Spino-pelvic sagittal alignment and back and hip pain prevalence in young elite athletes

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Cover illustration by Pontus Andersson
Layout design by Gudni Olafsson/GO Grafik

Spino-pelvic sagittal alignment and back and hip pain prevalence in young elite athletes
Clinical and radiological studies

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ISBN: 978-91-628-9896-0 (PRINT)
978-91-628-9897-7 (PDF)
http://hdl.handle.net/2077/50866
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Printed in Gothenburg, Sweden 2017
INEKO

“What ever you do in life, always strive to be the best”

A FATHER’S ADVICE TO HIS SON
(SAMUEL CLIFFORD TODD,
CIRCA 1980’S)

Abstract

Young athletes that perform regular intense training and sports competions have been shown to increase the risk of low back pain (LBP) and spinal pathologies, e.g. early disc degeneration. This may be the result of heavy loading in different planes to the spine, heavy training in young age, overuse injuries or from postural positions associated with particular sports that sustain heavy loads to the spine, at a young age. Throughout the past 20 years, several studies have reported on the spino-pelvic sagittal alignment values within young and aging populations. Whilst specific spinal pathologies have been shown to correlate with types of spinal curvature according to Roussouly et al. (2003), little is known about how pelvic or hip morphology may effect spinal alignment. Although a correlation between these regions due to their anatomical, morphological and functional proximities may exist; it is not fully understood how hip joint conditions such as whether Femoro-acetabular impingement (FAI) and sporting activities may affect the spino-pelvic sagittal alignment in young Elite athletes.

This thesis aims to investigate the results from clinical and radiological studies that compared the spino-pelvic sagittal alignment and the prevalence and correlation of back and hip pain in young Elites athletes to a non-athletic population. The athletes were young Elite skiers (n=75) and were all High School pupils (grades 1-4, between 16-20 years of age) as the control group (n=27) were first year High School pupils.

Study I is a validation study of spinal sagittal alignment using plain radiographs and the Debrunner Kyphometer comparing young Elite skiers and non-athletes. Measurement of the thoracic kyphosis showed good levels of agreement for comparison of both methods. Measurement of lumbar lordosis was shown to have poor levels of agreement for comparison of both methods.

Study II is a radiological study comparing the spino-pelvic sagittal parameters between young Elite skiers and non-athletes. Elite skiers were shown to have a greater prevalence of

Type I spinal curves according to Roussouly et al. (2003), which is a long thoraco-lumbar kyphosis that may cause specific pathologies such as disc hernias.

Study III is a clinical study comparing the spino-pelvic parameters in standing and sitting between young Elite skiers and non-athletes. Elite skiers were shown to have significantly lower values for spino-pelvic sagittal alignment in sitting and standing compared with the non-sporting population. This is suggested to be due to adaptation from heavy loads on the spine, pelvis and hips from skiing and training activities.

Study IV is a radiological study comparing spino-pelvic sagittal alignment in relation to hip joint cam-type FAI between young Elite skiers and non-athletes. A significant difference was shown for an increased Pelvic Tilt (PT) value in an age-matched mixed-group of Elite skiers and non-athletes in the presence of increased morphological hip joint cam-type FAI. Elite skiers were also shown to have an increased prevalence of spinal Type II classification according to Roussouly et al. (2003), in the presence of an increased frequency of cam-type FAI. Therefore, individuals with a low Pelvic Incidence (PI) angle (pelvic retoversion), may be more prone to develop cam-type FAI, this may result from an inability to accommodate pelvic retroversion and subsequently lead to the development of Type II Roussouly spine ("flat back").

Study V investigated the prevalence of spine and hip pain in athletes using a three-part questionnaire, a specific back and hip pain questionnaire, Oswestry Diasbility Index and EuroQoL. Young Elite skiers were shown not to have a significant difference for lifetime prevalence of back pain or hip pain compared with non-athletes. In spite of this a high percentage of skiers reported duration of back pain prevalence >5 years, however, this was not statistically significant.

In conclusion, the Debrunner Kyphometer is shown to have limited value to measure spinal sagittal alignment for lumbar lordosis compared with radiological methods. Young Elite skiers are shown to have an altered spino-pelvic sagittal alignment resulting in a retroverted pelvis and low lumbar lordosis ("flat back") especially in the presence of increased morphological hip joint cam-type FAI. No significant differences were shown in terms of the prevalence of back and hip pain and disability or for a correlation between back and hip pain in Young Elite skiers compared with non-athletes.

Keywords
Athletes, cam, Femoro-acetabular impingement, Debrunner Kyphometer, Low back pain, Pelvic parameters, Pelvic Tilt, Skiers, Spino-pelvic alignment.

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Sammanfattning på svenska

Unga idrottare som regelbundet tränar och tävlar på hög nivå har en ökad risk för ländryggssmärta och ryggförändringar, som visats på Röntgenbilder, till exempel tidig diskdegeneration. Detta kan vara ett resultat av tung belastning med hård träning i unga år, eller överbelastningsskador. Annan möