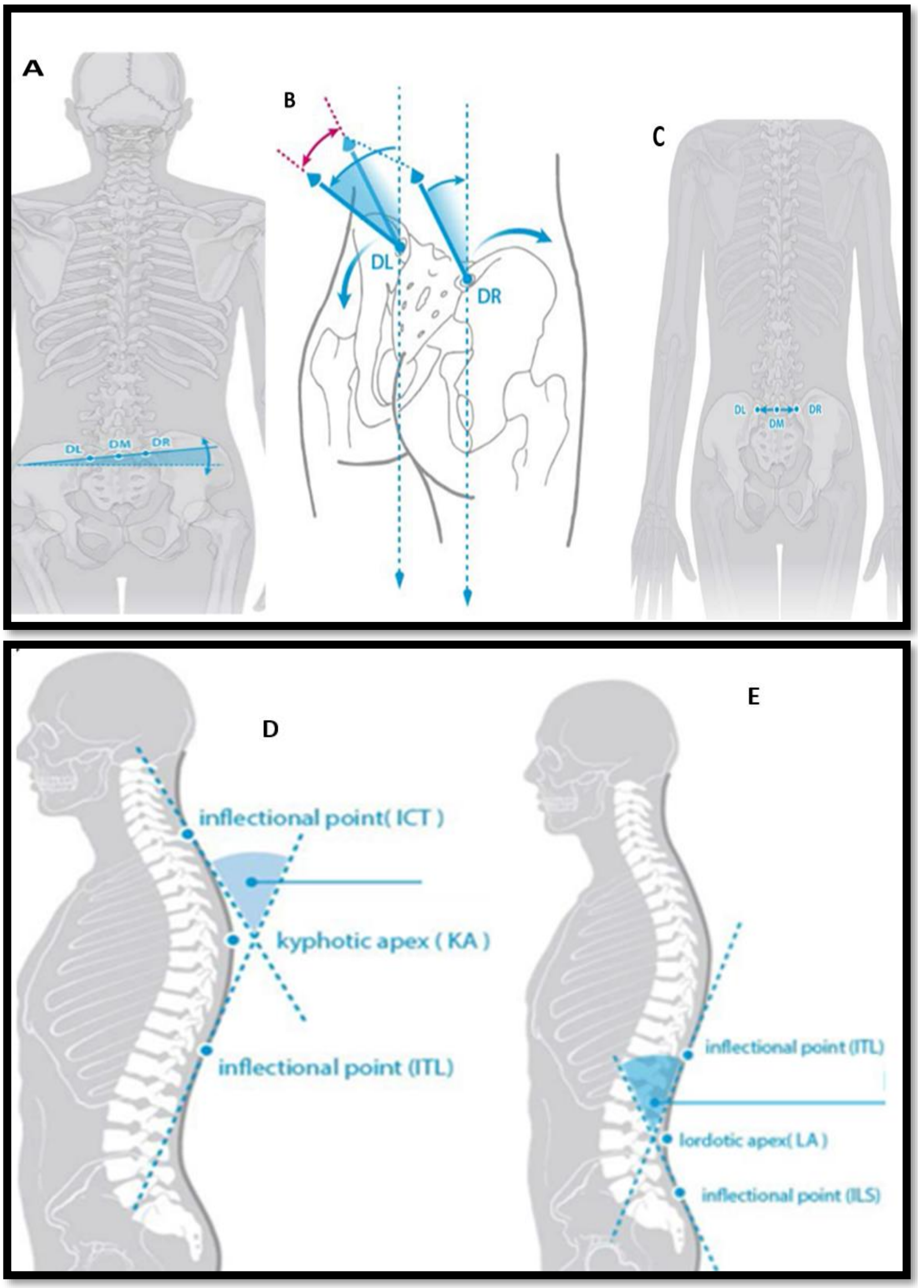


Figure 4-9: Illustrates the pelvic and spine measurements obtained during this study. A: PT_{cor}, B: PTor, C:DD, D:TK, E: LL.

The measurements selected above are the most common parameters measured within the literature (Furian et al., 2013; Knott et al., 2016; Schroeder et al., 2014; Tabard-Fougère et al., 2017) and would provide an indication of the 3D orientation of the pelvis in different positions. Moreover, it has been reported in previous works that using the standard deviation of intra-individual lumbar dimple distance was an accurate parameter for evaluating positional variation (Dankerl et al., 2016).

For each participant, the Diers camera height was adjusted so that the spine was in the centre when acquiring postural data. Horizontal light lines were projected onto the participants' backs to allow the Diers system to collect data. In the examination room the light was dimmed appropriately, so the projected lines on the participants' backs were clearly visible for the system. Each of the eight positions took around 6 seconds to acquire Diers data. Participants were instructed to walk around between different positions to give them an opportunity to relax (Mohokum et al., 2010).

4.6.8 Special considerations

As each participant needed to perform eight different standing positions three times, the variation between the positions needed to be considered between each trial. In order to overcome this problem and minimise the variation between positions for the same participant and between the participants, the researcher constructed a special tool for foot position standardisation. This was developed from the recommendations by Auleley et al. (2001). This tool allows the participants to stand with their feet at shoulder width apart and with 20° of internal rotation (both feet have blocks on each side which stop foot rotation at 20° (see **Figure 4-10**). The foot plate has two-foot prints for left and right feet. The left is fixed, and the right can be moved so that all possible shoulder width differences can be covered for all participants. 20° was selected to cover the maximum degree (recommended) that can be achieved when undergoing pelvic radiography (Whitley et al., 2005). Therefore, the effect of the maximum foot angle on PT could be determined. The tool has a measuring tab in front as the participants need to stand with their feet a shoulder width apart. This allows this distance to be fixed for each participant.

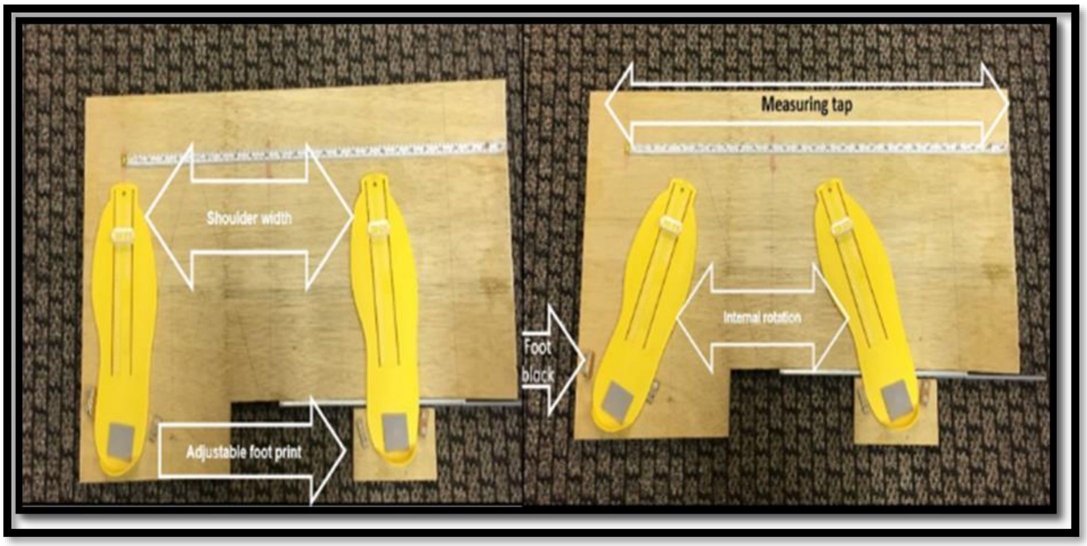


Figure 4-10: Feet standardisation tool. This allows each participant to stand with their feet at shoulder width apart and provides a consistent 20° of internal rotation.

For the position that required hand supports, two hand supports were constructed that allowed the participants to hold and maintain a stable position. The researcher marked the standing support with a marker, indicating the precise location of each participant's hands. This provided the same hand holding position for each participant every time (see **Figure 4-11**). This hand support was used to obtain the standing position during phase three in this PhD thesis.

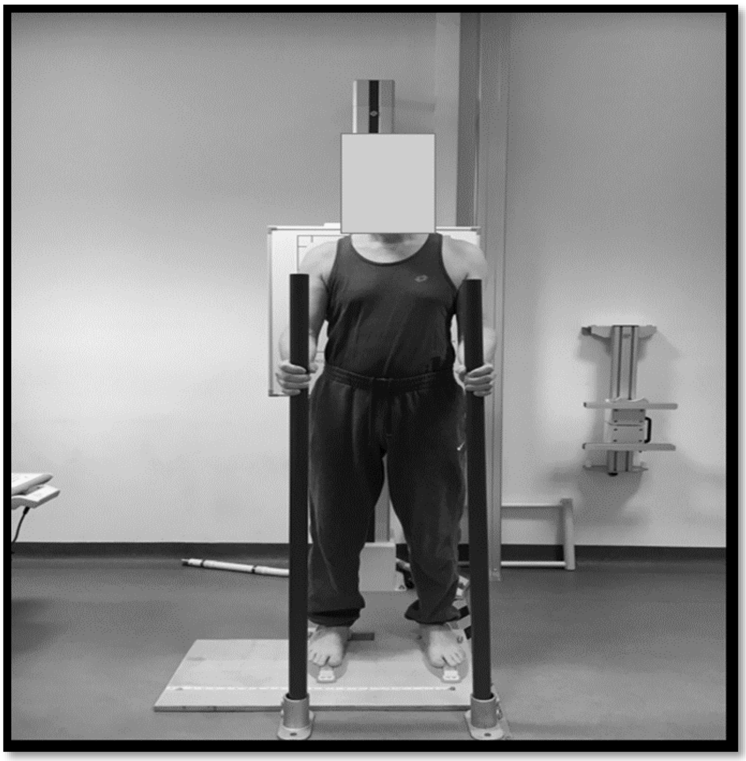


Figure 4-11: Hand stand for the positions with hand on supports.

4.6.9 Data analysis

Normality was checked visually and using the Shapiro-Wilk test (Ghasemi & Zahediasl, 2012; Yap & Sim, 2011). P values greater or equal to 0.05 indicated an approximately normal distribution. Measurements of DD, PTor, PT_{cor}, TK, LL and PT_{sag} were averaged over the 3 trials for each test position. the mean values for each test position were then compared to the CONTROL position (position 1) by subtracting the CONTROL mean from each test position mean for each participant. The data was represented in graphical format for more clarity. SPSS (version 20.0; IBM Corporation, Armonk, NY) was used for the statistical analysis of the data. The Independent t-test (for parametric data) or Mann-Whitney U (non- parametric data) were used to compare the mean differences between males and females. To evaluate the effect of different arm and feet positions, a paired sample t test was used for parametric data and Wilcoxon test was used for non-parametric data. To compare the differences between different BMI, the one-way ANOVA was used for parametric data and the Kruskal- Wallis test was used for non-parametric data. Also, the repeated measures of ANOVA were used to find the difference between the different measurements for all positions for normal distributed data. The Friedman test was used for non-parametric data. In the presence of a significant main effect, Bonferroni post hoc tests were conducted to compare differences between position 1 and other standing positions. Position 1 was used as a basis for statistical comparison as it represents the ideal position for the static assessment of spinal and pelvic alignment (Marks et al., 2003). Intra-class correlation coefficients, with a 95% confidence interval (ICC 95% CI), were used for reliability evaluation. ICC values less than 0.5 were indicative of poor reliability; values between 0.5 and 0.75 indicated moderate reliability; values between 0.75 and 0.9 indicated good reliability; and values greater than 0.90 indicated excellent reliability (Koo & Li, 2016; Portney & Watkins, 1993). The difference between equivalent measures was considered to be statistically significant if the corresponding P value was less than 0.05.

4.7 Results

There were no statistically significant differences in the demographic data of the participants (age, BMI; see **Table 4-7**).

Table 4-7: Demographic data of the included participants. The data represents the mean (SD).

Variable	Count (%)	Age (y)	Height (m)	Weight (kg)	BMI (kg/m^2)
All	67	37.5 (12.4)	1.7 (0.1)	72.3 (19.9)	26.0 (6.1)
Female	34 (50.7%)	37.1 (12.6)	1.6 (0.1)	68.0 (15.6)	25.3(5.2)
Male	33 (49.3%)	37.8 (12.5)	1.8 (0.1)	77.2 (22.0)	26.9 (7.1)
P value		0.8			0.3

4.7.1 Normality of the data

For the given data, the Shapiro-Wilks test demonstrated that the data for all of the spinal and pelvic metrics conformed to an approximately normal distribution ($P \geq 0.05$; see **Table 4-8**). This was with the exception of DD, PTor and inclinometer assessed PT_{sag} which had a P value ≤ 0.05 for the Shapiro-Wilk test in some positions.

Table 4-8: Normality (Shapiro-Wilk test) results for all metrics across all eight erect positions.

	Shapiro-Wilk					
Position/Metric	**DD**	**PTor**	**PT_{cor}**	**TK**	**LL**	**PT_{sag}**
1	0.274	0.120	0.093	0.973	0.574	0.099
2	0.043	0.001	0.136	0.942	0.610	0.168
3	0.043	0.006	0.386	0.878	0.895	0.067
4	0.029	0.009	0.252	0.829	0.251	0.064
5	0.021	0.009	0.331	0.946	0.308	0.042
6	0.046	0.113	0.420	0.888	0.186	0.073
7	0.031	0.016	0.333	0.882	0.162	0.065
8	0.051	0.047	0.341	0.855	0.315	0.030

DD: Dimple Distance; PTor: Pelvic Torsion; PT_{cor}: coronal Pelvic Tilt; TK: Thoracic Kyphosis; LL: Lumber Lordosis; PT_{sag}: sagittal Pelvic Tilt.

4.7.2 The effect of eight erect positions on different pelvic and spinal measurements.

4.7.3 The effect of different erect positions on DD

Figure 4-12 illustrates the differences in DD among all eight erect positions that were found to be statistically significant (P<0.001). Differences were found between position 1 and position 6 and 7 (p=0.04 & 0.03, respectively). The mean (±SD) DD for the relaxed standing position (position 1) was 98.9 ±11.5 mm. There were increases in DD for all test positions relative to control by almost 3 mm. The maximum and minimum mean differences (SD) were for position 7 (3.19 ±3.65 mm) and position 4 (2.76 ±3.40 mm), respectively.

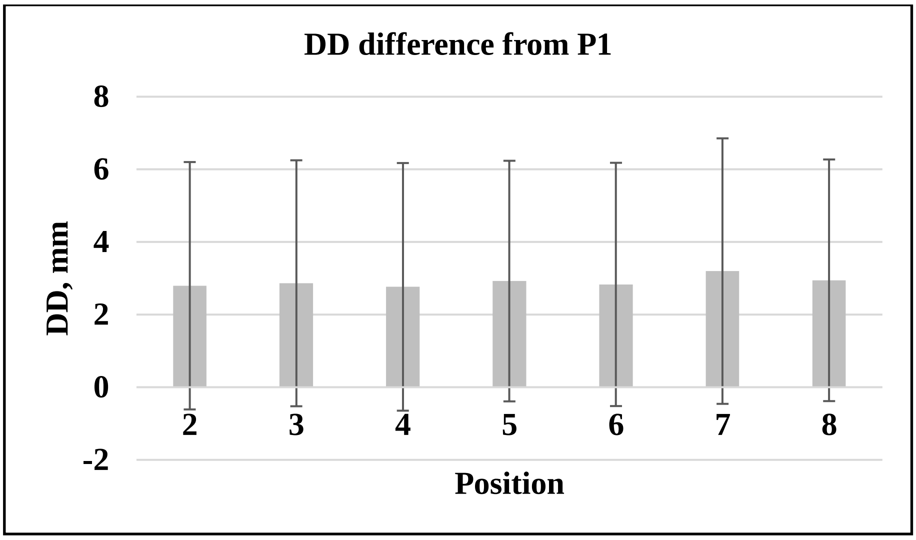


Figure 4-12: Mean (SD) differences from position 1 in DD during each of the 7 experimental standing positions.

4.7.3.1 The effect of the different erect positions on PTor

The differences in PTor between all eight erect positions were not statistically significant (P=0.99). The mean (±SD) PTor for position 1 was 0.096°± 2.9°. The maximum PTor was at position 3 (0.141°±2.9°) and the minimum at position 5 (0.02°± 3.1°). There was an increase in PTor for all test positions relative to position 1 by almost 4°. The maximum and minimum mean differences (±SD) were at position 7 (1.65°±1.89°) and position 8 (1.42°±1.80°), respectively (see **Figure 4-13).** The effect of different arms positions and different feet positions in PTor was found not to be significant (P≥0.05).

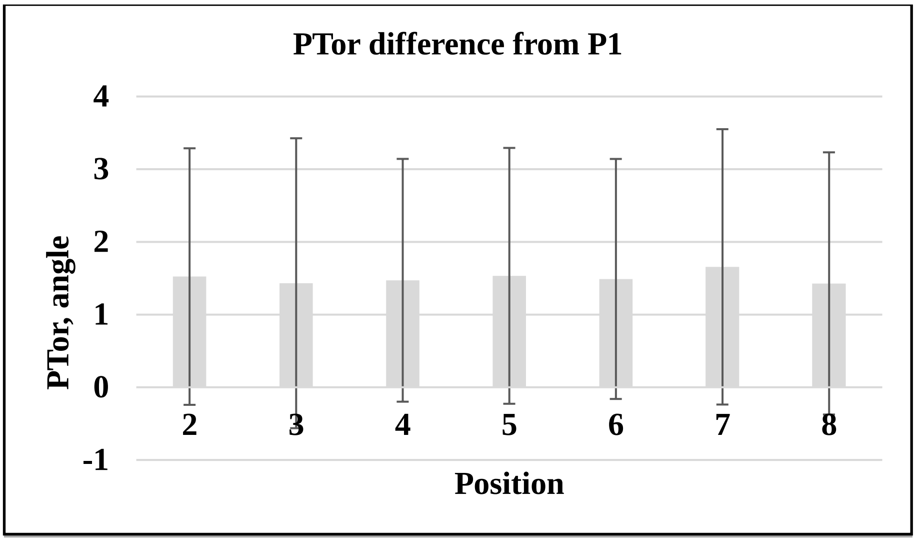


Figure 4-13: Mean (SD) differences from position 1 in PTor during each of the 7 experimental standing positions.

4.7.3.2 The effect of the different erect positions on PT_{cor}

The differences in PT_{cor} between the eight erect positions were not statistically significant (P=0.42). The mean PT_{cor} (±SD) for position 1 was -1.05°±2.8°. The minimum differences between the mean values relative to position 1 was 0.72° at position 4 and the maximum was at position 7 by 1.1° (see **Figure 4-14**). The effect of different arms positions and different feet positions in PT_{cor} was found not to be significant (P≥0.05).

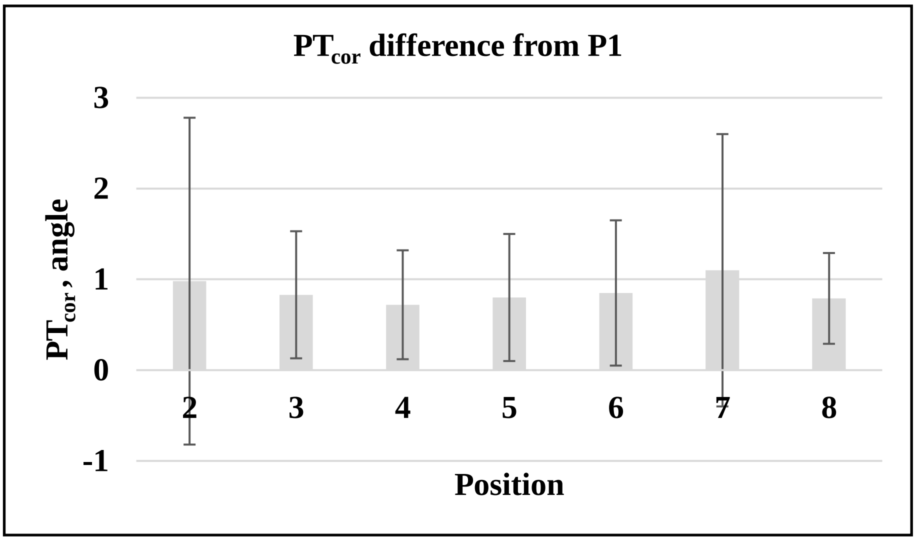


Figure 4-14: Mean (SD) differences from position 1 in PT_{cor} during each of the 7 experimental standing positions.

4.7.3.3 The effect of different erect positions on TK

There were statistically significant differences in the TK angle among the eight different erect positions (P=0.006; see **Figure 4-15**). However, there were no significance differences between position 1 and any of the remaining experimental positions. The mean TK(±SD) for position 1 was 47.7°±8°. The maximum mean differences between all positions relative to position 1 was 2.3° at position 8, and the minimum was 1.6º for position 2. The effect of different arm positions in TK was found not to be significant (P≥0.05), except for in position 4 and position 7 (P<0.05). The effect of different feet positions in TK was found not to be significant (P≥0.05).

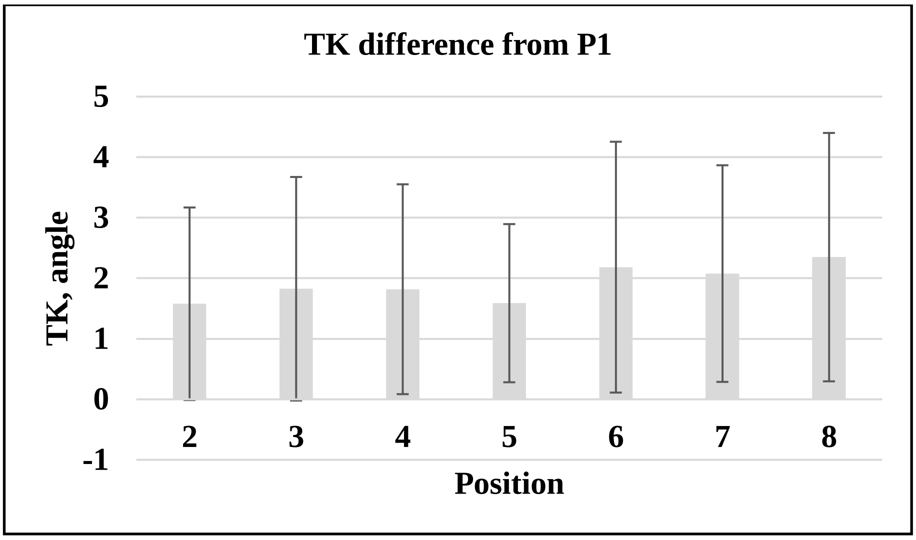


Figure 4-15: Mean (SD) differences from position 1 in TK during each of the 7 experimental standing positions.

4.7.3.4 The effect of different erect positions on LL

There was a statistically significant difference between the eight different erect positions in terms of on the LL angle (P<0.001). The significant differences were between position 1 and all positions with the feet internally rotated (position 5, 6, 7, 8). The mean LL was 36.2°±7.8° for position 1. The maximum difference in the average LL angle relative to position 1 was 2.34° in position 8 and the minimum was 1.58° in position 4 (see **Figure 4-16**). The effect of different arm positions in LL was found to be significant (P<0.05), except for in position 4 (P≥0.05). The effect of different feet positions in LL was found to be significant (P<0.05).

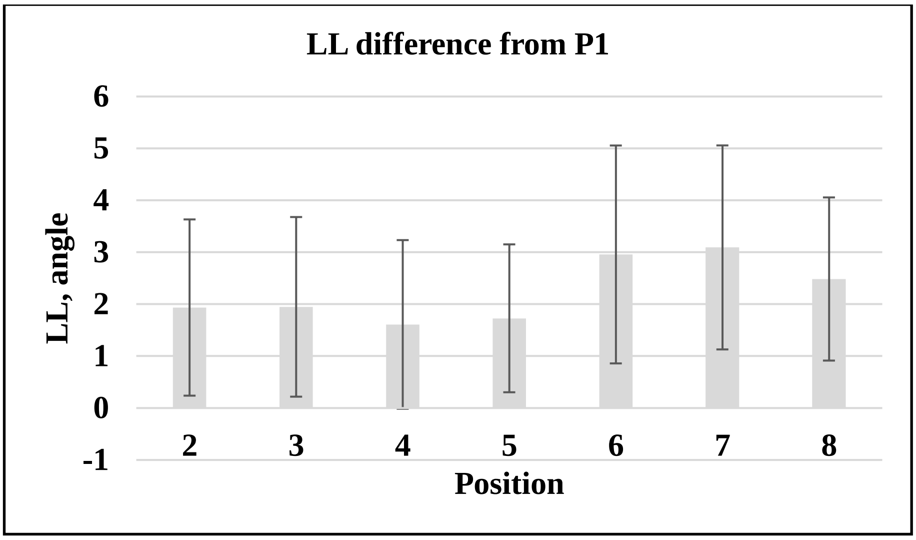


Figure 4-16: Mean (SD) differences from position 1 in LL during each of the 7 experimental standing positions.

4.7.4 The effect of eight erect positions on pelvic and spinal measurements, between different BMI groups

4.7.4.1 The effect of different erect positions on PTor between different BMI groups

The differences between the three different BMI groups for PTor was not statistically significant (P>0.05). The maximum mean differences for the three BMI groups were 1.7º (position 2), 1.3º (position 3) and 1.6º (position 7) for normal, overweight and obese, respectively. The minimum mean differences for the three BMIs were 1.2º (position 3), 0.8° (position 8) and 1.2° (position 2) for normal, overweight and obese respectively (see **Figure 4-17**).

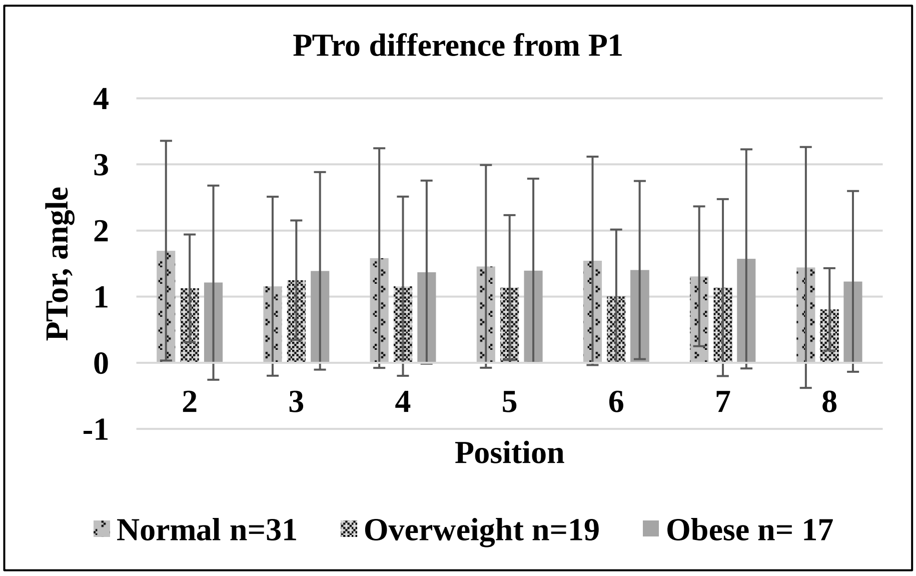


Figure 4-17: Mean (SD) differences from position 1 in PTor during each of the 7 experimental standing positions for different BMI.

4.7.4.2 The effect of different erect positions on PT_{cor} between different BMI groups

The differences in PT_{cor} between the different erect positions, for the BMI range, were found not to be statistically significant (P>0.05). The maximum mean difference for each BMI group were 1.1º (position 5), 1.6º (position 7) and 0.8º (position 5) for normal, overweight and obese participants, respectively. Also, the minimum mean differences between all BMI groups were 0.8º (position 6), 0.8º (position 2) and 0.6º (position 7) for normal, overweight and obese, respectively (see **Figure 4-18**).

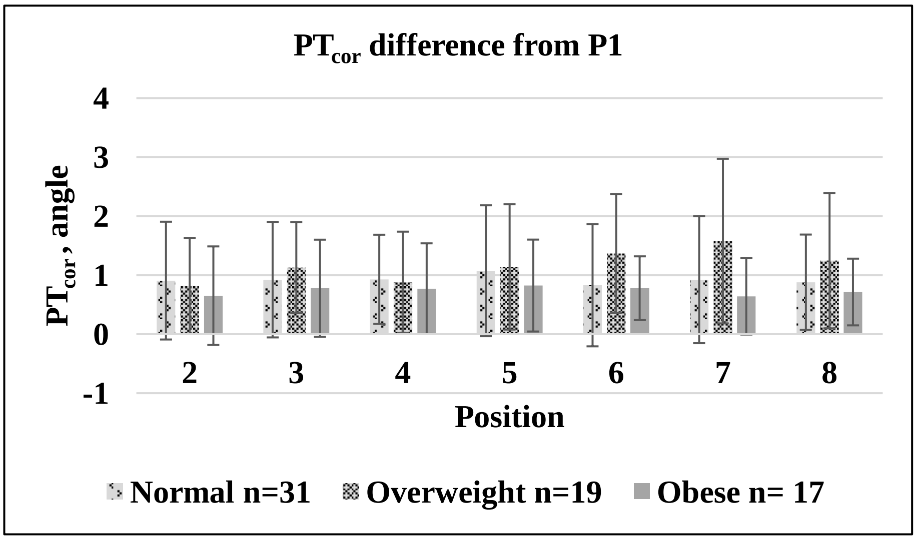


Figure 4-18: Mean (SD) differences from position 1 in PT_{cor} during each of the 7 experimental standing positions for different BMI.

4.7.4.3 The effect of different erect positions on TK angle between different BMI groups

The difference between the BMI groups in the TK angle for all erect positions, was not to be statistically significant (P>0.05). The maximum difference in means, for each BMI group, were 2.5º (position 8), 2.4º (position 7) and 2.3º (position 8) for normal, overweight and obese, respectively. The minimum mean differences were 1.4º (position 5) for normal and overweight and 1.3° (position 4) for obese (see **Figure 4-19**).

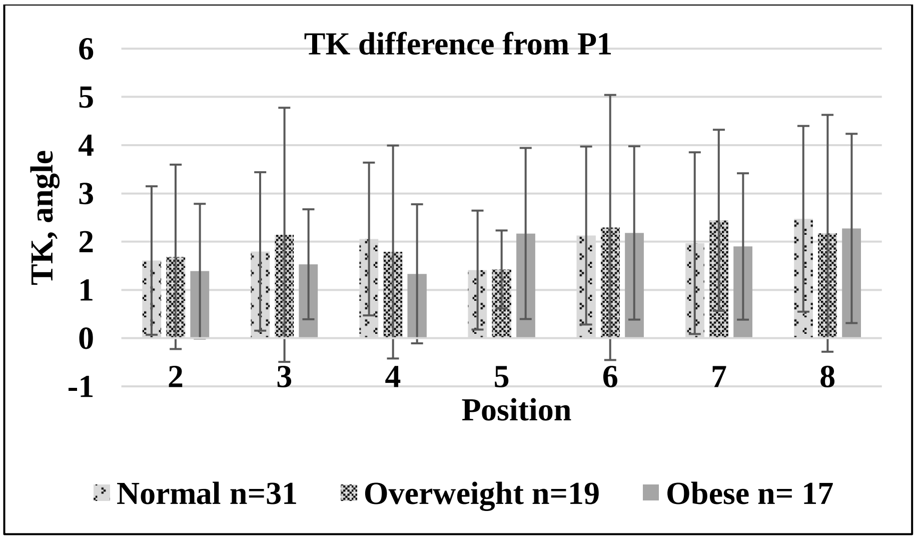


Figure 4-19: Mean (SD) differences from position 1 in TK during each of the 7 experimental standing positions for different BMI.

4.7.4.4 The effect of different erect positions on LL angle between different BMI groups

Differences were not statistically significant between the different BMI groups for LL measurements (P>0.05). The maximum mean differences for each group were 3.7º (position 7), 2.4º (position 7) and 2.5º (position 5) for normal, overweight and obese participants, respectively. The minimum of the mean differences was 1.4º (position 4), 0.9° (position 5) and 1.5° (position 5) (see **Figure 4-20**).

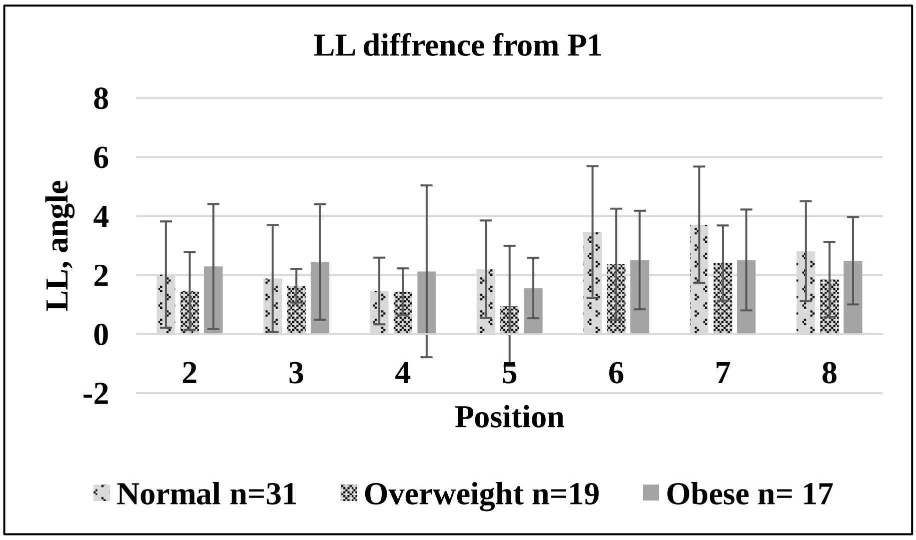


Figure 4-20: Mean (SD) differences from position 1 in LL during each of the 7 experimental standing positions for different BMI.

4.7.5 Differences in pelvic and spinal measurements, between males and females, for the erect positions

Initially, data was analysed for males and females separately. This was to investigate whether gender had an effect on pelvic and spinal measurements across the erect positions. Next, data analysis was performed by comparing the effect of the erect positions on the pelvic and spinal measurements between genders. For male, the results showed no statistically significant differences in TK, PT_{cor} and PTor ($P>0.05$). Statistically significant differences in DD ($P<0.001$) and LL ($P=0.004$) were demonstrated. The maximum differences in the mean DD were 1 mm and 2.6º for LL. In contrast, for females the results showed statistically significant differences for DD, TK and LL ($P<0.001$, 0.016 and <0.001, respectively). For PT_{cor} and PTor the results showed no statistically significant differences for female participants ($P>0.05$). The differences between males and females are presented in the following subsections. The graphs will be expressed only for the data that showed significant differences.

4.7.5.1 Differences in PTor, between males and females, among the erect positions

The differences in the mean PTor between genders were not to be statistically significant ($P>0.05$). The maximum differences between genders were 1.5º (position 4) and 1.8° (position 7) for male and female, respectively. The minimum difference was 1.1° (position 6) in male and 1.3° (position 2) in female. PTor in females was always larger than in males for all positions.

4.7.5.2 Differences in PT_{cor}, between males and females, among the different erect positions

The results showed a not statistically significant difference in mean PT_{cor} between the gender groups ($P>0.05$) for the erect positions. The maximum differences in the mean were 1.3º (position 7) and 0.8° (position 8) for male and female, respectively. The minimum mean difference was 0.7° (position 4) in male and 0.8 (position 2) in female.

4.7.5.3 Differences in TK, between males and females, among the erect positions

The results showed no statistically significant difference in mean TK angles between genders ($P>0.05$) for the erect positions. The maximum mean difference was 2.5º (position 6) in male and 2.5° (position 8) in female. The minimum mean difference was 1.6° (position 3) and 1.6° (position 5) in males and females, respectively.

4.7.5.4 Differences in LL, between males and females, among the different erect positions

The results showed a statistically significant difference in mean LL, between gender groups ($P \leq 0.002$) for the eight erect positions. The maximum difference was 2.9 and 3.7° in position 7 for male and female respectively. The minimum difference was 1.4° (position 5) in men and 1.6° (position 4) in women (see **Figure 4-21**).

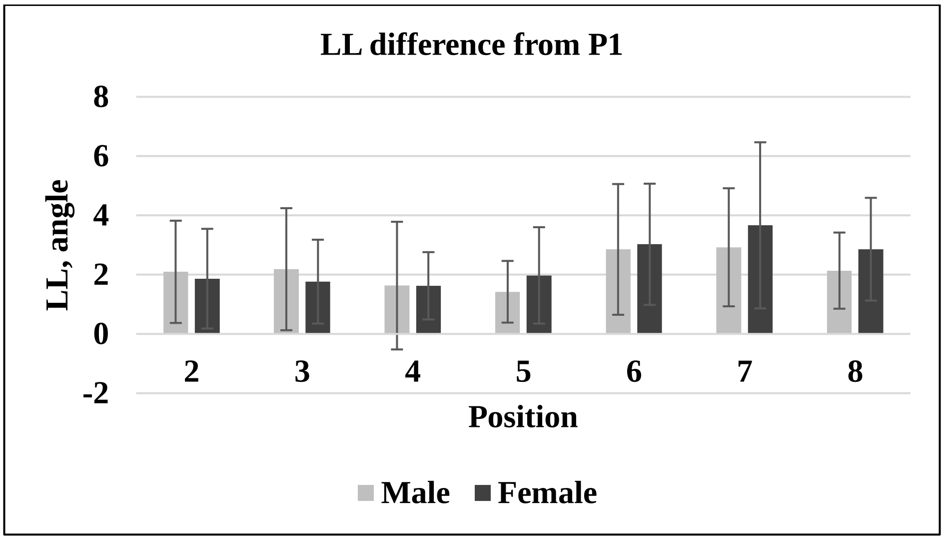


Figure 4-21: Mean (SD) differences from position 1 in LL during each of the 7 experimental standing positions between gender.

4.7.6 The effect of the eight erect positions on PT_{sag} as measured using the inclinometer

The results for PT_{sag}, from the inclinometer, are illustrated in **Figure 4-22**. The results showed significant differences between the positions ($P<0.001$). The differences were found between position 1 and positions 5, 6, 7 and 8. Further analysis was performed to compare each position using parallel feet and the corresponding position with internal rotation. The results showed significant differences between parallel feet placement and the internal rotation of the feet ($P<0.001$). Further analysis was performed to evaluate the effect of different arm positions. The results showed that there were no statistical differences between different arm position ($P \geq 0.05$), except for positioning the arms on support, wherein the differences were significant ($P<0.05$).

The maximum mean PT_{sag} was -9.7 ±6.65 ° (for position 8), and the minimum was -8.9°±6.4° (for position 1). The maximum mean difference between all positions was 0.6°. Further analysis was performed for males and females separately. Results showed significant differences in PT_{sag} for males ($P=0.027$). These differences were between position 2 and 7 and position 2 and 8. The results for females showed significant differences in PT_{sag} ($P<0.001$). These were between position 1 and positions 5, 6, 7 and 8. A comparison between genders was also undertaken for each position. The results showed that there were no significant differences in the PT_{sag} for the different gender groups ($P>0.05$). Further analysis was done to find the differences in PT_{sag} between different BMIs for all standing positions, and the results shows there were no statistical differences between all different BMIs ($P>0.05$).

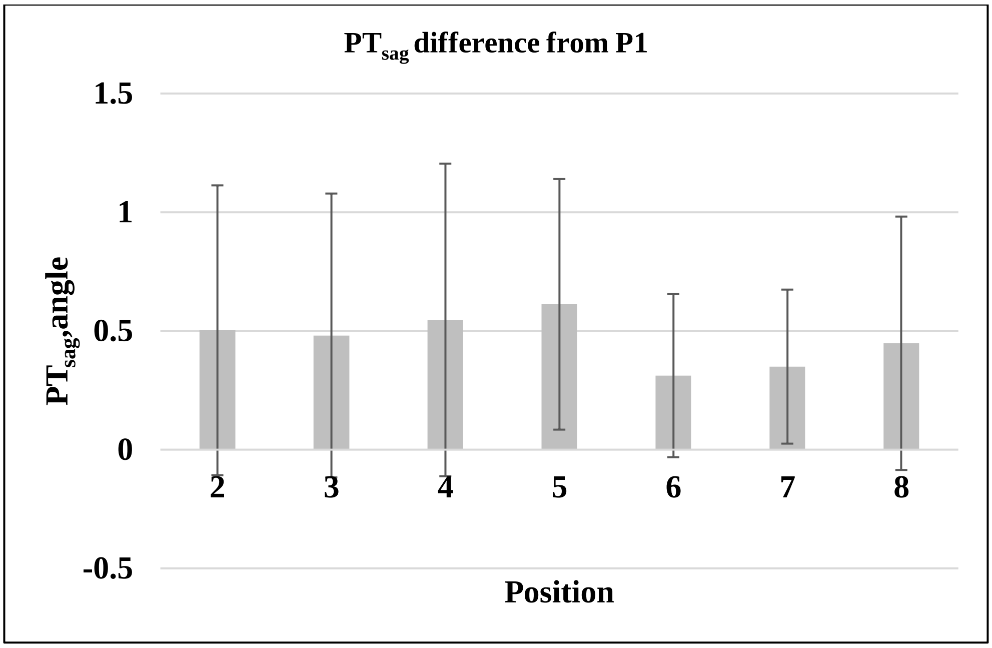


Figure 4-22: Mean (SD) differences from position 1 in PT_{sag} during each of the 7 experimental standing positions using an inclinometer.

4.7.7 ICC for the 7-experimental erect positions with Position 1

The ICC was evaluated for the 7 experimental positions with position 1 (see **Table 4-9**). The results showed good to excellent reliability for all pelvic and spinal measurements among all experimental positions (Koo & Li, 2016; Portney & Watkins, 1993). The highest ICC (95%) for PT_{cor} (0.979 [0.948-0.981]) and PT_{sag} (0.996 [0.992-0.997]) was found at position 8, indicating it to be a highly reproducible position.

Table 4-9: ICC for all 7 experimental positions versus position 1 for pelvic and spine measurements.

	ICC (95% CI)				
Metric/ Position	PTor	PT_{cor}	TK	LL	PT_{sag}
2	0.804 (0.673-0.882)	0.851 (0.751-0.911)	0.982 (0.970-0.989)	0.982 (0.970-0.989)	0.994 (0.994-0.998)
3	0.786 (0.644- 0.872)	0.963 (0.938-0.978)	0.976 (0.959-0.985)	0.983 (0.971-0.990)	0.994 (0.990-0.996)
4	0.813 (0.688-0.888)	0.973 (0.954-0.984)	0.978 (0.963-0.987)	0.980 (0.967-0.988	0.995 (0.991-0.997)
5	0.825 (0.709-0.895)	0.964 (0.940-0.978)	0.969 (0.949-0.981)	0.984 (0.974-0.991)	0.995 (0.991-0.997)
6	0.836 (0.727-0.902)	0.957 (0.928-0.974)	0.984 (0.974-0.991)	0.976 (0.961-0.986)	0.994 (0.990-0.997)
7	0.779 (0.632-0.868)	0.875 (0.791-0.925)	0.974 (0.957-0.984)	0.978 (0.964-0.987)	0.994 (0.990-0.996)
8	0.813 (0.688-0.888)	0.979 (0.948-0.981)	0.963 (0.938-0.978)	0.978 (0.963-0.987)	0.996 (0.992-0.997)

4.8 Discussion

Studies using the Diers system have previously concentrated on reporting either the reliability (Betsch, Wild, et al., 2011; Frerich et al., 2012; Schroeder et al., 2014) of the system or on evaluating pathological conditions, such as scoliosis or neuromuscular simulation (Dankerl et al., 2016; Tabard-Fougère et al., 2017). None of the previous studies have evaluated the effect of different standing positions on pelvic and spine measurements using video rasterstereographic (VR) methods. Erect pelvis imaging is recommended as an option in order to help diagnose OA (Fuchs-Winkelmann et al., 2008; Troelsen et al., 2008). The aim of this study was to evaluate different standing positions on pelvic and spinal posture in order to suggest an optimal standing position for pelvic radiography.

VR is a method for the stereophotogrammetric surface measuring of the back, and was developed in the 80s by Hierholzer and Drerup (Drerup & Hierholzer, 1987a). The basic principles behind this method is based on triangulation (Drerup & Hierholzer, 1992; Hackenberg, Liljenqvist, Hierholzer, & Halm, 2000; Schulte et al., 2006). It allows a contact and radiation-free determination of the body's surface and is a precise and highly reliable technique (Betsch, Wild, et al., 2011; Betsch et al., 2010). Moreover, these devices can allow assessment for both spinal posture and pelvic positions simultaneously. Drerup and Hierholzer confirmed that by comparing measurements obtained from radiographic images and the VR device, they found excellent correlations (0.99) between the two modalities (Drerup & Hierholzer, 1987b). Furthermore, the researchers showed that the VR can localize landmarks with a ±1 SD accuracy (Drerup & Hierholzer, 1987a). Moreover, within this chapter participants were required to stand in eight different positions, if radiography was used then this could expose them to potential harm from repeated exposures to ionising radiation. This increases the risks of deterministic and stochastic effects. The main problem for imaging techniques, including VR, is that they acquire only a snap-shot of the posture. However, posture is not static, but a dynamic process. It depends on many dynamic factors such as muscle contraction and the position of the vertebral joints. Even standing still is a dynamic process, and is affected by psychological factors such as breathing (Betsch, Wild, et al., 2011).

Within this study, the reference position was a relaxed standing position (position 1), with no researcher control over feet or arm positioning. The only instruction was that the participant stands in their 'normal' position. Within radiography, there will be a need to potentially control the visualisation of the femoral neck by internally rotating the feet. Additionally, these positions were considered to represent a range of common standing positions used within pelvic X-ray imaging. These modifications in standing positions are in needed because pelvis radiography should be obtained without artefacts from the upper arms, which could cover the interest area. The internal rotation of the feet is traditionally recommended when performing pelvic radiography in order to provide more information about the femoral head and neck (Whitley et al., 2005). It was therefore included as a variable within this thesis. Also, there is evidence that the work in this thesis was necessary by way of an example. Duval et al. (2010) evaluated the effect of the internal and external rotation of the feet using a 3D motion analysis system. Their results provide evidence of a relationship between the internal rotation and anterior PT, the internal rotation of the feet which causes internal thigh rotation, and the pelvic tilted anteriorly that occurs as a result (Duval et al., 2010). Supports are often provided for patients with balance and mobility issues and as such should be included within any evaluation of standing positions. All of the positions tested within this chapter could be considered potentially suitable for routine pelvic X-ray imaging examinations. As a result, a range of alternative positions were compared with the relaxed standing position for each of the participants.

The positions examined during this study were obtained from the studies that used these positions to evaluate the spine. The effect of different positions should also be evaluated for the pelvis because the pelvis is connected to the lumbar spine with strong fibrous tissue at the sacroiliac join (Hamidi-Ravari, Tafazoli, Chen, & Perret, 2014). It is a fact that pelvic positioning is strongly correlated to lumbar positioning. So, it can be assumed that any changes in one of these could possibly lead to alterations of the other’s posture (Levine & Whittle, 1996; Morton, Eftekhary, Schwarzkopf, & Vigdorchik, 2019). The five pelvic and spinal metrics used in this chapter were chosen based on an extensive literature review by Dankerl et al. (2016). They found that these five metrics within the most different rasterstereographic posture parameters that have been shown to demonstrate postural changes representing movement in all directions. It should be noted that the majority of the examined positions have not previously been reported in the literature which makes comparison between the results difficult. This is particularly true for the positions that were performed with the feet internally rotated. This could be because the examined positions during this study are not the optimal position for the Diers system. However, the effect of different feet positioning on pelvic measurement should be evaluated as internal rotation is optimal feet positioning for supine pelvic X-ray imaging. Therefore, the comparison with previous studies will be mainly with position 1. Also, a comparison between different arm positions will be provided.

4.8.1 The effect of eight erect positions on different pelvic and spinal measurements.

The results of the DD from this study showed there were significant differences between position 1 and 7 (feet internally rotated and fists on clavicle). The average DD for position 1 was 98.9±11.5 mm. The maximum mean differences with position 1 were at position 7 (3.2±3.7 mm) (see Figure 4.12). There were increases in DD for all test positions relative to the control by almost 3 mm. However, these differences are considered within the variation in the sample size (standard deviation). These results suggest that there is an effect of internal rotation of the feet on this distance, as all internally rotated feet positions have larger distance compared with that of parallel feet positions. It should be noted that no previous research has reported similar findings. However, this value has been established by previous rasterstereographic studies as the parameter for measuring accuracy. This study demonstrated a standard deviation of 0.54 mm. Comparing this SD with previous publications, it can be seen that they produced DL-DR distances of 2.67 mm (Dankerl et al., 2016), 4.6 mm (Meyer zu Bentrup F,2000,cited in Dankerl et al., 2016), 1.04 mm (Betsch, Wild, et al., 2011) and 1.8 mm (Hierholzer E,1993,cited in Dankerl et al., 2016). Therefore, the accuracy of this study could be rated as better than previous research.

Pelvic torsion (PTor) is the torsion between the right and left side of the pelvic bone. It is the rotation of the surface of the two lumbar dimples (DL and DR). A positive PTor means that the right hipbone is oriented farther to the anterior than the left hipbone, and a negative value indicates that the left hipbone is farther to the anterior than the right hipbone (Betsch et al., 2013). It is present when the right and left side of the hip bones are rotated in the opposite direction around the horizontal axis (Cooperstein & Lew, 2009). It is an indicator used to observe pelvic changes in the sagittal plane. All suggested positions increase the differences in PTor by less than 2º compared with position 1 (see Figure 4-13). However, these differences were not statistically significant. As in DD, the maximum differences from position 1 were found in position 7 (1.6±1.9º), while the minimum was in position 8 (1.4±1.8 º). It seems that the position of the arms on the clavicle increases the variation between the subjects on pelvic measurements. The mean pelvic torsion for position 1 during this study was 0.1º. This finding is similar to the finding by (Schroeder, Schaar, & Mattes, 2013) who evaluated 187 healthy volunteers and measured their pelvic torsion by 0.1º. Similar pelvic torsion was found in other research (Betsch, Wild, Große, Rapp, & Horstmann, 2012; Wild et al., 2014). However, pelvic torsion in this study was much smaller than the torsion in the study of Schroeder (Schroeder et al., 2014), which was 2.3º. This could be explained by the small sample size of the Schroeder and the group age (20 participants with a mean age of 25.4 years). Also, Kwon et al. (2015) found same results as were found in Schroeder's study for 20 participants (mean age 20.1 years). They also found the pelvic torsion to be 2.2º (Kwon, Song, Baek, & Lee, 2015). During this chapter 67 healthy volunteers with average age of 37.5 ±12.4º were evaluated.

Pelvic tilt is the most important metric in this study. As described in the literature it has an effect on pelvic measurements. The mean PT_{cor} for Position 1 in this study was -1.1°, the minus sign indicated a posterior PT, and the mean PT for the internally feet rotated positions was -0.9° (see Figure 4-14). This potentially supports the decrease in PT for all internal rotation feet positions when compared with that of the parallel feet positions in this chapter. This shows that internally rotating the feet position increases the anterior PT. These results are in line with Duval et al. (2010). They found that internal rotation of the legs increased the anterior pelvic tilt. This is explained by the fact that as the feet rotates internally, the femoral heads push backwards against the acetabulum. The pelvis responds to this backwards push by tilting forwards (Duval et al., 2010).

The results of the present study corroborate that all examined radiographic positions increase the PT compared with the control position. However, this increase was almost 1º, and was not statistically significant. Using the hand support with feet internally rotated (position 8) had the lowest differences from position 1. A possible explanation is that the positioning of the hands over the support provided stabilization through which subjects could assume a "near" neutral position. when adapting this position, the trunk extension, which acts to counterweight the anterior displacement of arms and maintain the body's centre of gravity over the base of support, was not necessary (Marks et al., 2009). Positioning the hands on the supports could have partly compensated for the weight of the arms being borne by the trunk and therefore indirectly decrease the differences from the control position (Vedantam et al., 2000). The results in this chapter indicate that during this position, variability was smaller between subjects than for the other positions suggesting that the use of hand supports may provide a more reproducible PT. This can be concluded from the standard deviation which was the smallest in position 8 (2.8). Marks et al. (2009) recommended this position for acquiring lateral spine X-ray imaging in their department. This recommendation was made because this position has the smallest SD among four different standing positions and adopted for multicentre use (Marks et al., 2009).

The highest mean difference in PT was found at position 7 (1.1°±1.5°). In this position, the hands rested on the clavicle and the feet were internally rotated. Faro et al. (2004) found 2±5° differences in PT between having the fists on the clavicle and the control position for normal people without previous operations. They found 3°±4° for patients with previous scoliosis arthodeses using a lateral radiograph. In the study of Marks et al. (2009) in their study, they experienced a wide variety of explanations for the positioning fists on the clavicle from radiographers at their institution. Also, when they adapted this position, the sagittal spinal parameters were affected even for normal patients without previous changes or deformities to the spine. These kinds of results suggest that, despite there being no significant differences in pelvic tilt between this position and the relaxed 'neutral' position, positioning the hands on the clavicle could increase the variation and affect pelvic measurements.

In contrast with PT_{cor} and PTor results, the results of the mean differences for TK and LL were significant for the examined standing positions (see Figures 4-15 and 4-16). The significant differences were not between position 1 and any of the remaining positions in terms of TK. The mean TK for position 1 was 47.7±8°. There was an increase in TK across all experimental positions when compared to position 1 by almost 2°. The maximum difference (mean) between all positions relative to position 1 was 2.3° in position 8, and the minimum was 1.8º for position 2. In contrast, Marks et al. (2009) found a decrease in TK for the position wherein the hands were supported (1°± 6°), and for the clavicle position (3°± 8°) when compared with the relaxed standing position. A possible explanation for the variances between this chapter results and Marks' study is that in Marks' they evaluated a small age range using lateral radiography (13±2 vs in this study 37.5 ±12.4). Also, female adolescents performed the two positions, and it was proven that the adolescents had more negative sagittal spinal alignment than adults (Marks et al., 2009).

The mean LL for position 1 was 36.2°±7.8°. The maximum LL was found at position 7 (39.1°±8.2°). There were increases in all experimental positions in the LL relative to the relaxed position by a maximum of 3.0°. The maximum mean difference in the LL relative to position 1 was 3.0°at position 7, and the minimum was 1.6°at position 4. The results of the study by Marks et al. (2009) found an increase in the LL by 4°±7° for the position with hands resting on supports and 4°±6° for the position with fists on the clavicles. The results showed an increase in the LL angle when compared to the position with arms at sides (control), but these findings were not statistically significant (Marks et al., 2009). The position with the hands resting on the supports provided the closest parameters to the control positions. In the study by Marks, the focused sample could be the reason behind their not detecting significant changes to the LL angle like in this experiment during this chapter.

Within this chapter, the effect of different feet positioning on TK, PT_{cor} and PTor was not found to be statistically significant. This is in line with other research findings regarding TK and PT_{cor} (Betsch, Schneppendahl, et al., 2011). However, for LL there was a significant difference between the two feet positionings (parallel and internal rotation). A possible explanation for this is the strong fibrous tissue that is connected to the pelvic girdle between the lumber spine and the sacro-iliac joints (Duval et al., 2010; Levine & Whittle, 1996) Thus, it is expected that these changes to the pelvis can possibly lead to changes in the spinal posture, particularly in the lumbar spine. This is because of their direct anatomical relationship. This can be described by the high correlation between pelvic position and lumbar positioning (Egund, Olsson, Schmid, & Selvik, 1978; Levine & Whittle, 1996; Morton et al., 2019)

Duval et al. (2010) found no differences between feet positions and spinal posture using 3D motion analysis system. They argued that was because the degree of PT that affected the spinal posture did not reach a limit at which it could make a change. In their study, the internal rotation was 40°and their results showed no differences. However, during this thesis there was 20° of internal rotation, and the differences were significant in lumber spine. This could be because of the small sample size used in the Duval study (n=15) and the mean age of the participants (25.4±1.7 years). Previous research has demonstrated that the degree of lumber lordosis changes with age (Amonoo-Kuofi, 1992; Skaf et al., 2011; Tuzun, Yorulma, Cindas, & Vatan, 1999). Also, it was proven that muscle performance decreases with aging (Rudolph, Schmitt, & Lewek, 2007; Siparsky, Kirkendall, Garrett, & Jr, 2014).

The effect of the upper extremity positions did not affect the PT_{cor}, PTor or TK (except for in position 7; p=0.004). These findings are in line with a previous study that evaluated the effect of different arm positions on spinal measurements (Faro et al., 2004). In contrast, the effect of arm positioning was significant on the LL angle in this chapter. This is in line with the results obtained from a study by Faro et al. (2004), who evaluated the effect of the upper arms on spinal posture in order to determine the best positioning for the lateral spine X-ray imaging (Faro et al., 2004). In their study, two arm positions were used during lateral spine radiography; including those with arms fully extended and with fists on the clavicle. Their results showed that there were significant differences in the LL angle between the two arms positions.

Aota et al. (2011) found significant differences in the TK angle when evaluating the optimal arm position for lateral spine radiography. However, their results were not significant for the LL angle and PT. During their study, they compared four different arm positions (arms without hand supports, arms rested on the clavicle, arms crossed over the chest and arms relaxed in front with hands loosely clasped) with the control position (arms by the side - relaxed standing). This is in contradiction with the results from this chapter in regard to the TK angle. This could be explained by the population age (24.4 ±2.4 years) and sample size (21 healthy participants). Also, these significant changes were found in the position with arms without hand supports when compared with the relaxed position. Differences in the use of arm supports could explain the different results between work in this thesis and the results of Aota et al..

4.8.2 The effect of eight erect positions on pelvic and spinal measurements, between different BMI groups and gender

The effect of different BMIs across the different standing positions was examined in this chapter. The results show no significant differences between all three BMI groups and all pelvic and spine measurements for all examined positions (see Figures 4-17 to 4-20). These results are similar to previous research undertaken by Romero-Vargas et al (2013) wherein they studied the impact of BMI on pelvic and spinal parameters. They found no correlation between increasing the BMI and increasing the spino-pelvic parameter.

The results from this chapter contain no significant differences between females and males for PTor, PT_{cor}, PT_{sag} and TK. These results are similar to the results obtained by Betsch et al. (2011) wherein they found no gender differences in pelvic and spine measurements for different feet positions. They also concluded that the physiological response of different feet positions does not vary between the genders (Betsch, Schneppendahl, et al., 2011). In contrast, the mean differences were significant for the LL among all of the different standing positions in this chapter. LL in females was greater than in males. This can explained by the differences in spine shape between the genders (Hay et al., 2015). Although different measurement devices and different methods were used across studies, lordosis measurements consistently reflected more lordotic curvature for women than for men (Norton, Sahrmann, & Van Dillen, 2004; K. Wood, Kos, Schendel, & Persson, 1996). This is in line with the results obtained from this chapter.

4.8.3 The effect of eight erect positions on sagittal pelvic tilt (PT_{sag}) as measured using the inclinometer

The results obtained from the inclinometer when measuring pelvic tilt in sagittal plan (PT_{sag}), showed significant differences between the positions. The differences were found between all of the feet internally rotated positions (5, 6, 7, and 8) relative to position 1 (see Figure 4-22). Also, there were significant differences between parallel feet positions and the corresponding internally rotated feet positions. This was mainly the case in females. These results suggest that there is an effect of feet positioning on pelvic tilt in the sagittal plane. The mean pelvic tilt for position 1 was -8.9± 6.4º, while the maximum mean pelvic tilt was at position 8 (-9.7±6.7º). The minus sign her indicates posterior pelvic tilt. Despite the differences found, the maximum mean difference between the positions was 0.6º, which is considered to be within participants variations. This did not reflect any clinical indications. Lembeck et al.(2005) reported that there is a 0.7° change in cup anteversion for each 1° of PT. An inclinometer was used during this study to evaluate the differences in PT between different standing positions in the sagittal plane. This was needed because the pelvic and hip pathology is usually evaluated in the coronal and sagittal planes. The inclinometer is considered quick and easy to use, small, portable, inexpensive compared with other devices as well as relatively safe when compared to X-ray. The PT reporetd in this study (for position 1) was simillllar to those reported by Salian et al. (2015). When they evaluated PT, their results were found to be 8.8º and 9.2º by two researchers when using hand held inclinometers.

4.8.4 ICC for the 7-experimental erect positions compared with Position 1

The ICC results demonstrate that all the experimental positions have good to excellent reliability when compared to position 1. These results indicate that any of these positions could be used for erect pelvic radiography. However, position 8 (position with the arms on supports with feet internally rotated) is recommend. These recommendations were made depending on the ICC results for PT_{cor} and PT_{sag}. The results showed that this position (position 8) has the highest ICC among all the rest of the positions when measuring with both the Diers and inclinometer. The importance of pelvic tilt on hip and pelvic pathology was described previously. It was said to have an effect on diagnosis and treatment outcome. An increase in pelvic tilt will lead to an increase in the appearance of anterior head coverage and ultimately to an image with pronounced acetabular retroversion and vice versa (Siebenrock et al., 2003; Watanabe, Sato, Itoi, Yang, & Watanabe, 2002). Variations in pelvic tilt can directly change the radiographic measurement of cup orientation on AP X-ray images (Dandachli, Islam, Richards, Hall-Craggs, & Witt, 2013; Tannast, Langlotz, et al., 2005). It has been described that small changes of pelvic tilt are capable of altering the radiographic appearance of acetabular retroversion and could result in misguided treatment and surgery (Siebenrock et al., 2003). Pelvic tilt affects cup anteversion. This effect has been quantified as causing approximately 0.7º of change in the radiographic anteversion for each degree of change in pelvic tilt (Lembeck et al., 2005). Pelvic tilt affects the functional orientation of the acetabulum, as acetabular anteversion decreases with the anterior tilting of the pelvis (Lazennec et al., 2011). Thus, the cup placement angles must be planned with sufficient attention given to the effects of pelvic tilt (Inaba et al., 2016).

Calliper-based inclinometers seem to be among the most common tools used by clinicians for measuring pelvic tilt for several reasons. They display good reliability for measuring iliac crest height differences (Krawiec et al., 2003; Petrone et al., 2003; Salian et al., 2015). The ICC for pelvic tilt, that was measured by inclinometer in this study, ranged from 0.994 to 0.996 which indicated an excellent reliability. These results are in line with previous research wherein it was found that the ICC of the PT measured by the inclinometer ranged from 0.8 to 0.9 (Beardsley et al., 2016; Salian et al., 2015). The ICC pelvic tilt obtained from the Diers system ranged from 0.851 to 0.979. Also, this is in line with previous ICCs reported for pelvic tilt using Diers (Guidetti et al., 2013; Schroeder et al., 2014, 2013).

Despite the above recommendations about the positioning for pelvis radiography, it should be noted that for some positions and for some participants, the differences from the control positions was large, in particular for the LL angle. For instance, in position 7 the differences reached 8° for some participants. These results indicate that further research is needed to show the relationship between the lumbar lordosis and pelvic tilt. Also, more research is needed to evaluate what levels of lumbar lordosis may affect pelvic tilt. Moreover, more research is needed to see if these differences are relative to specific genders or BMI groups.

4.9 Limitations

A limitation of this work could be that the average BMI for female and male participants in this study was predominantly 'overweight'. However, no significant differences were found between age and BMI. Also, the number of participants across the different BMI groups was not equal. The number of obese participants was just 17, despite it being proven that obesity has an effect on postural instability (Son, 2016). Although the results did not reveal statistically significant differences, they did indicate that the obese measurements were slightly different from that of the normally weighted people. Therefore, these differences deserve future attention. It is also must be noted that a 'healthy' group of participants were evaluated in this study. The effect of different standing positions on a symptomatic group is not known and should be considered in future work. It was proven that there is an effect on pelvic tilt and lumbar lordosis for asymptomatic people, such as those who suffer from low back pain. There is increase in anterior pelvic tilt and lumbar lordosis with low back pain (Youdas, Garrett, Egan, & Therneau, 2000). However, the main aim of this study was to examine different standing positions in order to propose an optimal standing position for pelvic radiography. Pathological disorders could affect the pelvic and spinal measurements and should therefore be considered when interpreting these results.

4.10 Conclusion

Eight erect positions were assessed in order to propose one optimal position for erect pelvic radiography. An optical and radiation free videorasteography method was used to achieve this aim. Also, an inclinometer was used to obtain pelvic tilt in sagittal plane for the participant in each erect position.

The results from this study demonstrated no statistical differences in PT and PTor between the eight different erect positions using the Diers system and inclinometer, suggesting either of them could be used. However, the position with internal feet rotation and rested hands on supports is recommended as the optimal position for erect pelvic radiography. This position had the highest ICC among all the examined positions. Moreover, internal feet rotation is recommended for optimal femoral head and neck visualisation. Positioning hands on supports, as supported by previous research, demonstrated the lowest variation between the participants and should be considered when screening patients with mobility/balance issues. The outcome from this chapter will be used to help inform the methods in the clinical patient study (**Phase Three; Chapter Seven**).

Chapter 5: Image quality and radiation dose in digital radiography

5.1 Chapter overview

Within this chapter the background for image quality and radiation dose will be provided. The aim of this chapter is to provide background information for Chapter 6 and 7. This information will include the types of digital radiography system, radiographic acquisition parameters, radiation dosimetry methods and image quality parameters and the methods for it is assessment.

5.2 Digital radiography (DR)

Digital systems are not too different from film-screen (FS) radiography in terms of physical image formation principles. However, film-screen is used as both an imaging receptor and storage medium, while digital systems are only used as an image receptor. The information for these is stored in a digital medium. There are several advantages of digital imaging, such as: more effective data management from acquisition through to storage and ultimately display, the high detective quantum efficiency of digital detectors, the wide dynamic range of the display components, and the available post-processing adjustments (Ekpo, Hoban, & McEntee, 2014). Digital imaging consists of four main steps: generation, processing, archiving and the presentation of the image. After exposure to radiation, the receptor transforms the absorbed energy into an electrical charge. This is then recorded, digitised and displayed on a grey scale which indicates the amount of X-ray energy deposited in the receptor. Afterwards, the post-processing software that was used, is sampled in order to display the required clinical information. The image is then sent to a digitised storage archive such as a picture archiving and communication system (PACS). Digital images can be manipulated during viewing using methods such as panning, zooming, windowing and measuring (angles, distances) (Oppelt, 2011). Digital radiography systems can be divided into two types namely computed radiography (CR) and digital radiography (DR). This classification is made according to the X-ray detection and the read-out performance (Lança & Silva, 2009). In this thesis, DR was used solely for the data collection, and therefore more details will be provided for DR in the following subsections (**5.2.1 and 5.2.2**).

DR systems were introduced in the late 1990s. They are also known as a flat panel X-ray systems or large area X-ray detectors. DR systems are based on thin-film transistor (TFT) arrays. The TFT is located in a glass underlying layer with the read-out electronics situated in a lower layer and the charge collector arrays at a higher layer. This is known as an ‘‘electronic sandwich’’(Lança & Silva, 2009). This design is considered more advantageous due to its compact size and ability to almost immediately read out a digital image. In addition, the performance of DR systems is said to be largely superior to that of CR and FS systems (Lança & Silva, 2009). DR can be divided into two types, namely indirect DR and direct DR.

5.2.1 Indirect digital radiography (IDR)

Caesium iodide (CsI) or gadolinium oxisulphide (Gd_2O_2S) are used in IDR systems as the X-ray imaging receptor. IDR detectors consist, from top to the bottom, of scintillators and phosphors that can be structured or unstructured. Unstructured scintillators cause large amounts of scattered light and this decreases the spatial resolution. In contrast, structural scintillators are constructed perpendicular to the surface, which increases the number of photon interactions and reduces scattered light (Lança & Silva, 2009). After the scintillator layer is exposed to the radiation, it converts the incident X-ray photons into light. The next step is to convert the visible light into an electric charge using an a-Si photodiode array (Lança & Silva, 2012)

5.2.2 Direct digital radiography (DDR)

DDR uses amorphous selenium (a-Se) as the semiconductor material. Selenium is the most common material used for this kind of detector. However, there are other materials, such as lead iodide, lead oxide, thallium bromide, and gadolinium compounds, which can also be used. These materials are characterised by high X-ray absorption and high spatial resolution (Fauber, 2016; Körner et al., 2007). In this system, an electric field is applied to the selenium layer before exposure to ionising radiation. The exposure to radiation generates electrons and holes. Due to the electric field, these charges move nearly vertically to both surfaces of the selenium layer. At the bottom of the selenium layer, the charge-collection electrodes collect and store these charges until readout. In the readout, the charge in every row is conducted by the transistors to the amplifiers (Kotter & Langer, 2002).

5.3 Radiographic acquisition parameters

The production of an X-ray image is affected by many factors. These factors determine the quantity and the energy of the X-ray photon. The relationship between these factors and the effect of each one on image quality and radiation dose should be understood in order to achieve successful dose optimisation. Acquisition factors in this section typically focus on the tube voltage (kVp), tube current time product (mAs), inclusion of an antiscatter radiation grid, additional filter, source to image distance (SID) and use of the automatic exposure control (AEC). These factors have direct effect on image quality and radiation dose. Also, the factors may have an indirect effect on each other when considered in combination.

5.3.1 Tube potential (kVp)

The difference in the applied potential between the anode and the cathode in the X-ray tube is called the tube potential. This controls the speed of the electron beam towards the anode, and describes both the X-ray quality and quantity reaching the patient. Increasing kVp leads to an increase in the maximum photon energy and controls the amount of penetration the X-ray photons have through the tissue. Therefore, the higher the kVp, the higher the photon energy, which means more photon penetration and a reduction in image contrast (Fauber, Cohen, & Dempsey, 2011). Moreover, increasing kVp introduces more scattered radiation in a forward direction and this can increase image noise (S. Walker, Allen, Burnside, & Small, 2011). In contrast, by using a lower kVp, higher image contrast will be obtained due to the relative absorption differences of the low energy radiation by different densities within the body (Carroll, 2007; Dowsett, Kenny, & Johnston, 2006). However, previous research argued that, with certain radiographic examinations, using a higher kVp can result in lower patient doses. Such a strategy reduces the image contrast and can mean that the resultant images are still diagnostically acceptable. Within radiography, there are many factors that control the selection of tube potential, such as the size of the anatomical part under examination, image receptor construction, and the required diagnostic information in each specific clinical case.

There have been several studies which have sought to optimise tube potential for DR. Some of the results from these studies are contradictory as to whether they recommend using high or low kVp. A reduction in radiation dose and improved image quality for lumbar spine radiography was found by reducing kVp (Geijer, Norrman, & Persliden, 2009). Similar results were concluded in chest and pelvic examinations in a study performed in 2005 (Tingberg & Sjöström, 2005). In contrast, Lanca and colleagues, found in 2004 that when utilising a high kVp the visual image quality was decreased. However, a reduction in radiation dose was also reported (Lança et al., 2014). Many other studies found the same results relating to a reduction in the radiation dose when using a higher kVp (Lorusso, Fitzgeorge, Lorusso, & Lorusso, 2015; Martin, 2007; Ramanaidu, Sta Maria, Ng, George, & Kumar, 2006).

5.3.2 Tube current time product (mAs)

Tube current is defined as the number of electrons per unit time moving from the cathode to the anode (Dowsett et al., 2006; Fauber, 2016). The number of X-ray photons is not only controlled by variation in mA, but also by the time over which the cathode is permitted to generate electrons. The mAs is the main controller of the radiation dose that reaches the patient and the image receptor, and hence is a key controller of image quality or signal-to-noise ratio (Carver & Carver, 2012). It has been noted previously that applying 15% and 10% rules for increasing kVp whilst decreasing the mAs by half can be used as an optimisation strategy in clinical practice (Allen, Hogg, Ma, & Szczepura, 2013; Brindhaban & Al Khalifah, 2005)

5.3.3 Tube filtration

The radiation exiting from the X-ray tube is termed the *primary beam*. This primary beam has a wide range of energies, including low, medium and high radiation energy. The medium and high energies provide the main contribution to the resultant image. In contrast, the low energy radiation is not able to penetrate and exit the human body. Therefore, this radiation does not contribute to the image formation process. Low energies are totally absorbed by the body and have a significant effect on radiation dose (Fauber, 2016). Tube filtration is used to minimise this issue, and a sheet of filter material is positioned in the path of the primary X-ray beam to achieve this. Filtration is measured in millimetres of aluminium equivalent (Carroll, 2007), and is classified into two groups- inherent and added filtration. Inherent relates to the glass envelop of the X-ray tube, cooling oil and tube head (fixed components within the X-ray tube). For most X-ray tubes the typical inherent filtration ranges from 0.5 to 1.0 mm of aluminium equivalence. In contrast, any additional material added to the tube port is termed added filtration. The summation of the inherent and added filtration gives the total tube filtration. This usually ranges from 1.5 to 2.5 mm (Graham, Cloke, & Vosper, 2011). At least 2.5 mm aluminium equivalent of total filtration is suggested by the National Council on Radiation Protection and Measurements (NCRP) (National Council on Radiation Protection and Measurements (NCRP), 1978). Improvements in the energy spectrum of the X-ray tube output can be achieved by using additional filters, and this has effects on both the radiation dose and image quality. Several studies have demonstrated comparable dose reductions with and without decrease in image quality, at varying thicknesses of Cu filtration (Brosi, Stuessi, Verdun, Vock, & Wolf, 2011; Ekpo et al., 2014; Smans, Struelens, Smet, Bosmans, & Vanhavere, 2010).

5.3.4 Source to image receptor distance (SID)

SID is the distance between the focal spot of the X-ray tube and the image receptor. It influences the intensity of the radiation that reaches the image receptor. The relationship between this distance and the intensity of radiation is governed by the inverse square law. This states that the intensity of radiation is inversely related to the square of the distance between the focus and the image receptor. So, a larger SID means a greater divergence of the radiation field and as such a lower intensity of radiation reaching the image receptor (Graham et al., 2011; J. Johnston & Fauber, 2015).

The effect of changing SID on image quality and radiation dose has been investigated previously. It was found that increasing the SID from 100 to 130 cm reduces the radiation dose whilst maintaining image quality using AEC for lumbar and pelvis X-ray imaging (Brennan, McDonnell, & O'Leary, 2004; Brennan & Nash, 1998). A further study investigated increasing the distance from 100 to 150 cm for skull radiography. The authors found a significant decrease in radiation dose but with maintained image quality (Joyce, McEntee, Brennan, & O'Leary, 2013). The effects of increasing the SID from 100 to 147 cm on pelvic radiography were studied by Heath et al. (2011). Within this work, they found a significant reduction in the entrance surface dose (ESD) without an effect on image quality (ESD at 147 cm = 2.56 mGy; at 100 cm = 3 mGy). This study used DR technology, and the AEC and the kVp were fixed at 80 kVp (R. Heath et al., 2011). Tugwell and colleagues studied the effect of increasing the SID from 90 to 140 cm on image quality and radiation dose using CR and an anthropomorphic pelvis phantom. The images were acquired with and without an AEC. The results were similar to those obtained by Heath and colleagues in 2011. Again, by increasing the SID from 110 to 140 cm, the effective dose and ESD were reduced (3.7% and 17.3% with the AEC; and 50.3% and 41.8% without the AEC). No significant differences were found in image quality scores across the different SIDs, however there was a slight reduction in the signal to noise ratio (SNR) when the SID was increased. This reduction was found to be not statistically significant (J. Tugwell et al., 2014). It should be noted that increasing SID is not always possible because of vertical space restrictions within the X-ray room and 'cut-off'. This is because of the radiation grid focal range.

A clinical study undertaken by England and colleagues in 2015 found a reduction in radiation dose along with the maintenance of image quality. During this study, DR was used, and pelvic X-ray images were obtained at 115 and 135 cm or greater (maximum distance achievable). Two outer AEC chambers were selected with a fixed tube potential of 75 kVp.

The images were scored by expert radiographers. Reductions in the ESD and effective dose were 39% and 41%, respectively, and this occurred without any compromise to the image quality (England et al., 2015).

5.3.5 Automatic exposure control (AEC)

The AEC is a device that controls the amount of radiation delivered to the patient whilst maintaining adequate image quality. It is a widely used system in radiography and assists radiographers in determining the correct exposure parameters (J. Johnston & Fauber, 2015). The AEC automatically terminates the exposure when the desired amount of radiation reaches the image receptor. There are two types of AEC, detectors namely photo-timers and ionisation chambers. AEC devices tend to have three chambers- one in the centre and two in the lateral upper sides. Depending on the examination, the radiographer can decide which AEC configuration should be used to obtain the optimum performance of the device, thereby attaining the correct image quality. When using the AEC, a careful selection of an appropriate tube potential and careful patient positioning, centring and collimation is necessary. Also, regular calibration of the AEC is required to ensure consistent performance and to achieve the predetermined image quality (Mazzocchi et al., 2006).

5.3.6 Anti-scatter radiation grids

An anti-scatter radiation grid is a device within the imaging system that can reduce the scattered radiation exiting the patient and prevent it reaching the image receptor. Anti-scatter radiation grids improve the image quality by reducing the noise from scattered radiation. Usually a grid is included when examining thick / dense anatomical parts. Theses introduce more scattered radiation and include the pelvis and thoracolumbar spine. Anti-scatter grids consist of two materials- a highly radio-lucent material (for example carbon fibre) and a highly radio-absorbent material (for example lead). These materials are aligned alternatively. The main task of the grid is to permit the primary beam to transmit and absorb all the scattered radiation. However, grids will inevitably absorb some of the primary beam which can lead to an increase in the radiation dose to compensate this absorption (Jessen, 2004).

There are two types of anti-scatter radiation grids, namely stationary and reciprocating (moving). A stationary grid can be mounted between the patient and image detector. It can be used when a moving grid is not feasible, such as when imaging patients on a trolley. In contrast, a reciprocating (moving) grid is incorporated within the X-ray table Bucky and moves forward and backward during the X-ray exposure to blur out the shadows of the grid strips on the image (Fauber, 2016). Grids are characterised by several factors, for example the grid frequency and grid ratio. Grid frequency is number of strips over the length of the grid. It typically ranges from 25 to 45 lines /cm. Grid ratio is defined as the strip height to the distance between two strips and it typically ranges from 4:1 to 16:1 (Bushong, 2013).

5.4 Radiation dosimetry

It is well known that medical radiological procedures contribute most to the population's overall radiation dose from non-natural sources (Zontar, Zdesar, Kuhelj, Pekarovic, & Skrk, 2015). It is important to limit organ and tissue absorbed dose from these procedures, and therefore optimisation is paramount (Kramer, Khoury, & Vieira, 2008). This section will focus on methods that have been used for dose assessment.

5.4.1 Dose area product (DAP)

DAP is a measurement of the absorbed dose to air multiplied by the irradiated X-ray area ($mGy.cm^2$). It is related to both the radiation field and the area of tissue irradiated, which means it gives a good estimation of the total energy directed towards the patient. A DAP meter is fixed onto the X-ray tube in front of the collimator (Tootell, Szczepura, & Hogg, 2014). DAP consists of an ionisation chamber which captures the whole primary radiation field. It is a direct measure of the patient dose and does not take into account the distance between the X-ray source and the patient (source to object distance, SOD). Thus, when adapting DAP for dose calculations details on the SOD, field size and the area exposed are required (Moores, 2005).

5.4.2 Entrance surface dose (ESD)

Like DAP, ESD is another direct measure of radiation dose. It describes the absorbed dose in the air, including the scattered radiation at the point where the radiation enters the patient (Tootell et al., 2014). It is recommended by the International Atomic Energy Agency (IAEA) as it meets the same criteria for DAP. Thus, it is simple, direct and provides a good representation of the radiation dose received by the patient (International Atomic Energy Agency (IAEA), 2005). ESD allows for easy comparison with dose reference levels (DRLs) (E. K. Ofori, 2013; Škrk, Zdešar, & Žontar, 2006; Wall, 2006). ESD can be measured using either thermoluminescent dosimeters (TLDs) or ionisation chambers.

5.4.3 Effective dose (E)

In contrast with the above-mentioned indices, E considers both the radiation and tissue types (Harrison & Ortíz-Lópes, 2015). It also considers the radiation sensitivity for the different tissues. E is calculated by applying the tissue weighting factor and the equivalent dose for each organ. Next, the E value of all the body parts is summed up as by the whole-body effective dose. Tissue weighting factors determine the sensitivity of the tissue or organ to radiation. For example, the radiosensitivity of active bone marrow is greater than the sensitivity of the brain tissue (Tootell et al., 2014). E is measured in joules per kilogram (J kg^{-1}), while Sievert (Sv) is the SI unit. The equation for E is, $E= \sum W_T * H_T$, wherein E is the effective dose, W_T is tissue weighting factor and H_T is equivalent dose for tissue (T) (ICRP, 2007).

E has been utilised in radiation protection principles and dose optimisation studies (Pradhan, Kim, & Lee, 2012). It gives an indication of the stochastic effect (the risk of the cancer) (Harrison & Ortíz-Lópes, 2015; ICRP, 2007; T. Okano & Sur, 2010). E is commonly used in radiology departments to compare the risk from the different modalities (for example, CT compared with conventional radiography). Also, it is used to compare between examinations with different dose distributions (Tootell et al., 2014). Moreover, it can be applied to in the justification and optimisation of studies that use ionizing radiation (Butt & Walkowiak, 2002; Oritz, 2013). However, the tissue weighting factors represent the average over all ages and genders for a general population. Thus, it can't be applied to an individual (Wall et al., 2011). There is a difference in the sensitivity due to the age and gender, which is not taken into account when calculating E. Therefore, Brenner introduced an alternative risk estimation that could be applied to individual patients. This is called effective risk (ER). It takes into account the life time risk of cancer induction from an absorbed dose of radiation (Brenner, 2009, 2012). For the ER calculation, the organ specific radiation induced cancer risk is replaced by the tissue weighting factor in the E calculations. These organ specific radiation induced cancer risks are obtained from the publications by The Nuclear and Radiation Studies Board (National Research Council, 2006), or from Wall et al. publication (Wall et al., 2011). They represent up to date knowledge of the biological effect of radiation and distinguish between different age and gender.

Conversion coefficients of absorbed dose or equivalent dose are commonly calculated by Monte Carlo (MC) methods to estimate the radiation dose or risk for irradiated organs. Whereas commercially available PC based MC simulation software has been used for cost effective dose estimations. These are common methods for calculating the E and ER, which cannot be measured directly in patients undergoing X-ray examinations. They are also problematic and time consuming to acquire using physical phantoms, but can easily be estimated using MC methods (Kramer et al., 2008).

PCXMC is one of the most common MC software programs available in medical imaging for this application and has been used for calculating E within the literature (Ladia, Messaris, Delis, & Panayiotakis, 2015; J. R. Tugwell, England, & Hogg, 2017; T. J. Wood, Moore, Saunderson, & Beavis, 2015). The principles behind this software are based on the MC radiation transport method. This calculates the absorbed dose by organs and tissues for a series of computational human phantoms which represent human anatomy. It allows the user to determine many radiographic parameters such as field size, tube potential, anatomical area and the thickness of filtration in order to estimate E (Borrego, Lowe, Kitahara, & Lee, 2018). The use of PCXMC has been widely reported in the literature (Allen et al., 2013; C. T. P. Chan & Fung, 2015; Ma et al., 2013; Schultz, Geleijns, Spoelstra, & Zoetelief, 2003). The results from these studies show that PCXMC data are comparable with other dose measurements and calculations. Moreover, PCXMC has been utilised by the National Cancer Institute for the estimation of the medical radiation exposure over eight decades for different radiation procedures (Chang et al., 2017; Melo et al., 2016).

PCXMC does however have two limitations which may affect its accuracy. First, it features over-simplified anatomical structures in which the body outline and the internal organs are explained by simple mathematical equations. Second, the adjustment of body size is not possible with a high level of accuracy as the programme uniformly increases or decreases the length of the axis of the cylinder to simulate the change in body contour (Borrego et al., 2018). These limitations are solved in hybrid phantoms, which are built based on patient-specific CT or MRI datasets and allow for modification to suit the morphometry of the population. Modifications to the height and weight, using PCXMC, were undertaken by Borrego et.al (2018) to represent different patient sizes. They compared with data from hybrid phantoms for chest and abdomen examinations with this. The results show that PCXMC doses may be overestimates of the actual doses administered to children - particularly those who would be considered as obese. This is because of how the different phantoms distribute the adipose tissue as BMI increases. In the PCXMC software, the excess adipose tissue is distributed by applying constant scaling factors for all coordinates in the reference phantom (fat is distributed in a homogeneous way across the whole phantom).

However in the hybrid phantoms the distribution of excess adipose tissue is mostly in the anterior region, as the weight increases the depth of this section (Borrego et al., 2018).

CALDose X is another MC simulation software that provides the option for calculating incident air kerma (INAK) and entrance surface air kerma (ESAK) based on the output of the X-ray equipment. This software also provides the user with the conversion coefficients that are used to assess calculations of absorbed dose for the body organs, as well as the cancer risk from radiographic examinations. It uses developed voxel phantoms for various projections and different x-ray spectra. These phantoms are made based on the CT images, anatomical textbooks and on skeletal data provided by ICRP70 (ICRP, 1995). It provides the absorbed dose for 34 projections of the 10 most common X-ray examinations. The tube potential that can be used ranges from 50 to 120kVp, and the filtration ranges from 2 to 5 mm of aluminium. The user needs to insert the gender, age, examination and patient position. The software needs the tube potential, mAs and SID for the acquisition parameters. Each examination has limited kVp and SID options. The programme uses a standard field size and position which represents the field location mostly used for each examination according to previous studies, and based on textbooks for X-ray practitioners (Kramer et al., 2008). After that, the user can determine the ESD and the absorbed dose is calculated as a result for individual organs and for the whole body.

5.5 Image quality assessment methods for DR

There are several methods that have been widely used for image quality evaluation and to assess DR imaging system performance (Alsleem & Davidson, 2012; Pascoal, Lawinski, Honey, & Blake, 2005). These methods include physical (SNR, CNR) and psychological or clinical performance (observers/diagnostic) (Krupinski & Berbaum, 2009)**.** More details for each method are provided in the next subsections alongside a discussion of the advantages and disadvantages of each.

5.5.1 SNR

SNR measures the relationship between the signal and the noise in the image. While the signal sensitivity and the noise are important by themselves, the ratio between them is more significant and represents a more important indicator of image quality (Beutel, Kundel, & Van Metter, 2000). It can be obtained by calculating the ratio between the mean signal in the object and the standard deviation of the signal value of the background (Bath, 2010). It has been found that a ratio of around 5:1 is needed for the structure to be detectable by human observers (Beutel et al., 2000). SNR is a simple method that has been used to describe one's ability to visualise the object in the image (Lança & Silva, 2009). SNR has been previously used for describing image quality because it is able to describe the noise which has a key role in determining the level of image quality combined with the resolution and human visual system (Borasi, Samei, Bertolini, Nitrosi, & Tassoni, 2006).

There are several problems associated with SNR calculations that influence the validity and reliability of this method. First, the size of the object under scrutiny is not considered in the SNR calculation. Second, the method for determining the noise (SD of the background) is very simple for the observers who are used to discriminating noise properties. The SNR calculation is based mainly on the quantum noise (detector noise), however there are other types of the noise which human observers are familiar with, such as anatomical noise, system noise and detector noise (Bath, 2010; Bochud, Valley, Verdun, Hessler, & Schnyder, 1999). Third, to obtain the same image characteristics, large numbers of photons are needed for a small pixel size. In reality, the observer is interested in all of the image and is not affected by the variations between individual pixels (Bath, 2010). Fourth, in regards to the location of the noise region for measuring background signal, when placing it in a non-homogenous area to obtain the SD of the noise, the variation in the pixel value of the anatomical region could greatly influence the calculations (Bath, 2010; Bochud et al., 1999).

Even in view of the above, SNR is considered to be an efficient tool for measuring image quality in order to evaluate the consistency and quality assurance of the imaging system. However, using SNR for obtaining measurements that are related to observers' perception has not yet been proven. Thus, SNR should be supported with measures of image quality using observer perception. This increases validity and reliability when measuring image quality (McCollough, Bruesewitz, & Kofler Jr, 2006). SNR has been used frequently in optimisation studies as a good indicator of image quality (Burgess, 1995; Månsson, 2000; J. Tugwell et al., 2014).

5.5.2 CNR

CNR is considered to be a good method for describing the distinctiveness of the object when compared with the surrounding background. Thus, CNR is an important tool for assessing the imaging system in terms of it is allowing one to visualise the anatomical structures and to distinguish pathologies (Dhawan, 2011). CNR evaluates the contrast resolution in an X-ray image and provides results similar to those obtained from observer evaluations.

Therefore, it is commonly used in clinical departments for image quality control, when comparing between the different modalities and measuring the detectability of a lesion (Mori et al., 2013). When comparing CNR with SNR, CNR provides more information about the effect of noise on detectability. A possible explanation for this is that an overexposed image may contain a high SNR, but demonstrate no valuable information on the structure of interest. Thus, a high SNR does not necessarily imply that an image has high contrast, unless it has high CNR too. This is especially the case when differentiation between pathologies and normal anatomy is required (Lyra, Kordolaimi, & Salvara, 2010; N. Smith & Webb, 2011). Mathematically, CNR is obtained from subtracting the signal from the ROI of the object under investigation and the signal from the noise ROI then divided by the SD of the noise ROI, as described in the bellow equation

CNR= (S ROI_1 –S ROI_2)/σ ROI_2, where S ROI_1 is the signal from the region of interest, S ROI_2 is the signal from the noise and σ ROI_2 is the SD from the noise region.

5.5.3 Psychophysical measurement

These measurements require a response from an observer to a physical stimulus. Usually in this method simple test objects are used, such as a line pair test object, which is used to measure the spatial resolution. Other examples use discs with different densities, and these discs contain cylinder-shaped holes with different attenuation coefficients to identify the contrast details (C-d) (Zarb, Rainford, & McEntee, 2010). In order to obtain reliable results from these methods, the variation between the observers should be considered, and the average of findings from all observers is recommended.

5.5.4 Diagnosis performance (Receiver Operating Characteristic-ROC)

In medical imaging, the end of the diagnostic process is evaluated by the observer, who decides whether a pathology is present or not. ROC is widely used to evaluate the diagnostic image and the observer performance. The principle of this method is based on signal detection theory. In this theory, an observer should detect a low contrast signal in a noisy background. In the clinical task, this corresponds to the detecting of abnormal cases from a set of normal background cases (Månsson, 2000).

ROC is a type of forced choice methodology where, in it is simplest form, a set of images are presented to the observer. Some of these images are normal, whilst the others have pathologies. The task for the observer is to make a binary decision regarding the absence or presence of disease. Following that, a graph can be plotted between the true positive (correctly identifying the lesion wherein it is present (sensitivity)) versus false positive (correctly ruling out the lesion wherein it is absent (specificity)). ROC methods have a limitation in that the observer is affected by the prevalence of the disease. In addition, this method needs to divide the images into normal and abnormal images, so large a number of the images are required to perform the task. In clinical practice, this is difficult to achieve because of the busy schedule of the observer (radiologist or radiographer), which prevents them from evaluating a large number of cases (D. Altman & Bland, 1994; Metz, 1986; Obuchowski, 2007; Vining & Gladish, 1992). Furthermore, it is not efficient in images with multiple lesions, and the location of these lesions cannot be considered using this method. Therefore, the observer can assume the presence of the lesion without needing to indicate it is location in the image. It is very time consuming because it needs the establishment of truth for all cases, which requires a large number of images in order for it to obtain suitable statistical power. This can lead to fatigue, which in turn has an effect on reliability (Chakraborty, 2005). In order to overcome these limitations, many other ROCs methods have been developed, such as localisation ROC (LROC), free-response ROC (FROC) and Jackknife free-response ROC (JAFROC).

5.5.5 Observer performance (visual grading analysis -VGA)

VGA is a very common clinical method for evaluating image quality. It is based on the ability of the observers to detect and realize the normal anatomy or pathology in the image. Quality criteria are used for each radiographic image to assess the quality for a particular examination. These criteria are developed by radiologists, radiographers, technologists and physicists, who describe the anatomical and physical characteristics of image features (Alsleem & Davidson, 2012). For example, pelvic examination criteria are used to evaluate pelvic images through letting observers decide whether each image satisfies specific criteria (Lança et al., 2014; Manning-Stanley et al., 2012; Seeram et al., 2016; J. Tugwell et al., 2014).

There are two types of VGA evaluation, namely absolute grading and relative grading (Ludewig, Richter, & Frame, 2010). In the relative approaches, the task of the observers is to compare and rate the visibility of anatomical structures in an experimental image against that of a reference image (Alsleem & Davidson, 2012; Hogg & Blindell, 2012). The observers compare whether the quality is better, equal or worse than the matching (paired) landmarks on the reference image (Tingberg et al., 2005). The decisions of the observers are then categorised into 3, 5 or 7 point Likert scales (Ludewig et al., 2010). In contrast to a relative VGA approach, an absolute VGA system sees the observers make image quality decisions without using a reference image. Their decision depends on the state of the visibility for specific features in the display image. For the analysis of the data obtained by VGA, the numerical values are used to calculate the VGA score by averaging the overall rating of cases, observers and structures (Bath, 2010).

There are many factors that make VGA both useful and preferable. First, by using this method almost all components of the imaging system are included within the evaluation. This includes image processing, image recording, image post-processing and the final diagnosis by the observer. Therefore, it is very possible that this method has high validity, because the selection of anatomical structures is based on clinical relevancy, and the image is evaluated by expert observers (Bath, 2010). Second, VGA processes are similar to the review processes undertaken in daily clinical practice. This is because they are based on identifying the clinically relevant standard to evaluate image quality. Third, this method is considered easier to conduct and needs less work when compared to other methods, such as ROC (there is no need for specialist software). This is an important issue, especially in optimisation studies. Fourth, the time for evaluating image quality by VGA is considered reasonable, and thus there are no difficulties facing the observer for participating in the evaluation process. This means it can be implemented almost at any hospital (Bath, 2010; Ludewig et al., 2010). In contrast, this method suffers from it is susceptibility to bias, and which as such decreases its reliability (Bath, 2010). Thus, to reduce the risk of bias, the European quality criteria were established by an international team of imaging professionals (European Comission, 1999; European Commission, 1996). Also, the image criteria that is used by the observer may correspond to an unacceptable image (Båth & Månsson, 2007). The uncertainty of VGA data is difficult to analyse, hence the reasons for this uncertainty cannot be put down to poor image quality or observer influence (Ludewig et al., 2010).

To conclude, DAP was chosen as a direct measure since it was available to the radiographer following imaging acquisition, and then it was subsequently used in the MC dose simulations. Whereas the commercially available PC based MC simulation software (PCXMC) was used for the effective dose estimations. These are common methods for calculating the E and ER, which cannot be measured directly in patients undergoing X-ray examinations. They are also problematic and time consuming to acquire using physical phantoms but can easily be estimated using the described MC methods. For image quality evaluation, SNR and CNR were used to support measures of image quality using VGA.

VGA methods are useful and preferable as all of the components of the imaging system are included within the evaluation. Moreover, it is similar to the image review process undertaken in daily clinical practice.

Chapter 6: An investigation into the effect of posture on image quality and radiation dose during pelvic radiography – a phantom study (*phase two*).

6.1 Chapter overview

As suggested previously in Chapter 3, an erect pelvic X-ray image is recommended for evaluating pelvic and hip pathologies. Consequently, the effect of this position on image quality and radiation dose should be evaluated, as should the differences between the erect and supine positions in term of image quality and radiation dose. This is essential, because the results from the literature review indicate that there were effects on both image quality and radiation dose when moving from one position to the other (see section 3.7). Therefore, the focus of this chapter is to evaluate image quality and radiation dose. There are three separate experiments reported in this chapter. The first experiment is a phantom-based study, conducted to understand how radiation dose and image quality vary as fat thickness increases. The second experiment uses humans to assess how the anterior thickness of the pelvis changes between erect and supine positions. The third experiment is another phantom-based study, conducted to understand how the radiation dose and image quality vary for simulated fat thicknesses (determined from the previous human study – experiment 2), for erect and supine positions.

It should be noted that the same methodology was used in both phantom experiments within this chapter. Therefore, to avoid repetition, the main methods that were used in both experiments are described first. Specific mentions of things such as study design, dose calculations are made when specifically required for individual experiments. Results from this chapter will ultimately be used to inform the methods for the final section of this thesis ***(*Phase three; Chapter 7*)*** see **Figure 6-1.**

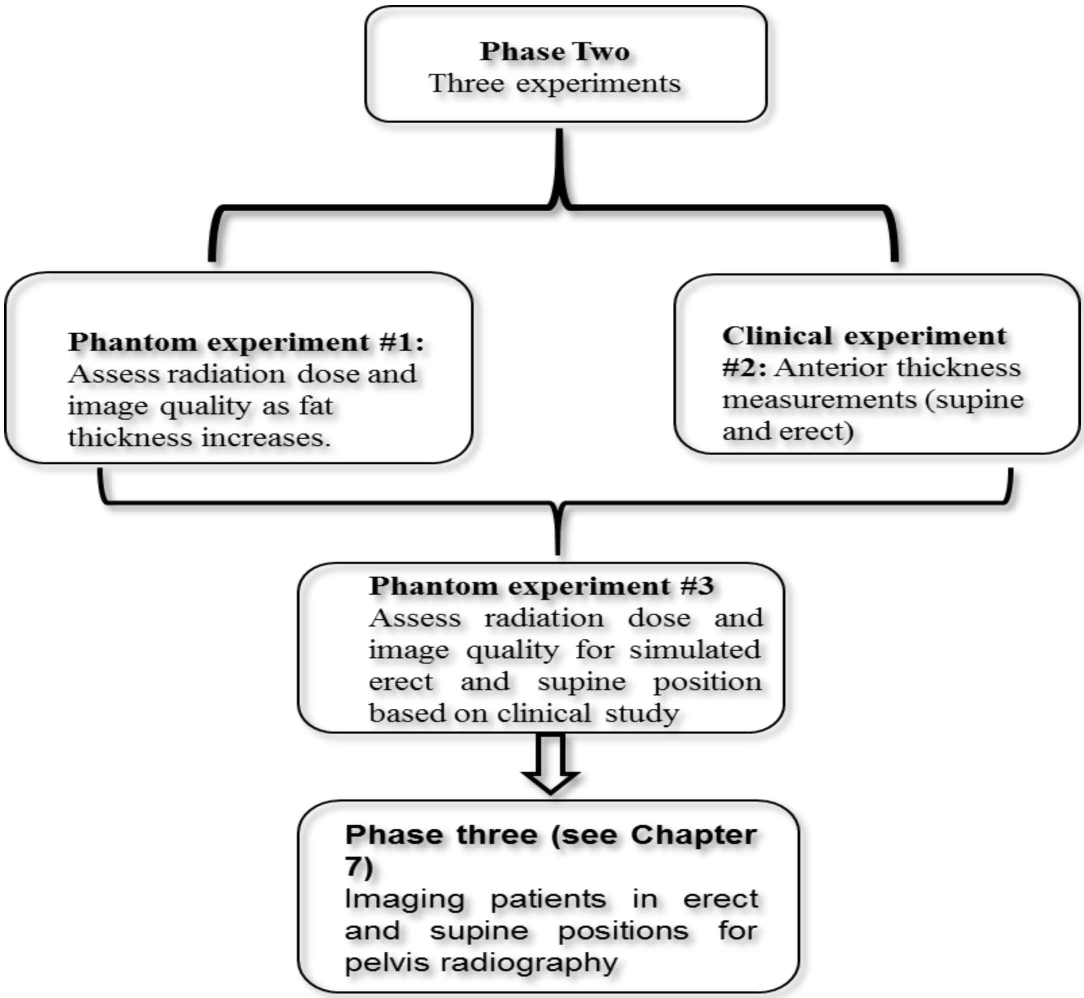


Figure 6-1: Illustrates the three experiments reported within this chapter and their relationship between each other and to phase three. Experiment #1 and the data collected from clinical study (Experment#2) help inform the methods for Experiment #3 in this phase. Then, the results from this phase help to inform the methods used within phase three (chapter 7).

This chapter starts with the aims and objectives (**section 6.2**). The next section then focuses on the details regarding the methods used (**section 6.3**), which include image acquisition parameters, display, fat simulation, radiation dosimetry and image quality assessment. The results from phantom experiments #1 and #3 will inform the next section (**section 6.4).** The chapter will finish with a discussion on the results of the two phantom experiments (**section 6.5**), the limitations (**section 6.6**) and conclusions (**section 6.7**).

6.2 Aims and objectives

The aims of this study are to determine the optimal radiation acquisition parameters for erect pelvic radiography. This will help inform the methods for the **Phase three (Chapter 7)**, and to determine if supine acquisition parameters are appropriate for erect imaging. To achieve these aims, the following objectives were established:

1. To evaluate the effect of increasing anterior soft tissue thickness on image quality, radiation dose and effective risk (**Experiment #1**)
2. To determine the correlations between visual and physical image quality and radiation dose when the anterior soft tissue thickness increases **(Experiment #1)**
3. To determine the differences in anterior thickness between erect and supine positions (**Experiment #2**)
4. To modify the phantom, with added soft tissue, to represent the erect and supine positions and acquire images for a range of parameters (for example kVp and AEC combinations; **Experiment #3**)
5. To evaluate the differences in image quality and radiation dose between supine and erect pelvic radiography and determine the effect of switching to an erect position on image quality and radiation dose **(Experiment #3)**
6. To identify which anatomical areas within the pelvis region are affected most by moving from supine to erect position (**Experiment #3)**
7. To evaluate if there are further optimisation possibilities (acquisition parameters) which can help reduce the radiation dose and maintain image quality, such as increasing SID and adding filtration **(Experiment #3).**

6.3 Methods

6.3.1 X-ray equipment and image detector

This experimental work was conducted in the Directorate of Radiography at the University of Salford. The X-ray equipment used during this study included a Wolverson Arcoma Arco Ceil general radiography system (Arcoma, Annavägen, Sweden) with a high frequency generator and a VARIAN 130 HS X-ray tube. The total filtration of this system is 3 mm Al (inherent 0.5 and added 2.5 mm). There are many routine quality tests performed prior to and during the experiment for evaluating the system's performance. These tests are continually amended according to the recommendations for the evaluation of the routine performance of diagnostic radiography systems made by the Institute of Physics and Engineering in Medicine's (IPEM) (IPEM, 2005) and the National Council on Radiological Protection and Measurements (NCRP, 1988). Within this thesis quality assurance testing was undertaken, including checks on system output, tube potential, time consistency, tube potential accuracy and linearity. The light beam alignment was also checked, as were the dose output variation between different kVp and mAs settings, and AEC sensitivity. The results from these tests fell within the manufacturer tolerance levels (Appendix 13 and 14)

A Konica DR system, a Cesium Iodide (CsI) Aero image detector (Konica Minolta Medical Imaging USA INC, Wayne, NJ, USA), was used in this study. This image capture system had an image area of 35 ∗ 43 cm with a 1,994 * 2,430-pixel matrix, and it is pixel size was 175µm. The same detector was used during the whole experiment in order to avoid any variation in the data. A reciprocating anti-scatter radiation grid within the table Bucky with a grid ratio of 10:1, 40 lines/cm frequency, and focus and linear strips was used too (Wolverson, Willenhall, UK). This kind of grid is commonly used in clinical radiography departments (Fauber, 2016). The image detector used during this study undergoes routine testing by local medical physicists and the manufacturer. During the study period the equipment was working normally.

6.3.2 Anthropomorphic phantom

All images were acquired using an adult lower sectional torso RS-113T anthropomorphic pelvic phantom (Radiology Support Devices, Long Beach, CA) (see **Figure 6-2)**. This phantom represents the absorption equivalent when compared to an adult of 175 cm in height and 74 kg in weight. This type of phantom is made of equivalent material to simulate human soft tissue and has a human skeleton embedded within it to simulate a human body

("Radiology Support Devices," 2017). These specifications allow for unlimited exposures, and data that allows for a comparable assessment of radiation dose and image quality between different acquisition protocols (Winslow, Hyer, Fisher, Tien, & Hintenlang, 2009).

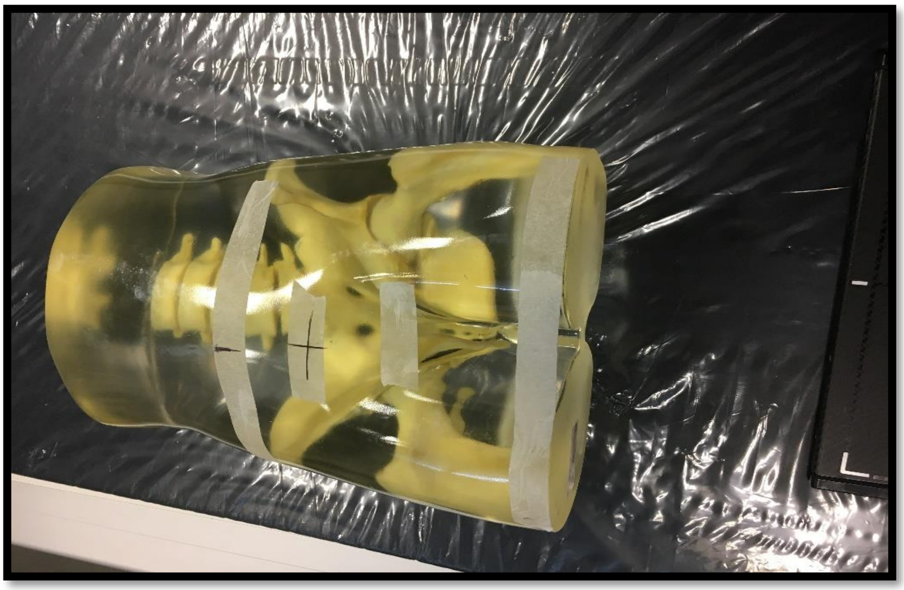


Figure 6-2: lower sectional torso RS-113T anthropomorphic pelvis phantom. The figure illustrates the central ray location (cross-hair). The field size was defined by the tape and was kept constant during the experiment.

6.3.3 Display monitors and conditions

For displaying the images, high quality 5 MP class monochrome liquid crystal (LCD) monitors DOME E5 (by NDSsi, Santa Rosa, ca) were used (23.2 inches in size). These high-resolution monitors were chosen to simulate common clinical situations and improve the displaying conditions recommended for better detection and interpretation. Also, such display systems are recommended by The Royal College of Radiologists (The Royal College of Radiologists, 2012). The light of the viewing room was maintained at constant levels (30-40 lux) and dimmed during the image quality assessment in accordance with European Guidelines on Quality Criteria for Diagnostic Radiographic Images (Allen et al., 2013; Norweck et al., 2013). Both of the display monitors used in the study were also calibrated to the Digital Imaging and Communications in Medicine (DICOM) grey scale standard display function (GSDF) prior to use (luminance of >400 cd/m2).

6.3.4 Fat simulation: fat material validation and stability at room temperature

The main hypothesis for this thesis was that the gravity's effect during erect positioning changes the thickness of the anterior abdominal soft tissue. In order to study the effect of the differences between erect and supine positioning on image quality and radiation dose, for different sized people, the simulation of human fat layers was required. This meant making modifications to the pelvic anthropomorphic phantom. Commercial animal fat (lard) was chosen to simulate human fat. Justification for it is use included that it is widely available, simple, easy to handle and cost-effective; and that the literature review that was undertaken to find a fat mimicking material that had the same human X-ray attenuation characteristics as adipose tissue found that many researchers believe lard can be used to replicate human fat (Bauer et al., 2015; Browne, Watson, Hoskins, & Elliott, 2005; Glickman, Marn, Supiano, & Dengel, 2004; Valentine, Misic, Kessinger, Mojtahedi, & Evans, 2008). Many of these studies positioned the lard as fat material on the phantom in order to measure the precision of DEXA in detecting extra fat. They added it to available phantoms in general X-ray, ultrasound and MRI examinations (Browne et al., 2005; Glickman et al., 2004; Valentine et al., 2008; Yu, Thomas, Brown, & Finkelstein, 2012).

It was reported previously that the mean (SD) CT attenuation (HU: Hounsfield unit) of human fat was -93 (±25) (Fisher & Hintenlang, 2014; Yoshizumi et al., 1999). These results were obtained from CT scans conducted on a range of ages and body weights across 120 patients. Within other studies, fat was measured as being between -190 to -30 HU (Glickman et al., 2004; Morsbach, Bickelhaupt, Rätzer, Schmidt, & Alkadhi, 2014; Zamboni et al., 1998). Once this was known, it was then feasible to attempt to match the X-ray attenuation characteristics of lard to that of human fat. Therefore, a CT scanner (Toshiba CT scan 16 slices; Toshiba Medical Systems, Tokyo, Japan) was used to measure the HU of lard. This was achieved by scanning the lard and drawing regions of interest (ROIs). The HU was then recorded across a number of different cross-sectional slices (see **Figure 6-3)**. Within the CT scanner there were anonymous CT scans available and abdomen and pelvic CT scans were chosen for many previously scanned patients. ROIs were drawn on different parts of abdominal fat (anterior, posterior and both sides) and it is HU was then recorded (see **Figure 6-4)**. The results obtained from the comparison between the lard and human adipose tissue indicated that the HU for the lard ranged from –77 to -81 HU, whereas for humans it was almost -100 HU. These results prove that the lard used within this thesis had similar X-ray attenuation properties to human adipose tissue.

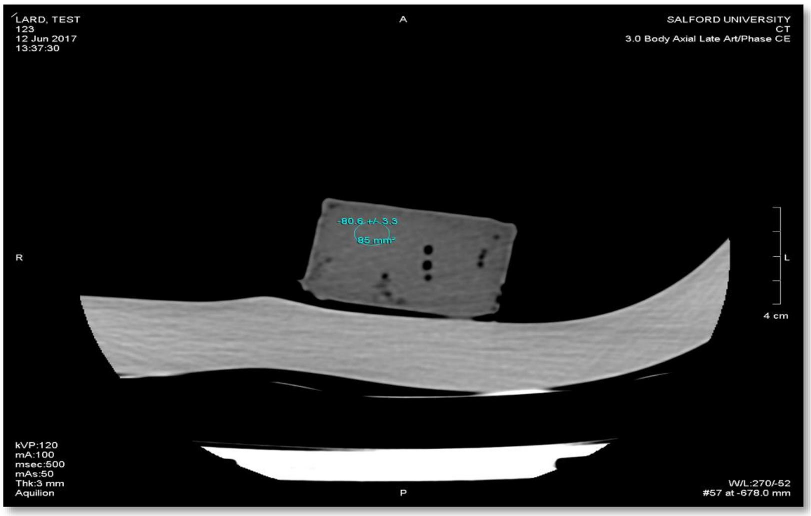


Figure 6-3: Illustrates the method used for measuring the CT density of lard in order to match it with human CT data (adipose tissue). The ROI was drawn on the lard and the mean HU was recorded.

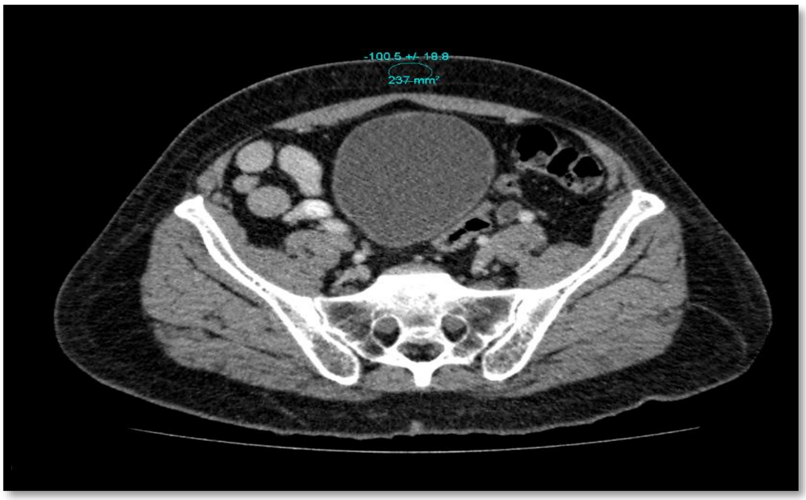


Figure 6-4: ROI was drawn on patient CT images and the HU was recorded.

Since working with phantoms with the incorporation of animal fat would take many hours, it was valuable to examine the stability of fat during long periods of sitting at room temperature. Therefore, the stability of fat, in terms of the HU at room temperature, was evaluated. To achieve this, an LCD digital thermometer (TP101) was inserted into the block of lard and positioned in the freezer for a 12-hour period (see **Figure 6-5)**. Another thermometer (BEE-KA COLDE-MIL LINE) was left in the room for the same period of time to measure the room temperature. The lard temperature was recorded for the first-time when it was taken out of the freezer (-14^{o}C). A CT scan was obtained at this time too. An ROI also was drawn, and the HU was recorded. The lard was then left in the room, elevating the temperature of it to eventually reach room temperature. A CT scan was performed at 30-

minute intervals and the HU was recorded against each temperature until it reached room temperature (22^{o}C).

Figure 6-5: A thermometer was inserted into the lard for measuring the internal temperature

The results showed that the lard had a stable HU at room temperature. Moreover, at room temperature the CT density of lard was -100 HU which was closer to human adipose tissue. Even at the freezer temperature (-14^{o}C) the CT density was -64 HU which is within the range of the fat HU previously reported in the literature (see **Figure 6-6)**.

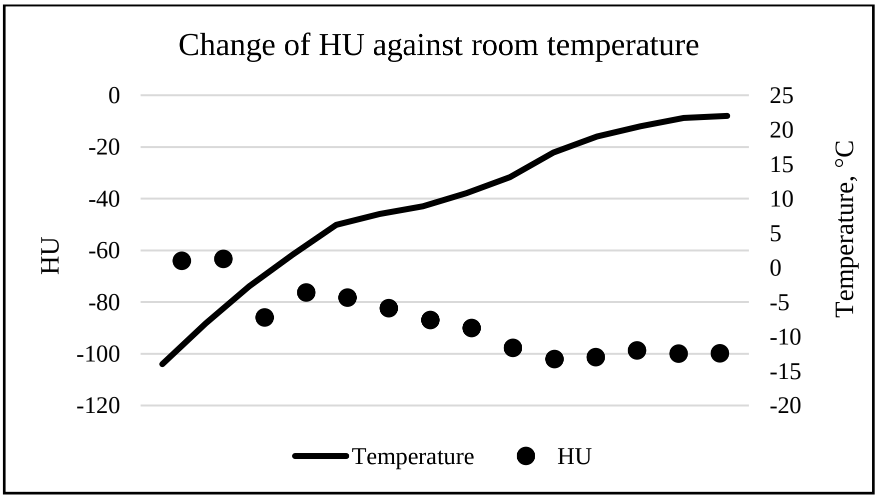


Figure 6-6: A graph illustrating the change in the CT density (HU) of the lard with the temperature. As the temperature increases and eventually reaches room temperature, the HU change stabilises.

6.3.5 Radiation dose assessment

In this experimental work, DAP was measured using a Kerma X plus model 120-131 meter (Scanditronix. Wellhöfer, Schwarzenbruck, Germany). This was located immediately after the X-ray tube exit window. The DAP meter was calibrated before and during the experiments with the agreement referenced against the manufacturer's datasheet (C. Lee et al., 2016). The DAP was recorded three times for each protocol and the average was used for the E calculations. Intra-class correlation coefficients (ICC) were calculated to evaluate the consistency between the three recorded readings, and the results demonstrated excellent performance overall - ICC 0.999 to 1.000 (95% CI 0.998 to 1.000, P<0.0001).

PCXMC Version 2 (STUK, Finnish Centre for Radiation and Nuclear Safety, Helsinki, Finland) was used to conduct the MC simulations. The tissue weighting factors used by this software were obtained from the ICRP 103 report (ICRP, 2007). In order to obtain the same area of interest, the collimation size remained constant. As such the beam width and height was kept constant in the PCXMC calculation for all circumstances**.** PCXMC was used in the two phantom based experiments during this chapter (phantom experiments #1 and #3). It is important to note that for the two different experiments, different parameters were introduced into PCXMC. As such, the calculation methods will be described in detail for each experiment. In order to overcome the problem that PCXMC could overestimate the effective dose, the number of the simulated photons was increased to $1x10^6$ which has been recommended in previous studies in order to lower the error by 0.1% (Davies et al., 2014; Ladia et al., 2015)

6.3.6 Image quality assessment

6.3.6.1 Physical assessment of image quality

Images were evaluated physically by calculating the SNR and CNR. SNR values were calculated based on standard calculations and represented the ratio between the mean pixel signals and the variation (standard deviation σ of the noise) (Bushberg, Boone, Leidholdt, & Boone, 2011) see the formula below. Four regions of interest (ROIs) were drawn for determining the mean of the signal value, and two ROIs were used in a homogeneous area within the image to determine the noise. **Figure 6-7** illustrates the location of the ROIs. Two ROIs were located on the iliac crest and the other two were located on the femoral head. These were selected to represent the whole pelvic area, and therefore give an overall objective measurement of image quality evaluation. This calculation of SNR has been used by many studies previously published (Lin et al., 2012; H. Mraity, 2015; Sandborg, Tingberg, Ullman, Dance, & Alm Carlsson, 2006). SNR= $\frac{mean\ signal}{\sigma_{noise}}$ (Bushberg et al., 2011). σ was calculated as $\sqrt{\frac{[(SD1)^2+(SD2)^2]}{2}}$ (Alves et al., 2016), where SD1 and SD2 are the standard deviation for region 1 and 2 of noise.

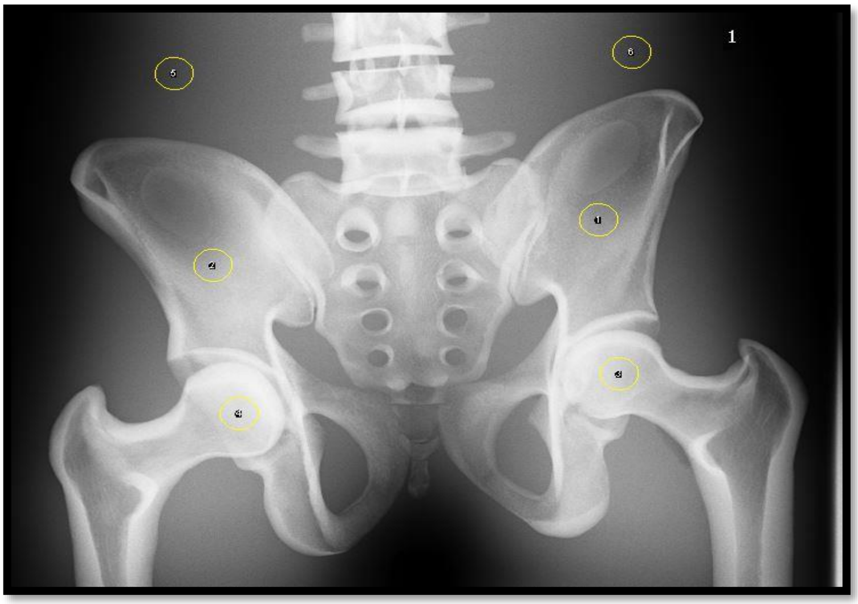


Figure 6-7: Illustrates the four ROIs that were used to calculate the mean signal and the ROI (number five +six) was used for noise calculations.

CNR was calculated to support the conclusion drawn from the SNR calculations. By calculating the CNR, the main image quality features were evaluated, namely contrast and noise. CNR considers the effect of noise on a person's ability to see objects within images, as it depends on the contrast. Moreover, the CNR calculation has been used in many studies for image quality evaluation (Hess & Neitzel, 2012; Martin, 2007; Mori et al., 2013). The contrast is determined by calculating the differences between the signal in the region of interest and the noise region. The same ROIs that were used for calculating the SNR were used for calculating the CNR during this phase.

CNR $=\frac{(ROI_1 - ROI_2)}{\sigma ROI_2}$, where ROI_1 is the mean signal from the area of interest (anatomy) and ROI_2 is the mean signal from the noise. σROI_2 was calculated as $\sqrt{\frac{[(SD1)^2+(SD2)^2]}{2}}$, where SD1 and SD2 are the standard deviation for region 1 and 2 of noise.

Image J software (National Institutes of Health, Bethesda,MD) was used for SNR and CNR calculations. Image J has been widely used by other researchers for the same kinds of calculations (Desai, Singh, & Valentino, 2010; Keun Jo et al., 2011; Lança et al., 2014; J. R. Tugwell et al., 2017). The ROIs manager, in ImageJ, was utilised to save the locations for all ROIs over all the images. Thus, the consistency of averaging values across the same anatomy was preserved.

6.3.6.2 Visual assessment of image quality

To complete the evaluation of the whole imaging process, image quality was assessed perceptually by using a relative VGA method (Burgess, 2011) and absolute grading. This approach was used because it is sensitive to the detection of small changes in image quality, and it decreases subjective bias (Lança et al., 2014; Pelli & Farell, 1995; Tingberg et al., 2004). Also, it is considered to be time efficient, and has the smallest measurement variance (Tingberg et al., 2004). This is mainly because the reference image aids that are used as a fixation point during the rating, rather than having scoring based on subjective and inconsistent impression decisions (Månsson, 2000; Tapiovaara, 2006).

The reference image and the experimental images were displayed on two monitors (side-by-side) (see **Figure 6-8)**. The determination of the reference image is explained in detail in the two different experiments summaries of this chapter. The reference image was fixed on the right monitor, while the experimental images were displayed in a random order in the left monitor. Throughout the evaluation of image quality, the observers were blinded to the image acquisition factors. The experimental images were evaluated against the reference image and scored using a visual grading scale and image criteria, which will be discussed in the next subsection.

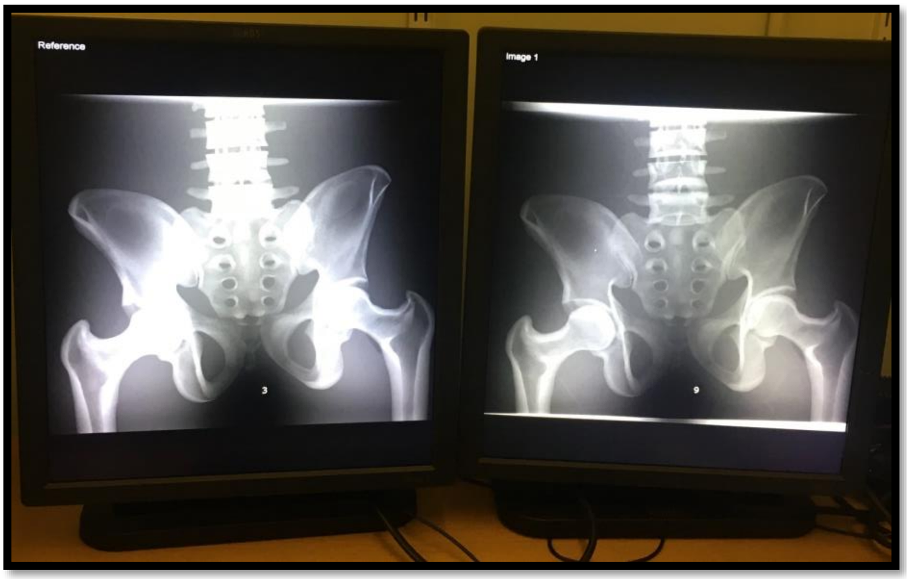


Figure 6-8: The reference image was displayed on the right side and the experimental images on the left monitor.

6.3.6.2.1 Image quality criteria

Until recently, the criteria for visual image quality assessment were published only by the Commission of European Communities (CEC). This is the primary reason behind utilising these criteria, as they have been included in many studies for evaluating image quality using visual methods (Allen et al., 2013; C. T. P. Chan & Fung, 2015; Davey & England, 2015; Mekiš et al., 2010). However, the CEC criteria were developed in the FS era, and consequently many of these criteria are not applicable for DR and other important features of DR are missing.

In 2016, a new psychometric image quality scale for DR AP pelvic images was published by Mraity and colleagues (H. A. A. B. Mraity et al., 2016). This scale was developed using a methodology confirming its internal reliability and validity. Cronbach's Alpha coefficient was used to describe the internal consistency of the scale items. The initial scale consisted of 24 items. All items produced a high Cronbach's Alpha coefficient between 0.803 and 0.913, which proves it is high level of internal reliability. In this scale, 15 out 24 items were anatomical in nature. The remaining nine items related to the technical factors. **Table 6-1** illustrates the 15 items that were used during this phase.

A five-point Likert scale was utilised for scoring the 15 items on the image quality scale. Each of the five possible responses had a numerical value which was used for scoring each image. Using the score sheet and Likert scale, the participants decided whether the image quality was: much worse (score of 1), slightly worse (score of 2), equal to (score of 3), slightly better (score of 4), or much better than (score of 5) that of the reference image. Therefore, the scores ranged from 15 to 75. A score of 45 represented equal image quality to that of the reference image. A score of more than 45 meant enhanced in the image quality, while a score of less than 45 indicated a decline in image quality.

Table 6-1: Criteria used for the visual grading (adapted from (Mraity et al., 2016))

Criteria
The left hip joint is adequately visualised.
The right hip joint is adequately visualised.
The left lesser trochanter is visualised adequately.
The right lesser trochanter is visualised adequately
The left greater trochanter is visualised adequately
The right greater trochanter is visualised adequately
The right sacro-iliac joint is adequately visualised.
The left iliac crest is visualised adequately.
The right iliac crest is visualised adequately
Left acetabulum is visualised clearly
Right acetabulum is visualised clearly.
The pubic and ischial rami are NOT adequately visualised.
The both femoral necks are visualised adequately
The medulla and cortex of the pelvis are adequately demonstrated.
The sacrum and its intervertebral foramina are NOT visualized adequately.

Following the ethical approval obtained from the University of Salford (HSR1718-022; Appendix 3), the images were evaluated by six observers. These observers had more than five years' experience working as radiographers in radiology departments. This was in line with Chan & Fung (2015). No clear advice has been given in the literature regarding the number of the observers that should be used in visual grading analysis. It was suggested by Burgess that four observers are needed (Burgess, 2011). Obuchowsk however, recommended that three observers were needed (Obuchowsk, 2004). Radiographers were chosen in this study because they acquire and evaluate medical images routinely and decide if the images are acceptable or not, before radiologist/reporting radiographer makes a formal comment on the image. The six radiographer observers also had experience in evaluating radiographic images using relative VGA methods. Despite this, all observers undertook a training session before conducting the evaluation process. This allowed the observer to become familiar with the task and to ask the researcher about anything they were unclear on. During this session, different images were displayed to the observers and the anatomical criteria were discussed in detail. Images were divided into separate folders, allowing the observer to take a break after completing each folder to minimise the effect of tiredness and fatigue on their eyes (Alers, Bos, & Heynderickx, 2011).

6.3.7 Impact of body part thickness on AP pelvic radiographic image quality and effective dose and risk (*Phantom Experiment # 1*)

This experiment sought to evaluate the impact of increasing body part thickness on IQ, E and ER and identify optimum exposure parameters. The aim was to identify the behaviour of IQ and E as the fat thickness increased. Thus, as a result, for any known thickness, the correct exposure parameters could be determined. This will help in identifying the optimal acquisition parameters for experiment #3.

6.3.7.1 Study design

The pelvic phantom was used during this experiment **(**see **section 6.3.2).** The phantom was positioned supine on the table top. A fixed collimation field of 40 *35 cm was used with beam centring based on recommendations found within the literature. These included in the midline, halfway along an imaginary line connecting the ASIS and PSIS and over the symphysis pubis (Ballinger & Frank, 1999; Whitley et al., 2005). The location of the central X- ray was identified and fixed by opaque tape during the experiment. The collimation was marked by tape placed on the table top and on the image receptor. Also, the location of the phantom was marked on the table top to ensure a fixed and consistent phantom location throughout the experiment (see **Figure 6-9)**.

In order to simulate the increasing body part thickness, commercially available animal fat (lard) was placed inside a rectangular plastic box, which was placed on the anterior surface of the phantom. The rationale for using a plastic box was that it this was the simplest way to position the fat over the phantom and was also a practical way to add fat in 1 cm intervals. The rationale and validation for using commercial lard as a substitute for human fat has been explained in the previous section (see **sections 6.3.4**).

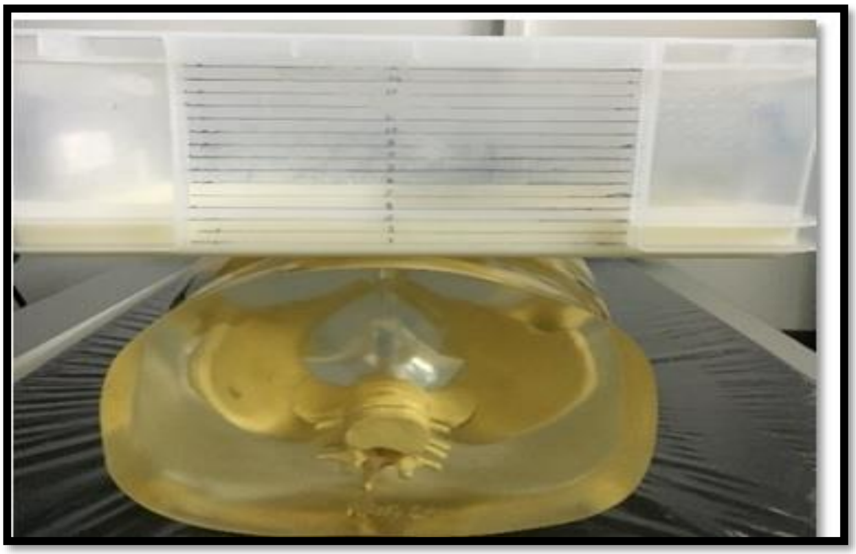


Figure 6-9: Experimental setup for the pelvis phantom and additional fat container (scaled 1 cm increment box). This photograph is taken from the superior aspect of the phantom looking inferiorly.

It is important to note that positioning the fat anteriorly is unlikely to reflect the actual distribution of adipose tissue within the human body. However, the method of adding fat as described within this experiment was a simplification of the "apples" and "pears" fat distributions more typically observed in adult body types (Despres, 2001; Sturman-Floyd, 2013; Yanch, Behrman, Hendricks, & McCall, 2009). This would be where the additional body fat would predominantly accumulate in the anterior body structures, as simulated within this experiment. It was reported by Borrego et al. (2018) that, when comparing dose calculations between the PCXMC phantom and a hybrid, as the weight of the phantom increased, the depth from the anterior end of abdominal organ increased for the hybrid phantom more than the PCXMC phantom (Borrego et al., 2018). Moreover, many studies have simulated adding additional soft tissue material either above or below the phantom (Neitzel, Pralow, Schaefer-Prokop, & Prokop, 1998; Otto et al., 2000; Sanchez et al., 2012; Ubeda, Vano, Gonzalez, & Miranda, 2013). Yanch et al. (2009) simulated overweight and obese patients using MC simulation in 2009. In Yanch's study, the simulation of increasing patient size was performed with five different fat distributions predominately anterior, posterior, lateral or equally across the four (Yanch et al., 2009). The most important reason for positioning of the fat anteriorly in this thesis is that gravity has an effect on the anterior part of the body when we stand up.

In order to understand the effect of increasing body part thickness on IQ and radiation dose, the acquisition parameters initially chosen were based on those used in local clinical practice and on those recommended in published works (C. T. P. Chan & Fung, 2015; R. Heath et al., 2011; Manning-Stanley et al., 2012). Therefore, a reference image was acquired at 80kVp, 100cm, using both outer chambers, and this was later used for evaluating IQ. Following this, 144 experimental images were acquired with 1 to 15 cm of additional fat (using 1 cm intervals) and a range of tube potentials (70 to 110, in 5 kVp intervals). All other exposure conditions remained constant. Three exposures were performed for each of the kVp/fat thickness combinations. To minimise random error, three DAP readings were taken and averaged for each acquisition, and these were recorded along with the respective acquisition parameters. Post-exposure mAs and exposure index values were also recorded.

6.3.7.2 Image quality assessment

Image quality was assessed using both physical and visual methods within this phase. The physical methods were those described in **section 6.3.6.1**. Visual IQ was assessed using both relative and absolute VGA. A relative VGA method was first selected since it provides the ability to measure subtle changes in IQ. For this part, the reference image was chosen according to the clinical practice. Observers were invited to evaluate images using a validated visual scale consisting of 15 criteria (**section 6.3.6.2.1**). For each image, observers independently graded the different criteria using a 5-point Likert scale.

Absolute grading was also chosen to provide a definitive opinion on whether images were acceptable for diagnostic purposes, thus reflecting clinical practice. Two radiographers with more than 20 years of reporting experience (a consultant radiographer and an advanced practitioner) made a binary decision as to whether images were suitable for diagnosis (yes or no). Within this process, using their professional experience they considered five anatomical areas which have previously been used for evaluating pelvis X-ray images. These include: -

- Sacro-iliac joints (assessing integrity/ankylosis)
- Iliac bones (bilaterally) (bony lesions)
- Pubic rami (insufficiency fractures/lesions)
- Hip joints (bilaterally) (OA)
- Proximal femora – suggest intertrochanteric line (bony lesions).

Since the data obtained from this phase will be used for providing recommendations for the acquisition parameters in **Phase Three (see Chapter 7),** the compatibility between the behaviour of the X- ray imaging system at the University of Salford and the X-ray imaging system at the clinical site **(Phase Three**) was also experienced. Thus, this experiment was repeated in the hospital under the same conditions but with less fat layers. Due to time constraints within the clinical department, it was impractical to image all of the fat thicknesses from 0 to 15 cm. So, the decision was made to choose just four fat thicknesses to be imaged in the hospital. The choosing of which four layers would be imaged was done based on the results obtained from the University study. The results showed that the main changes in IQ and radiation dose were at 5 cm, 10 cm and 15 cm. Therefore, three boxes (using the same construction as previously used in the University experiment) were filled with 5, 10 and 15 cm of fat. There was also an empty box for obtaining the images without additional fat for comparison. The images were then analysed in the same way as the university study. The results showed comparable data between the X- ray equipment in the university and the hospital.

6.3.7.3 Dose calculations

Effective dose was calculated using the MC software PCXMC 2.0 (STUK, Radiation and Nuclear Safety Authority, Helsinki, Finland). PCXMC has successfully been used in previous research studies for similar radiation dose calculations (Ekpo et al., 2014; Grewal, Young, Collins, Karunaratne, & Sabharwal, 2012; Kawasaki, Aoyama, Yamauchi-Kawaura, Fujii, & Koyama, 2013; Khelassi-Toutaoui et al., 2008; Ladia et al., 2015; J. R. Tugwell et al., 2017; T. J. Wood et al., 2015). The X, Y and Z references were fixed for all phantoms; the beam width and height were 31 and 32 cm, respectively. And the X-ray spectrum was changed continuously to match the X-ray tube potential that was used for each individual exposure. In order to accurately simulate the differences, in body part thicknesses the source to skin distance (SSD) was measured at the level of central ray for each fat thickness and used in the PCXMC calculations. Moreover, the weight of the phantom in the simulations was modified for each one cm increase in AP fat thickness (1 kg for each cm increase in AP diameter). This formula was based on the study conducted by Miyatake (Miyatake, Matsumoto, Miyachi, Fujii, & Numata, 2007), who reported that, for each 3 cm decrease in waist circumference, a 3 kg decrease in weight took place. The assumption was that there was a linear relationship between increasing waist circumferences and weight, as confirmed by Fontaine (Fontaine et al., 2002). PCXMC provides the ER depending on the dose data simulation that is used for the E calculations. Therefore, the ER was recorded for each simulation.

6.3.8 Data collection from the clinical site for fat modelling (*Experiment #2*)

Individuals were recruited for body habitus measurements in both the supine and erect positions. Inclusion criteria included patients attending from their general practitioner or an outpatient orthopaedic clinic for X-ray images of their hips or pelvis. Exclusion criteria were paediatric patients, those unable to stand unaided, those with an inability to communicate. The participant's height and weight were measured by a study researcher in order to calculate BMI. Based on World Health Organisation report (WHO, 2005), BMI was then grouped into three categories: underweight / normal (BMI <24.9), overweight (BMI 25.0 – 29.9) and obese (BMI >30.0) (Wadden & Bray, 2018).

A cohort of 180 patients who attended for radiography of the hip or pelvis from either an outpatient clinic or their general practitioner was recruited. More detail on the participants used during this experimental study are illustrated in **Table 6-2**. The data are demonstrated for different genders and different BMIs.

Table 6-2: Demographic data of the included participants. Data are presented as the mean (SD).

Variable	Count	Age (y)	Height (m)	Weight (kg)	BMI (kg/m^2)
All	180	63.5 (13.2)	1.6 (0.1)	78.8 (17.8)	28.8 (5.7)
Male	43	61.6 (13.4)	1.7 (0.1)	86.6 (15.3)	29.1 (4.9)
Female	65	63.2 (13.2)	1.6 (0.1)	73.7 (17.6)	28.6 (6.2)
Normal BMI	31	61.4 (16.6)	1.6 (0.1)	61.5 (1.5)	22.7 (1.9)
Overweight BMI	34	63.8 (12.5)	1.6 (0.1)	74.9 (9.6)	27.5 (1.5)
Obese BMI	43	62.4 (10.9)	1.7 (0.1)	94.3 (4.2)	34.3 (4.2)

For each participant, AP body thickness were measured at the levels of three different body parts namely: 1) lower costal margin (LCM), 2) iliac crests (IC) and 3) greater trochanter (GT). The body circumference was measured using a flexible tape measured halfway between the 10th rib and the hipbone (Waninge et al., 2010). The AP body thickness was measured by a tape measure mechanically attached to the collimator box of the X-ray equipment, with a minimum increment of 0.1cm. The same tape measure was used to measure the SID. Next, the SSD was measured for the anatomical thickness of the patient's above anatomical levels (centre of the anatomy) for both positions (see **Figure 6-10** & **Figure 6-11)**. Three radiographers were trained to undertake these specific measurements to ensure consistent data collection. The measurements of the average anterior diameters for the three different locations are illustrated in **Table 6-3**. These measurements were then used for the fat modifications of the phantoms (models) in both supine and erect positions in the experiment #3.

Figure 6-10: Measuring the AP body part thickness and waist circumferences in a standing position.

Figure 6-11: Measuring the AP body part thickness and waist circumferences in a supine position.

Table 6-3: Measurements of the anterior diameters for different body locations. Mean (SD) values.

	Anterior diameters thickness, cm		
	LCM	**IC**	**GT**
Supine	24.7 (3.7)	23.9 (3.6)	21.7 (2.9)
Erect	24.7 (4.4)	29.3 (4.5)	26.7 (4.2)

6.3.9 Impact of changing body habitus on radiation dose and image quality for DR pelvis examinations (*Phantom Experiment #3*)

In this section, the impact of body habitus (repositioning from supine to erect) will be simulated. As mentioned above, the main differences between the Experiment #1 and Experiment #3 will be in study design (fat simulation), dose simulation using PCXMC and in choosing the reference image. To avoid repetition, only the key differences will be explained in detail. The results from this experiment will help inform the methods for **Phase Three** (see **Chapter 7**) in this thesis. Ethical approval for this experiment was obtained both from the University of Salford and from the local clinical site (Appendix 4 and 5).

6.3.9.1 Fat modelling to represent standing and supine positions

As previously specified, the thickness of the phantom was measured at the level of the three main anatomical landmarks (LCM, IC, and GT), which were 22, 24, and 23 cm respectively. A decision was made to simulate the fat differences between the two positions by adding the mean of the anterior thickness – 1SD and the mean of the anterior thickness + 1SD to the three main anatomical landmarks. However, the mean -1SD was smaller than the current geometry of the phantom. Thus, the aim was modified to be simulating the fat by adding the mean +1 and +2 SDs. The following diagrams explain the original phantom size and the fat thickness required to simulate +1 and +2SD. **Figure 6-12** and **Figure 6-13** illustrate the mean of the patient and the thickness of the fat layer needed to add +1 and +2 SD on the front of the phantom.

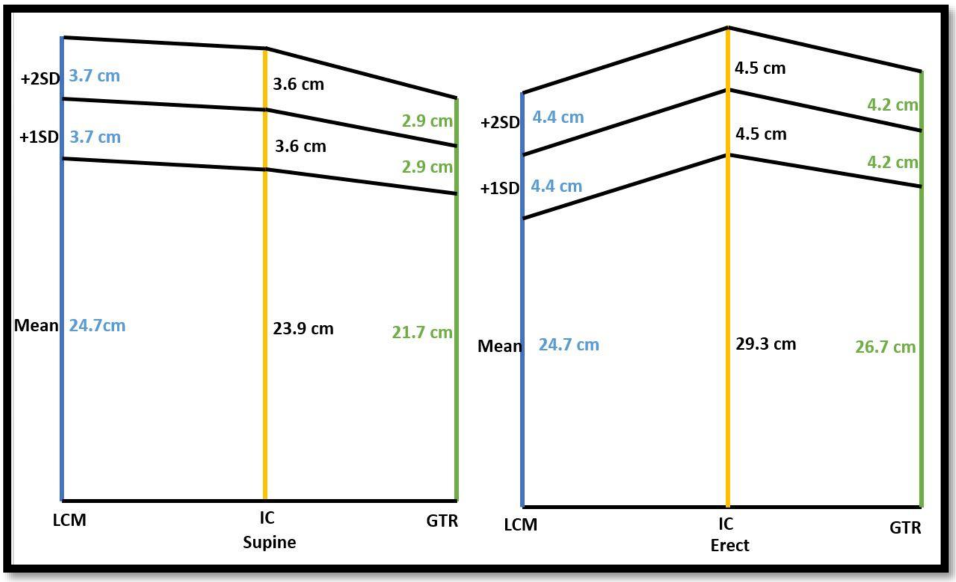


Figure 6-12: Illustrates the mean of the real patient thickness, at the three anatomical landmarks, and the fat layer thickness needed

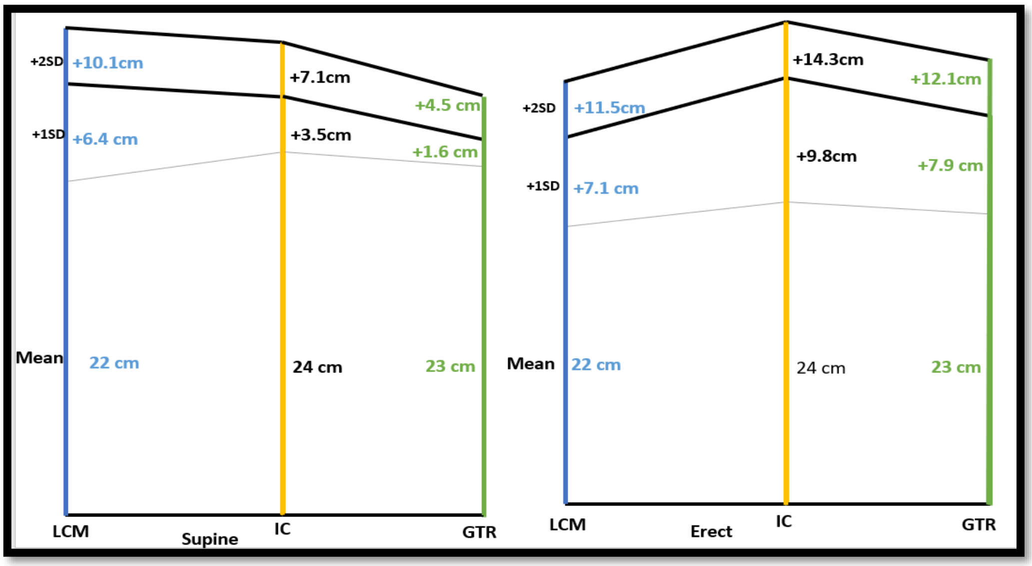


Figure 6-13: The phantom measurements and the +1 and +2 SD of the fat layer needed to be added after subtracting the mean phantom size for the three anatomical areas.

6.3.9.2 Supine and erect phantoms imaging

The same equipment was used during this stage, as described in sections **6.3.1 to 6.3.3**. The phantom position, radiographic centring and all elements of the experimental setup were the same as previously described in experiment #1 (**see section 6.3.7**). The fat thickness layers, determined as above described (see **section 6.3.9.1**), were positioned at the different three anatomical landmarks to represent the erect and supine positions and the phantoms with two sizes (1+2 SD). **Figure 6-14** and **Figure 6-15** illustrate the two phantoms size and corresponding X- ray image**.**

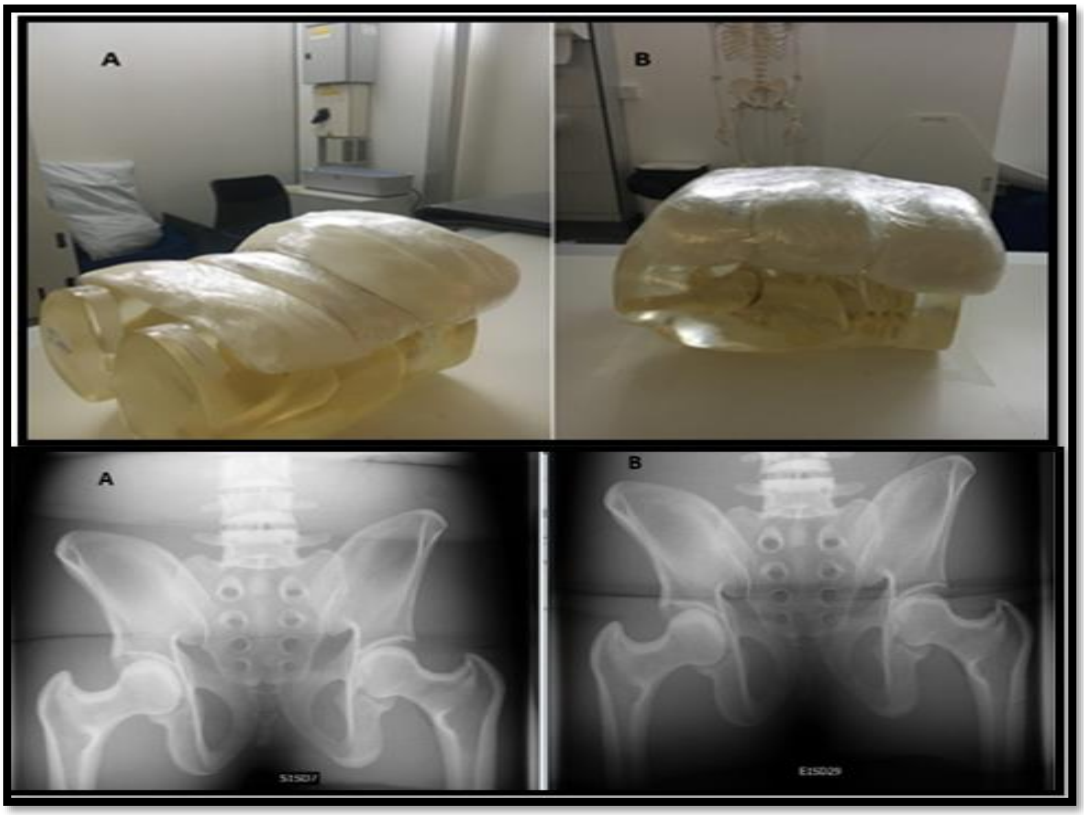


Figure 6-14: Illustrates the +1SD size modified phantoms and corresponding X-ray images. A: supine and B: erect

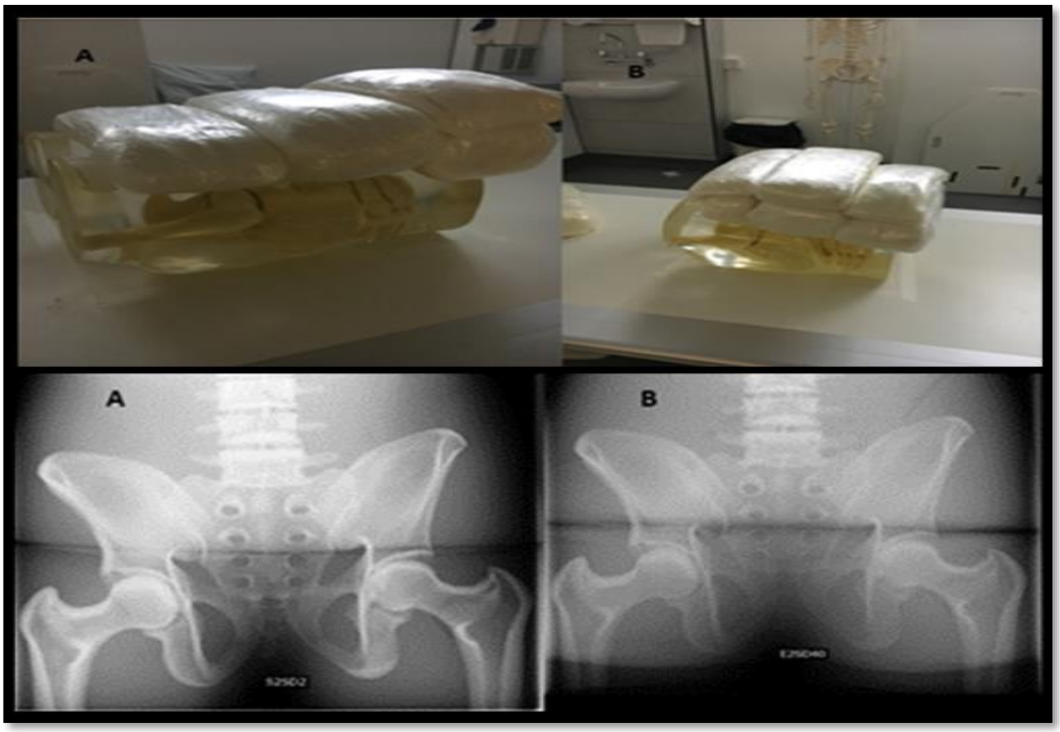


Figure 6-15: Illustrates the +2SD size modified phantoms and corresponding X-ray images. A: supine and B: erect.

216 images were obtained using a kVP of between 80 and 100 (in 10 kVP intervals). This range was chosen based on the results obtained from experiment #1. Different SIDs were chosen, from 115 to 145 cm SID (using 15 cm intervals). Different AEC combinations [both outer (B), central (C) and all (A)] were examined. Also, the images were obtained with and without 0.1 mm additional Copper filtration (Cu).

6.3.9.3 Radiation dose assessment

The effective dose was calculated using the MC software PCXMC. In order to simulate the +1 SD phantom size, the +1SD was added to the average patient's weight. For the +2SD phantom, +2SD was added to the average patient's weight. This method was used to represent the real measurements obtained from the patients in the hospital. Therefore, the weight for the +1SD phantom was 96.4 kg, and for the +2SD phantom it was 114.4 kg. The standard height was fixed at 178.6 cm for all phantoms, as the calculated E depends only on phantom weight (Kruger, Flynn, Judy, Cagnon, & Seibert, 2013). These methods were adapted from the existing literature (Davies et al., 2014; Kruger et al., 2013). The beam width and height were 31 and 32 cm, respectively. The X-ray spectrum was changed continuously to match the X-ray exposure that was used (kVp; 80, 90 & 100- and 0.1-mm additional Cu or no filtration). The SSD was measured for each phantom and for each SID and was used during the dose simulation - see **Table 6-4.**

Table 6-4: A summary of the main parameters that were inserted to the PCXMC software (for every simulation for each phantom).

Size	**+1SD**		**+2SD**	
Phantom	**Erect**	**Supine**	**Erect**	**Supine**
SSD* (cm)	84, 99, 109	90, 115, 119	79, 84, 105	87, 101, 112
SID (cm)	115, 130, 145		115, 130, 145	
Weight (kg)	96.6	96.6	114.4	114.4
kVp	80, 90, 100			
Filtration	No added filtration, 0.1mm cu added filter			

* SSD at 115,130,145 SID respectively.

6.3.9.4 Image quality assessment

Image quality for experiment #3 was assessed using both physical and visual methods. The physical methods were the same as described in section **6.3.6.1,** and the visual methods were the same as described in section **6.3.6.2**. The reference image was selected based on routine clinical practice parameters for pelvic radiographs (80kVp, using both outer AEC chambers and without any additional filtration for erect and supine phantoms in each size).

6.3.10 Ethical considerations

Since evaluations of IQ depend on observer responses, ethical approval was further obtained from the clinical site and from an ethics committee at the University of Salford (Appendix 4 and 5). Participants were invited to sign a consent form after reading the participant information sheet (Appendix 10). Confidentiality was preserved by coding any gathered data using a unique coding number for each participant. Participants right for their data to be removed from the study for a period of 3 months after data collection, which was also made clear to participants during recruitment. All of the X-ray images were acquired using phantoms and therefore there could not be any incidental findings encountered.

6.3.11 Statistical analysis

Data was inputted into SPSS Version 22.0 (IBM Inc, Armonk, NY) for analysis and the normality of the data was assessed using the Shapiro-Wilk test (Ghasemi & Zahediasl, 2012; Yap & Sim, 2011) for both experiment #1 and #3. Inter-observer variability was assessed using an inter-class correlation coefficient (ICC). ICC values of less than 0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability (Koo & Li, 2016; Portney & Watkins, 1993). For ***Experiment #1*** Spearman correlation coefficients were generated to investigate correlations between the E, VGA and physical IQ. The interpretation of the strength of the correlation (r) was considered weak for r=0.1-0.29, medium for r=0.30-0.49, and strong for r=0.50-1.0 strong (Cohen, 1988; Field, 2013). All of the data was expressed as percentage change values relative to the reference image. Inferential analyses between different tube potentials were undertaken using repeated measures ANOVA for parametric data, while the Friedman test was used for non- parametric data. For ***experiment #3,*** the differences between the two positions for all different acquisition parameters were expressed and the percentage differences were calculated. For normally distributed data, a paired sample t test was used for the comparison between the two positions, while the Wilcoxon test was used for non-parametric data. P values of <0.05 were considered to be statistically significant in both experiments.

6.4 Results

6.4.1 Impact of Body Part Thickness on AP Pelvis Radiographic IQ and E and ER (E*xperiment #1*)

6.4.1.1 Normality of the data

The Shapiro-Wilk test demonstrated that the data for the VGA (image quality) analysis conformed to an approximately normal distribution ($P \geq 0.05$). Data for SNR, CNR and E were found to have a non-parametric distribution ($P \leq 0.05$). For the visual image quality analyses, inter-observer agreement was measured using ICC in order to assess the variability between the six observers when evaluating image quality. Inter-observer variation is the term given to the degree of agreement amongst more than one observer for the same task/measurements (Cheong et al., 2010), with '1' being a perfect agreement. The mean of the ICC (95% CI) values for all six observers was 0.908 (0.882-0.902), implying a high level of agreement (Rosner, 2010).

6.4.1.2 The effect of fat thickness on SNR

The SNR data for both the iliac crest and the femoral regions will be presented separately, as the images show significant differences in the signal. Data is presented as a change graph relative to the reference image, which was acquired at 80kVp. **Figure 6-16** illustrates the SNR for the femoral regions. For all kVp values, SNR decreased as fat thickness increased ($r=-0.8$ to -0.9; $P<0.001$). 70 kVp had the highest SNR for the femur (98.3 at 0 cm and 36.8 at 15 cm). The lowest SNR was at 110 kVp, with 53.3 at 0 cm and 27.2 at 15 cm. The smallest decrease in SNR was at 70 kVp (-3% at 4 cm thickness). At 70 kVp, the SNR for the femur was more than that of the reference image, with between 5 to 9 cm additional fat. The decrease in SNR was almost 50% after adding 10 cm of fat.

For the iliac region (see **Figure 6-17**), across all kVp values, SNR decreased as fat thickness increased ($r=-0.5$ to -0.7; $P \leq 0.05$, except for at 70kVp [$P=0.07$]). 70kVp had the highest SNR (46.6 at 0 cm and 22.6 at 15 cm). The lowest SNR was at 110 kVp, 30.2 at 0 cm and 19.6 at 15 cm. The smallest decrease in SNR was at 70 kVp (-2% at 4cm thickness) across all thicknesses. The results showed that using a lower kVp (70, 75, and 80) would increase the SNR at the ilium for 5 to 10 cm of additional fat.

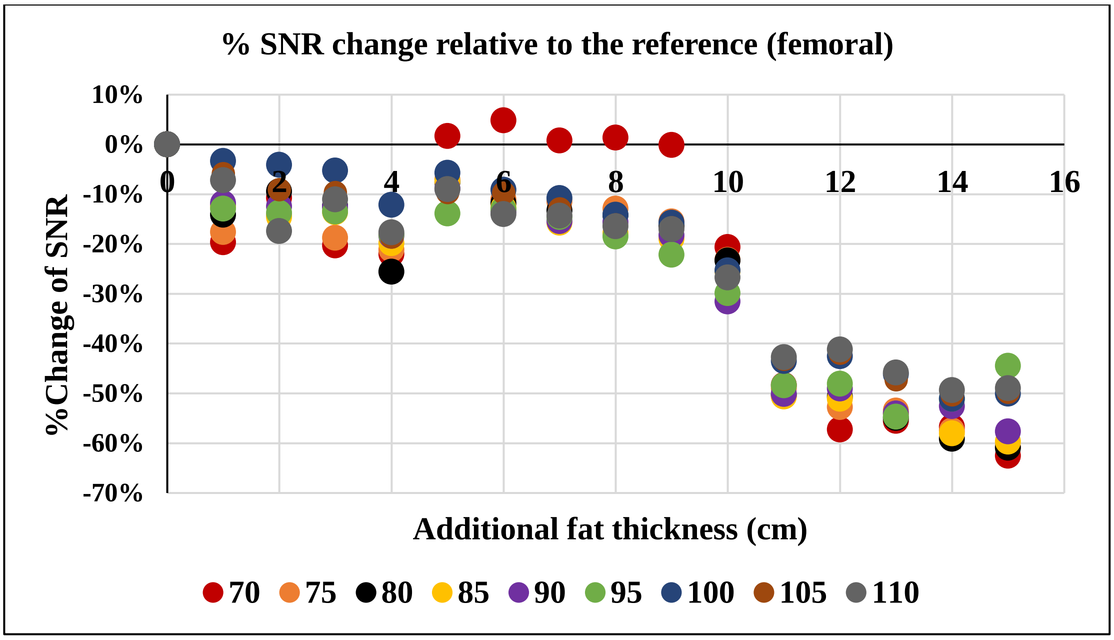


Figure 6-16: Percentage change of femoral SNR relative to the reference image (80 kVp) for all body part thicknesses. Values in the figure legend correspond to the respective tube potentials.

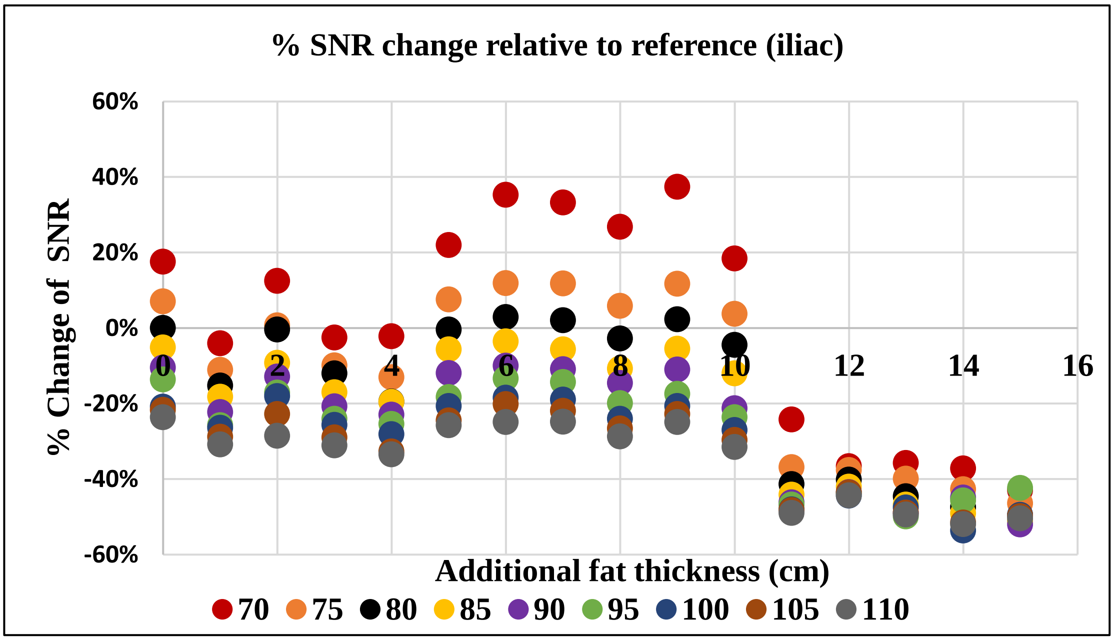


Figure 6-17: Percentage change of Ilium SNR relative to the reference image (80 kVp) for all body part thicknesses. Values in the figure legend correspond to the respective tube potentials.

6.4.1.3 Effect of fat thickness on CNR

A similar trend was found for the CNR for both the ilium and femoral regions. For the femoral regions, across all kVp values, CNR decreased as fat thickness increased (r=-0.6 to-0.8; P<0.05). 70 kVp had the highest CNR for the femoral regions (69.2 at 0 cm and 31.9 at

15 cm). The lowest CNR was at 110 kVp 38.6 at 0cm and 20.4 at 15 cm. The smallest decrease in CNR was at 70kVp (17%) at 11 cm thickness (see **Figure 6-18**). The same trend was found for the ilium region. As the fat thickness increased, the CNR decreased, across all kVp values (r=-0.5 to -0.7; P<0.05, except for 70kVp [P=0.06]). The highest CNR was 42.4 at 0 cm using 70kVp, and the lowest was 12.8 at 15 cm using 110kVp. The same trend demonstrated in the femoral region was noticed for the ilium, between 6 and 10cm.

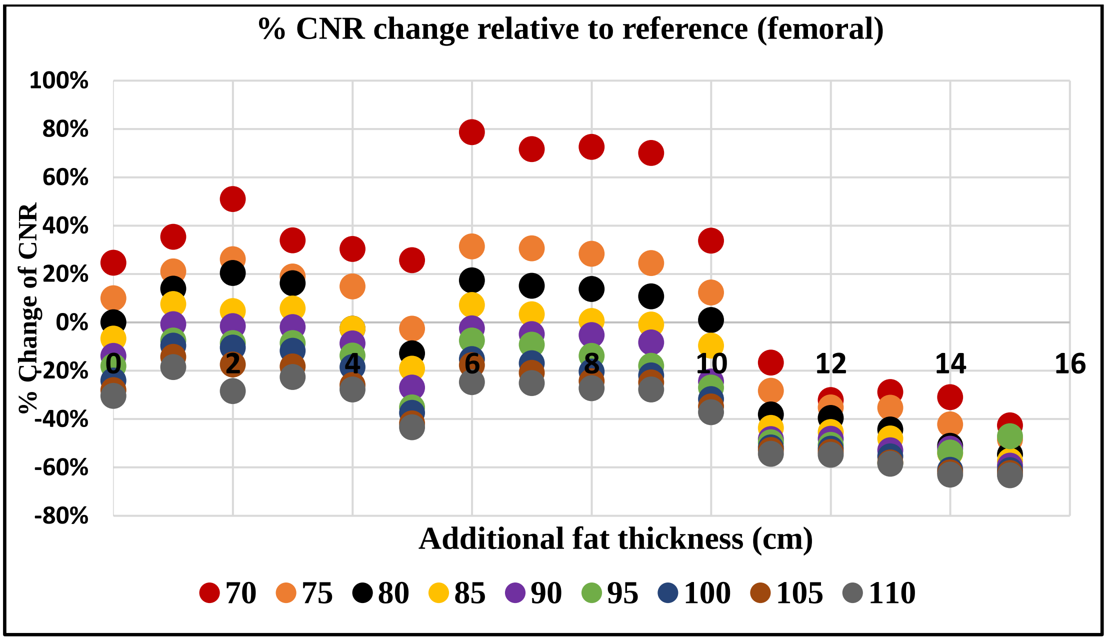


Figure 6-18: Percentage change of femoral CNR relative to the reference image (80 kVp) for all body part thicknesses. Values in the figure legend correspond to the respective tube potentials.

6.4.1.4 The effect of fat thickness on VGA

Relative VGA showed the highest IQ scores for acquisitions at 70 kVp and 75 kVp. These kVps had higher image quality scores than the reference image when using a phantom with between 1 to 8 cm of additional fat thickness. The highest score was at 70 kVp (57.5) and the lowest was at 110 kVp (15.0), for all thicknesses. After 10 cm of additional fat was added, the IQ score decreased for all tube potentials. It decreased dramatically, for high tube potentials (using 100, 105, 110 kVp). This decrease reached it is maximum (-68%) at 15 cm fat with 110 kVp (see **Figure 6-19**).

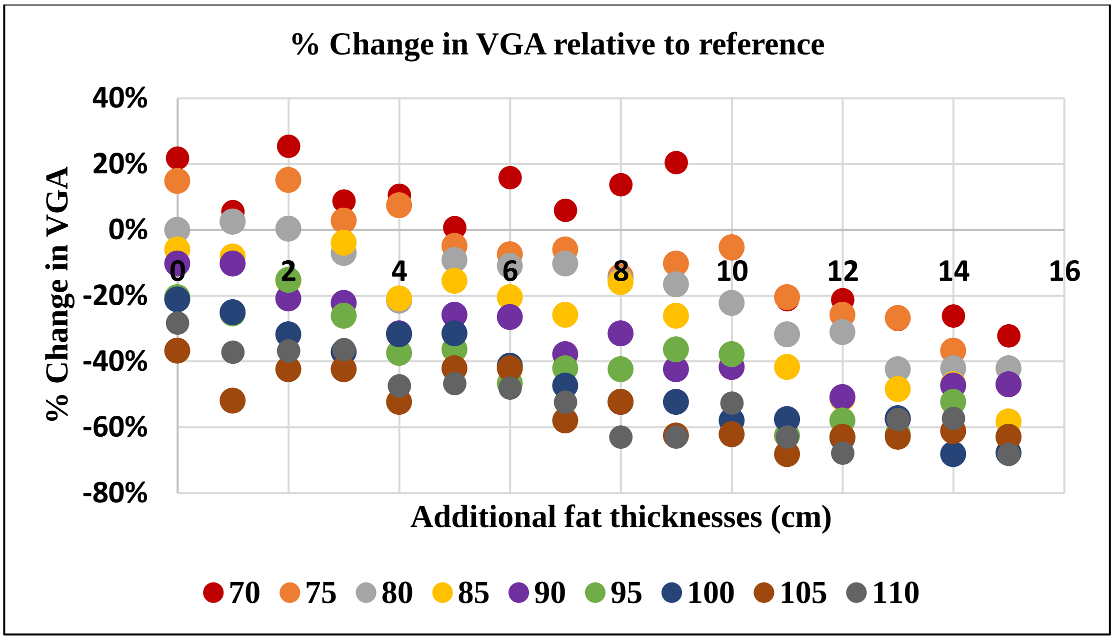


Figure 6-19: Percentage change of VGA relative to the reference image (80 kVp) for all body part thicknesses. Values in the figure legend correspond to the respective tube potentials.

6.4.1.5 The effect of fat thickness on effective dose (E)

E for the reference image (80 kVp) was 0.12 mSv. However, at the same kVp, with an additional 15 cm of fat, this increased by 856% to 1.13 mSv. At 110 kVp, E was the lowest for all fat thicknesses (0 cm fat, 0.06 mSv, vs 15 cm fat, 0.43 mSv [646% increase]). E was highest when using 70 kVp, with 0 cm fat, wherein it was 0.17 mSv. This had increased by 1371% when compared to the reference image (1.73 mSv for 15 cm of additional fat). Among all fat thicknesses there were significant differences in E across all tube potentials, from 70kVp to 110kVp ($P<0.05$). As fat thickness increases, E increased exponentially ($r=0.96$, $P<0.001$; see **Figure 6-20**).

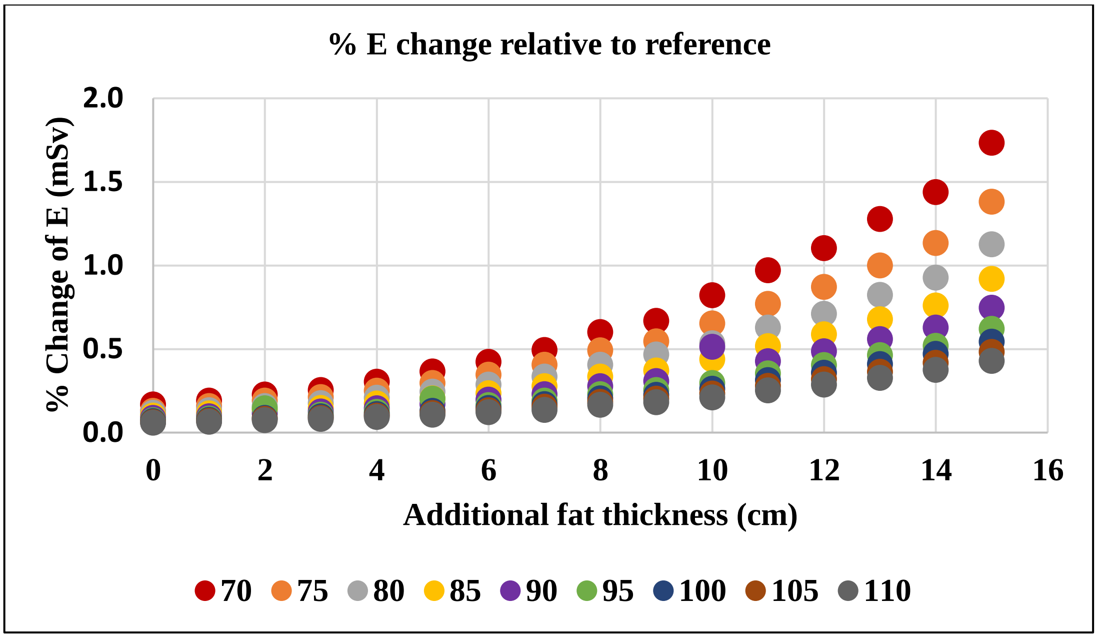


Figure 6-20: Percentage change of E relative to the reference image (80 kVp) for all body part thicknesses. Values in the figure legend correspond to the respective tube potentials (kVp).

6.4.1.6 The effect of fat thickness on effective risk

Results indicate a higher probability of cancer induction as body part thickness increases (relative risk (RR) 8.74). This was higher at lower tube potentials in both genders (r= 0.96, P<0.001). The impact on males was greater than that for females, RR 1.34 **(**see **Figure 6-21 and 6-22).**

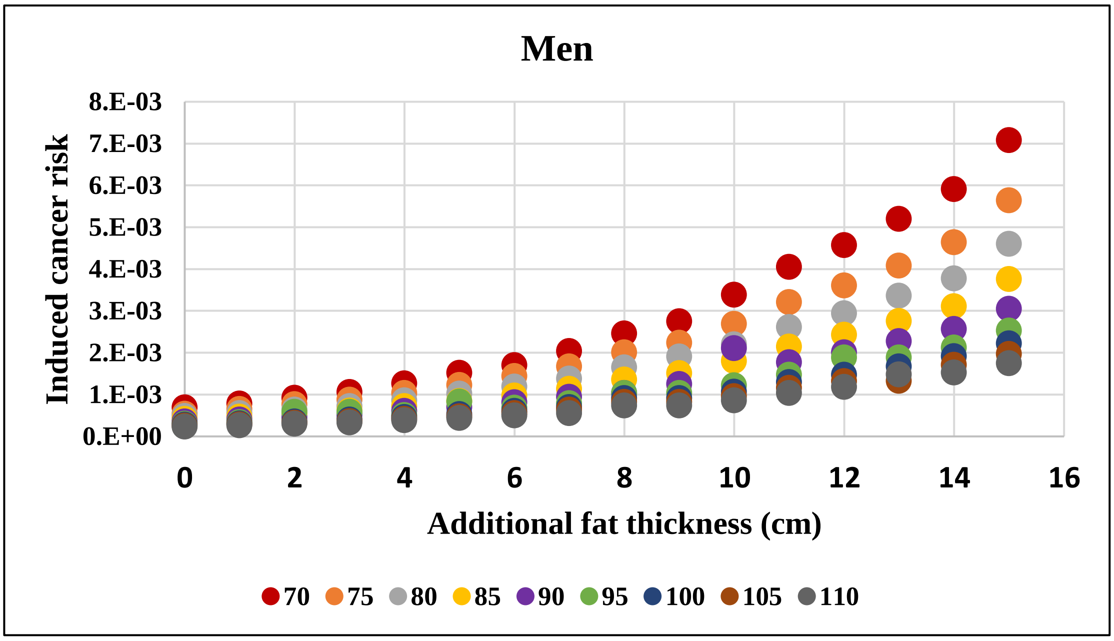


Figure 6-21: Induced cancer risk for males when thickness increases. Values in the figure legend correspond to the respective tube potential.

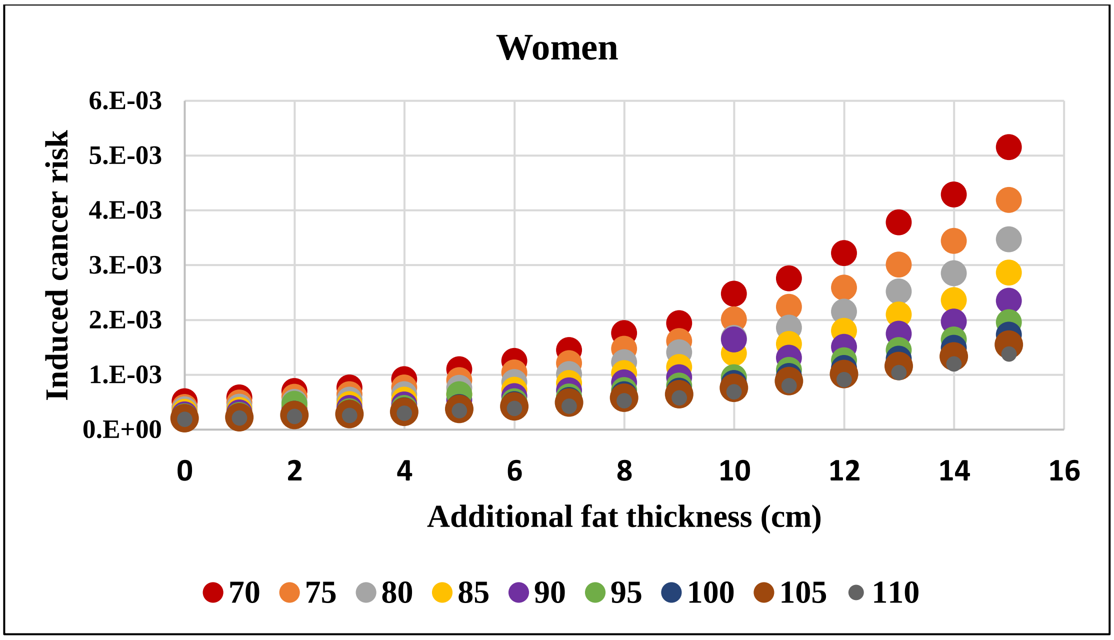


Figure 6-22: Induced cancer risk for women when thickness increases. Values in the figure legend correspond to the respective tube potential.

6.4.1.7 The relationship between E, IQ, SNR and CNR

In order to assess the correlation between E, VGA, SNR and CNR, a Spearman correlation coefficient was calculated to identify if a linear relationship existed between these continuous variables. There was a strong positive correlation between VGA, SNR/CNR and E. Results indicate that there was a strong correlation between physical (SNR & CNR) and visual IQ (VGA) scores. **Table 6-5** summarises the results of all correlations.

Table 6-5: The level of correlation between E and the IQ, SNR and CNR.

	E	VGA	SNR	CNR
E		0.98 (P<0.001)	0.99 (P<0.001)	0.99 (P<0.001)
VGA	0.98 (P<0.001)		0.97 (P<0.001)	0.98 (P<0.001)

6.4.2 Impact of changing body habitus on radiation dose and image quality for DR pelvis examinations (E*xperiment #3*)

Experimentation included the acquisition of 216 images using two modified pelvic anthropomorphic phantoms (average +1SD acquisitions n=108; average +2SD acquisitions n=108). Of the 108 acquisitions, there was an equal split between simulating imaging in both the supine and erect positions. Examination of the data for normality revealed that SNR, CNR and E values were mostly not normally distributed (Shapiro-Wilk test, P≤0.05), while VGA data were approximately normally distributed (Shapiro-Wilk test, P>0.05). Data are presented as means (SD) for normal distributed data and medians (IQR) for non-parametric data, while the choice of the statistical test was dependent on the normality of the data.

6.4.2.1 The effect of position (supine vs erect) and phantom size on SNR

The data was analysed to investigate the effect of phantom size and different positioning on SNR. The results are illustrated in **Table 6-6** and show that as the phantom size increases there is a statistically significant difference in SNR (P=0.001). However, this effect was not significant for the smaller phantom size (P=0.53). The SNR was shown to decrease when moving to an erect position by -5.6% for the +2SD phantom. Further analysis was performed to evaluate the effect of each acquisition parameter on SNR, for each phantom size (Appendix 15).

Table 6-6: Effect of position (supine and erect) and phantom size on SNR

	SNR, median (IQR)					
Phantom/ size	**Supine**	**Erect**	**%Difference***	**Max (S; E)**	**Min (S; E) ***	**P value**
+1SD	21.5 (2.7)	21.1 (6.1)	-1.8	23.9; 26.4	17.5; 15.5	0.53
+2SD	22.9 (1.2)	21.6 (7.9)	-5.6	26.8; 25.9	21.1; 14.3	0.001

* S: supine; E: Erect. * % differences relative to supine position.

The effect of increasing tube potential on SNR for both positions is illustrated in **Table 6-7**. There were significant differences for the supine position as the tube potential increased, however this was not the case for the erect position (P>0.05). The lowest differences between the two positions were found at 90 kVp, and these were not statistically significant.

Table 6-7: Effect of increasing tube potential on SNR for supine and erect positions.					
	SNR, median (IQR)				
kVp/ position	**80**	**90**	**100**	**% Diff.***	**P value**
Supine	22.7 (1.7)	22.08 (0.8)	22.05 (1.2)	-2.7 vs -2.8	0.009 vs 0.01
Erect	21.2 (7.2)	21.2 (8.3)	21.1 (5.9)	0 vs -0.47	0.8 vs 0.1
%Differences	-6.6	-3.9	-4.3		
P value	0.03	0.35	0.49		
* Percentage difference was calculated relative to 80kVp (representing clinical practice)					

The effect of increasing SID was significant in the supine position at 145 cm, while the differences in SNR were not significant in erect position as the SID increased (**Table 6-8)**. The smallest differences between the two positions were found at 145 cm SID, and were found not to be significant.

Table 6-8: Effect of increasing SID on SNR for supine and erect positions.					
	SNR, median (IQR)				
SID/position	**115**	**130**	**145**	**% Diff.***	**P value**
Supine	22.8 (1.02)	23.2 (2.4)	20.8 (3.7)	1.7 vs -8.8	0.6 vs 0.01
Erect	22.06 (6.8)	21.6 (4.4)	20.2 (9.7)	-2.08 vs -8.4	0.6 vs 0.5
% Differences	-3.4	-7.4	-2.9		
P value	0.320	0.001	0.350		
* Percentage difference was calculated relative to 115cm SID.					

Using different AEC configurations was not found to generate statistically significant differences in SNR when using the central chamber compared to using both outer chambers. This was the case for both supine and erect positions. Moreover, there was an increase in SNR when using the central chamber in both supine and erect positions (3.1%; 2.3% respectively) - see **Table 6-9**. The smallest differences between the two positions were found when using both outer chambers. However, the differences between the two positions for all different AEC configurations were not significant.

Table 6-9: Effect of different AEC combinations on SNR for supine and erect positions					
	SNR, median (IQR)				
AEC	**ALL**	**BOTH**	**CENTRAL**	**% Diff.***	**P value**
Supine	22.02 (1.2)	22.1 (1.3)	22.7 (1.6)	0.4 vs 3.1	<0.001 vs 0.5
Erect	21.01 (7.3)	21.6 (7.5)	22.1 (5.2)	-2.7 vs 2.3	<0.001 vs 0.3
%Differences	-4.6	-2.3	-2.6		
P value	0.18	0.08	0.51		
* Percentage difference was calculated relative to both outer AEC chambers (representing clinical practice).					

There were statistically significant differences in SNR for both positions, with and without additional filtration (**Table 6-10**). The smallest differences between the two positions occurred when adding additional filtration, however this was found to be not significant. The differences between the positions were significant when not adding filtration.

Table 6-10: Effect of adding additional filtration on SNR for supine and erect positions.				
	SNR, median (IQR)			
Filtration	**YES**	**NO**	**% Diff.***	**P value**
Supine	22.1 (1.0)	22.4 (1.5)	-1.3	0.04
Erect	21.5 (7.2)	21.1 (7.1)	1.9	0.03
% Differences	-2.7	-5.8		
P value	0.31	0.04		
* Percentage difference was calculated relative to no additional filter.				

6.4.2.2 The effect of position (supine vs erect) and phantom size on CNR

There were statistically significant differences in CNR for both phantoms when moving from supine to erect (P<0.001; **Table 6-11**). CNR decreased when moving from supine to erect positions. For the smaller phantom the decrease was -43.5% As the size increased (+2SD phantom), this effect was lower (-20.1%). Further analysis was performed to evaluate the effect of each acquisition parameter on CNR for each phantom size separately (Appendix 16).

Table 6-11: Effect of position and phantom size on CNR						
	CNR, median (IQR)					
Phantom	**Supine**	**Erect**	**% Difference***	**Max (S; E)**	**Min (S; E)**	**P value**
+1SD	11.3 (6.8)	6.6 (3.9)	-43.5	14.9;10.2	6.8;3.9	<0.001
+2SD	8.01 (2.5)	6.4 (2.2)	-20.1	11.3; 9.4	2.5; 2.2	<0.001
S: Supine, E: Erect. * % differences relative to supine position.						

Table 6-12 illustrates the effect of increasing tube potential on CNR for both positions. As the kVp increased, the CNR decreased, and this decrease was statistically significant for erect versus supine (P<0.001). The smallest differences between the erect and supine positions were found at 90 kVp.

Table 6-12: Effect of increasing tube potential on CNR for supine and erect positions.					
	CNR, median (IQR)				
kVp/ Position	**80**	**90**	**100**	**% Diff.***	**P value**
Supine	10.9 (4.5)	9.7 (4.4)	8.8 (4.3)	-25.6vs -19.2	<0.001
Erect	7.5 (2.8)	6.3 (3.4)	5.7 (3.5)	-23.8 vs -31.7	<0.001
% Differences	-95	-35	-92		
P value	<0.001	<0.001	<0.001		
*Percentage difference was calculated relative to 80kVp (representing clinical practice)					

The results show that there is a statistically significant difference in CNR as the SID increases to 145 cm (**Table 6-13**) between erect and supine positions (P<0.05). As the distance increased, the CNR also decreased in both positions. The differences were not significant when increasing the distance from 115 cm to 145 cm (P=0.2) in the erect position, however. The smallest differences between the positions were found at 145 cm, and these were significant.

Table 6-13: Effect of increasing SID on CNR for supine and erect positions.					
	CNR, median (IQR)				
SID/Position	**115**	**130**	**145**	**% Diff.***	**P value**
Supine	11.04 (3.4)	11.02 (3.9)	7.3 (1.9)	-0.2vs -33.9	0.9 vs 0.001
Erect	7.04 (2.8)	6.1 (1.9)	6.3 (5.7)	-13.4 vs -10.5	0.001 vs 0.2
% Differences	-36.2	-44.6	-13.7		
P value	<0.001	<0.001	0.030		
* Percentage difference was calculated relative to 115cm SID.					

The effect on CNR when using different AEC configurations is demonstrated in **Table 6-14**. The results show that using the central AEC chamber had the highest CNR in both positions. The differences between the two positions were significant for all AEC combinations (P≤0.001). The smallest differences between the two positions were found when using central AEC.

Table 6-14: Effect of different AEC combination on CNR for supine and erect positions.					
	CNR, median (IQR)				
AEC	**ALL**	**BOTH**	**CENTRAL**	**% Diff.***	**P value**
Supine	9.7 (4.2)	9.7 (4.0)	9.9 (3.8)	0vs -90	0.6 vs 0.001
Erect	6.4 (3.2)	6.3 (3.6)	6.8 (2.5)	1.5vs 7.9	0.07 vs 0.001
% Differences	-34	-35	-31		
P value	<0.001	<0.001	<0.001		
*Percentage difference was calculated relative to both outer AEC chambers (representing clinical practice).					

The effect of using additional filtration on CNR for erect and supine was illustrated in **Table 6-15**. CNR decreased with additional filtration, and this was greater in the supine position. The differences between the two positions were smallest when adding filtration, and these were significant (P<0.001).

Table 6-15: Effect of adding additional filtration on CNR for supine and erect positions.				
	CNR, median (IQR)			
Filtration	**YES**	**NO**	**% Diff.***	**P value**
Supine	9.6 (1.8)	9.9 (1.3)	-7.5	<0.001
Erect	6.3 (3.4)	6.6 (3.5)	-4	0.002
% Differences	-34	-94		
P Value	<0.001	<0.001		

* Percentage difference was calculated relative to no additional filter.

6.4.2.3 The effect of position on image quality for different anatomical locations within the pelvis

Further analysis of data was performed to assess if the differences between erect and supine generated differences in image quality at specific locations within the pelvis. Data was analysed for the iliac crest, femoral regions and sacral bone. **Table 6-16 and Table 6-17** illustrate the differences in SNR and CNR between these different pelvic regions for erect and supine positioning. Differences were not statistically significant for the iliac crest for SNR (P=0.2), however they were significant for the femoral head and sacrum regions (P< 0.05). For CNR, there were statistically significant differences between the two positions for all pelvis locations (P<0.001). The sacral region was found to be the most affected anatomical location in terms of SNR and CNR within the pelvis when repositioning from supine to erect.

Table 6-16: Differences in SNR, for specific anatomical locations, between erect and supine positions.						
	SNR, median (IQR)					
	Supine	**Erect**	**% Diff.***	**Max (S; E)**	**Min (S; E)**	**P value**
Iliac crest	23.7 (3.6)	23.9 (4.2)	0.8	29.8;27.4	17.1;17.5	0.200
Femoral head	23.2 (1.6)	22.8 (6.8)	-1.7	26.8;29.1	21.1;13	0.001
Sacrum	19.6 (1.9)	18.9 (5.4)	-3.6	22.9;26.4	17.5;13.3	0.007

S: Supine; E: Erect. * % differences between erect and supine.

Table 6-17: Differences in CNR, for specific anatomical locations, between erect and supine positions.						
	CNR, median (IQR)					
	Supine	**Erect**	**% Diff.***	**Max (S; E)**	**Min (S; E)**	**P value**
Iliac crest	11.9 (4.4)	8.4 (1.8)	-29	14.9;11.4	6.5;6.6	<0.001
Femoral head	11.6 (5.2)	6.9 (3.8)	-40.5	15.4;12.5	5.6;1.1	<0.001
Sacrum	7.4 (3.4)	3.1(2.1)	-58	11;10.2	4.1;0.02	<0.001
S: Supine; E: Erect. *% differences relative to supine position						

6.4.2.4 The effect of position (supine vs erect) and phantom size on VGA

The differences in VGA scores, between the erect and supine projections, and between the phantom sizes, are demonstrated in **Table 6-18**. The differences between positions increased as the phantom size increased (-16), and these were statistically significant (P<0.001). Differences were not statistically significant between the positions for the +1SD phantom (P=0.05). Further analysis was performed to evaluate the effect of each acquisition parameter on VGA for each phantom size separately (Appendix 17).

Table 6-18: Effect of position and phantom size on VGA image quality						
	VGA, mean (SD)					
Phantom	**Supine**	**Erect**	**% Difference**	**Max (S; E)**	**Min (S; E)**	**P value**
+1SD	43.7 (12)	40.7 (7.4)	-6.8	66.8; 55	18.8; 26.2	0.05
+2SD	37.2 (8.8)	31.2 (9.4)	-16	57.6; 47	22.2; 17	<0.001
S: Supine, E: Erect. * % differences relative to supine position.						

The effect of increasing tube potential on VGA for supine and erect positions was explored in **Table 6-19**. As the tube potential increased from 80 to 100 kVp, the differences increased. This was significant (P<0.001) for the same position. The smallest differences between erect and supine positions were found at 90 kVp, and these were not statistically significant. In contrast, the differences between erect and supine were significant when using 80 kVp.

Table 6-19: Effect of increasing tube potential on VGA scores for supine and erect positions					
	VGA, mean (SD)				
kVp/ Position	**80**	**90**	**100**	**% Diff.***	**P value**
Supine	51.2 (7.5)	38.2 (7.7)	35.0 (7.4)	-25.4 vs -37.6	<0.001
Erect	40.2 (9.9)	35.5 (9.2)	32.2 (8.4)	-11.7 vs -19.9	<0.001
% Differences	-21.5	-7	-8		
P value	<0.001	0.06	0.8		
*Percentage difference was calculated relative to 80kVp (representing clinical practice)					

Table 6-20 illustrates the effect of increasing SID on VGA for erect and supine positions. As SID increased, the differences also increased, whereas the overall VGA decreased. These differences were not statistically significant for the supine position (P>0.05). In contrast, for the erect position when increasing the distance from 115 to 145 cm, the differences in VGA were statistically significant (P=0.04). At 130 cm, the smallest differences in the VQA between the erect and supine were found which were statistically significant.

Table 6-20: Effect of increasing SID on VGA for supine and erect positions.					
	VGA, mean (SD)				
SID/Position	**115**	**130**	**145**	**% Diff.***	**P value**
Supine	41.7 (9.8)	40.7 (8.9)	38.9 (13.7)	-2.4 vs -6.7	0.3 vs 0.2
Erect	37.1 (6.8)	38.4 (6.8)	32.5 (13.3)	3.5 vs -12.4	0.3 vs 0.04
% Differences	-11	-5	-16		
P value	<0.001	0.04	0.01		
* Percentage difference was calculated relative to 115cm SID.					

The effect of using different AEC combinations on VGA for supine and erect positions was presented in (**Table 6-21**). The effect was not statistically significant when using all AEC combinations for both supine and erect positions (P=0.3, 0.5, respectively). The differences between erect and supine were significant for all different AEC configurations, and the smallest differences were found when using central AEC.

Table 6-21: Effect of different AEC combinations on VGA scores for supine and erect positions.					
	VGA, mean (SD)				
AEC	**ALL**	**BOTH**	**CENTRAL**	**% Diff.***	**P value**
Supine	39.5 (10.6)	38.6 (10.9)	43.2 (11.2)	2.3 vs 11.9	0.3 vs <0.001
Erect	34.9 (8.4)	33.7 (8.8)	39.4 (11.1)	3.5 vs 16.9	0.5 vs <0.001
% Differences	-12	-12	-9		
P value	0.005	0.010	0.020		
*Percentage difference was calculated relative to both outer AEC chambers (representing clinical practice).					

Table 6-22 shows the effect of adding additional filtration on the VGA scores for both positions. The differences were found not to be significant in both the supine and erect positions (P=0.5; 0.4, respectively). The differences were found to be significant between erect and supine positions either when adding or not adding filtration. The smallest differences between the two positions were found when adding additional filter material.

Table 6-22: Effect of adding filtration on VGA for supine and erect positions.				
	VGA, mean (SD)			
Filtration	**YES**	**NO**	**% Diff.***	**P value**
Supine	39.3 (11.1)	41.6 (10.8)	-5.5	0.50
Erect	35.7 (9.9)	36.3 (9.6)	-1.6	0.40
% Differences	-9	-13		
P value	0.02	<0.001		
* Percentage difference was calculated relative to no additional filter (representing clinical practice).				

6.4.2.5 The effect of position (supine vs erect) and phantom size on E

Comparisons (median [IQR]) between supine (0.136 [0.072] mSv) and erect (0.364 [0.347]) positions demonstrated a statistically significant difference (P<0.001) in E. Sub-analysis by phantom size also revealed statistically significant differences (range of 53.4 to 192%; P<0.001) in E between the positions **Table 6-23**. The differences were more obvious as the size of the phantom increased. A 192% increase in E was seen when repositioning from supine to erect for the larger phantom. Further analysis was performed to evaluate the effect of each acquisition parameters on E for each phantom size (Appendix 18).

Table 6-23: Effect of position and phantom size on E						
	E(mSv), median (IQR)					
Phantom	**Supine**	**Erect**	**% Diff.***	**Max (S; E)**	**Min (S; E)**	**P value**
1SD	0.118 (0.06)	0.181 (0.19)	53.4	0.36;0.78	0.03;0.97	<0.001
2SD	0.165 (0.09)	0.482 (0.23)	192	0.67;0.97	0.9;0.21	<0.001
S: Supine, E: Erect. * % differences relative to supine position.						

Table 6-24 demonstrates the data of the effect of increasing tube potential on E for erect and supine positions. There were statistically significant differences when increasing the kVp from 80 to 100 (P<0.001), for both supine and erect positions. Increasing kVp decreased the radiation dose. Erect positioning increased the radiation dose for all of the used kVps, and the differences between the two positions were significant. The lowest radiation dose was found at 100 kVp for the erect position.

Table 6-24: Effect of increasing tube potential on E for supine and erect positions.					
	E(mSv), median (IQR)				
kVp/ Position	**80**	**90**	**100**	**% Diff.***	**P value**
Supine	0.176 (0.049)	0.129 (0.035)	0.100 (0.022)	-27vs -43	<0.001
Erect	0.514 (0.358)	0.384 (0.305)	0.299 (0.258)	-25vs -42	<0.001
% Differences	192	197	199		
P value	<0.001	<0.001	<0.001		
*Percentage difference was calculated relative to 80kVp (representing clinical practice).					

The effect of increasing SID on E is illustrated in **Table 6-25,** for supine and erect positions. Increasing the SID from 115 cm to 145 cm increased the radiation dose in both supine and erect positions and this was statistically significant (p<0.001). The differences between erect and supine position were found to be significant among all SIDs used, and the lowest differences between the two positions was found at 115 cm.

Table 6-25: Effect of increasing SID on E for supine and erect positions.					
	E(mSv), median (IQR)				
SID/Position	**115**	**130**	**145**	**% Diff.***	**P value**
Supine	0.123 (0.058)	0.127 (0.061)	0.172 (0.108)	3vs 21	0.043 vs 0.001
Erect	0.294 (0.339)	0.321 (0.386)	0.417 (0.272)	9vs 42	0.307 vs 0.010
% Differences	139	152	142		
P value	<0.001	<0.001	<0.001		
* Percentage difference was calculated relative to 115cm SID.					

Table 6-26 demonstrates the effect of AEC configurations on E. The differences were significant for erect and supine positions (P<0.05). Using the central AEC chamber had the highest radiation dose amongst all AEC combinations in both erect and supine position, while using both outer chambers had the lowest dose in both positions. The differences between the two positions were found to be significant for all AEC configurations (P<0.001).

Table 6-26: Effect of different AEC combinations on E for supine and erect positions.					
	E(mSv), median (IQR)				
AEC	**ALL**	**BOTH**	**CENTRAL**	**% Diff.***	**P value**
Supine	0.133 (0.072)	0.125 (0.064)	0.157 (0.083)	6.4vs 26	<0.001
Erect	0.347 (0.304)	0.343 (0.365)	0.428 (0.326)	1vs 25	0.004 vs 0.035
% Differences	160	174	172		
P value	<0.001	<0.001	<0.001		
*Percentage difference was calculated relative to both outer AEC chambers (representing clinical practice).					

The effect of adding additional filtration on the radiation dose was demonstrated in **Table 6-27.** The results show that by adding extra filtration the radiation dose decreased in erect and supine positions. The differences between erect and supine positions were found to be significant both when adding or not adding filtration (P<0.001). The lowest dose was found when applying extra filtration within the erect position.

Table 6-27: Effect of adding filtration on E for supine and erect positions.

	E(mSv), median (IQR)			
Filtration	**YES**	**NO**	**% Diff.**	**P value**
Supine	0.131 (0.066)	0.149 (0.074)	-12	<0.001
Erect	0.336 (0.337)	0.378 (0.339)	-11	<0.001
% Differences	156	153		
P value	<0.001	<0.001		

* Percentage difference was calculated relative to no additional filter (representing clinical practice).

6.4.2.6 Suggested acquisition parameters for erect pelvis X-ray image

Table 6-28 summaries the smallest differences between erect and supine in terms of image quality assessment (physical and visual), as well as the lower radiation dose for erect positions among all acquisition parameters. The smallest difference between the two positions in all image quality parameters was found when using 90 kVp, while the lowest dose was at 100 kVp. A central AEC chamber generated the lower differences between the erect and supine positions, whereas both outer AEC provided the lower radiation dose. A large SID (145 and 130 cm) provided the smallest differences in image quality between the positions and 115 cm displayed the lowest radiation dose. Finally, using additional filtration produced the smallest differences in image quality and a lower radiation dose between the two positions.

Table 6-28: An illustration of the smallest differences between erect and supine positions in image quality and the lower radiation doses for different acquisition parameters.

Metric/parameters	SNR	CNR	VGA	E
kVp	90	90	90	100
AEC	Central	Central	Central	Both outer
SID (cm)	145	145	130	115
Add filter	Yes	Yes	Yes	Yes

6.5 Discussion

6.5.1 The Impact of Body Part Thickness on AP Pelvis Radiographic Image Quality and Effective Dose (*Phantom* E*xperiment #1*)

6.5.1.1 The effect of fat thickness on image quality (physical and visual)

When reviewing the physical image quality metrics (SNR & CNR) at 70 and 75 kVp, the SNR and CNR values were greater (~10%) than the reference image across all additional fat thicknesses (**Figure 6-16-18)**. There were a number of further trends noted when changing body part thickness regarding the SNR and CNR. For 0 to 4 cm of additional fat, across all tube potentials, there was a slight reduction in SNR and CNR. Between 4 and 10 cm of additional fat, there was an increase in IQ (relative to the reference image) for lower kVps, and then there was a marked decrease in the physical IQ metrics between 10 and 15 cm of additional fat. Minor increases in additional fat could have been insignificant in their ability to cause changes in SNR and CNR up to 4 cm. After 4 cm of added fat thickness, the AEC chambers may be better able to compensate for the increase in body part thicknesses. This could also be supported by the post-processing ability of the DR system, which may also be able to compensate for an increase in exposure resulting in enhanced IQ. After 10 cm of additional fat, there was a decrease in the SNR and CNR. This may be due to an increase in the quantity of scattered radiation reaching the image receptor. It is also possible that the image receptor and electronic post-processing are unable to effectively compensate for increases in scattered radiation from the primary beam caused 10 cm of additional fat, and this will have a negative effect on IQ. This trend was not clearly evidenced on the visual IQ graph and this may have resulted from physical measures of IQ (SNR & CNR) being more sensitive to subtle changes in IQ.

Within the literature, methods have been described to overcome the poor penetration of the X-ray photons. One such method is by increasing the kVp, however this was seen to have a resultant negative effect on IQ as a result of the increased noise (Buckley et al., 2009). The increase in scattered radiation when using high tube potentials will also have a negative effect on the overall IQ (Carucci, 2013). Furthermore, increasing the body part thickness increases the attenuation of the primary beam, leading to a decrease in IQ as less photons reach the image receptor (Egbe, Heaton, & Sharp, 2010; Yanch et al., 2009).

Findings from this experiment were similar to Ullman et al., who found that SNR increased when using low tube potentials, however they only investigated patients of 'average' size and their study was distinctly different (Ullman et al., 2004). Using lower kVps is recommended for several reasons: 1) DR detectors have high photon absorption levels, which are increased at low tube potentials; 2) the detector quantum efficiency (DQE) increases as the tube voltage is decreased; 3) the k edge for DR is lower than that of FS, which means an increase in image quality is seen for low tube voltages (Tingberg & Sjostrom, 2003). Research has indicated that the sensitivity of the phosphor plate is lower when using high tube potentials. Fetterley and Hangiandreou showed that the DQE of CR decreased when increasing the tube voltage (70 to 120 kVp) (Fetterly & Hangiandreou, 2001). A further explanation for decreases in IQ when the tube potential increases is due to the higher mean energy of the X-ray photons. At higher energy levels the photon interaction moves away from predominantly the photoelectric effect to an increase in the proportion of interactions involving Compton scattering (Egbe et al., 2010).

Figure 6-19 compares the visual grading score results with those from the reference image. The results from visual IQ scores decreased by more than 60% as body part thickness increased when using high tube potentials. This decrease was less than 20% when using 70 and 75 kVp, even for 15 cm of additional fat. For all kVps, visual IQ was highest at 70 kVp (57.5) for all body part thicknesses. This does not reflect typical clinical practice wherein practitioners commonly increase the tube potential as the thickness increases. Using 70 kVp provided a superior level of IQ when compared to the reference image when the fat thickness increased up to 10 cm. At high tube potentials (105 & 110 kVps), there was approximately a 68% reduction in IQ relative to the reference image. Reductions in IQ at higher kVps could be expected due to the anticipated reductions in contrast and increases in scattered radiation. This result is in line with the conclusion from the study by Egbe et al (2010), wherein they studied the impact of decreasing the dose on the lung lesion detectability by using high kVps. They found that the perception of detectability reduced when decreasing the dose. This is due to an increase in noise and a decrease in SNR. Importantly, the results from this experiment raise questions regarding the justification for increasing the tube potential as body part thickness increases.

6.5.1.2 The effect of fat thickness on effective dose and effective risk

Figure 6-20 highlights the effect of increasing fat thicknesses on radiation dose for pelvic X-ray images. The results show that as the fat thickness increased the dose also increased. Effective dose increased by 856% at 15 cm additional fat. There were significant differences in E across all tube potentials, from 70 kVp to 110 kVp (P<0.05). The lower dose was found at 110 kVp for all fat thicknesses. This is due to an increase in penetration as tube potential increases, which in turn leads to a decrease in the absorption by the body. 70 and 75 kVp had the highest radiation dose. This is explained by a common rule in radiography which indicates that when kVp decreases, the mAs should be increased to compensate for the low radiation output yield. These results indicate the need of further optimisation studies for larger people wherein they are being imaged for pelvic X-ray images. Moreover, the routine clinical practice is not applicable for larger people and modifications to acquisition parameters should be conducted by radiographers.

To the best of the author of this thesis' knowledge, this is the first study to investigate the effect of different fat thicknesses on radiation dose and image quality during pelvic radiography. This makes comparison with other studies difficult. However, there is still opportunity to compare the trends with other body parts and other imaging modalities. Previous studies were undertaken to evaluate the impact of patient size on IQ and radiation dose for other parts of the body. Two studies by Sebastian et al., in 2007 and 2008, explored the effect of patient size on IQ and patient radiation dose using CT (Schindera et al., 2007, 2008). Within these studies, a whole-body anthropomorphic phantom was modified by adding one or more circumferential layers of fat rings (8 cm). Abdominal CT scans were performed using a range of different protocols. The results showed an increase in radiation dose as the size of the patient increased and that maintaining the image quality at constant levels required higher radiation doses (Schindera et al., 2008). Another study was conducted to identify the impact of imaging overweight and obese people on patient dose during radiographic examinations (Yanch et al., 2009). Chest and abdomen radiographic examinations were evaluated, and five different body shapes were simulated by adding fat equivalent material onto a whole-body anthropomorphic phantom. The results demonstrated an increased radiation dose for patients who have more body fat. Adding 25 cm of fat around the abdomen increased the effective dose by 40 times more than that received by a normal adult during abdominal radiography. Results from this thesis show that adding 15 cm of fat increased the radiation dose by 156% at 70 kVp. However, when using 110 kVp the percentage dose difference between 0 cm and 15 cm was lower (37%). **Figure 6-21 and Figure 6-22** highlight the potential stochastic effects, such as radiation-induced cancer for males and females. The results indicate that there is a higher probability of induced cancer with increased fat, and that this is higher at low kVp for both genders. Also, the impact on males is greater than on females.

Strong correlations were found between physical and visual image quality. This agreement is interesting for evaluating and predicting imaging system performance, and suggests that clinical images can be described by using physical measurements. Also, strong correlation was found between image quality (physical and visual) and radiation dose. The correlation results in this study are in line with previous studies in that they found a strong correlation between physical and visual image quality (Sandborg et al., 2006). Sandborg and colleges (2006) compared the physical measures (SNR) and clinical assessment (VGA) of image quality for AP pelvis and PA chest radiography. They found a positive correlation between the clinical and physical assessments (pelvis: r=0.94; chest: r=0.91). A strong correlation between clinical evaluation of image quality and physical measurements (e.g. CNR) has been found in many previous studies (De Crop et al., 2012; Moore, Wood, Beavis, & Saunderson, 2013).

The results from the radiographer's binary decision task, in which they evaluated the images from a general clinical practice perspective, indicated that all experimental images were acceptable, and that a clinical decision can be made regardless of the physical and visual measurements. In this experiment, the fat was positioned in order for it to have a consistent thickness level across the phantom. In clinical practice, differences may occur within specific anatomical regions, degrading the image. The results would indicate that even images obtained using high tube potentials were sufficient. Since the images were considered clinically acceptable across a wide range of acquisition factors, taking dose into consideration means that using high tube potentials when imaging obese patients for pelvic radiography may be the optimum choice. This is because it appears to promote the ALARP principle, however needs further research.

Acceptable IQ was evident across a wide range of acquisition factors, and the optimum IQ was obtained at 70 and 75 kVp for all fat thicknesses. This is at odds with professional practice wherein there is a tendency for radiographers to increase kVp as patient thickness increases. If radiation dose is considered a primary factor, the results from this experiment suggest that high kVp could be used for radiography of the pelvis on those with increased body part thickness. Clinical indications for pelvic radiography should be carefully reviewed by radiographers prior to examination so that the optimum tube potential for the examination can be identified. If the clinical question requires a high level of detail, e.g. primary pathology detection, then images may be obtained at lower tube potentials. However, for follow-ups, a higher tube potential could reduce the dose, but with a slight reduction in image quality. This reduction would still be diagnostically acceptable.

6.5.2 The Impact of changing body habitus on radiation dose and image quality for DR pelvic examinations (*Phantom* E*xperiment #3*)

The main aim of this experiment would have been achieved if the acquisition parameters for supine pelvis radiography were applicable for erect imaging, and provided acquisition parameters for erect pelvis radiography in order to be used in *phase three* of this thesis. Also, the aim is achieved if differences are identified between the two positions in terms of image quality and radiation dose. This section includes detailed discussions of the research findings. The discussion has the same structure as the results chapter. It discusses the results of changing the body habitus on image quality and radiation dose. According to this experiment's results and discussion, the recommendations will be made for the acquisition parameters in phase three in this thesis (**Chapter 7**). It should be noted that no previous research has considered the effect of repositioning from supine to erect on image quality and radiation dose in either phantom or patient studies. This makes the comparison between this thesis' findings and previous findings difficult. However, a comparison will be made in terms of the trends which evaluate the effect of different acquisition parameters on image quality and radiation dose in the literature. If any comparison with previous research regarding pelvic radiography is found, then this will be considered for the supine position and for 'average' sized patients, as this position is the standard in clinical practice. The smallest differences between the erect and supine positions in image quality and lower radiation dose will be considered as important indications for choosing the optimum parameters for erect positioning in phase three. This decision will be made depending on the considerations of using supine pelvic radiographs as the basic position in clinical practice. Therefore, erect positions should not be differed from it.

6.5.2.1 The effect of position (supine vs erect) and phantom size on SNR

SNR is a ratio and measures the relationship between the image signal and noise. The results demonstrate that there were differences between the supine and erect position in terms of SNR. The differences were greater as the phantom size increased, while there were no significant differences between the two positions for the +1SD size phantom. The erect position decreased the SNR by 5.6% for the +2SD phantom (P=0.001). These results could be explained by the fact that increasing the anterior fat thickness in erect position reduced the number of photons that reached the image receptor, which in turn reduced the signal (**Table 6-6**). Further analyses of the differences in SNR between the erect and supine position for different acquisition parameters and different phantom size were conducted. The results illustrate that the erect position decreased the SNR for all kVp values used in this study. The maximum difference between the two positions was -9 for the +1SD phantom at 80 kVp. As the phantom size increased, the differences between the two positions increased along with rising kVp. Significant differences were found at 80 kVp, while the differences were not significant for 90 and 100 kVp. This suggests that 80 kVp, currently used for the supine position, may not applicable for erect radiography. Furthermore, when imaging people for erect radiography a high kVp should be used. The smallest differences between the supine and erect were found at 90 kVp.

When assessing the data for both phantoms and comparing the differences between the two positions for different tube potentials, it was observed that the SNR decreased as kVp increased for both positions. However, this effect was more notable in the erect position. This increase was not significant (**Table 6-7**). The observation that the SNR decreased as the kVp increased is in line with the general understanding that using a high kVp reduces image contrast. This reduction in SNR is a result of increasing the radiation energy (increasing the tube potential). The relative proportion of scatter radiation leaving the patient increases because of the higher energy compared to the scatter radiation produced at lower tube potentials. The scattered photons can more easily leave the patient and reach the image detector, thus reducing the SNR (McEntee, Brennan, & Connor, 2004). This trend was found in chest radiography when using CR (Chotas, Floyd, Dobbins, & Ravin, 1993; Launders, Cowen, Bury, & Hawkridge, 2001; Oda, Tabata, & Nakano, 1996). Also, this trend was found in previous research performed by Brindhaban et al. (2005) wherein they studied the effect of kVp on SNR using pelvic and lumbar phantoms. In their study, using CR, they found that as the kVp increased and the mAs decreased (15% kVp rule), the SNR decreased

(Brindhaban, Khalifah, Wathiqi, & Ostath, 2005). Sandborg et al. (2006) evaluated the effect of tube potential on SNR for pelvis radiography. The results of their work stated that as the kVp increased from 50 to 110, the SNR value decreased proportionately from 60 to around 20 (Sandborg et al., 2006).

Table 6-8 illustrates the effect of increasing SID on SNR for both the supine and erect positions. The SNR for erect phantoms was lower than the supine phantom among all used SIDs. The smallest differences in SNR between the two positions were found at 145 cm, and these differences were not significant (P=0.35). In this experiment, as the SID increased the SNR decreased. The differences between erect and supine were significant when using 130 cm SID. The effect of increasing SID on SNR in this experiment were similar to the results obtained from the study by Tugwell et al (2014). The authors considered the effect of SID changes on the SNR for AP pelvic X-ray images acquired using CR system. In their study, SID was varied from 90 cm to 140 cm with two exposures made at each 5 cm interval, one using the AEC and another without AEC. The results showed reduction in SNR by AEC (38%) and no AEC (36%) with increasing SID.

In clinical radiography, it is typical for the termination of an exposure to be determined by the use of AEC (Manning-Stanley et al., 2012). The effect of using different AEC configurations on SNR for both supine and erect phantoms was demonstrated in **Table 6-9.** SNR decreased for the erect phantom when compared with supine for all of the different AEC configurations**.** The results show that using central AEC has the highest SNR for both positions. Moreover, using central AEC had the smallest differences between the two positions. However, there were no significant differences between using the three different AEC configurations (P≥0.05). There is no previous research that has evaluated the effect of different AEC configuration on SNR between different positions, or even in the same projections. This shortfall in the research regarding the effect of AEC combinations on physical image quality makes the comparison of this experiment results difficult.

Using additional filtration has been investigated previously as a method for dose reduction (Brosi et al., 2011; Ekpo et al., 2014; Hansson, Finnbogason, Schuwert, & Persliden, 1997). The main influence of this filter is to remove the photons with low energy between 20 and 50 keV, which makes a significant contribution to patient radiation dose (Martin, 2007). In contrast, this could reduce the image quality, as hardening the beam reduces the image contrast (Jangland & Axelsson, 1990). Typically, adding filtration decreases the SNR. This effect was found in the supine position but not for the erect position in this experiment. This could be a result of increasing the dose in the erect position, which means more photons were used, increasing the SNR. The smallest differences between the supine and erect position were found when using 0.1mm of Cu when compared with using no additional filtration (**Table 6-10)**, and these differences in SNR were not statistically significant between positions. These findings were similar to another study that optimised lumbar spine radiography (Al Qaroot, Hogg, Twiste, & Howard, 2014). Decreases in the SNR were also found in another previous study which evaluated the effect of adding different thickness of Cu filters on SNR for chest X- rays (Ekpo et al., 2014). The results of Ekpo et al.'s study showed that, as the thickness of the filter increased, the SNR decreased.

6.5.2.2 The effect of position (supine vs erect) and phantom size on CNR

The differences between the erect and supine position on CNR were not too different from the SNR results. However, the effect on CNR was more than the SNR. This is because CNR provides good information on the effect of noise, which increased in this experiment as fat was added to the phantom to demonstrate the effect of different positions on body weight. This was in contrast to the detectability when compared with SNR measurements. The erect position in this experiment saw a decrease in the CNR by 43.5%. The differences between the two positions were less as the phantom size increased (20.1%), however, these differences were significant for both phantoms ($p \leq 0.05$) (**Table 6-11)**. This suggests that, by increasing the phantom size, the CNR will be worse regardless of the position. Thus, the differences will be less.

Table 6-12 illustrates the differences between the two positions using a different kVp. These differences were significant for all kVp values ($P<0.001$). By increasing the kVp, CNR decreased in both positions. The smallest differences between erect and supine were found at 90 kVp, which was the same as for SNR. Brindhaban et al. (2005) found a decrease in CNR as the kVp increased, which is in line with the findings reported in this thesis (Brindhaban et al., 2005). Increasing the SID decreased the CNR for both positions (**Table 6-13)**. However, the effect of the erect position was more pronounced than that of supine. This is due to the increase in distance from the X-ray source, which typically increases the divergence of the radiation field meaning a less intense radiation will reach the image detector (Graham et al., 2011; J. Johnston & Fauber, 2015). The smallest differences between two positions in CNR were found at 145 cm. This is in line with the SNR results in this experiment wherein 145 cm had the smallest differences between the two positions. The differences between erect and supine in CNR were significant (P<0.05) in regard to their using different AEC configurations. The erect position decreased the CNR for all of the different AEC combinations when compared to supine (**Table 6-14)**. The smallest differences were found when using central AEC. These results are similar to the SNR results of this experiment, and these differences were significant amongst all of the different AEC combinations (P<0.05).

Using additional filtration decreased the CNR for both positions (**Table 6-15)**. When adding a 0.1 mm Cu filter, the difference between supine and erect was 34% compared with 94% wherein no filter material was added. These differences were significant for both supine and erect. This is explained by the beam hardening after the adding of the filter, which reduces the image contrast. This effect of adding Cu filtration onto CNR was similar to the results of the study by Moore et al. (2008).When adding different Cu thicknesses, they found a decrease in CNR as the thickness of filter increased.

As described previously, there were negative impacts of erect positioning on physical image quality measurements (SNR, CNR) among all of the different acquisition parameters. This could be explained by the effect of using different anterior soft tissue thicknesses between erect and supine, and could be evidenced by the data which was obtained from the patient measurements in the clinical study of this phase. This data demonstrated an increase in anterior thickness for the erect position. Further data analysis was conducted in order to find if this effect was for all anatomical areas or for specific areas. **Table 6-16 and Table 6-17** show the analyses of the differences in SNR and CNR between erect and supine positions for three different pelvic areas (iliac crest, femoral head, sacrum). There were significant differences between the erect and supine positions for all three different pelvic areas, with the exception of the SNR for the iliac crest. In addition, the results suggest that the femoral head and sacrum area were affected by the erect position more than the iliac crest. Such results should be considered when requesting erect projections, especially for diseases affecting the femoral head and sacrum (such as osteoarthritis).

6.5.2.3 The effect of position (supine vs erect) and phantom size on visual image quality

The results for visual image quality are similar to those obtained from physical image quality. The erect position decreases the visual image quality in both phantoms size (**Table 6-18).** As the phantom size increased, the differences were increased by 16%, and these differences were significant ($P<0.05$). It should be noted that the decrease in visual image quality in the erect position was less than the decrease in the physical image quality that was described in previous sections. This may be due to the fact that physical measures of image quality have been found to be more sensitive to changes in image quality compared to visual evaluation. This is because the human eye is not as sensitive to subtle changes in image quality in comparison to a computer programme's calculations. It has been suggested that human observers' visual systems can adapt to the noise levels within an image (Abbey, 2013; Sund, Båth, Kheddache, & Månsson, 2004). These variations are not detectable by the human eye (S. Smith, 1997). Further analysis was done for each phantom size. The effect of kVp and SID was found to have the most impact on the differences on visual scoring between the two positions. Using 80 kVp and 145 SID had the largest differences in VGA between the two positions.

In regard to the impact of kVp on VGA, as the kVp increased, the VGA decreased. This was the case for both positions. This decrease in VGA can be explained by the increase in noise caused by the low mAs, set to compensate for the high kVp. VGA decreased in the erect position when compared with the supine position, across all kVp values that were used in this study (**Table 6-19)**. The small differences in VGA were found at 90 kVp, which is the same finding as for physical image quality results. This suggests that using 90 kVp is the most appropriate tube potential that can be used for the erect position in order to obtain images as near as possible to supine image quality. The differences in VGA between the two positions were significant at 80kVp, which is the same finding as for SNR during this experiment. These findings indicate that the erect position could be optimised at high kVp. The findings on the effect of increasing kVp on VGA in this experiment are similar to the finding obtained previously in pelvic radiography, as well as in other body parts (Manning-Stanley et al., 2012; Sandborg et al., 2006; Tingberg et al., 2004).

The impact of increasing SID on VGA is comparable with the effects on physical image quality results. As the SID increased, the VGA decreased (**Table 6-20)**. This could be because increasing SID reduces the X-ray intensity, which in turn leads to an increase in the noise and a reduction in the image quality. The differences between the two positions were found to be significant for all SIDs used in this study (P<0.05). The smallest differences were found at 130 cm SID. Also, the largest VGA score was found at 130 cm SID. This trend of the decrease in VGA as the SID increases was found by Brennan and Nash (1998). They found reduced sharpness of the superior and inferior endplates with increasing the SID from 100 to 130cm in a lateral lumbar exposure. Also, the same trend was investigated in the study for evaluating the effect of increasing the SID on image quality and radiation dose for lateral spine projection (Al Qaroot et al., 2014). These results show a decrease in the image quality when increasing the SID more than 130 cm. Brennan & Nash (1998) suggest that this decrease in image quality along with an increase in SID is due to grid cut off. This was also proven by Al Qaroot et al. (2014) when they found enhanced sharpness in the superior and inferior endplates without using grid. This trend is also supported by (England et al., 2015; Joyce et al., 2013).

Regarding the effect of different AEC configurations on VGA, using a central AEC had the highest score amongst all the different combinations (**Table 6-21)**. The differences between the erect and supine position were significant for all AEC configurations (P<0.05). This result is in line with the physical image quality assessments in the previous sections. The smallest differences between the two positions were found when using the central AEC. This result is similar to findings from previous sections, suggesting that using the central AEC is the best choice for erect pelvic radiography in obtaining image quality that is similar to that of routine supine positioning.

Additional filtration had a negative impact on VGA. This was the same impact as was had on physical image quality in this experiment (**Table 6-22**). Using filtration decreased the image quality by 5.5% in the supine position and 1.6% in the erect position, suggesting using filtration during pelvic radiography in the erect position could be favourable. There were significant differences between the two positions, either with or without additional filtration (P<0.05). However, the smallest differences between the two positions were found when using additional filtration. The common concern when using filtration is that it disturbs the image quality, since hardening the beam could reduce the contrast (Jangland & Axelsson, 1990). Despite no previous studies being published to optimise AP pelvic radiographs in erect position, or comparing the differences between erect and supine using added filtration, the results from this experiment agreed with previous studies that investigated the significance of different filtration types' impacts on image quality (Hamer et al., 2005; Lehnert et al., 2011).

6.5.2.4 The effect of position (supine vs erect) and phantom size on effective dose

An erect position has been recommended by many researchers (Jackson et al., 2016; Pierrepont et al., 2017; Tamura et al., 2017; Uemura et al., 2017; Yun et al., 2018). All these studies concentrate on the effect of the differences between the supine and erect in terms of radiographic appearances, their impact on diagnosis, and their impact on the early detection of pathologies. However, none of these studies assess the effect of this position on radiation dose. Therefore, this thesis fills a significant gap in the literature by finding the effect of erect positioning on radiation dose and image quality. This makes the comparison between this study's results and previous studies unavailable. However, the trend in the effect of different acquisition parameters on radiation dose will be provided. It should be noted that the previous research making their effort on finding the alternative position which reduce the radiation dose without compromising the image quality (Ben-Shlomo et al., 2016; Chaparian et al., 2014; Davey & England, 2015; Dhakal et al., 2015). The erect pelvis radiography conducted during this experiment demonstrates different situations, and the E results were the most surprising finding.

There was a great difference between the supine and erect positions on E. These differences increase as the phantom size increase **Table 6-23**. An erect position increases the E by 53.4% and 192% for +1SD and +2SD phantom, respectively. These differences in E were significant in both phantoms ($P<0.001$). Further data stratification by tube potential, AEC configuration, SID and the use of additional filtration are confirmed that the high differences between the two positions were at different kVp, SID and using filtration in both phantoms. These differences were significant ($P<0.05$) among all acquisition parameters that has been used during this experiment.

There were significant differences between erect and supine positions as the kVp increased ($P<0.05$) (**Table 6-24**). As the kVp increased, the E decreased in both positions. The erect position increased the E across all different kVps that were used. In the erect position, the highest dose was at 80 kVp (0.514 mSv), while the lowest dose was when using 100 kVp (0.299). The maximum differences in E between the two positions was 0.338 mSv at 80 kVp, and this was significant ($P<0.05$). As kVp increased, the penetration power increased and this decreased the energy deposition within the organs tissues, leading to a further decrease in radiation dose (Brosi et al., 2011; Martin, 2007). There have been many attempts to reduce patient radiation dose during AP pelvis examinations by altering the kVp. It has been found in many of these attempts that dose reduction occurs as the kVp increases (Al Khalifah & Brindhaban, 2004; Egbe et al., 2010; Fauber et al., 2011; Martin, 2007; Tingberg & Sjöström, 2005). Previous research found the same effect of increasing kVp on chest and abdomen radiography (Grewal et al., 2012; Guo et al., 2013; Jang et al., 2018). Although those studies focused on other body parts, the results in this thesis agreed with those of previous studies regarding the effects of the use of high kVp on radiation dose in both positions.

In regard to the SID effect, as it increased, the radiation dose increased in both supine and erect positions (**Table 6-25**). There were significant differences in radiation dose among all SIDs used in this experiment ($P<0.001$). The erect position had a higher dose when compared with that of supine for all the SIDs used during this study. The maximum dose was found at 145 cm - 0.172 mSv and 0.417 mSv - for supine and erect positions, respectively. The maximum differences in dose between erect and supine were found also at 145 cm, as 0.245 mSv. The general impact of SID on radiation dose is clear. It is described by the inverse square law - as the SID increases the dose will be decreased. This general understanding of the effect of SID is not supported by the findings from this experiment. It should be noted that no previous studies have proven this general understanding for different patient sizes or different radiographic positions.

An acknowledged limitation of the current work is that the 130 and 145 cm images were acquired with radiographic grids that were not focused to each specific SID. The results from this study could be explained by the grid cut off (the absorption of primary-beam x-rays by the grid). However, no gridline marks were seen on any of the images (Joyce et al., 2013). The grid cut off was tested by the visualisation, although visual testing may not be as consistent as using a physical measurement. A recommendation for future work would be to use image quality test tools in the methodology to acquire an objective measure of image detail. Joyce et al. (2013) also found an increase in radiation dose when increasing the SID to 150 cm. (Brennan & Nash, 1998) found an increase in radiation dose for lumbar spine radiography when increasing the SID from 130 to 150cm. They explained this by asserting that at 150 cm it is likely that, per unit time, the radiation reaching the film is reduced. Therefore, to maintain the correct image density, the AEC will increase exposure times. This, in turn, will eliminate or reduce the probability of dose reduction. Moreover, in the study was done by Heath and colleges to evaluate the effect of increasing the SID from 80 to 147 cm on E for pelvis radiography, the results were showed the deceased in E was when increasing the SID from 80 to 120 cm after this the E was stable and no more reduction on the E. In Heath study 100cm grid was used (as in this experiment) and the authors explained their results regarding the radiation dose and image quality by grid cut off (R. Heath et al., 2011).

The main function of the AEC is to control the exposure time (Carroll, 2007). The imaging specialist should select the best configuration of the three chambers for best performance. In this experiment, there were significant differences in E between erect and supine when using different AEC configurations ($P<0.001$) (**Table 6-26**). Erect positions increased the dose for all different AEC combinations. These results are surprising, as small variations in the AEC chamber in this study produced relatively large variations in radiation dose between two positions. However, a properly calibrated AEC device is considered to be the best method of controlling radiographic exposure (Mazzocchi et al., 2006).

The largest dose was found when used central AEC for erect (0.528 mSv) and in supine (0.157 mSv). The lowest dose was found when using both outer AEC chambers for erect (0.343 mSv) and supine (0.125 mSv). The lowest radiation dose when using both outer chambers could be related to the nature of the pelvis' main anatomy. This is because the 2 outer chambers are located laterally to the sacrum and inferior to the centring point (off-centred). This would require a lower radiation dose for the AEC to terminate the exposure. By contrast, when all chambers or the single central chamber are in use, the centre chamber will be located over the sacrum, requiring a higher radiation exposure to terminate (Manning-Stanley et al., 2012). The findings regarding reducing the radiation dose when using the outer chambers, like the results from this experiment, have been obtained in previous studies. Manning-Stanley et al. (2012) found that using both outer chambers could reduce the radiation dose by 44% when compared to other the AEC configurations, using a pelvis phantom. Also, Hawking and Elmore (2009) found that the radiation dose reduced significantly when using both outer chambers, and the highest dose was with the central AEC using both pelvis and abdomen phantoms.

The effect of additional filtration was illustrated on **Table 6-27.** The results from this experiment were found to decrease the E by adding 0.1 mm of Cu in both supine and erect positions. There were significant differences in the erect position between using, or not using additional filtration (P<0.001). Adding filtration reduced the dose in the erect position by 0.042 mSv. Filtration can be used to harden (more penetration) the radiation and reduce the dose (Jones, Ansell, Jerrom, & Honey, 2015). Adding filtration decreases the low energy photons which reduces the total dose delivered (Costa, Nova, & Canevaro, 2009). In a study for paediatric radiology, the main indication for adding filtration was to reduce the skin dose (Huda, 2004). This trend in radiation reduction when adding filter material was similar to previous studies (Barba & Culp, 2015; Brosi et al., 2011; Hamer et al., 2005; Hansson et al., 1997; Jones et al., 2015; Lehnert et al., 2011; Martin, 2007).

6.5.2.5 Suggested acquisition parameters for erect pelvis radiography

The acquisition parameters for erect pelvis radiography will be recommended in this section in line with the previous discussion regarding the differences between erect and supine positions. Using 90 kVp, 130/145 cm SID, both outer chambers and additional filtration (0.1 mm Cu) will be suggested as the optimal parameter set to obtain erect radiographs during phase three (**Chapter 7**). This decision was made according to the parameters that provided the smallest differences in image quality between erect and supine positions. Additionally, the lowest radiation dose delivered by the parameter combinations was considered. This is because the results from experiment #3 illustrate that an erect pelvis X-ray image decrease image quality amongst all used parameter combinations, and increased the radiation dose. The image quality for the supine position was considered to be the reference, as this is the routine position that is currently used in clinical practice. Ideally, images from the erect position should have at least the same image quality. Therefore, the parameters that provided the image with the smallest differences in image quality between erect and supine with the lowest radiation dose were considered to be the ‘optimum’ parameters. **Table 6-28** illustrates the smallest differences in image quality between the two positions. 90 kVp appears to be optimum for erect pelvis radiography as it demonstrates the smallest differences in image quality (physical and visual). Although 100 kVp has a lower E, the differences in E between 90 and 100 kVp were small and would fall within the data variation. As such, the resultant ‘marginal’ additional radiation dose could be justified with the given benefit of improving image quality. This is especially important as high image quality for hip radiography is likely to be necessary. This is because the diagnosis for some diseases depends on identifying small changes (more details are provided in chapter 2). Both outer chambers were chosen as it provided the lowest radiation dose. Central AEC demonstrated the smallest differences between erect and supine in image quality, however the differences between the two positions were too small (-12 and -9 for both outer and central, respectively) to choose the central instead of both of the outers. Despite increasing the SID, this did not demonstrate any dose reduction. However, using a focused grid was considered as limitation in this study and could have affected the dose results. Moreover, this recommendation further supported an additional experiment in the hospital using a pelvis phantom to see if there is a benefit from increasing the SID on reducing the dose using a focused grid. The results of this showed a decrease in radiation dose when moving from 115 to 140 cm. Therefore, using large SIDs of 130/145 cm was recommended for obtaining erect pelvis X-ray images. The results obtained from adding additional filter material have demonstrated that the filter reduces patient radiation risk and decreases the differences between two positions in term of image quality. The results of this thesis should encourage using added filtration when obtaining pelvis X-ray images in the erect position.

6.6 Limitations

There are further considerations that must be explored as limitations. These are as follows:

- The phantom studies were conducted in the university laboratory using single DR system. As there are some centres still only using CR or different types of DR, results must be obtained using CR for comparison. Different DR units may also produce a slightly different set of results and should be assessed. However, the DR system is the most system used within the clinical environment. Furthermore, DR and CR have almost the same manufactural materials
- The modification of the acquisition parameter was performed using tube potential, however, different combinations between kVp and mAs or a change in SID may be helpful (*Experiment #1*)
- The fat was positioned anteriorly. The effect of different fat positions, such as posteriorly or at the sides, could affect these results. However, this simulation represents the apple and pear shapes of the human, where the is fat more accumulated anterior to the hips
- The fat simulation was done only to replicate subcutaneous fat. Visceral fat should have an effect on radiation dose and image quality too. It could act as a shield around the organs and may reduce the dose that is absorbed by it
- The dose calculation using PCXMC could have been overestimated. However, the number of photons was increased to reduce the error to less than 1%. Also, the

differences between the erect and supine positions on E calculations represent obese people. This needs to be done for normal and overweight people to evaluate the real differences between the two positions

- There were some limitations on the experiment equipment's, such as the X-ray tube automatically terminating exposure when adding more than 15 cm of fat. Also, the unavailability of the focused grid made the evaluation of the effect of increasing SID on dose and image quality difficult (*Experiment #1+3*)
- In practical Pelvis radiography, there are other attenuators positioned on the pelvis, such as orthopaedic devices or gonads shielding. This may affect exposure control (Manning-Stanley et al., 2012).

6.7 Conclusion

The aims of this study were to determine if differences existed between the erect and supine positions in image quality and radiation dose, and if the supine acquisition parameters are applicable for erect position. Also, it aimed to propose the optimal parameters to obtain pelvis radiographs in the erect position for **Phase three (Chapter 7**) in this thesis.

For objectives one and two, a pelvis anthropomorphic phantom was modified by adding commercial fat to represent different patients' sizes. Increasing patient size increases the radiation dose and decrease the image quality. Acceptable image quality was found in a wide range of tube potentials, however, using a low kVp increase the radiation dose. Using a high tube potential is recommended for patients who are referred for follow-up or who do not need high-quality imaging. Strong correlation was found between physical and visual image quality and radiation dose. For the third to seventh objectives, the differences in the anterior thickness between erect and supine were obtained from patients. The phantom was modified to represents humans in erect and supine positionings by adding different fat thickness and, was imaged using different acquisition parameters. Erect pelvis radiography has shown an increase in radiation dose and a decrease in image quality when compared with the routine supine pelvis radiograph. Using 90kVp, both outer chambers, 130/145 SID and adding filter is recommended as the acquisition parameters set for erect positioning. These parameters provided the smallest differences in image quality between erect and supine along with the lowest radiation dose. They will also be used to obtain the erect and supine clinical images during phase three (**Chapter 7**) in this thesis.

Chapter 7: Clinical impact of erect pelvic radiography on image quality and radiation dose

7.1 Chapter overview

This chapter describes the final experimental phase in this thesis. This phase is the clinical component of the thesis and builds on previous phases, including: phase one (Chapter four), which recommended the most reliable standing position for erect pelvis radiography; and phase two (Chapter six), which recommended the optimal radiographic acquisition parameters for undertaking pelvis radiography in the erect position. Chapter 7 commences with its aims and objectives. It then progresses to its methods, which includes details on participant inclusion and exclusion criteria, recruitment process, study design, data collection and study management and ethical considerations. Following this, the results will be presented together with a discussion on the reported findings. The limitations of the study explored in this chapter will be presented before the it concludes with information on the comparison between erect and supine positioning.

7.2 Aim and objectives

The aim of the study described in this chapter was to evaluate the differences between erect and supine positioning using human (clinical) data. Such data would be used to validate the results obtained from phase two (Chapter 6) in this thesis. To achieve the aim, the following objectives were established:

- Perform erect and supine pelvis radiography imaging on the same patients to facilitate comparisons to be made between image quality and radiation dose
- Calculate the radiation dose for erect and supine projections and determine if any differences exist between the two positions
- Measure the image quality for erect and supine and determine if any differences exist between the two positions
- Determine if the image quality changes are uniform across the pelvis, between the different projections.

7.3 Study methods

7.3.1 Participants, inclusion and exclusion criteria

A total of 60 patients (21 male, 39 female) took part in the study. Participants were classified into different BMI groups based on a World Health Organisation report (WHO, 2005) (normal BMI: n=10; overweight BMI: 23; obese BMI: 27). The clinical history of the referred patients included pain (28 patients; 46%), OA (19 patients; 32%) and THR follow up (13 patients; 22%). The inclusion criteria were patients who attended for radiography of the hip or pelvis X-ray imaging as referred by their general practitioner or outpatient clinic. The exclusion criteria were as follows:

- Patients who were under the age of 18
- Those who are pregnant or who had had recent trauma, or undergone hip or knee surgery within the previous six months
- Patients who had had a pelvic X-ray or pelvic radiotherapy in the preceding 6 months to minimise any additional radiation exposure
- Patients who were unable to stand unaided, as weight bearing is a key requirement of an X-ray in the erect position.

7.3.2 Ethical Considerations

The key ethical issue associated with this phase of work was the requirement for an additional X-ray projection, which is above that would be needed for the clinical imaging. Research Ethics Committee (REC) and Health Research Authority (HRA) approval was sought to ensure the additional radiation dose was managed within an appropriate framework. This included establishing protocols to limit radiation exposure during the study. If repeat X-rays were required due to quality reasons, then the patient was excluded from the study. Patients had only one X-ray image taken in the erect position, regardless of final image appearances. This ensured that the maximum additional dose for a single patient was limited to one exposure, whilst maintaining the integrity of their clinical examination. This also provided information regarding the potential repeat rate for erect radiographs in possible future work.

The number of radiographers able to obtain study images was limited to four. This was to provide quality assurance in using the erect technique, as it is non-standard practice. These radiographers underwent specific training and the images was assessed for quality throughout the study. This provided opportunity for interventions if any problems were identified. Additional radiation dose reduction techniques were adopted, and these were optimised during phase two of this thesis (chapter six). From phase two's results (chapter six), the acquisition parameters were determined. These parameters provided lower radiation doses and minimal image quality differences between the erect and supine positions. The patient's radiation dose was monitored as part of the imaging protocol study. The monitoring results indicated that the radiation dose increased for the patients in erect position, causing the research team to increase the SID from 140cm to 180cm part way through data collection. This is because this action is said to reduce the radiation dose (R. Heath et al., 2011; Joyce et al., 2013; J. Tugwell et al., 2014)

Any participant could withdraw from the study at any point prior to final data analysis. If this was the case, then their data would be excluded from the study and the relevant study records destroyed. However, X-ray images would be retained as part of their personal clinical record. Source data, consent forms and patient's information were stored in a locked filing cabinet within a locked research office. Data transfer used encrypted techniques. Only the research team had access to this data and the decryption methodology.

7.3.3 Recruitment process

A patient information sheet was sent along with X-ray appointment letters to potential recruits who were referred from their general practitioner (**Appendix 21**). These patients were known by the radiology appointments team at the time of their booking an examination. The information sheet provided an introduction to the study and specified the aim of the research, together with an explanation of the risks and benefits of taking part. Using this approach allowed time for patients to read the patient information leaflet and, if required, discuss with family or friends or approach the study team prior to giving informed written consent. Within the hospital outpatient areas, posters with all relevant study information were displayed so that patients could understand the study prior to attending the radiology department.

A member of the radiology team confirmed the eligibility of the patient to participate in the study by reviewing the inclusion and exclusion criteria with them. When the patient attended the radiology department for their examination, a Good Clinical Practice (National Institute for Health Research, 2005) (https://www.nihr.ac.uk/our-research-community/clinical-research-staff/learning-and-development/national-directory/good-clinical-practice/) trained member of staff (HCPC registered radiographer who works permanently within the radiology department) met the patient, introduced themselves, and explained the study and what was required from them to take part.

7.3.4 Study procedures

Equipment quality assurance testing was performed prior to image acquisition. This included testing voltage accuracy, exposure time, field size collimation and AEC sensitivity. In addition, the consistency of the radiation dose output from measuring different kVp and mAs levels was assessed. Testing followed IPEM 91 guidance (IPEM, 2005; National Institute for Health Research, 2005), and all results were found to be within the expected manufacturer tolerances. The images were obtained using a Carestream Evolution DRX-1 system. A grid was used for both supine and erect examinations. The settings for supine were: 80lp/cm, 12:1, focussed at 110 cm; erect at 140cm SID, 80 lp/cm, 12:1, focussed at 140 cm. Those for erect images were: 180 cm SID, 80 lp/cm, 15:1 focussed at 180 cm. An initial image review was conducted on a Carestream Directview system within the imaging rooms.

Imaging was performed by specialised radiographers who received training in undertaking pelvic radiography in the erect position. The training was controlled by study investigators who have experience in this sort of imaging. They also hold qualifications in image reporting. Each patient was radiographed in two positions, both at 90kVp, using both outer chambers and with a SID of 140 cm. The SID was increased to 180 cm for the last 23 patients in erect position due to radiation dose concerns from a mid-study review of the data (part of the study protocol). For supine images, the patient's arms were placed across their chests, and feet were internally rotated by 15-20° (using a specially adapted foam pad). For erect imaging, the patient's arms were again placed across the chest if they were able to stand still, otherwise they were allowed to hang loose or on a support for balance (the same arm support that was used in phase one). Feet were internally rotated by 15- 20° (using the same foam pad). For both positions, the central ray was positioned at the midline - 5cm above the level of the greater trochanter - unless a hip replacement was present, in which case it was centred at the level of the greater trochanter. A data collection sheet was used to record information about each study participant and the imaging parameters (**Appendix 22**). The data was transcribed as soon as it was practicable into a research management system with patient identifiable information being removed.

7.3.5 Image quality assessment

The image quality was assessed by VGA only in this study. The justification behind not including the physical assessment of image quality was that, during clinical practice, VGA is usually used in isolation by the radiographer or reporter when evaluating the images. So, VGA can be considered as the most important indicator of image quality as this reflects clinical practice. Images were assessed by four experienced radiographers who have between 10-32 years of clinical experience. All of the images were displayed on two five-megapixel DOME E5 (NDSsi, Santa Rosa, CA) monitors (2048 by 2560 pixels). Monitors were calibrated to the grey scale digital imaging and communications in medicine (DICOM) standard (The Royal College of Radiologists, 2014). The MicroDicom viewer software [0.9.1 (Build 918) 64 bit, Simeon Antonov Stoykov] was used to display the images. All 120 images were assessed on a 5-point Likert scale, in the same way as in the study conducted by Mraity et al (H. A. A. B. Mraity et al., 2016). For each criterion, the minimum possible score was 1 and the maximum was 5 (1, strongly disagree; 2, disagree; 3, neither agree/disagree; 4, agree; 5, strongly agree). Scores were calculated in a way so that each image could receive a minimum of 22 and a maximum of 110. For the two criteria that were negatively worded, the scoring affirmation was reversed during calculations. When anatomy was missing from an image (for example iliac crests on patients with hip prostheses), the number of scale items were reduced accordingly. The minimum and maximum possible scores were also recalculated for the individual image. Next, the percentage of the maximum permissible scores across of all the images were calculated for each of the four observers, and an average of the four observer scores was determined. Images were assessed according to the following 22 criteria (see **Table 7-1**), which have been validated by Mraity et al. (2016) study. During the assessment, observers were not permitted to change the contrast of the image or use magnification.

Table 7-1: The criteria used for the visual grading (H. A. A. B. Mraity et al., 2016).

Item	Descriptor
1	The right iliac crest is adequately visualized
2	The right sacroiliac joint is adequately visualized
3	The right hip joint is adequately visualized
4	The right femoral neck is adequately visualized
5	The right greater trochanter is adequately visualized
6	The right lesser trochanter is adequately visualized
7	The right proximal femur is adequately visualized
8	The sacrum and foramina are NOT adequately visualized
9	The pubic and ischial rami are NOT adequately visualized
10	The left iliac crest is adequately visualized
11	The left sacroiliac joint is adequately visualized
12	The left hip joint is adequately visualized
13	The left greater trochanter is adequately visualized
14	The left lesser trochanter is adequately visualized
15	The left femoral neck is adequately visualized
16	The left proximal femur is visualized adequately
17	There is appropriate differentiation between soft tissues
18	The exposure factors used for this image are correct
19	The image is sufficient for diagnostic purposes
20	The medulla and cortex of the pelvis are adequately demonstrated
21	Both acetabula are visualised clearly
22	Fine bony detail is sufficiently demonstrated

7.3.6 Radiation dose assessment

To facilitate the dosimetry calculations, the DAP was measured using a built-in meter. The mAs for each patient was recorded in both positions. During this phase, two different Monte Carlo (MC) PCXMC 2.0 (STUK, Radiation and Nuclear Safety Authority in Finland) with CALDose software (CALDose_ X 5) were used. The reason behind using two MC simulations was that PCXMC does not take into account the patient position (i.e. erect and supine). Positional adjustment in mathematical modelling is important during dose calculations because there can be changes in organ position imposed by posture. For instance, it has been proven that gravity acts on all the internal common organs in the abdominal cavity (Howes, Hardy, & Beillas, 2013), and therefore different positions have an effect on the locations of them (Beillas, Lafon, & Smith, 2009; Hayes, Gayzik, Moreno, Martin, & Stitzel, 2013). Therefore, CALDose software was used because it provides the option to consider the position of the internal organs. However, CALDose does not give the option to determine the radiation field size (it uses a standard predefined field size) and different exposure factors (such as SSD). It has been previously proven that ESD is affected by SSD (Aliasgharzadeh, Mihandoost, Masoumbeigi, Salimian, & Mohseni, 2015; E. K. Ofori, 2013; Tung & Tsai, 1999). In regards to field size, Fauber and colleagues found statistically significant reductions in radiation dose (>60%) when the field size was decreases in lumbar radiography, especially in organs further from the lumbar spine (Fauber & Dempsey, 2013). Also, CALDose does not allow the user to manipulate the SID. For pelvis it is fixed at 115cm while in PCXMC the SID can be determined. Moreover, CALDose does not calculate the effective dose; rather it calculates the absorbed dose. Therefore, ESD was calculated by PCXMC and then inserted into CALDose for the dose calculations.

For the PCXMC calculations, the weight, height and SID were inputted for each patient in the different positions. The field size (31 cm beam width and 32 cm beam height) was fixed for all patients. The SSD was calculated by subtracting the body part thickness (average of the IC and GT regions) from the SID for each patient to assist with the dose calculations (Alqahtani et al., 2019; Uniyal, Chaturvedi, Sharma, & Raghuvanshi, 2017) in each project, according to the Monte Carlo simulation and the measured DAP value. The dose determining factors required by the software were patient weight and height, tube potential, filtration, field size and the reference points on the X-, Y-, and Z-axes for the location of the radiation field. The number of X-ray photons involved in each simulation was $1*10^6$ in order to assure a low relative statistical uncertainty of 1 % (Davies et al., 2014). 90 kVp, and 3mm AL filtration was used to generate an appropriate X-ray spectrum.

For the absorbed dose calculations by CALDose, the age of the patient, gender, examination and projection were determined for each patient and projection. The SID was 115 cm which is the largest distance that can be used for pelvis radiography. The standard field size was selected because the programme does not allow the user to select the field size. After that, the ESD was calculated from PCXMC was inserted to the CALDose programme, after which the whole body absorbed dose was calculated.

7.3.7 Statistical analysis

All the measurements were processed using IBM SPSS Version 23. The normality of the data was examined visually by a frequency distribution (histogram). Also, a Shapiro-Wilk test was used to check the distribution of the data - $P \leq 0.05$ was considered non parametric data (Ghasemi & Zahediasl, 2012; Yap & Sim, 2011). The Wilcoxon test was used to determine whether significant differences existed between erect and supine positions for the non-parametric data, while a paired sample t-test was used for the comparison between the two position for parametric data. A significance value of $p<0.05$ was used for all the tests. Box and Whisker graphs were used to illustrate the differences between the erect and supine position in term of radiation dose and image quality. As the data for radiation dose and image quality was non-parametric distribution the box and Whiskers represented the median, interquartile and maximum and minimum values.

For demographic data, the data was displayed as the mean ± SD for parametric data, while the median (IQR) was displayed for non-parametric data. For parametric data, the differences between the two SIDs were evaluated using an independent sample t -test. While for non- parametric data the Mann -Whitney U test was used.

The reliability between the four observers was evaluated by an intra-class correlation coefficient (ICC) using SPSS, and 95% confidence levels were also reported. ICC values less than 0.5 were indicative of poor reliability, values between 0.5 and 0.75 indicated moderate reliability, values between 0.75 and 0.9 indicated good reliability, and values greater than 0.90 indicated excellent reliability (Koo & Li, 2016; Portney & Watkins, 1993). On the other hand, Spearman correlation coefficients (the data was non-parametric) were used to evaluate the relationship between BMIs and the differences between erect and supine in image quality, and radiation dose. The interpretation of the strength of the correlation (r) was considered as weak (≤0.39), moderate (0.40–0.69) or strong (≥0.70)(Lomax, 1998).

7.4 Study results

Study data showed an approximately non-normal distribution for the anterior thickness of the body, dose calculations and IQ in both the erect and supine positions ($P<0.001$), (see **Table 7-2**), so the appropriate statistical test was selected.

Table 7-2: Normality (Shapiro-Wilk test) results for all metrics.

Metric/Position	Supine	Erect
Antero-posterior patient thickness	0.03	0.05
DAP	<0.001	<0.001
Absorbed dose	<0.001	<0.001
Effective dose	<0.001	<0.001
% of the maximum possible scores	<0.001	<0.001

7.4.1 Baseline demographics data and the differences between the SID groups

Demographic data from the participants is presented in **Table 7-3**. The decision was made to increase the SID from 140 cm to 180cm as per the study protocol requirements when actively monitoring patient dose during the study. The outcome of this procedure effectively spilt the data into two subgroups depending on the SID used. However, further analysis showed that there were no statistically significant differences between the patients (baseline demographics) for the different SID groups (see **Table 7-3**). Additional analyses were undertaken to evaluate the radiation dose and image quality differences between the two SID groups. These results also indicate that there were no statistically significant differences between the SID groups ($P>0.05$; **Table 7-4**). Therefore, subsequent analysis focused on treating all 60 patients as a single group.

Table 7-3: Demographic data of the included patients with a split according to the different SIDs. The P value represents the differences between the two SID groups.							
			Mean ±SD/ Median (IQR)				
Variable	**SID, cm (supine/ erect)**	**N**	**Age, year**	**Weight, kg**	**Height, m**	**BMI, kg/m^2**
All	**Total**	60	64.5 ±12.2	80.5 (67.9-98.4)	1.7 ±0.1	29.4 (25.2-33.4)
	140/140	37	63.4 ±13.4	81.0 (72.7-98.7)	1.7 ±0.1	30.5 (26.1-34.2)
	140/180	23	66.3 ±10.2	71.2 (65.9-97.4)	1.7 (0.1)	28.4 (25-32)
	P value		***0.31***	***0.29***	***0.63***	***0.24***
Male	**Total**	22	64.1 ±13.9	96.6 ±18.2	1.7 ±0.1	31.6 ±4.5
	140/140	14	63.6 ±17.0	96.9 ±20.4	1.7 ±0.1	31.8 ±5.3
	140/180	8	65.1 ±6.7	96.2 ±14.5	1.8 ±0.1	31.3 ±2.8
	P value		***0.80***	***0.98***	***0.74***	***0.73***
Female	**Total**	38	64.7 ±11.2	70.0 (64.2-83.5)	1.6 ±0.1	27.6 (24.9-32.9)
	140/140	23	63.3 ±11.2	78.0 (65.2-92.9)	1.7 ±0.1	30.0 (25.2-34.1)
	140/180	15	66.9 ±11.2	66.5 (61.7-71.2)	1.6 ±0.1	25.3 (24.6-28.5)
	P value		***0.41***	***0.17***	***0.40***	***0.25***

Table 7-4: P value when comparing the 140cm and 180cm SID groups with respect to antero-posterior patient thickness, radiation dose and image quality.			
Metrics	**Median (IQR)**		**P value**
	140 cm	**180 cm**	
Anteroposterior thickness (cm)	28.5 (24.0-32.0)	26.0 (24.5-29.5)	0.11
DAP (mGy. cm^2)	1100.0(840.5-2886.0)	1125.0 (851.0-1814.0)	0.71
Absorbed dose (mGy)	0.098 (0.072-0.256)	0.103 (0.077-0.151)	0.98
Effective dose (mSv)	0.178 (0.139-0.390)	0.194 (0.153-0.272)	0.93
VGA	90 (13-94)	84 (81-90)	0.56

7.4.2 Effect of switching from the supine to an erect position on anterior-posterior patient thickness

The differences between erect and supine for antero-posterior patient thickness are illustrated in **Figure 7-1**. Anterior patient thickness was 17% higher in the erect position (median 27.8, IQR [24.0-31.5] cm) when compared to the supine position [median 23.8, IQR (21.5-26.4) cm; P<0.001].

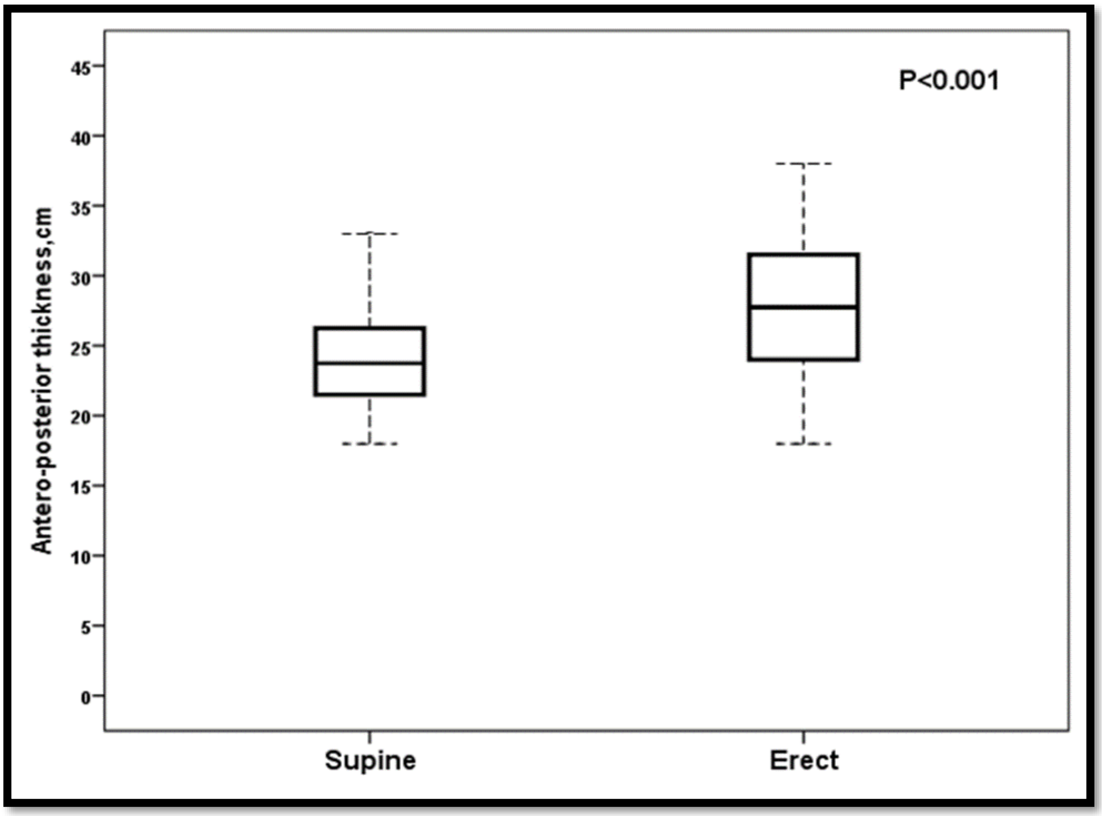


Figure 7-1: Comparison of patient thickness between supine and erect positions.

7.4.3 Effect of switching from supine to erect position on radiation dose

Data for the whole-body absorbed dose are illustrated in the **Figure 7-2.** The DAP was 46% greater in the erect position [median 1121.0, IQR (858.8-2303.4) mGy. cm^2], and this was statistically significant (P<0.001) when compared with the supine position [median 756.5, IQR (547.5-1142.3)]. The absorbed dose was 45% higher in the erect position [median 0.103, IQR (0.074-0.193) mGy] when compared to the supine position [median 0.069, IQR (0.051-0.099) mGy; P<0.001].

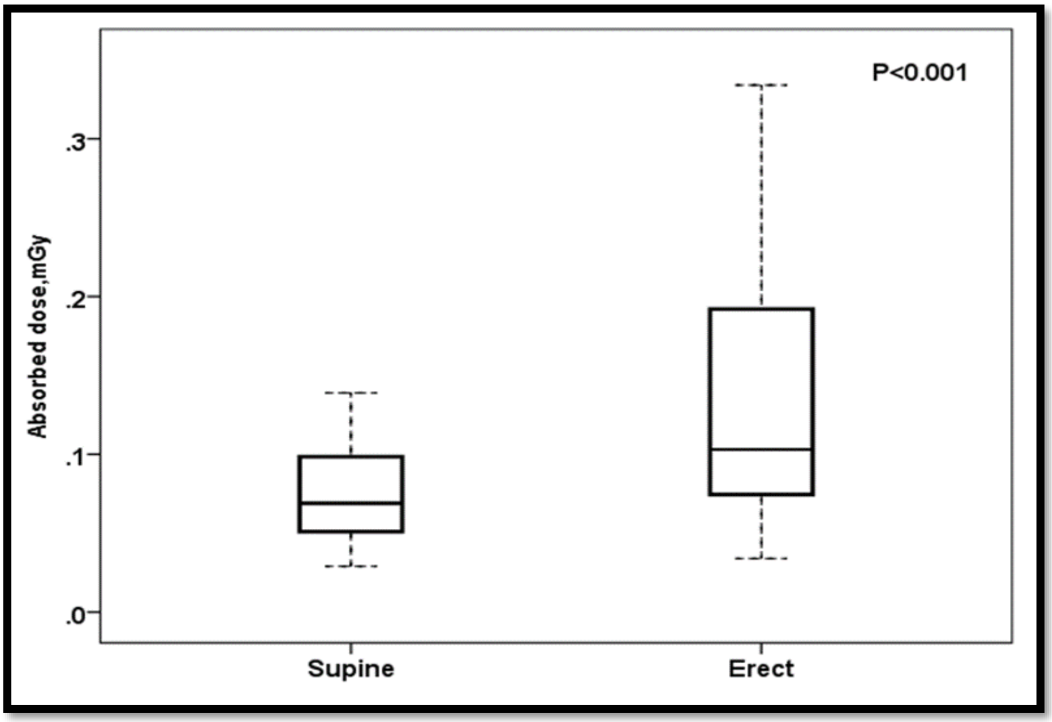


Figure 7-2: Comparison of absorbed dose using CALDose between erect and supine positions.

7.4.4 Effect of switching from the supine to an erect position on effective dose

Figure 7-3 demonstrates the data for the effective dose resulting from the PCXMC calculations. E was 67% higher in the erect position [median 0.194, IQR (0.143-0.319) mSv] when compared to the supine position [median 0.116, IQR (0.089-0.146) mSv; P<0.001].

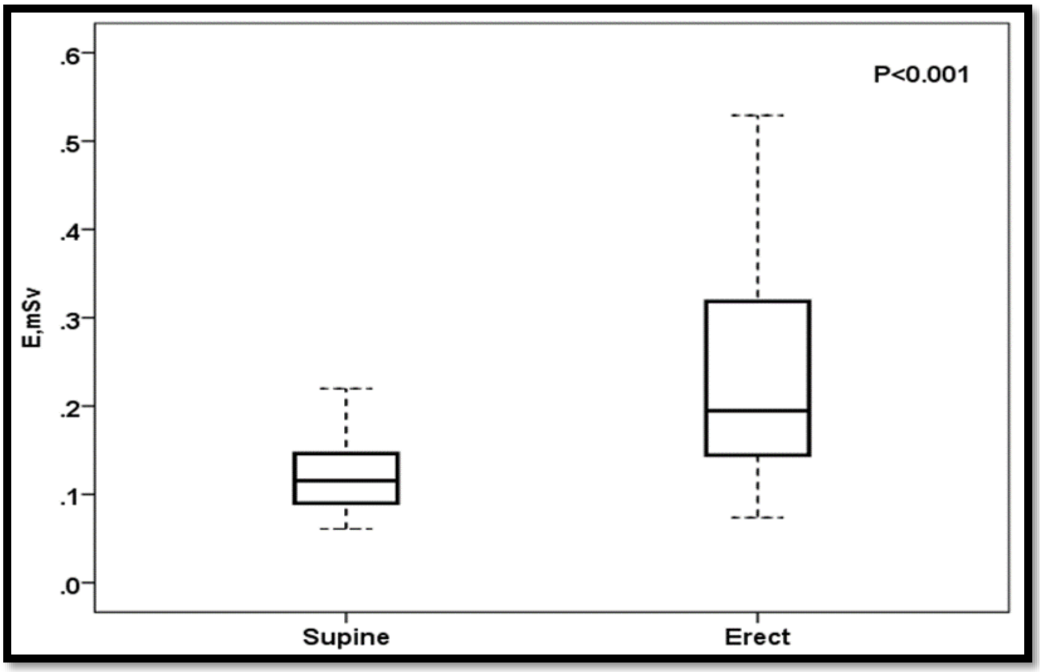


Figure 7-3: Comparison of E using PCXMC between erect and supine positions.

7.4.5 Effect of switching from the supine to an erect position on IQ

In terms of ICC, the ICC (95% CI) between the four observers in the supine position was 0.965 (0.948-0.977), and for the erect position it was 0.958 (0.937-0.973). These results imply a high level of agreement between observers (Rosner, 2010).

The % maximum possible scores were determined by calculating the maximum score by multiplying the number of criteria available in the image by 5 (maximum score) and then dividing this over the sum of the image score. The median (IQR) maximum possible IQ scores were 78% (69-85) and 87% (81-91) for erect and supine projections, respectively. There was a 10% decrease in the % of maximum IQ score when using the erect position instead of supine. The differences between the erect and supine projections were found to be statistically significant (P<0.001) see **Figure 7-4.**

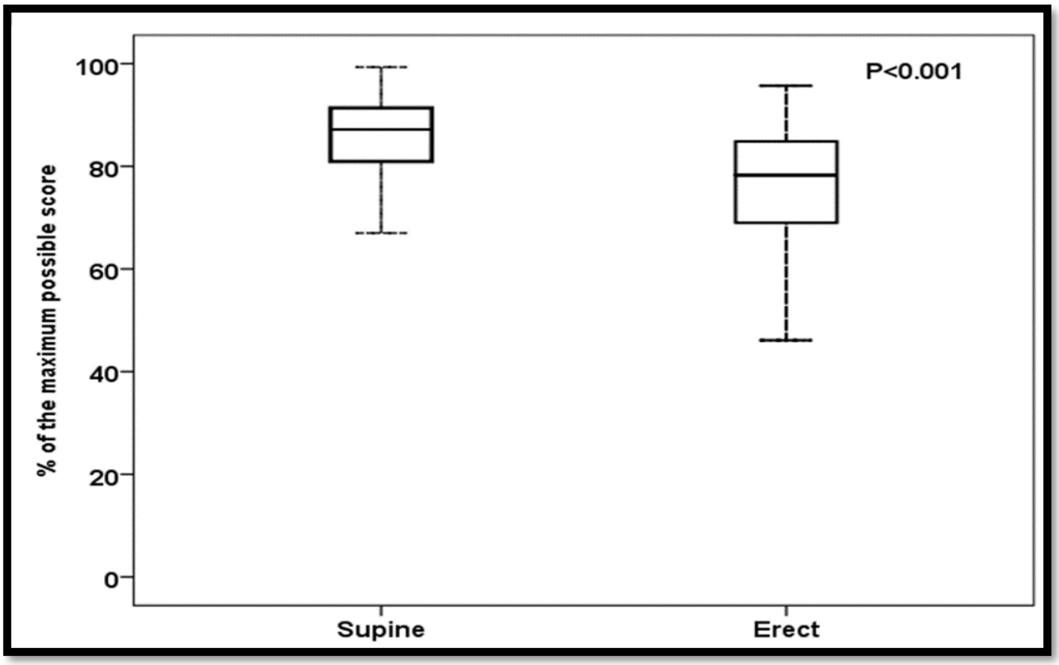


Figure 7-4: Comparison of the % of the maximum IQ scores between erect and supine positions.

Figure 7-5 illustrates the differences in the maximum possible score for the different anatomical areas within the pelvis region. The erect position decreased the IQ for all criteria evaluated, but this was not statistically significant (P=0.307). The sacrum and it is foramina were found to be the most affected anatomical locations by the move to an erect position wherein IQ decreased by 26%. The pubic and ischial rami, SI and hip joints were the next most affected after the sacrum, wherein the IQ decreased by 20%, 17% and 16%, respectively. Image quality for both acetabula decreased by 12%.

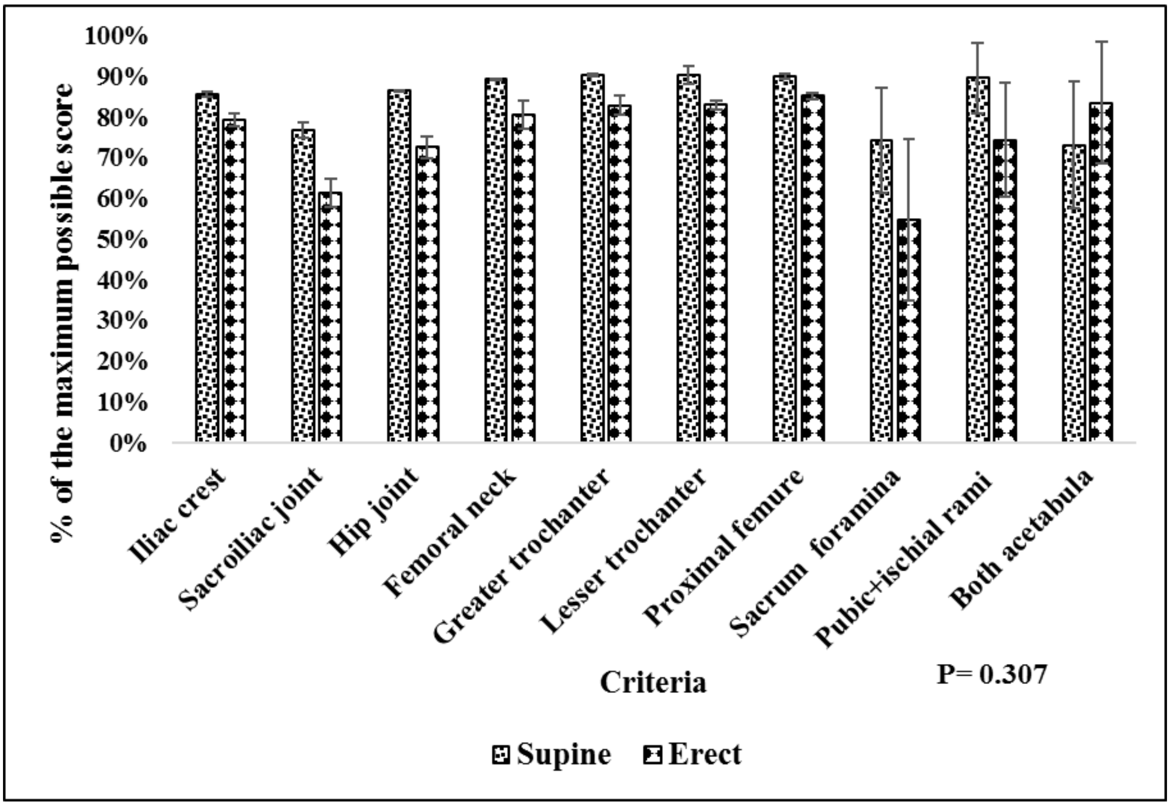


Figure 7-5: The maximum possible score for different regions with in the pelvis area. The graph represents the mean and the error bars represent the SD.

7.4.6 Comparisons between the erect and supine positions for different BMI groups

Table 7-5 illustrates the differences between erect and supine positions for the different BMI groups. There were increases in the anterior thickness in the erect position by 13%, 24% and 19% for normal, overweight and obese BMI groups, respectively. The increase in anteroposterior body thickness was statistically significant for all BMI groups ($P<0.001$). For DAP, there were increases in the erect position by 42% for patients with a normal BMI, but this was just outside the level of statistical significance ($P=0.074$). It was 55% higher ($P<0.001$) in the overweight BMI group and 105% higher for those with an obese BMI ($P<0.001$). An erect position increased the whole-body absorbed dose by 40% ($P=0.074$), 50% ($P<0.001$) and 92% ($P<0.001$) for normal, overweight and obese BMI groups, respectively. With regard to effective dose (PCXMC calculations), an erect position increased the radiation dose by 38% for those with a normal BMI (P=0.074), and 65% (P<0.001) and 120% (P<0.001) for overweight and obese BMI groups, respectively. Moving to an erect position decreased the image quality by 6% and was statistically significant (P=0.009) for those with a normal BMI. This decreased by 10% (P<0.001) and 15% for overweight and obese BMI patients (P<0.001), respectively.

Table 7-5: The results of the differences between erect and supine positions, analysed separately by BMI group. Data represents the median (IQR).

BMI group	Normal BMI		Overweight BMI		Obese BMI	
Position	Supine	Erect	Supine	Erect	Supine	Erect
Antero posterior thickness, cm	21.0 (20-22)	23.8 (22-25)	21.8 (20-24)	26.0 (24-29)	26.5 (25-29)	31.5 (29-34)
DAP ($mGy*cm^2$)	508.5 (404-665)	724.5 (455-1106)	596.0 (519-667)	921.5 (816-1075)	1174 (885-1347)	2401(1630-3237)
Absorbed dose (mGy)	0.048 (0.036-0.058)	0.067 (0.042-0.093)	0.053 (0.048-0.063)	0.079 (0.071-0.102)	0.101 (0.081-0.120)	0.194 (0.139-0.272)
Effective dose (mSv)	0.094 (0.075-0.113)	0.130 (0.088-0.183)	0.095 (0.088-0.112)	0.157 (0.136-0.190)	0.147 (0.141-0.191)	0.324 (0.240-0.417)
% of maximum possible score	91 (89-94)	86 (75-90)	90 (82-92)	81 (78-85)	82 (78-90)	70 (58-79)

Spearman's correlation coefficient, calculated between the BMI and the differences in absorbed dose between erect and supine, was r= 0.660 (P<0.001) - see **Figure 7-6**. This indicates a moderate correlation between the increases in BMI and the differences between the erect and supine absorbed dose.

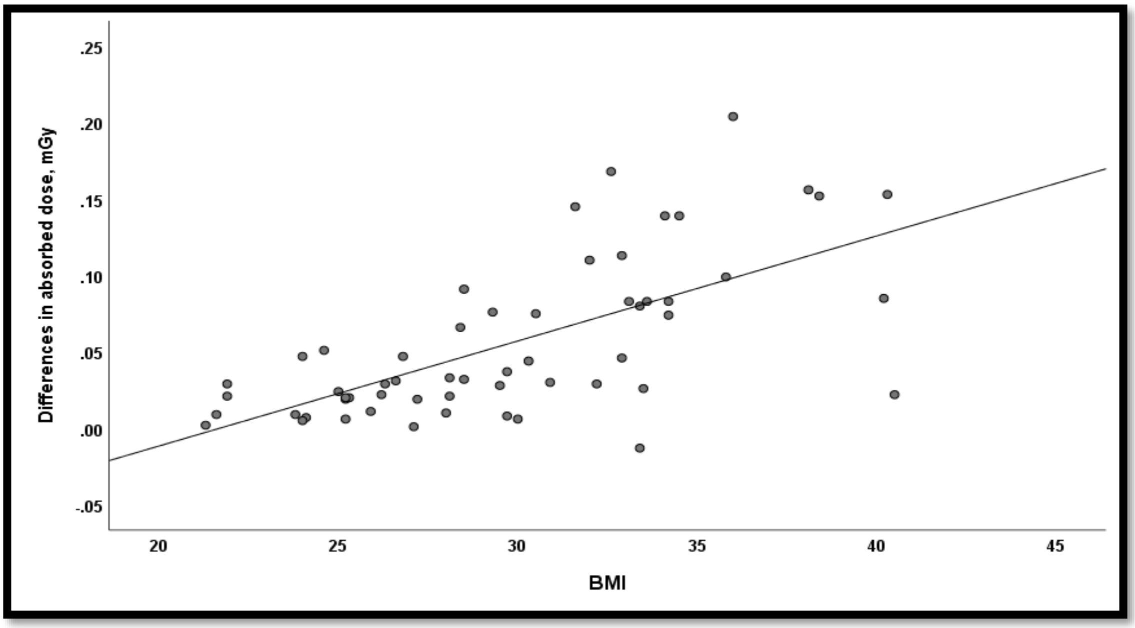


Figure 7-6: Illustrates the correlation between increasing BMI and the differences between the erect and supine position for the whole-body absorbed dose.

The Spearman's correlation coefficient, calculated between the BMI and the differences in image quality between the erect and supine, was r= - 0.304 (P=0.018) - see **Figure 7-7**. This indicates that there was a weak correlation between changes in the variables.

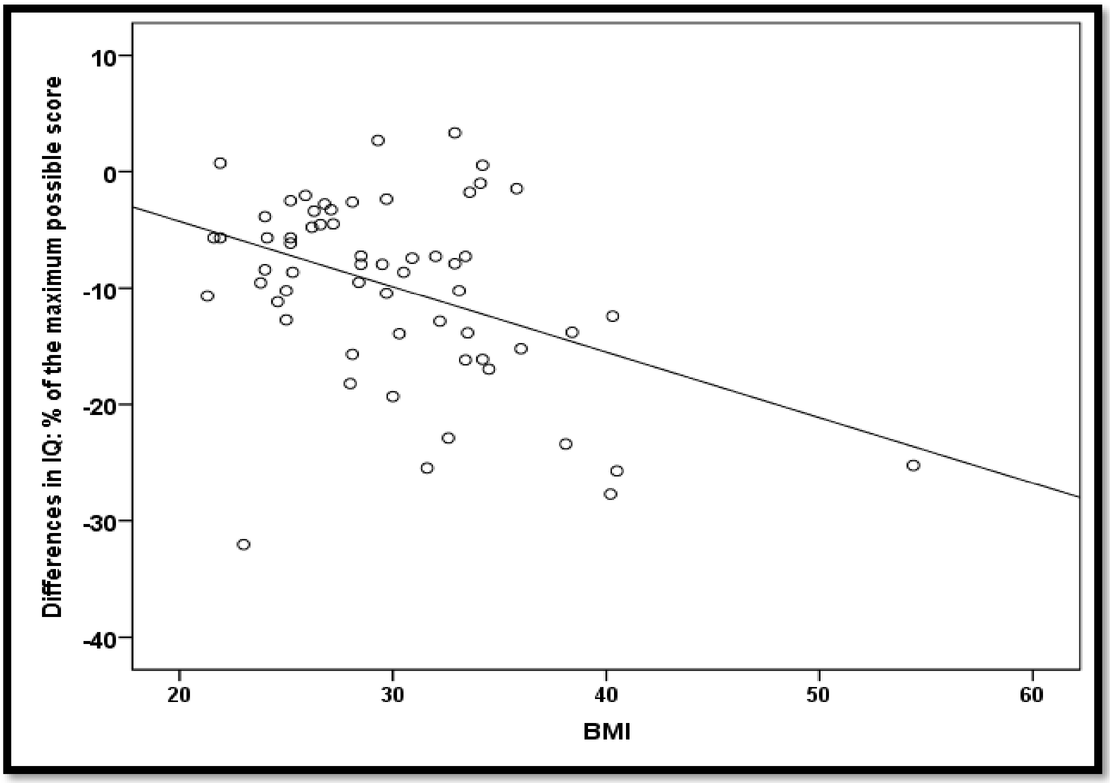


Figure 7-7: Illustrates the correlation between increasing BMI and the differences between the erect and supine position in image quality.

7.5 Discussion

Radiography of the pelvis and hips is the 3rd most frequent examination in terms of it is radiation dose contribution in the United Kingdom (UK) (D. Hart, Wall, Hillier, & Shrimpton, 2010). In addition, the pelvis contains the reproductive organs, which have been classified as the second most radiosensitive organs according to the ICRP publication 103 (ICRP, 2007). AP pelvis projections have been traditionally acquired in the supine position and literature still quotes the supine AP projection as the method of choice for most clinical indications (Alukic et al., 2018; Ballinger & Frank, 1999; Whitley et al., 2005). However, more recent studies have provided evidence that erect X-ray imaging of the pelvis offers better visualisation of functional anatomy (Fuchs-Winkelmann et al., 2008; Jackson et al., 2016; Troelsen et al., 2008). Many of these studies were undertaken by orthopaedic surgeons, with a focus on clinical outcomes rather than the development of radiographic techniques. Research involving medical imaging professionals is important to better understand the effects of moving from a supine to an erect position on radiation dose and IQ. The effect of different postures on IQ and radiation dose has been reported in several studies for different body parts, such as the lumbar spine, knee and abdomen (Alukic et al., 2018; Ben-Shlomo et al., 2016; Chaparian et al., 2014; Davey & England, 2015; Mc Entee & Kinsella, 2010; Mekiš et al., 2010; Nic An Ghearr & Brennan, 1998). Moreover, differences in IQ and radiation dose have also been identified for different patient and tube orientations (Chaparian et al., 2014; Davis & Hopkins, 2013; H. Mraity, England, & Hogg, 2017). Pelvic radiography was investigated in these previous research studies however only the differences between supine (AP) and prone (PA) projections were evaluated in terms of their radiation dose and IQ. No previous research has evaluated the differences in IQ and radiation dose between erect and supine positions for pelvis radiography.

7.5.1 Effect of switching from the supine to an erect position on anterior- posterior patient thickness

There were significant differences between the erect and supine positions in terms of anteroposterior patient thickness (see **Figure 7-1**). The use of the erect projection instead of a standard supine projection resulted in an increase in AP patient thickness of 17% [mean 3.9 (SD 2.7) cm]. The distribution of the fat could alter with respect to patient positioning. Metaxas et al. (2018) argued that, in the supine position, the abdomen, lumbar spine and pelvis absorbed lower effective dose than in the erect position. This is because, in the supine position, the percentage of the fat tissue may shift to the lateral positions. Importantly, the results of this study in this chapter and those of previous studies confirm that the diameter of the patient has a large influence on the radiation dose (Alukic et al., 2018; Brennan & Madigan, 2000). Differences between the erect and supine positions in terms of body part thickness could be mainly explained by the effects of gravity. Cassola et al (Cassola, Kramer, Brayner, & Khoury, 2010), when developing supine phantoms for dose calculations, found that when a standing person takes up a supine posture, the gravitational force causes a reduction of sagittal diameters - especially the abdominal, along with an increase of lateral diameters, especially at the dorsal part of the lower abdomen.

This effect is exacerbated as the BMI increases and as such more fat or soft tissue will be accumulated anteroposterior (**Table 7-5**). O'Neill et al (2018) found a strong correlation (r=0.83) between increasing BMI and the AP diameter used in CT scans for 50 patients with different BMIs. Also, Venara et al (2013) evaluated the distance between the abdominal organs and the surface. Their results showed a strong correlation between the distance and BMI (mean r 0.72), and the abdominal diameter (mean r=0.73).

There were almost an 8 cm increase in AP thickness between patients with normal and obese BMI in the erect position. When a person moves from supine to standing, gravitational forces will redistribute anterior fat by moving it inferiorly over the pelvis. This will have an effect on radiation dose, as has been reported previously (Alukic et al., 2018; V. O. Chan et al., 2012). This effect of positioning on changing body part thickness was reported in a lumbar spine radiography study too (Davis & Hopkins, 2013). Davis and colleagues found that the measurements on volunteer tissue thickness increased between 2 and 9 cm (mean 5 cm) for the lumbar region when rotating the patients from their side (decubitus) to their back (supine). This also increased the radiation dose. It is important to note that the work by Davis et al. did not evaluate volunteers standing in the erect position, but they did investigate two widely used radiographic positions for lumbar spine radiography. Alukic et al. found a 10% reduction in abdominal diameter when imaging patients in the supine PA [mean (SD); 21.2 (2.8)cm] position instead of AP [(mean (SD); 23.6 (4) cm] (Alukic et al., 2018). The results from Alukic et al. agreed with another study which found a decrease in abdominal thicknesses by 9.6% when using PA projection. The mean was 18.8 cm in AP, while in PA it was 17cm (Brennan & Madigan, 2000). The authors explained this reduction on patient thickness as being due to compression of the abdomen from lying prone in a PA position.

7.5.2 Effect of switching from the supine to an erect position on radiation dose

As this is the first study to evaluate the erect position, it is important to consider DAP in the erect position and how this differs from supine. DAP is available to the radiographer for evaluation after imaging acquisition, and is relevant for monitoring patient exposure in diagnostic radiology (Faulkner, Broadhead, & Harrison, 1999). DAP is used to determine dose reference levels (DRLs) (I. Heath, 2018), and it is often reported by researchers when comparing their results by use of DRLs (Alqahtani et al., 2019; Ciraj, Marković, & Košutić, 2005; Shandiz et al., 2014). The DAP was typically 46% greater in the erect position and was statistically significant ($P<0.001$). When comparing the whole-body absorbed dose, using the CALDose software, there was a 45% increase for the erect position ($P<0.001$) compared to that of the supine position (see **Figure 7-2**). This can be explained by the increase in the anterior-posterior patient thickness as gravity redistributes anterior fat by moving it inferiorly over the pelvis and increases as the BMI increases (see **Figure 7-8**). Increasing the thickness of the body part under investigation in AEC examination increases the radiation dose, as more X-ray photons are needed to penetrate the thicker body part. Another parameter that would potentially influence the radiation dose is BMI. This remained unchanged, and the size of the imaging field was also kept constant. It should be noted that during experiment #3 (phase two) the modification on phantoms was performed by only modelling the differences in anterior thickness between the two positions. The results indicated that the erect position increased the effective dose by 53% when compared with supine imaging. These results, together with the results presented in this chapter, confirmed that the difference between the two positions, in terms of anteroposterior thickness, is the main reason behind increasing the radiation dose.

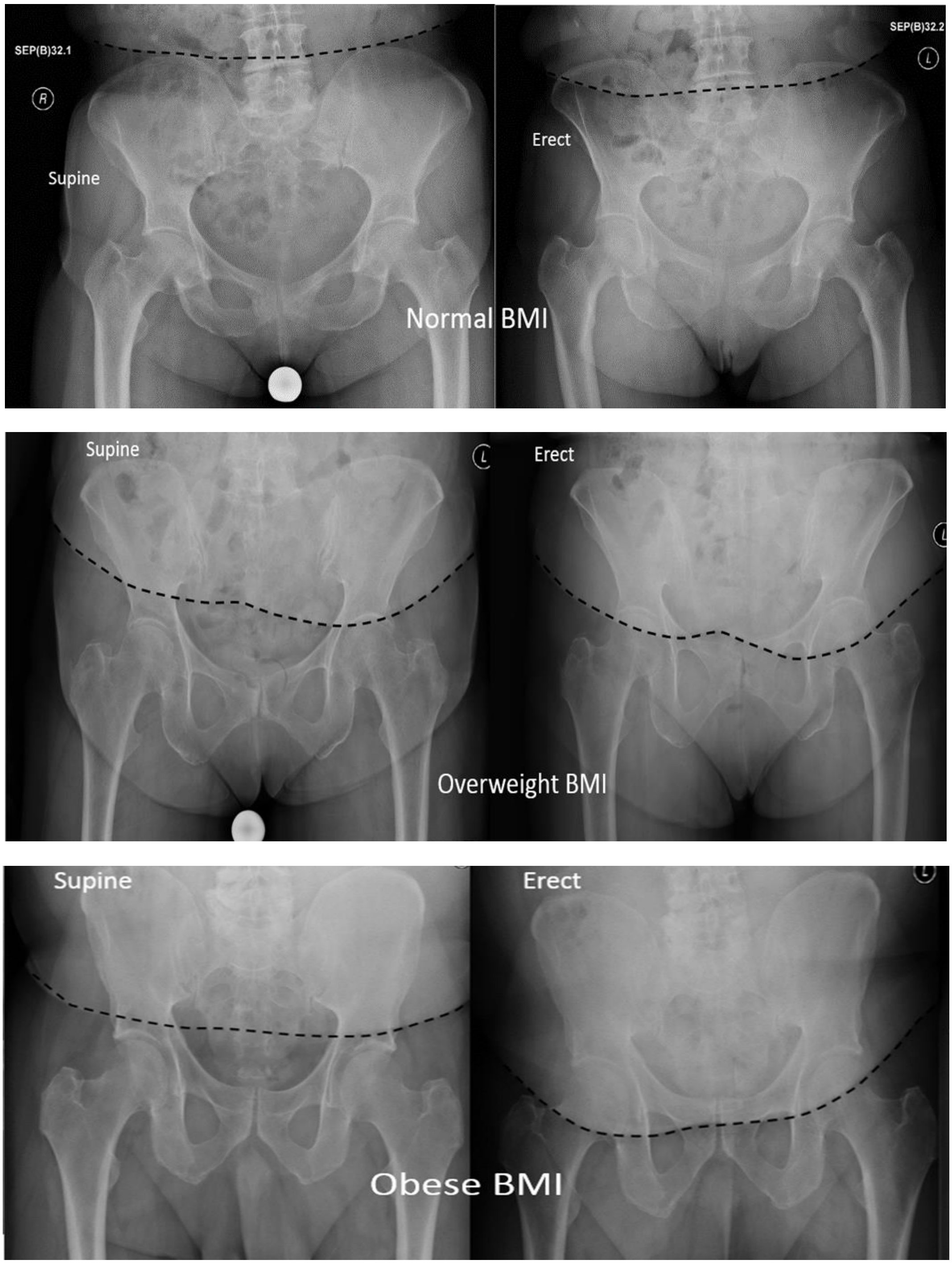


Figure 7-8: An example of clinical images in the supine and erect positions, demonstrating inferior displacement of anterior abdominal tissue with gravity for different BMIs. Dotted line is the level of the anterior soft tissue.

It is important to note that no previous research has evaluated a position that increased the radiation dose. However, efforts have previously been made to find a position that reduces radiation dose compared to the standard position (AP vs PA for lumbar spine radiography). The results reported in this thesis draw attention to a different situation. The erect projection increases the radiation dose. Moreover, no previous studies have considered the radiation dose while repositioning from supine to erect during pelvis radiography, which make comparison between other studies difficult. However, the effect of different positions for other body part on radiation dose will be explained. This is essential and valuable for understanding how varying the position can affect radiation dose. Using a PA projection instead of an AP has been used previously as a method for dose reduction (Alukic et al., 2018; Ben-Shlomo et al., 2016; Chaparian et al., 2014; Davey & England, 2015; Heriard, Terry, & Arnold, 1993; D. Johnston & Brennan, 2000; Mc Entee & Kinsella, 2010; Mekiš et al., 2010; Neto et al., 2018; Nic An Ghearr & Brennan, 1998). Clavicle radiography using a PA projection was shown to reduce the radiation dose administered to the breast by 56%, and 78% for the thyroid. Although this projection did reduce the image quality by 6.3% when compared with the AP projection, all of the PA images were diagnostically acceptable (Mc Entee & Kinsella, 2010). The results from a study performed by Mekis et al.(2010) demonstrated a dose reduction when comparing AP and PA projections of the sacroiliac joint. The reduction in DAP and ESD were 12.6% and 21% respectively, when using a PA projection. Hence, this reduced the volume of tissue being irradiated due to the compression effects of the PA position. There are different explanations for dose reduction when using a PA projection, such as tissue compression (smaller body part thickness), bones acting as a filter for radiosensitive internal organs and the increased distance of critical organs from the X-ray source. Displacement of tissue is the main factor that reduces dose in PA projection (Milner, 1989).

It has been proven that gravity acts on all the organs in the abdominal cavity (Howes et al., 2013; Polgar, 1946), and that different positions have an effect on the repositioning of the internal organs (Beillas et al., 2009; Hayes et al., 2013). Therefore, another possible explanation for the increased the absorbed dose in the erect position could be that some of the denser abdominopelvic organs move over the AEC chambers because of gravity. This would make the AEC increase the tube output to reach the required exposure level. However, this hypothesis is not supported by previous research and was not specifically studied within this thesis. Beillas and colleagues evaluated the effect of posture (standing, supine, steated) on internal organ positioning, volume and shape using erect MRI scanning in 9 males with normal BMI. They found 35 to 44mm of motion varaition of the abdominal organs (liver, kidneys, and spleen) between supine position and standing (Beillas et al., 2009). There were statistically significant differences in the positioning of the abdominal organs between the supine position and all other positions. Furthermore, besides the positional variations the anatomical position varied from person to person, especially for the kidneys. For this thesis, it is likely that the mobility of abdominal/pelvis tissues would have varied between patients and, as such, it is very difficult to predict organ motion. Such differences could affect the termination of the AEC and also the resultant dose modelling. For example, three patients with same BMI could have very different levels of abdominal/pelvic musculature. For one patient there may be no movement of the internal organs or soft tissue during repositioning, while for another there could be significant movement of soft tissues.

Ben-Shlomo et al. (2016) found that the main organs that account for the differences in absorbed dose are the breasts, colon, stomach, liver, and urinary bladder, in PA projections of the spine. The stomach, spleen, lower large intestine, small intestine, and pancreas were more affected in right lateral projections. Therefore, the moving of the more radiosensitive organs (such as colon and small intestine) to positions within the primary radiation field in the erect position may offer an explanation as to why the whole-body absorbed dose increased. CALDose software was used in dose calculations during this chapter, as it provides the calculations for the differences between the positions. In order to evaluate how the different positions of the organs, in the erect and supine positions, affected the dose calculations, further analysis was undertaken. A simulation of dose calculations was performed for males and females, along with range of different BMIs, but using the same ESD for both positions. Results showed only small variations between the two positions (0.003mGy for female and 0.004mGy for male), which provides further evidence that the variation in anterior thickness is the main cause of the increases in the radiation dose in the erect position.

Despite providing comprehensive training for the radiographers involved in this research on how to acquire erect pelvis radiography and the required centring points, subsequent variations in patient positioning and centring will affect the radiation dose (Manning-Stanley et al., 2012). An erect position is not the basic projection for examinations of the pelvis. Thus, increasing the experience of radiographers in how to obtain images in this position will likely reduce the radiation dose. Moreover, the AEC chamber locations between the two positions should be carefully considered, since, for the erect position, the vertical Bucky was used. However, the location and the orientation of the vertical Bucky were checked, and there were no differences in the AEC locations between the table and the vertical Bucky.

It should be noted that two different MC simulations were used in order to overcome the limitations for each of the simulations (PCXMX and CALDose). Study data showed an increase in ESD when using shorter SSDs, in both overweight and obese patients. The SSD should be used during the dose calculations in order to avoid the underestimation of the ESD calculations (Metaxas et al., 2018). SID is critically important, since a shorter SSD is associated with higher radiation doses and decreases the geometric sharpness. Also, there is a direct relationship between the field size and the quantity of scattered radiation. As the field size increases, the irradiated area increases, as does the scattered radiation. This can account for additional patient radiation doses without providing additional anatomic information (Modica, Kanal, & Gunn, 2011).

7.5.3 Effect of switching from the supine to an erect position on effective dose using PCXMC

The effective dose characterises the total body radiation damage from an exposure and is calculated by summing the mean absorbed dose of each tissue/organ multiplied by the relevant radiation tissue weighting factor. Different projections cause differences in the effective dose (D. R. Hart, Jones, Wall, & Great Britain., 1994; ICRP, 1996). These differences arise from the asymmetrical position of tissues and organs inside the body, the X-ray shielding of the organs by other organs or tissues, and the unique radiation sensitivity of each organ (Ben-Shlomo et al., 2016).

There was a 67% increase in E when moving from a supine to an erect position ($P<0.001$) (**Figure 7-3**). This can again be explained by the differences between the two positions in terms of anteroposterior patient thickness and/or internal organ re-positioning. The differences in the fat distribution between the positions will affect the effective dose (Metaxas et al., 2018). Therefore, the supine position results in a lower effective dose when compared with the erect position. It was proven that, as the abdominal fat thickness increases, the effective dose also increases (V. O. Chan et al., 2012). There was no previous effective dose data for to compare the erect positions with. However, a comparison is available for supine positions. The mean of the effective dose (0.1mSv) during this study is comparable with a study by Ofori et al. (2014) wherein they imaged 47 patients with an average age of 47 years. They found a 0.09 mSv effective dose for pelvis radiography.

Within this study, the acquisition parameters were determined from a pilot phantom study conducted during phase two (chapter six) of the experimental work in this thesis. It does, however, need to be considered that the results of the study could have been different if further dose optimisation had been performed for erect projections (using patients). Results from the phantom experiments must take into account that the phantom used was made of a rigid material that cannot represent the internal organ movement which could affect the dose. During this study, the erect position delivered a higher radiation dose. Therefore, as a part of the study protocol, the decision was made to increase the SID from 140 cm to 180 cm in order to minimise radiation dose. Previously, increasing SID has been used as a cheap and effective method to decrease the radiation dose, and has been reported by many authors (R. Heath et al., 2011; Joyce et al., 2013; J. Tugwell et al., 2014). However, the analysis comparing the differences in radiation dose between the two SIDs in this thesis did not show any statistical differences. This could be due to the small sample size which was not enough to achieve statistical significance.

The results from this study draw attention to a different situation that the erect projection increases the radiation dose. If this technique helps with the early diagnosis of osteoarthritis and can lead to early and more effective treatment, potentially saving the joint, then the erect position should be further optimised and included within practice. A further point for consideration is the potential for dose reduction by using high kVp. However, this could affect the contrast, and the corresponding image quality should always be taken into consideration during the optimisation process. This is because a very low dose may compromise the diagnostic quality of the images. In addition, by applying adequate/different filtration onto the X-ray beams, it is possible to achieve dose reduction while maintaining diagnostic information (Ekpo et al., 2014).

Using PA projection instead of AP has been used in the supine position as a method for dose reduction, and this can also be used in erect position in order to reduce the radiation dose. However, in order to implement this projection, the clinical implications should be evaluated in advance. Using compression is a method for dose reduction; however, this would also need further research to evaluate the effect of compression on pelvic tilt and whether it would be technically possible during erect imaging. Specific training of radiographers and continuous patient reviews would improve the radiographic practice for erect pelvis radiography (Aldrich, Duran, Dunlop, & Mayo, 2006; Vaño et al., 2007). In general, in order to obtain examination optimisation, it is necessary to know the factors that affect the radiation dose and image quality. Thus, the selection of the appropriate procedure can be achieved, given the clinical conditions (Uffmann & Schaefer-Prokop, 2009).

7.5.4 Effect of switching from the supine to an erect position on IQ

Figure 7-4 illustrates the percentage of the maximum possible image quality scores for erect and supine images. The maximum possible score was calculated because there were some image criteria that were missing from the image - for example, some patients were referred for hip and not pelvis radiography, and therefore the iliac crests were not visualised. The evaluation of image quality should consider this point. The evaluation was performed using 22 different criteria that were developed and validated by Mraity and colleges (H. A. A. B. Mraity et al., 2016). These 22 criteria cover anatomical, technical and positioning related items. It should be noted that all erect images were diagnostic, except three of the erect images for patients who were severely obese (BMI≥40). Therefore, it can be concluded that the acquisition factors proposed during phase two (chapter six) were generally fit for purpose. However, this should come with the caveat that further optimisation is needed. Moreover, this raises a question over the validity of the taking erect X-ray images of larger patients.

There was a 10% decrease in image quality when moving from a supine to an erect position, and this was statistically significant ($P<0.001$). This decrease in image quality is due to an increase in the scattered radiation as the anterior body part thickness increases. This effect appears to increase slightly as the BMI increases, as more fat or soft tissue accumulates anteriorly (**Table 7-5**. The increase in the thickness that covers the part under investigation decreases the image quality. The attenuation of the X-ray beam by the increased body fat results in reduced contrast resolution and increased noise in the X-ray images, as well as increased exposure times (Modica et al., 2011).

The quantity of scattered radiation is affected by patient thickness and degrades image contrast as it does not carry any information about the anatomy being imaged. Moreover, further data analysis was performed to evaluate if this reduction in image quality occurred in a consistent fashion across the whole [erect] image, or whether it just affected the area wherein the tissue was displaced to (the inferior anatomy). Results of this analysis showed that the area most affected by moving to an erect position was the sacrum and its foramina. Next were the pubic and ischium rami, the SI and hip joints. The clinician should understand that decreases in IQ predominantly affect these areas when they request erect pelvis radiography (**Figure 7-5**). The differences in IQ were less for structures around the hip joint and therefore may be acceptable for clinicians when seeking functional information on the hip joint.

7.5.5 Comparison between the erect and supine positions for different BMI groups

Further analysis of the differences between erect and supine positions, in terms of radiation dose and image quality was undertaken for different BMIs (**Table 7-5**). There was a statistically significant difference in anterior body part thickness between erect and supine for all different BMIs. As BMI increased, the anterior body thickness increased, and the differences between the erect and supine positions increased. There was an average increase in anterior body parts of 8 cm in the erect position, between normal and obese BMI patients. With regards to the radiation dose, an erect position increased the DAP, absorbed dose and effective dose by almost 40%, but this was not statistically significant for the normal BMI group. However, the differences between erect and supine in terms of DAP, absorbed dose and effective dose for patients in the overweight BMI group were more the 50%. This was statistically significant. For those in the obese BMI group, an erect position increased the DAP and effective dose by more than 100%. This can be explained by that, in an erect position, as BMI increases, antero-posterior body diameter measurement increases (**Table 7-5**). O'Neill et al. (2018) found a strong correlation (r=0.83) between BMI and anterior patient thickness.

Data for the normal BMI group, despite having increased the radiation dose, demonstrated that there were no significant differences between erect and supine positions. This suggests that using an erect position for people with normal BMI is acceptable and has no adverse consequences in term of radiation dose. However, this conclusion would need more consideration, as the sample size for normal BMI (10 patients) could be the reason its behind not achieving statistical significance despite having an increased dose of almost 40%. The correlation between the difference in the whole-body absorbed dose between erect and supine and increasing BMIs demonstrated a positive moderate correlation. As the BMI increased, the absorbed dose differences between erect and supine increased by 66%. This was statistically significant. This moderate correlation could be explained by the fact that there were differences in the fat distribution between the male and female torso: apple shapes for males and pear shapes for females (Fu, Hofker, & Wijmenga, 2015). These two shapes have differences in their accumulation anterior fat. If a person has an apple shaped, most of their weight will be above their hip compared, with those who are pear shaped wherein most is below the waist. Therefore, the radiation dose will be different between the shapes. Also, the correlation between the BMI and the differences in the radiation dose between the two positions could by stronger in the females (see **Figure 7-9**).

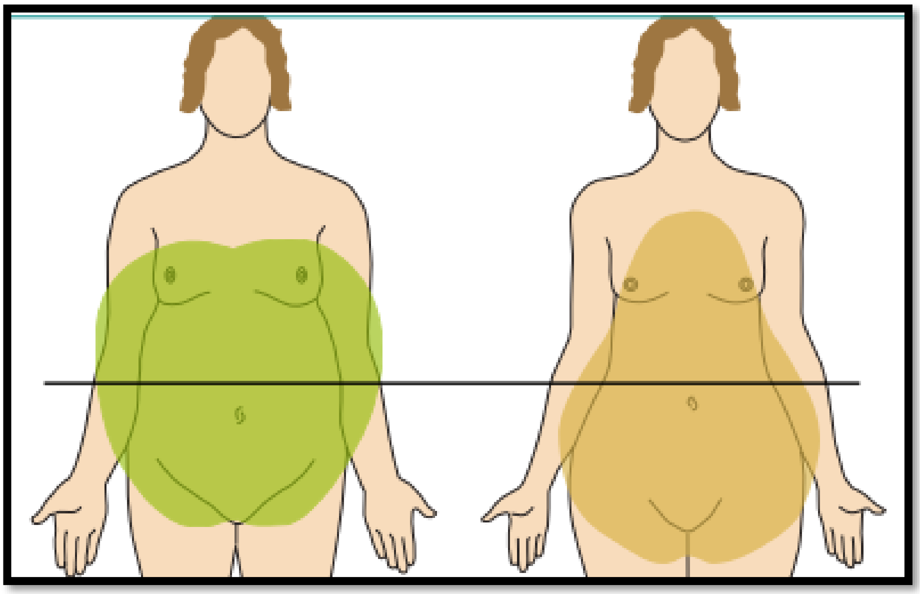


Figure 7-9: Appel and pear adipose tissue distribution. In an apple shape, most of the fat accumulates above the hips, compared to pear shaped where most of the fat accumulate below the waist (Sturman-Floyd, 2013).

With regard to the image quality, as the BMI increased the image quality decreased. The differences were not significant for normal BMI patients, however it decreased in the erect position by 15% for obese people. This was significant. There were weak correlations between increasing BMI and the differences in image quality between erect and supine, however this was significant. There was a -30% difference in image quality, between erect and supine positions, as the BMI increased (**Figure 7-7**). This was expected and could be explained by as the BMI increase the image quality will decrease regardless of the position, and therefore the image quality of both erect and supine will decrease as the BMI increase. Moreover, as the BMI increases there will be more soft tissue present, which produces more scattered radiation. This also will affect the IQ, regardless of the position. Also, subjective image quality evaluations contribute to the reasoning behind the research's not detecting any differences in IQ between the positions when BMI increased. This could because the reviewers gave the images of those with high BMIs low scores in both positions.

7.6 Limitations

The study reported in this chapter does suffer from a number of limitations. It must be noted that all patients were considered eligible for inclusion and the presence of hip prostheses and metallic implants impacted on the ability to evaluate some of the criteria. It might have been worthwhile selecting only the cases with the full range of pelvic anatomy. However, this would be difficult to achieve and would not reflect clinical practice, thereby limiting the generalisability of the study findings. During reporting it was noted that a number of erect images were of a lower image quality, whilst having a higher radiation dose. In line with the study protocol, it was decided that the SID would be increased to decrease the radiation dose. As a result, this has effectively split the erect data into two groups (140 and 180 cm SID). Data from both groups still supports the conclusion that switching from supine to erect causes a reduction in IQ and an increase in radiation dose. Erect acquisition parameters were formulated based on a phantom study (phase two, chapter six) and the intention was to identify the optimised parameters. It does, however, need to be considered that the results of the study could have been different if further dose optimisation was performed for erect projections, using patients instead of a phantom. The differences between the doses administered to internal organs in both positions was not investigated and thus the recommendation of using erect radiography for some cases cannot provided. The preference of performing the erect position by both the radiographers and patients was not evaluated and this could be the subject of further research. The effect of the erect position on patient and radiographer's examination time was also not evaluated.

As a result, data from this study can be considered indicative of likely trends, however a more comprehensive analysis of the differences between supine and erect pelvis radiography is warranted. Such studies should include a greater number of patients, greater attempts for dose optimisation and an evaluation of radiation dose, IQ and clinical metrics, i.e. joint space width, which could all help in the diagnosis of early OA.

7.7 Conclusion

An erect position for pelvis radiography was recommended by many researchers as it represents the functional position and may allow for the identification of more subtle pathologies. However, none of these studies have considered the effect of moving to an erect position on image quality and radiation dose. The results from this study demonstrated an increase in patient radiation dose and a decrease in image quality for erect pelvic radiography when compared with traditional supine positioning. This difference is mainly attributable to anterior body thickness which change due to gravity when moving to an erect position. Radiographers face a different situation when opting to use erect positions and the increasing in dose and reduction in image quality should be taken into account when justifying this type of examination. All erect images were diagnostically acceptable, except three for images, in which the patients were severely obese (≥40). This raises the question of the validity of using erect radiographs for larger patients. Ultimately, erect pelvis radiography is in need of further optimisation.

Chapter 8: Overall conclusion, limitations and recommendations for future work

8.1 Chapter overview

This final chapter starts with an overall summary of the thesis' achievements. The novelty of this thesis during the three experiments phases is also highlighted, and limitations and recommendations for future work are presented to help direct future researchers.

8.2 Overall summary of the thesis

This thesis aimed to ensure that X-ray images of the pelvis in erect position are performed using evidence-based protocols. It also determines if patient posture (erect or supine) has an effect on radiation dose and image quality. In this thesis the main findings from the literature about standing pelvic radiography were that there is variability in radiographic technique (see chapter 3). In these studies, the positions used to acquire images varied in different ways, such as using, or not using internal rotation of the patients 'feet. Also, within this literature, no explanations were given for the positions of the upper extremities during the procedures, which may also affect posture. A number of X-ray images were excluded from these studies as they did not meet the required criteria, and it is likely that variations negatively in posture might have influenced, negatively, image appearances. This therefore presents a limited and conflicting evidence base, with no agreed parameters for positioning. As a result, it was crucial in this work to understand the effects of variations of posture on the erect pelvic radiography technique. In this thesis, evaluation of posture was conducted without the use of ionising radiation to reduce potential risk. Therefore, due to these factors, the first study (**Phase one; chapter 4**) was conducted in this thesis. The aim of the first study was to evaluate the effect of different erect positions on pelvic and spine measurements. This was necessary to suggest a reliable and repeatable erect position which could be used in the clinical phase (**Phase Three; chapter seven**) in this thesis. Using video rasterstereography for pelvic and spine measurements was justified in this thesis as it carried no radiation risk. It is precise and highly reliable. Moreover, these devices can allow for the simultaneous assessment of both spine and pelvic posture. Eight different standing positions were examined during this study. The experimental positions were compared against a relaxed standing position. The results indicated that all experimental positions could be potentially used during erect pelvis radiography. The ICC for PT_{cor} ranged from 0.851-0.979, and the ICC of PT_{sag} ranged from 0.994-0.996 which indicated excellent reliability.

However, standing with an internal rotation of feet by 15-20° and with upper arms rested on support is recommended as it provided more information about the femoral head neck junction and proved to be the most reliable and repeatable position.

Importantly, no previous study has considered the radiation dose implications of having patient in the erect posture. Therefore, the second study (**Phase Two**; **chapter six**) in this thesis concentrated on identifying suitable acquisition parameters for erect pelvis radiography. The aim of this study was to propose, using phantoms, the optimal radiation acquisition parameters for erect pelvic radiography for use during the clinical study (**Phase Three; chapter seven**). It also looked to evaluate whether the practical supine acquisition parameters are applicable for erect position. This phase consisted of three experiments. In experiment #1, the pelvis phantom was modified by adding 1-15 cm of fat, and the images were acquired using different kVps. The results from this experiment provided the acquisition parameters for experiments #3. In experiment #2, anterior body thickness was collected from the patients who had been referred for pelvis radiography in both supine and erect positions. During experiment #3 a modification to a pelvis anthropomorphic phantom was performed in order to obtain pelvis X-ray images representing supine and erect positions. The modification was done by adding fat layers with different thicknesses to represents the erect and supine positions. Different acquisition parameters were used (kVp, SID, AEC). The comparison between radiation dose and image quality was performed between the positions. From the results, 90kVp, 145 SID and both outer chambers engaged were recommended for the clinical phase (**Phase Three; chapter seven**). These parameters provided the lowest differences between erect and supine in regard to image quality and delivering the lowest radiation dose. During the third phase (**chapter seven**), the pelvis X-ray images were obtained in both supine and erect positions from 60 patients. The aim of this study was to evaluate the differences between erect and supine positions on human volunteers. The results showed that the erect position increased the absorbed radiation dose by 45% ($P<0.001$) and decreased the image quality by 10% ($P<0.001$). This can be explained by the redistribution of the anterior thickness during the erect position. The erect position increases the anterior thickness by 17% ($P<0.001$) which has an effect on radiation dose and image quality.

To conclude, an erect AP projection should be obtained with the patient standing with their feet shoulder width apart and internally rotated by 15-20° and arms rest on supports. This position represents the most repeatable and reliable position see **Table 4-9.** Acquisitions should use 90kVp ,130/140cm SID and with additional Cu filtration using both outer chambers and will provide the lowest differences in image quality between supine and erect position and lower radiation dose.

8.3 Thesis novelty

The main novel contributions of this PhD thesis are summarised below:

- This is the first study to use videorasteography (Diers) methods to evaluate different positions for pelvis radiography. Also, for the first time, a series of postural measurement techniques, used to help define the optimum position for erect pelvic radiography based on the deficiencies identified in the literature have been described
- Seven patient positions have been recommended in order to obtain erect pelvis radiography images, and these can be used in clinical practice
- The differences between supine and erect pelvis radiography, in terms of image quality and radiation dose in both phantom and patient studies, were reported for the first time
- Acquisition parameters for erect pelvis radiograph based on phantom modifications have been recommended. These parameters assure the smallest differences between erect and supine in terms of radiation dose and image quality
- This is the first study to report radiation dose and image quality data for erect pelvis radiography. DAP and effective dose are reported too, giving more guidance to clinicians when imaging patients in the erect position for pelvis radiography
- Develop trial procedures, imaging protocols and patient information for a future study.

8.4 Limitations

This thesis suffers from limitations which should be considered:

Phase one: the average BMI of the participants was in the ‘overweight’ category, and increasing BMI could affect the performance of the standing position. The number of obese participants was just 17, although it was proven that obesity has an effect on postural instability (Son, 2016). Obese BMI should be considered in future work. Also, the number of females and males and the different BMI groups was not equal. A healthy group of participants was evaluated in this study. The effect of different standing positions on symptomatic groups is not known and should be considered in future work, as pelvic imaging is likely to involve such patients. However, this study could be considered as a basis for establishing positioning for erect pelvis radiographs. This is the main reason behind it is being focused on healthy group of participants.

Phase two: Using anthropomorphic phantoms is not representative of the human body as they have a lack of anatomical and pathological variation and are often at a set size. However, this limitation was over come in phase three. During ***experiment #1*** the only change was performed on kVp, though a full factorial analysis should have been considered. Also, using a single DR system should be considered as different DR and CR units may produce slightly different results. There are many different shapes for overweight and obese people, however this was not represented in the fat phantoms during ***experiment #3***. Moreover, in both experiment #1 and #3 the fat was positioned anteriorly. Different accumulation of the fat around the abdominal/pelvic regions could affect the results of the IQ and radiation dose. The effect of visceral fat should be considered when evaluating image quality and radiation dose. Using PCXMC could overestimate E, however 1^6 photons were used in order to reduce potential errors. Also, the phantoms represented obese BMIs. During practical pelvis radiography, there are other attenuators positioned on the pelvis, such as orthopaedic devices or gonad shielding, and these may affect exposure control.

Phase three: all patients were considered eligible for inclusion and the presence of hip prostheses and metallic implants impacted on the researchers' ability to evaluate some of the criteria. The number of the BMI groups was unequal, and a small number of 'normal' BMI patients participated in the study. In line with study protocol, it was decided to increase the SID and take advantage of the inverse effect of raising SID on radiation dose. As a result, this has effectively split the erect data into two groups (140 and 180 cm SID), however there were no significant differences between the groups in term of demographic data or radiation dose and image quality. Data from this study is considered indicative of likely trends, but such studies should include a greater number of patients, greater attempts for dose optimisation of technique and an evaluation of radiation dose, IQ and clinical metrics, i.e. joint space width, which could all help in the diagnosis of early OA.

8.5 Recommendations for future work

- The results from the first phase demonstrate seven options for positioning in erect pelvis X- ray imaging. However, further research is needed to find if a specific position is more favourable for each gender and for each BMI. Also, the effect of different standing positions with symptomatic patients should be evaluated

- A more comprehensive optimisation study is urgently needed for erect pelvis radiography to find the optimal acquisition parameters. Using high kVp and adding filtration are promising methods, as results from this thesis have demonstrated. Using compression could be used in order to reduce anterior patient thickness. However, the effect of compression on pelvic tilt should be evaluated first

- More research is needed to find if the erect position is appropriate for the investigation to any specific population group such as normal BMI or specific asymptomatic group such as OA patients

- Further research is needed to find differences between the two positions in regards of clinical appearance, and to evaluate if the change from supine erect has an effect on the overall diagnosis and radiological report. This research would need to restrict the erect position for a specific hip pathology

- Radiation dose and image quality comparisons between erect and supine positions for other anatomical areas, such as the abdomen and spine, could be carried out. The results from this thesis demonstrated the effect of gravity on the anterior abdominal thickness. This could affect the radiation dose and image quality when obtaining abdomen or spine images in an erect position

- Erect pelvis X- ray imaging needs to be explored more holistically using a variety of metrics, including examination time, patient comfort, and practitioner preference. This means further research would be needed to evaluate the erect position. The time needed to obtain this position should be evaluated and compared with the time needed for supine. Also, the impact of erect positioning on service delivery should be evaluated. Moreover, the ability of patients and radiographers to perform this position should be evaluated. This means finding out whether the position is acceptable for both patient and radiographer.

Appendices

Appendix 1: Summary of publications included within the review.

Table 1. Summary of publications included within the review.				
Authors/Year	**Aim / Purpose**	**Design / Methods**	**Key findings**	**Conclusions**
Evison et al.,1987	Determine if the joint space width (JSW) differs between supine and erect positions.	**n**=21 **Subjects:** with prostheses and normal. **Method:** supine and standing pelvis radiography.	Less than 1 mm difference in JSW between the two positions.	No significant differences.
Anda et al., 1990	Measured pelvis inclination in supine and standing positions.	**n**= 40 **Subjects:** healthy adults. **Method:** pelvic inclinometer.	Increased pelvis inclination by 0.4° in males and 2.3° in females, between positions.	No significant differences.
Konishi et al., 1993	Establish a method for estimating acetabular coverage.	**n**=54 **Subjects:** healthy volunteers. **Methods:** antero-posterior (AP) and lateral X-ray images.	Increased pelvic tilt (PT) by 5° between positions.	Significant differences identified (PT).

Auleley et al., 1998	Evaluate the effect of erect position on JSW measurements for pelvis radiography.	**n**= 46 **Subjects:** patients with and without osteoarthritis (OA). **Methods:** supine and standing pelvis radiography using fluoroscopy.	Differences in JSW were less than or equal to 0.64 mm.	No significant differences.
Ala Eddine et al., 2001	Determine whether the pelvic equilibrium is constant over time and between standing and supine positions.	**n**= 24 **Subjects:** healthy adults. **Methods:** standing and supine lateral X-ray images.	Increased angulation in erect position ranging from 6° to 8°.	Significant differences identified (pelvic version).
Nishihara et.al 2003	Evaluate the safe zone of the acetabular component between supine, erect and sitting.	**n**= 101 **Subjects:** total hip arthroplasty (THA) patients. **Methods:** erect, sitting pelvis X-ray images and supine images obtained from CT scans.	10º or less difference in pelvic flexion angle between the two positions.	No significant differences.
Lembeck et al 2005	Evaluate the impact of PT on cup orientation.	**n**= 30 **Subjects:** healthy people. **Methods:** inclinometer.	Increase PT by 4° in erect positions.	Significant differences identified (PT).

Mayr et.al, 2005	Evaluate the changes in pelvic inclination between erect and supine.	**n**= 120 **Subjects:** healthy adults. **Methods:** 3-dimensional digitising arm (equipment used for generating a computer model from a physical object by sampling 3D co-ordinates).	Increase PT by 1° in erect positions.	No significant differences.
Troelsen et al., 2008	Whether the weightbearing position alters radiographic interpretation	**n**= 41 **Subjects:** dysplasia patients. **Methods:** erect and supine X-ray images.	Increase in PT for males (6° to 7°) and females (13° to 14°).	Significant differences identified (PT).
Babisch et al., 2008	Study the effect of position on PT and cup values.	**n=** 40 **Subjects:** dysplasia and OA patients. **Methods:** CT and lateral X-ray images.	Decrease in PT by 5.4°in the erect position.	Significant differences identified in PT.
Fuchs-Winkelmann et al., 2008	Whether OA signs and angles differ between supine and erect.	**n=** 61 **Subjects:** developmental dysplasia of the hip (DDH) patients. **Methods:** supine and erect pelvis X-ray images.	Central edge angle (CEA) less for erect by 3.6° and JSW by 0.49 mm.	Significant differences identified in CEA & JSW.

Okano et al., 2008	Compare the differences in JSW between supine and erect.	**n=**162 **Subjects:** OA patients. **Methods:** erect and supine X-ray images using fluoroscopy.	JSW shorter by 0.52 mm in the erect position.	Significant differences identified (JSW).
Terjesen et al., 2012	Examine the reliability of radiographic measurements for DDH patients and if these differ between supine and erect.	**n=**51 **Subjects:** DDH patients. **Methods:** supine and erect pelvis X-ray images.	Difference in CEA from supine to erect was -1.1 to 0.0. Less than 0.1 mm difference in JSW between the two positions.	No significant differences.
Lazennecet al, 2011	Compare the acetabular component between erect, supine and sitting positions.	**n=**328 **Subjects**: THA patients. **Methods**: erect and sitting pelvis radiography while supine images obtained using computed tomography (CT) scans.	Increased cup anteversion by 7.5º in erect position.	Significant differences identified (cup anteversion).
Miki et al., 2012	Evaluate functional pelvis position in erect and supine.	**n=**91 **Subjects**: THA patients. **Methods**: navigation system.	Pelvis inclination ranged from -21º to 5º.	No significant differences.

Polkowski et al., 2012	Differences in acetabular cup measurements between erect and supine position.	**n=**46 **Subjects**: THA patients **Methods**: EOS for erect position. Supine position obtained from CT scan.	Increase of more than 5º in cup anteversion in the erect position.	Significant differences identified (cup anteversion).
Tamura et al., 2014	Evaluate the changes in pelvic sagittal inclination (PSI) between erect and supine.	**n=**163 **Subjects:** THA patients. **Methods:** pelvis and spine lateral radiography erect. Supine radiography obtained from CT scans.	Changes in PSI was -6.9° from supine to erect.	Significant differences identified (PSI).
Au et al., 2014	Identified if the safe zone varied between erect and supine.	**n=**30 **Subjects:** THA patients **Methods:** AP and lateral X-ray images in supine and erect positions.	Reduction in PT by 9.0° and increase in anteversion by 10.2° in erect. Increase pelvis inclination by 2.2° in the erect position	Significant differences identified (PT, anteversion & inclination).
Ross et al., 2015	Studied the impact of the position on acetabular version and range of motion (ROM).	**n=**50 **Subjects**: Femoroacetabular impingement (FAI) patients. **Methods**: erect pelvis X-ray images, supine X-ray images obtained from CT scans.	Increase by 2º on acetabular version and 3º on hip flexion in the erect position.	Significant differences identified (acetabular version & ROM)

Dhakal et al., 2015	Demonstrate the differences between erect and supine of lumbosacral region.	**n=**23 **Subjects**: spondylolisthesis patients **Methods**: erect and supine lateral X-ray images.	Increase lumbar lordosis by 8° in erect position.	Borderline significant differences identified (lordosis)
Tiberi et al., 2015	Evaluate the change in acetabular component between the erect and supine.	**n=**113 **Subjects**: THA patients **Methods**: supine pelvis radiography. EOS in the erect position.	Increase in acetabulum inclination and version was 4.6° and 5.9°, respectively in the erect position.	Significant differences identified (acetabular inclination and version)
Khan et al., 2016	Assess the changes of acetabular orientation between erect and supine.	**n=**14 **Subjects**: THA patients. **Methods**: supine and erect pelvis radiography.	Increase in cup anteversion by 1.84º in the erect position.	Significant differences identified (cup anteversion).
Jackson et al., 2016	Evaluate the differences between erect and supine for pincer-FAI patients.	**n=**46 **Subjects**: FAI patients **Methods**: erect and supine pelvis radiography.	Cross over sign decreased by 11% and inclination angle increased by 1.1°	Significant differences identified (crossover sign, inclination angle)

Pierrepont et al., 2017	Presented changes to PT for different functional positions.	**n=**1517 **Subjects**: THA patients. **Methods**: erect and sitting lateral X-ray images. Supine X-ray images obtained from CT scans.	Pelvis rotation by 6° from supine to erect.	Significant differences identified (PT).
Tamura et al., 2017	Evaluated the differences in PSI between erect and supine.	**n=**70 **Subjects**: THA patients **Methods**: erect pelvis radiography. Supine images obtained from CT scans.	More than 10º differences in PSI from erect to supine position.	Significant differences identified (PSI).

Appendix 2: Ethical approval letter for phase one.

University of Salford MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

26 June 2017

Dear Kholoud,

RE: ETHICS APPLICATION–HSR1617-142–'Evaluation of a range of different patient positions for undertaking erect pelvis radiography examinations using the Diers system.'

Based on the information you provided I am pleased to inform you that application HSR1617-142 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Appendix 3: Ethical approve for observer study (phase two)

University of Salford MANCHESTER

Research, Enterprise and Engagement
Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

14 November 2017

Dear Kholoud,

RE: ETHICS APPLICATION–HSR1718-022–'Evaluation of radiation dose and image quality for AP pelvis phantom imaging using a range of fat thickness.'

Based on the information you provided I am pleased to inform you that application HSR1718-022 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

Appendix 4: NHS approval letter

NHS
Health Research Authority

Mr Kevin Flintham
Advanced Radiographer Practitioner
Mid Yorkshire Hospitals NHS Trust
Aberford Road
Wakefield
W Yorkshire
WF1 4DG

Email: hra.approval@nhs.net

02 January 2018

Dear Mr Flintham

Letter of HRA Approval

Study title:	**A pilot study to compare supine and erect pelvis radiographs – assessment of impact on radiation dose and diagnostic quality**
IRAS project ID:	**234096**
REC reference:	**17/YH/0363**
Sponsor	**Mid Yorkshire Hospitals NHS Trust**

I am pleased to confirm that **HRA Approval** has been given for the above referenced study, on the basis described in the application form, protocol, supporting documentation and any clarifications noted in this letter.

Participation of NHS Organisations in England

The sponsor should now provide a copy of this letter to all participating NHS organisations in England.

Appendix B provides important information for sponsors and participating NHS organisations in England for arranging and confirming capacity and capability. **Please read *Appendix B* carefully**, in particular the following sections:

- *Participating NHS organisations in England* – this clarifies the types of participating organisations in the study and whether or not all organisations will be undertaking the same activities
- *Confirmation of capacity and capability* - this confirms whether or not each type of participating NHS organisation in England is expected to give formal confirmation of capacity and capability. Where formal confirmation is not expected, the section also provides details on the time limit given to participating organisations to opt out of the study, or request additional time, before their participation is assumed.
- *Allocation of responsibilities and rights are agreed and documented (4.1 of HRA assessment criteria)* - this provides detail on the form of agreement to be used in the study to confirm capacity and capability, where applicable.

Further information on funding, HR processes, and compliance with HRA criteria and standards is also provided.

Page **1** of **8**

Appendix 5: Ethical approval from university of Salford for NHS study

University of Salford MANCHESTER

Research, Enterprise and Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

23 February 2018

Dear Andrew and Kholoud,

RE: ETHICS APPLICATION–HSR1718-052 – 'A pilot study to compare supine and erect pelvis radiographs - assessment of impact on radiation dose and diagnostic quality.'

Based on the information that you have provided, I am pleased to inform you that approval is hereby granted to undertake the analysis of anonymised data at the University of Salford as part of the above-named project (for which the Mid Yorkshire NHS Trust has already gained HRA approval – IRAS project ID 234096).

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Appendix 6: Participant consent form for phase one

Title of study: Evaluation of a range of different patient positions for undertaking erect pelvis radiography examinations using the Diers system.

Name of Researcher: Kholoud Alzyoud

Ethics REF NO: HSR1617-142

Please complete and sign this **form after** you have read and understood the participant information sheet. Read the statements below and answer yes or no, as applicable in the box on the right-hand side.

1. I confirm that I have read and understand the participant information sheet version 2 dated 22-Jun-2017 for the above study. I have had opportunity to consider the information and ask questions (face to face and by email). **Yes/No**

2. I understand that my participation is voluntary and that I am free to withdraw at any time, **without giving any reason**. If I decide to withdraw I understand that the information I have given will be destroyed (provided that you withdraw in a period of 3 months from your data collection). **Yes/No**

3. My participation in this research will involve different standing postures, which have been explained to me by the researcher. **Yes/No**

4. I agree to participate by having my back-surface measurements taken using the Diers system and have my pelvis tilt angle measured using the goniometer. **Yes/No**

5. I understand that my data will be used in the researcher's thesis, academic publications and conferences presentations. However, I understand my data will be anonymised and will be stored by code on a password protected University computer. My data will be given a unique participant identifier code and no identifiable information will be retained. **Yes/No**

6. I agree to take part in the study. **Yes/No**

Name of participant: ...., Code: ....

Date: ....

Signature: ....

Name of researcher taking consent	**Kholoud alzyoud**
Researcher e-mail address	k.alzyoud@edu.salford.ac.uk
Research supervisor	Andrew England
Supervisor e-mail	a.england@salford.ac.uk

Appendix 7: Participant information sheet for phase one

PARTICIPANT INFORMATION SHEE

Title of study: Evaluation of a range of different patient positions for undertaking erect pelvis radiography examinations using the Diers system.

We are researchers who are interested in investigating variations in pelvis angle (orientation) during different standing positions. We are inviting you to take a part in our research study to find a standard (best) position for standing pelvis radiography.

If you are interested in the research topic and before you decide to participate in this study or not, you need to know the rationale, benefits, limitations and what would be involved for you. Please take your time and read the attached information as this provides more details. If you have any questions and need more explanation, please do not hesitate to contact the lead research (contact details at the end of this document).

What is the purpose of the study?

The purpose of this study is to investigate the effect of different standing posture on pelvis angle (tilt). Findings will help us to suggest a standard (best) position for pelvis radiography when performed in a standing (erect) position.

Why have I been invited to take part?

Osteoarthritis (OA) will be the fourth main cause of disability in UK by 2020. 2.46 million people in England currently have OA of hip joint and thankfully it is treatable. Treatment success is dependent on good monitoring of the hip joint and this is commonly by radiography. Radiography of the hip joint allows surgeons to plan treatment but the X-ray must accurately reflect the position of the bones and joints. Many hospitals now image the hip joint with the patient in a standing position. There are many options for different standing positions and it is important to know what effect this can have on the visibility of the hip anatomy. You have been invited to participate as we would like to know how the pelvis angle (orientation) varies for different standing positions when compared with how you would normally 'naturally' stand. Obtaining data in this area will allow us to recommend to hospitals an optimum position for pelvic / hip radiography.

Do I have to take part?

You are the only one who decides whether to take part in this study or not. We will provide you of all the information that you require. You can also decide whether to withdraw from study at any time. If you withdraw up to 3 months after data collection you can also opt to have all of your study data destroyed.

what will happen to me if I take part

If you are one of our study participants, you need to attend one measurement session which will last approximately 30 minutes (in the University of Salford).

During this session, you will be asked to read and sign the consent form. The researcher will help you to complete the information needed in a short data collection sheet i.e. age, height and weight. We will then ask you to change your clothes in private changing room, this includes taking off the upper part of your clothes and wearing a gown. The gown will cover the front part of your body while your back will be bare in order for the system to take a number of skin surface measurements using light. Also, you will be required to wear sport shorts in order to allow palpation of several pelvic bony landmarks. After changing yours clothes the researcher will mark the bony landmarks (anterior and posterior superior iliac spine) by temporary markers (stickers), which will be used for measuring pelvic tilt with the inclinometer. You will be instructed to stand at certain point on the floor with your back in front of Diers (measurement) system, you will perform eight different standing positions as follows:

1. Usual standing position, arms by sides.
2. Usual standing position, arms by sides, feet internally rotated.
3. Usual standing position, arms crossed over chest.
4. Usual standing position, arms crossed over chest, feet internally rotated.
5. Usual standing position, arms flexed and your hands rest on your clavicle.

6. Usual standing position, arms flexed and your hands resting on your collar bones, feet pointing inwards.
7. Usual standing position, hands on a support provided by the researcher.
8. Usual standing position, hands on a support (provided by the researcher), feet pointed inwards.

In order to help you, for each position, the researcher will show you how stand.
While you are standing for each position, pelvis tilt will be measure by putting the inclinometer against the markers (stickers) that were placed on your pelvis. Then the camera of the Diers system will be adjusted to a suitable height, so your spine will be at the center view for acquire posture data. Horizontal light lines will be projected on your back to allow Diers system to collect data. In the exam room the light will be dimmed appropriately, so the projected lines on your back are sharp and visible by the system. Each position (posture) will take approximately 6 seconds to complete. You will ask to take a few steps between the different positions. The purpose of these steps is to allow you chance to forget the previous position, so that we can capture new data.

Expenses and payments?

No payment will be provided for participates in this study

What are the possible disadvantages and risks of taking part?

There are no disadvantages or known risks from participating in this study. The Diers system is one of the most commonly used systems for non-invasive evaluations of body posture, and it is free from any known risks, it does not use ionising radiation. It only uses the light and camera to take a picture and measurements of your back. The inclinometer is safe and free from known risks, it has just two arms (plastic strips) and will be positioned two bony landmarks on your pelvis.

What are the possible benefits of taking part?

The information we get from you and the other participants will provide us with a clear idea about the effect of different standing positions on pelvis angle (tilt). This will help us to provide evidence for the optimum position for standard pelvis X-ray examinations performed in standing position. This will help people suffering from osteoarthritis and those with other diseases of the hip joint who are undergoing radiography.

What if there is a problem?

It is unlikely that problems will happen. However, if you have any concerns about this study please contact the lead researcher Kholoud Alzyoud or one of the research supervisors, Andrew England or Peter Hogg. However, if you remain dissatisfied please contact Dr Jo Cresswell, Associate Director Research, Research & Enterprise Division, Room 208, Joule House, University of Salford, Salford, M5 4WT. Tel: 0161 295 6355. E: j.e.cresswell@salford.ac.uk

Will my taking part in the study be kept confidential?

All information which collected as part of this research will be kept strictly confidential. All your information (name, contact details, Diers data) will be pseduoanonymised (coded) and stored on protected computer by password, used and transferred by only by the lead researcher or one of the supervisors. Any information which leaves the University of Salford relating to your participation will have your name and contact details removed so you can not be identified.

What will happen if I don't carry on with the study?

All the information that has been collected from you will be destroyed (provided that you withdraw in a period of 3 months from your data collection). There will be no other penalties for withdrawing from the study.

What will happen to the results of the research study?

The findings of this study will form a chapter in a PhD thesis. Any new and significant results will be published in academic journals and presented at scientific conferences.

Who is organising or sponsoring the research?

The University of Salford, Manchester, UK.

Further information and contact details:

If you need more information or enquires about this research, please contact
Kholoud Alzyoud

Appendix 8: Data collection sheet for phase one

Project title: Evaluation of a range of different patient positions for undertaking erect pelvis radic raphy examinations using the Diers system.

Today's Date:	Participant number:	
Date of birth:	Gender:	Phone Number:

Height:	Weight:	BMI:

	Yes	No
Do you suffer, or have you ever suffer from, musculoskeletal injury (spine, pelvis, hip)?		
Have you had presently spine or hip joint pain i.e. Low back pain?		
Have you had been injured or have pelvis or spine surgery during past six months (fracture, total hip arthroplasty)?		
Do you suffer, or have you ever suffer from, neurological problems, pathological or congenital abnormality in spin/hip/pelvis or gait i.e. scoliosis?		
Have you had ever lower limb fracture or surgery?		
Have you had Tattoos or scarring of the back?		
Have you had done you daily activity without any complain?		
Can you maintain a standing position (for 6 to 10 seconds) independently?		
For females: are you pregnant or has given birth within the last 12 months?		

Appendix 9: Participant information sheet for experiment #1

PARTICIPANT INFORMATION SHEET

Title of study: Evaluation of radiation dose and image quality for AP pelvis phantom imaging using a range of fat thickness

I am a researcher who is assessing the impact of fat thicknesses on AP pelvis x-ray imaging. I wish to invite you to take a part in my research study in order to find a set of exposure factors for imaging the pelvis of overweight and obese people.

If you are interested in the research topic and before you decide to participate in this study or not, you need to know the rationale, benefits, limitations and what would be involved for you. Please take your time and read the information as this provides more details. If you have any questions and need more explanation please do not hesitate to contact me (contact details at the end of this document).

What is the purpose of the study?

The purpose of this study is to investigate the effect of fat thicknesses on radiation dose and image quality for AP pelvis x-ray imaging.

Why have I been invited to take part?

In order to achieve the aims and objectives of this study I need six participants (qualified radiography PhD students and/or staff) to grade radiographic image quality. This will provide data on the variability of image quality scores both between and within participants. You have been approached because of your abilities in medical imaging.

Do I have to take part?

You are the only one who decides whether to take part in this study or not. You can also decide whether to withdraw from study at any time. If you withdraw all of your study data destroyed.

What will happen to me if I take part?

If you decide to take part in this study, then you will be asked to review some phantoms images on a radiology computer workstation (5 megapixel) and make judgements on the image quality. Regarding the adult anthropomorphic pelvis phantom images, the 2AFC method using the software described by (Hogg & Blindell 2012) will be used to assess the images by applying 5 point Likert scale. The observers will decide whether the image quality is: much worse, slightly worse, equal to, slightly better, or much better than that of a reference image. 15 criteria were chosen based on validated study done by (H. Mraity et al., 2017) as following:

In total, it will take two hours to evaluate the images; this time will be broken down into four image viewing sittings. For each sitting it is expected that you will be required to spend around 30 minutes evaluating images. Your visit will be arranged at a mutually convenient time. Any information that you provide will remain confidential and will only be used in obtaining the research objective.

Item	Criteria
1	The left hip joint is adequately visualized.
2	The right hip joint is adequately visualized.
3	The left lesser trochanter is visualized adequately.
4	The right lesser trochanter is visualized adequately
5	The left greater trochanter is visualized adequately
6	The right greater trochanter is visualized adequately
7	The right sacro-iliac joint is adequately visualized.
8	The left iliac crest is visualized adequately.
9	The right iliac crest is visualized adequately
10	Left acetabulum is visualized clearly
11	Right acetabulum is visualized clearly.
12	The pubic and ischial rami are not adequately visualized.
13	The both femoral necks are visualized adequately
14	The medulla and cortex of the pelvis are adequately demonstrated.
15	There is a significant amount of noise in this image.

Expenses and payments?

No payment will be provided for participates in this study.

What are the possible disadvantages and risks of taking part?

There are no disadvantages or known risks from participating in this study. The study will involve grading image quality for a series of images presented on a computer monitor. It is possible that you could realize that you have an eye sight related problem by participating in this study. The risk of this is extremely small and if this situation did arise then the study researcher would recommend that you see an Optician or your General Practitioner.

What are the possible benefits of taking part?

Your results will help me to develop a protocol for imaging pelvis for obese and overweight people.

What if there is a problem?

It is unlikely that problems will happen. However, if you have any concerns about this study please contact the lead researcher **Kholoud Alzyoud** (k.alzyoud@edu.salford.ac.uk) or one of the research supervisors, **Andrew England (**A.England@salford.ac.uk) or **Peter Hogg (**p.hogg@salford.ac.uk**)**. However, if you remain dissatisfied please contact Professor Sue McAndrew (S.McAndrew@Salford.ac.uk)

Will my taking part in the study be kept confidential?

All information which is to be collected as part of this research will be kept strictly confidential. All your information (name, contact details) will be (coded) and stored on a protected computer by password, used and transferred by only by the lead researcher or one of the supervisors. Any information which leaves the University of Salford relating to your participation will have your name and contact details removed so you can not be identified. Only data essential for the study objectives will be stored in hardcopy and electronic formats.

What will happen if I don't carry on with the study?

All the information that has been collected from you will be destroyed (provided that you withdraw in a period of 3 months from your data collection). There will be no other penalties for withdrawing from the study.

What will happen to the results of the research study?

The findings of this study will form a chapter in a PhD thesis. Any new and significant results will be published in academic journals and presented at scientific conferences.

Who is organizing or sponsoring the research?

The University of Salford, Manchester, UK.

Further information and contact details:

If you need more information or enquires about this research, please contact

Kholoud Alzyoud (k.alzyoud@edu.salford.ac.uk).

Appendix 10: Participant consent form for phase two

Title of study

Evaluation of radiation dose and image quality for AP pelvis phantom imaging using a range of fat thickness.

Ethics REF NO: HSR1718-022

Please complete and sign this **form after** you have read and understood the participant information sheet. Read the statements below and answer yes or no, as applicable in the box on the right-hand side.

1. I confirm that I have read and understand the participant information sheet version 3 Dated 7-Dec-2017 for the above study. I have had opportunity to consider the information and ask questions (face to face and by email).	Yes/No
2. I understand that my participation is voluntary, no financial benefit and that I am free to withdraw at any time, **without giving any reason**. If I decide to withdraw. I understand that the information I have given will be destroyed (provided that you withdraw in a period of 3 months from your data collection).	Yes/No
3. My participation in this research will involve scoring different pelvis radiography using relative visual grading, which have been explained to me by the researcher.	Yes/No

And if I decided to participate in the extra part (clinical part) I will evaluate the images (by answering the question is the image adequate for clinical diagnosis or not) depending on clinical criteria.

4. I understand that my data will be used in the researcher's thesis, academic publications and conferences presentations. However, I understand my data will be anonymized and will be stored by code on a password protected University computer. My data will be given a unique participant identifier code and no identifiable information will be retained.	Yes/No
5. I agree to take part in the study.	Yes/No

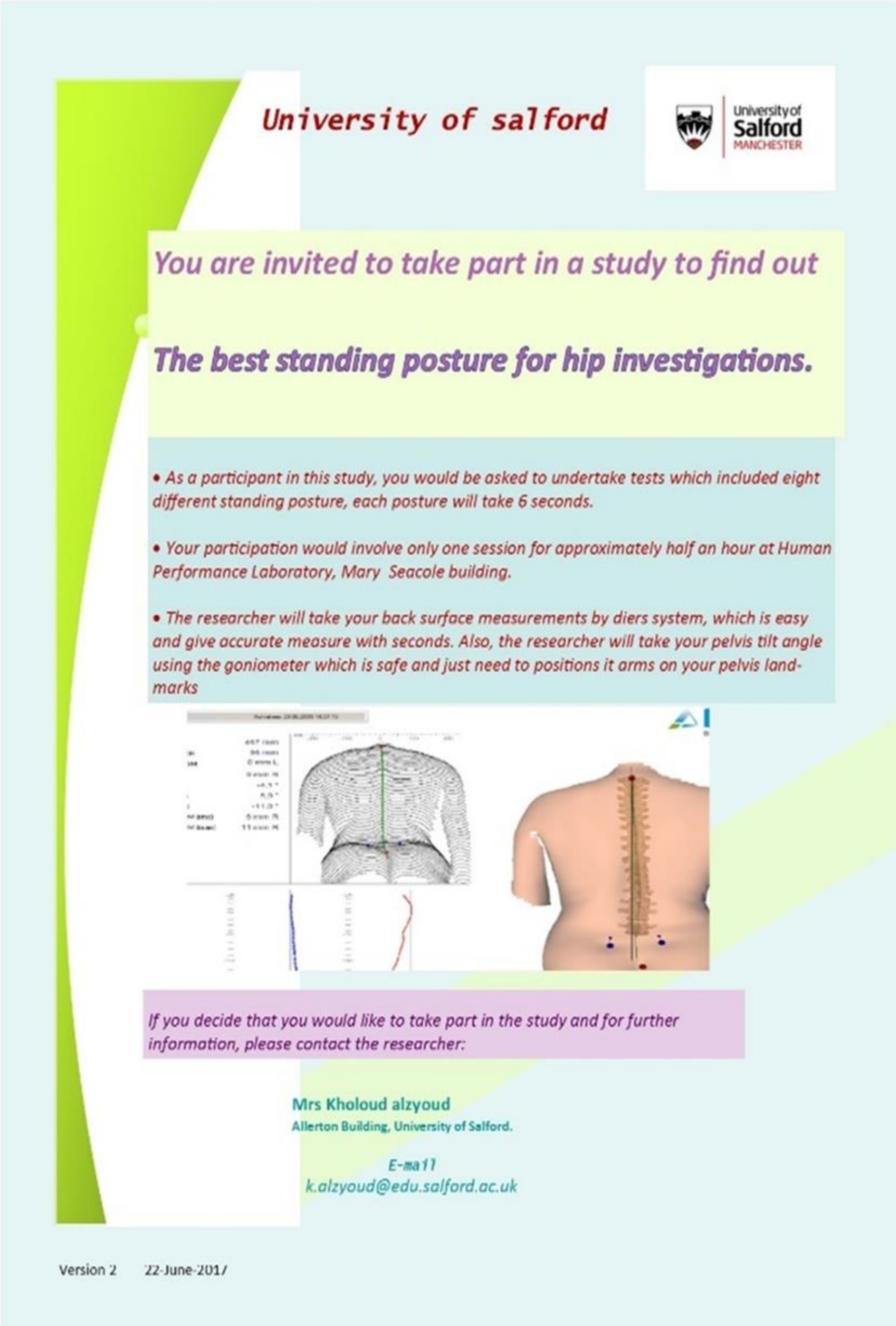
Name of participant: ...., **Code:** ....

Date: ....

Signature: ....

Name of researcher taking Consent	**Kholoud Alzyoud**
Researcher e-mail address	**k.alzyous@edu.salford.ac.uk**
Research supervisor	**Andrew England**
Supervisor e-mail	**A.England@salford.ac.uk**

Appendix 11: Recruitment poster for phase one



Appendix 12: Show case poster (50 years university celebrating)

Technique for Pelvis Standing Radiography: Accuracy and Reproducibility of Pelvic Tilt Measurements for Radiographic Imaging.

University of Salford MANCHESTER 1967-2017 50 YEARS

Kholoud Alzyoud[1,2], Peter Hogg[2], Preece Stephen[2], Snaith Beverly[3], Andrew England[2]
[1]Hashemite University, Jordan ;[2] University of Salford, United Kingdom; [3]Mid Yorkshire Hospitals NHS Trust

BACKGROUND

Pelvis X-rays are traditionally used for the identification of the changes in the hip joint and in the detection of osteoarthritis (OA). In England, 2.5 million people suffer from OA of the hip joint. Incidence rates are almost certain to rise with increases in obesity rates.(1) In 2012, 67% of men and 57% of women were overweight, and obesity accounted for 8.6% of disability.(1)

For patients suffering from hip pain, the supine pelvis radiograph is one of the initial diagnostic tests. However, many researchers have started to recommended a functional pelvis standing radiograph. Clinicians have started to advocate erect positioning since this better correlates with symptoms, function, hip abnormalities and pathogenesis.(2) A number of radiographic measurements have been developed in order to help evaluate acetabular impingement and dysplasia which are the earlier indications of OA. Such measures include acetabular version (cross over sign), center edge angle (CEA) and joint space width (JSW) and could be affected by posture.

Awareness of different body postures and pelvis orientation changes is increasing. Research has shown that as the posture of pelvis changes from supine to standing the orientation changes as well (pelvic tilt). Studies have reported significant changes to pelvic title when moving between standing and erect positions (4 to 8 degrees).(3,4) Pelvis tilt for male after repositioning was reported to 13°-14° and in female from 6°-7°. Moreover, the number of the patients who exceed the neutral pelvis limits reduced from 77% in the supine position to 35% in erect.(3) Many studies have provided evidence that standing pelvis X-rays examinations offer better visualization of functional anatomy.(2) Consequently, standing pelvis X-ray examinations need to a validated position which does not negatively affect diagnosis.

AIMS & OBJECTIVES

The aim of this study is to evaluate the effect of different standing postures on pelvis tilt, in order to develop a standard position for erect pelvis X-rays.

The following objectives have been formulated:

1. Evaluate eight different standing postures on pelvis tilt, rotation, kyphosis and lordosis in order to determine which is the optimum position for erect pelvis anteroposterior radiographic projection.

2. Evaluate the reproducibility of the eight different standing postures in terms of pelvic tilt, rotation and stability of each position.

METHODS

Healthy volunteers (18-60 years) will be recruited. Exclusion criteria include any history of spine or pelvis pain or surgery and participants with secondary degenerative arthritic changes in spine and hips.

The formatic 4D dynamic modelling system developed by Diers will used to evaluate posture. This non-invasive radiation free method provides analysis of spine and pelvis posture (**Figure 1**).

Participants will be invited to participate in this study by email and through posters. Participants need to attend one session which will last 30 minutes and stand with their back in front of Diers system in eight different positions. Kyphosis, lumber lordosis and pelvis tilt will be measured (**Figure 2**).

DIERS

Figure 1. Example for images obtained from DIERS system.(5)

Figure 2. Example for measurements obtained from DIERS system.(6)

Pelvis parameter	Shortcut	Definition
Lordosis angle	LA	Maximum lumber angle calculated from ITL and ILS triangles.
Pelvis torsion	P-Tors	Torsion between left and right side pelvis bones (os ilium)
Lordosis angle	LA	Maximum lumbar angle calculated from ITL and ILS triangles.

Table 1. Description and geometry of spine and pelvis parameters.(7)

ANTICIPATED RESULTS

This study will clarify the effect of different standing positon on pelvis tilt, rotation and stability of patient. It will provide evidence on how to position people correctly in their normal pelvis tilt during erect radiography.

After data collection and analysis the position for standing pelvis radiographs will be recommend.

REFERENCES

Appendix 13: Repeatability and reproducibility output results and Results for AEC sensitivity test

Set-up:	FFD (cm)	kV	Focus	mAs	Other
A	100	60	Fine	4	
B	100	80	Broad	10	
C	100	100	Broad	20	

Baseline:

Output A	Output B	Output C
71.0	353.8	1.2

Measurements:

Date	Initial	A1	A2	A3	Result	Average A	Result	B	Result	C	Result	Action taken
31/03/2016	CB/AKT	71.0	71.8	71.9	Pass	71.5	Pass	353.8	Pass	1.2	Pass	kV OK
12/07/2016	CB/AKT	69.8	70.5	70.8	Pass	70.4	Pass	353.4	Pass	1.2	Pass	
09/02/2017	CB/AKT	71.4	70.9	71.0	Pass	71.1	Pass	354.1	Pass	1.2	Pass	
27/03/2017	CB/AKT	66.8	67.9	68.0	Pass	67.6	Pass	338.4	Pass	1.2	Pass	Following Service
05/05/2017	CB/AKT	67.1	67.4	66.9	Pass	67.1	Pass	338.1	Pass	1.2	Pass	
05/06/0207	CB/AKT	66.4	66.9	66.8	Pass	66.7	Pass	338.5	Pass	1.2	Pass	
14/09/2017	CB	60.6	59.7	60.6	Pass	60.3	Pass	335.4	Pass	1.2	Pass	
23/03/2018	CB	70.7	70.5	70.8	Pass	70.7	Pass	337.2	Pass	1.1	Pass	
28/06/2018	CB	63.0	63.4	63.4	Pass	63.3	Pass	329.9	Pass	1.1	Pass	Service

AEC sensitivity (CR14) - Table bucky

Set-up:	FFD (cm)	kV	Filtration	Chamber	Grid	Density	Other
A	110	80	none	centre	y	0	
B	110	80	none	lateral x2	y	0	
C	110	80	none	all	y	0	

Baseline:

mAs (A)	DDI (A)	mAs (B)	DDI (B)	mAs (C)	DDI (C)
2.2	295.0	2.2	279.9	2.2	281.0

Measurements:

Date	Initial	mAs (A)	DDI (A)	Result	mAs (B)	DDI (B)	Result	mAs (C)	DDI (C)	Result	Action taken
31/03/2016	CB/AKT	2.2	295.3	Pass	2.2	279.8	Pass	2.2	281.1	Pass	
12/07/2016	CB/AKT	2.2	295.1	Pass	2.2	279.7	Pass	2.2	281.1	Pass	
09/02/2017	CB/AKT	2.2	294.6	Pass	2.2	280.2	Pass	2.2	280.7	Pass	
27/03/2017	CB/AKT	2.3	295.2	Pass	2.2	279.4	Pass	2.4	281.5	Pass	Following Service
05/05/2017	CB/AKT	2.3	294.8	Pass	2.2	278.9	Pass	2.4	280.9	Pass	
05/06/2017	CB/AKT	2.3	295.3	Pass	2.2	279.4	Pass	2.4	281.2	Pass	
14/09/2017	CB/AKT	2.2	294.2	Pass	2.2	279.1	Pass	2.3	280.6	Pass	
23/03/2018	CB/AKT	2.6	297.3	Pass	2.5	281.3	Pass	2.5	281.7	Pass	
28/06/2018	CB	2.6	248.9	Pass	2.6	226.0	Pass	2.6	231.1	Pass	Service

Appendix 14: Light beam alignment and centering

Set-up

FFD (cm)	kV	mAs	Focus
100	45	5	Fine

Measurements:

Date	Initial	Misalignment (cm)	Result	Miscentering (cm)	Result	Action taken
31/03/2016	CB/AKT	0.0	Pass	0.0	Pass	
12/07/2016	CB/AKT	0.0	Pass	0.0	Pass	
09/02/2017	CB/AKT	0.0	Pass	0.0	Pass	
27/03/2017	CB/AKT	0.0	Pass	0.0	Pass	
05/05/2017	CB/AKT	0.0	Pass	0.0	Pass	
05/06/2017	CB/AKT	0.0	Pass	0.0	Pass	
14/09/2017	CB/AKT	0.0	Pass	0.0	Pass	
23/03/2018	CB/AKT	0.0	Pass	0.0	Pass	
28/06/2018	CB/AKT	0.0	Pass	0.0	Pass	

Appendix 15: Differences between erect and supine in SNR for 1SD and 2SD phantoms size.

Effect of tube potential, AEC configuration, SID and additional filtration on SNR. Data presented are for the 1SD phantom.					
		SNR, median (IQR)			
Parameter		**Supine**	**Erect**	**% Difference**	**P value**
kVp	80	22.2 (2.5)	20.4(7.3)	-8.1	0.040
	90	21.3(3.7)	20.8(5.2)	-2.3	0.700
	100	21.1(3.9)	21.8(5.3)	3.3	0.400
AEC	All	21.5(3.2)	20.6(5.5)	-4.1	0.400
	Both outer	21.4(3.03)	19.9(7.4)	-7	0.300
	Central	21.7(3.1)	22.5(3.9)	3.7	0.200
SID (cm)	115	22.9(1.2)	18.8(3.7)	-17.9	0.001
	130	22.5(1.2)	19.6(3.5)	-12.8	0.006
	145	19.2(1.9)	17.6(1.6)	-8	0.01
Add. Filtration.	No	21.7(2.9)	20.5(5.01)	-5.5	0.200
	Yes	21.3(2.2)	21.5(6.3)	0.93	0.700

Effect of tube potential, AEC configuration, SID and additional filtration on SNR. Data presented for the 2SD phantom.					
		SNR, median (IQR)			
Parameter		**Supine**	**Erect**	**% Difference**	**P value**
kVp	80	23.1(2.7)	22.06(7.3)	-4.7	0.020
	90	22.9(0.7)	21.5(9.7)	-6.11	0.130
	100	23.1(0.8)	21.2(9.5)	-8.2	0.080
AEC	All	22.5(0.8)	21.4(9.8)	-4.8	0.100
	Both outer	22.8(1.2)	21.6(7.5)	-5.3	0.050
	Central	23.7(2.5)	21.8(8.5)	-8	0.040
SID (cm)	115	22.6(1.4)	25.3(0.6)	11.9	0.000
	130	24.02(3.3)	23.7(1)	-1.3	0.006
	145	22.4(0.8)	15.8(3.3)	-29.5	0.000
Add. Filtration.	No	23.09(2.1)	21.5(7.5)	-6.9	0.020
	Yes	22.9(1)	21.7(9.4)	-5.2	0.040

Appendix 16: Differences between erect and supine in CNR for 1SD and 2SD phantoms size.

Effect of tube potential, AEC configuration, SID and additional filtration on effective dose. 1SD phantom					
		CNR, median (IQR)			
Parameter		**Supine**	**Erect**	**% Difference**	**P value**
kVp	**80**	12.6(4.9)	7.4(3.6)	-41.2	<0.001
	90	11.2(4.4)	6.3(2.4)	-43.8	<0.001
	100	10.2(4.03)	6.04(3.4)	-40.7	0.001
AEC	**All**	11.3(4.4)	6.5(2.9)	-42.5	<0.001
	Both outer	11.3(4.2)	6.2(3.6)	-45.1	<0.001
	Central	11.4(4.3)	7.1(2.2)	-37.7	<0.001
SID (cm)	**115**	12.7(1.8)	5.7(1.3)	-55.1	<0.001
	130	13.02(2.7)	5.4(1.3)	-58.5	<0.001
	145	8.3(1.5)	8.7(1.5)	4.8	0.010
Add. Filtration.	**No**	11.4(7.5)	6.6(2.4)	-42.1	<0.001
	Yes	11.2(6.9)	6.6(3.1)	-41.1	<0.001

Effect of tube potential, AEC configuration, SID and additional filtration on effective dose. 2SD phantom					
		CNR, median (IQR)			
Parameter		**Supine**	**Erect**	**% Difference**	**P value**
kVp	**80**	9.3(3.4)	7.5(2.3)	-19.4	0.001
	90	8.1(2.9)	6.2(5.4)	-23.5	<0.001
	100	7.4(2.5)	5.4(5)	-27	<0.001
AEC	**All**	8.2(2.5)	6.4(4.9)	-22	<0.001
	Both outer	8.2(2.7)	6.4(4.7)	-22	<0.001
	Central	8.5(2.9)	6.4(4.8)	-25	<0.001
SID (cm)	**115**	9.4(1.8)	8.4(1)	-11	<0.001
	130	9.1(1.5)	6.8(1.1)	-25	<0.001
	145	6.4(1)	3.9(4.1)	-39	0.001
Add. Filtration.	**No**	8.5(2.6)	6.7(5)	-21	<0.001
	Yes	8.1(2.6)	6.1(5)	-25	<0.001

Appendix 17: Differences between erect and supine in VGA for 1SD and 2SD phantoms size.

Effect of tube potential, AEC configuration, SID and additional filtration on effective dose. 1SD phantom.					
		VGA mean (SD)			
Parameter		**Supine**	**Erect**	**% Difference**	**P value**
kVp	**80**	55.4(7.4)	44.9(5.9)	-18.9	<0.001
	90	40.7(9.3)	39.8(7.9)	-2.2	0.700
	100	35.1(8.6)	37.5(6.6)	6.8	0.300
AEC	**All**	42.7(11.1)	38(5.7)	-11	0.060
	Both outer	40.7(13)	37.1(7.5)	-8.8	0.300
	Central	47.7(11.5)	47.2(4.3)	-1	0.800
SID (cm)	**115**	44.2(10.9)	37.6(7.4)	-14.9	0.007
	130	43.1(9.5)	39.8(7.5)	-7.6	0.060
	145	43.8(15.6)	44.9(5.6)	2.5	0.700
Add. Filtration.	**No**	44.5(11.7)	40(7.2)	-10	0.004
	Yes	42.9(12.6)	41.5(6.8)	-3.3	0.600

Effect of tube potential, AEC configuration, SID and additional filtration on effective dose. 2SD phantom					
		VGA, mean (SD)			
Parameter		**Supine**	**Erect**	**% Difference**	**P value**
kVp	**80**	47(4.5)	35.5(11.1)	-24	0.000
	90	36.2(4.8)	31.1(8.5)	-14	0.01
	100	28.9(4.2)	26.9(6.9)	-6.9	0.1
AEC	**All**	36.6(9.1)	31.7(9.5)	-13.4	0.03
	Both outer	36.6(8.3)	31.7(9.6)	-13.4	0.03
	Central	38.9(8.8)	31.9(10.2)	-17.9	0.005
SID (cm)	**115**	39.2(8.2)	36.8(5.9)	-6.1	0.009
	130	38.2(7.8)	36.6(5.5)	-4.2	0.3
	145	34.7(9.5)	20.1(2.5)	-42	0.000
Add. Filtration.	**No**	38.9(9)	32.5(9.9)	-16.4	0.09
	Yes	35.8(8)	30.1(8.8)	-18.5	0.000

Appendix 18: Differences between erect and supine in E for 1SD and 2SD phantoms size.

Effect of tube potential, AEC configuration, SID and additional filtration on effective dose. 1SD phantom					
		E, median (IQR)			
Parameter		Supine	Erect	% Difference	P value
kVp	80	0.163(0.024)	0.266(0.277)	63.2	0.001
	90	0.118(0.019)	0.181(0.180)	53.4	0.001
	100	0.092(0.018)	0.143(0.134)	55.4	0.000
AEC	All	0.118(0.064)	0.167(0.156)	41.5	0.001
	Both outer	0.112(0.048)	0.142(0.174)	26.8	0.000
	Central	0.134(0.068)	0.254(0.328)	89.5	0.001
SID (cm)	115	0.115(0.062)	0.143(0.067)	24.3	0.006
	130	0.116(0.064)	0.142(0.076)	22.4	0.001
	145	0.123(0.058)	0.371(0.216)	201.6	0.000
Add. Filt.	No	0.124(0.059)	0.199(0.197)	60.5	0.000
	Yes	0.111(0.053)	0.169 (0.186)	52.3	0.000

Effect of tube potential, AEC configuration, SID and additional filtration on effective dose. 2SD phantom					
		E, median (IQR)			
Parameter		Supine	Erect	% Difference	P value
kVp	80	0.199(0.117)	0.621(0.164)	212.1	0.000
	90	0.145(0.084)	0.475(0.131)	227.6	0.000
	100	0.112(0.065)	0.378(0.129)	237.5	0.000
AEC	All	0.167(0.082)	0.465(0.264)	178.4	0.000
	Both outer	0.161(0.077)	0.499(0.243)	209.9	0.000
	Central	0.177(0.082)	0.513(0.223)	189.8	0.000
SID (cm)	115	0.133 (0.064)	0.476(0.290)	257.9	0.000
	130	0.140(0.066)	0.486(0.229)	247.1	0.000
	145	0.225(0.109)	0.489(0.219)	117.3	0.001
Add. Filt.	No	0.183(0.098)	0.523(0.227)	185.7	0.000
	Yes	0.163(0.084)	0.428(0.268)	162.5	0.000

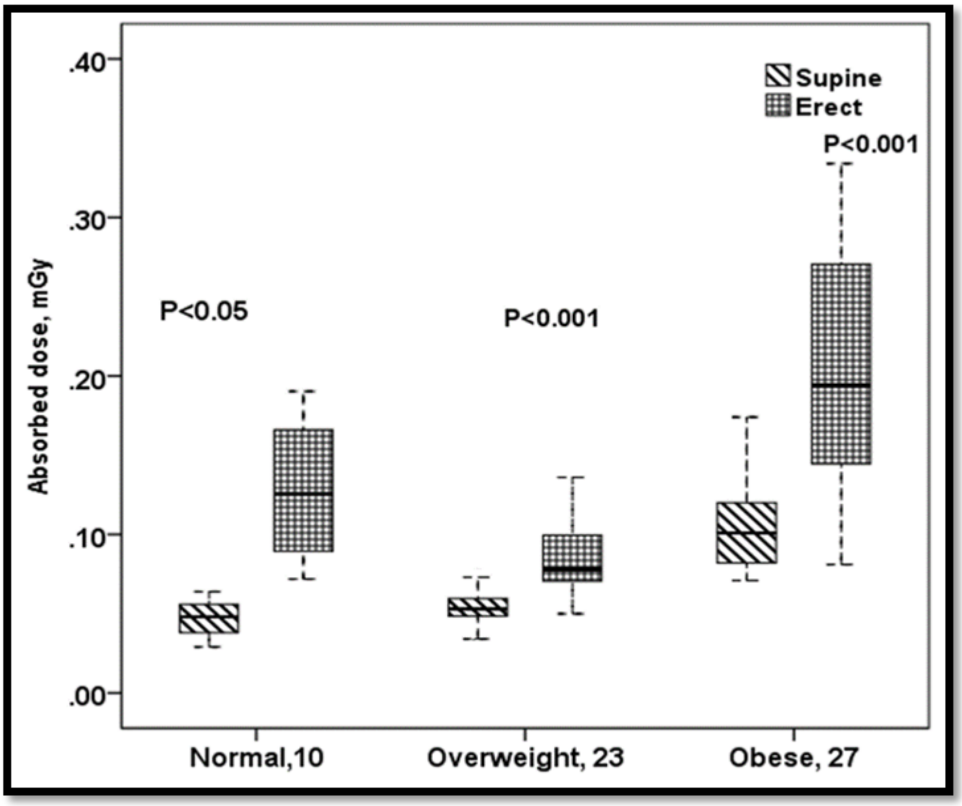
Appendix 19: Differences between erect and supine positions, analysed separately by SID group

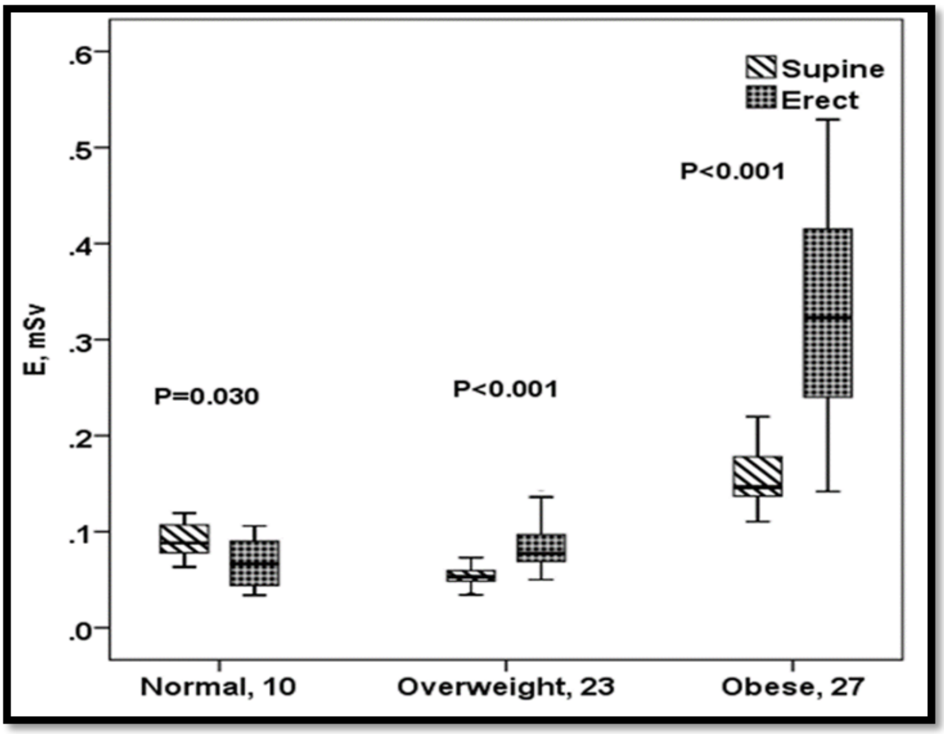
Results of the differences between erect and supine positions, analysed separately by SID group.

Variable	Projection	SID group (cm)	Mean (SD)	Median (IQR)	Min	Max
Patient thickness (cm)	**Supine**	140/140	24.5 (4.1)	24.5 (21.8-26.7)	18.0	34.5
		140/180	23.2 (3.1)	23.0 (21.0-25.5)	18.0	29.0
		Combined	24.0 (3.8)	23.8 (21.5-26.4)	18.0	34.5
	Erect	140/140	28.7 (5.5)	28.5 (24.0-32.0)	18.0	43.5
		140/180	26.6 (3.5)	26.0 (24.5-29.5)	19.5	33.0
		Combined	27.9 (4.9)	27.8 (24.0-31.5)	18.0	43.5
Dose area product (mGy* cm^2)	**Supine**	140/140	1046.0 (761.3)	850.0 (548.0-1248.0)	348.0	4048
		140/180	731.7 (284.6)	615.0 (521.0-944.0)	355.0	1347
		Combined	925.5 (638.5)	756.5 (547.5-1142.3)	348.0	4048
	Erect	140/140	1880.9 (1832.5)	1100.0 (840.5-2886.0)	376.0	10775
		140/180	1391.2 (704.0)	1125.0 (851.0-1814.0)	475.0	3157
		Combined	1693.2 (1513.7)	1121.0 (858.8-2303.4)	376.0	10775
Absorbed dose (mGy)	**Supine**	140/140	0.091 (0.062)	0.075 (0.051-0.106)	0.029	0.336
		140/180	0.067 (0.025)	0.057 (0.049-0.083)	0.031	0.119
		Combined	0.082 (0.052)	0.069 (0.051-0.099)	0.029	0.336
	Erect	140/140	0.162 (0.151)	0.098 (0.072-0.256)	0.034	0.875
		140/180	0.152 (0.162)	0.103 (0.077-0.151)	0.044	0.850
		Combined	0.157 (0.153)	0.103 (0.074-0.193)	0.034	0.875
Effective dose (mSv)	**Supine**	140/140	0.144 (0.074)	0.128 (0.090-0.164)	0.063	0.391
		140/180	0.111 (0.028)	0.110 (0.088-0.125)	0.061	0.175
		Combined	0.132 (0.062)	0.116 (0.089-0.146)	0.061	0.391
	Erect	140/140	0.261 (0.186)	0.178 (0.139-0.390)	0.073	1.036
		140/180	0.213 (0.078)	0.194 (0.153-0.272)	0.092	0.415
		Combined	0.243 (0.155)	0.194 (0.143-0.319)	0.073	1.037
% of maximum possible IQ score	**Supine**	140/140	76.0 (15)	80 (68-87)	35	96
		140/180	76.0 (9)	78 (73-81)	49	91
		Combined	86.0 (9)	87 (81-91)	60	99
	Erect	140/140	87 .0(9)	90 (13-94)	60	99
		140/180	84.0 (7)	84 (81-90)	61	92
		Combined	75.8 (13)	78 (69-85)	35	96

SD: Slandered deviation; IQR: interquartile; Min: minimum; Max: Maximum.

Appendix 20: Differences between erect and supine positions in absorbed dose and E for different BMI.





Appendix 21: Patient information sheet for phase three

Why we are inviting you to take part in this research?

You have been referred for an x-ray (radiograph) of your hip or pelvis and we want to invite you take part in a research study looking at the best way to take these x-rays. Before you make your decision it is important for you to understand why the research is being done and what it will involve.

Please take time to read the information carefully. You may want to talk to others about the study before taking part. Please ask us if there anything unclear or if you would like more information. A telephone number has also been provided overleaf.

What is the purpose of the study?

X-Ray images are the most common tool for investigating diseases of the hip joint. Being able to compare these images over time is important. When patients have pelvic x-rays taken they are asked to lie on an x-ray table. We want to know whether it would be beneficial to take the x-ray standing up.

For some patients this may be more comfortable or may show different abnormalities. In the first part of this research we want to look at how the body changes between lying and standing.

What would taking part involve?

You are being asked to consent to a member of the radiographic team taking measurements of your height and weight before your x-ray examination, followed by body measurements taken at three points when you are standing and lying down. You will still only have the x-ray taken in the standard lying down position.

What are the possible benefits of taking part?

There will be no direct benefit to you in taking part.

These measurements will enable us to work out the best technique to take x-rays in the standing position to ensure the highest quality with the lowest possible radiation dose. A future part of the research will be to take the x-rays in both lying and standing positions.

What are the potential disadvantages and risks of taking part?

The disadvantage is the time taken to complete the consent process, and to undertake the measurements required for the study. This may take up to fifteen minutes.

Do I have to take part in the study?

No, it is up to you whether you choose to take part in the study.

When you attend for your appointment you may be asked whether you want to take part. Participation in the research is voluntary and if you wish to participate in this study, you will be provided with a consent form to sign. Even if you agree to take part on the day of your x-ray appointment you can change your mind.

Data Sharing

Your data will be made anonymous as soon as possible and will only be accessed by staff directly involved within the study, including the Mid Yorkshire Hospitals NHS Trust and the Universities of Bradford and Salford.

All study data will be held in secure locations and will be destroyed three years after the end of the study.

Study Results

A newsletter style copy of the study outcomes will be freely available to any participant who wishes to view it. In order to receive this, please leave an electronic contact on your consent form.

The findings of this study will be reported nationally and locally in the hospital newsletter.

The data and results stated in these publications will be anonymous.

Supporting Information

If you change your mind and wish to withdraw from the study please contact us on the telephone number below, up to the start of data analysis (1 month from end of recruitment). This will not affect your medical care in any way.

Appendix 22: Record sheet for phase three

Study ID Number: ______________ **Imaging order**

Patient Hospital Number: ______________

Height: ____________m **Weight:** ____________kg

Age: ______________ **Gender:** M / F

Supine radiograph
Start time:

kV ______________

mAs ______________

DAP ______________

EI ______________
Image time:

Repeat Yes/No

kV ______________

mAs ______________

DAP ______________

EI ______________

Erect radiograph
Start time:

kV ______________

mAs ______________

DAP ______________

EI ______________
Image time:

Comments:

Patient preference

Supine / Erect

Radiographer code:

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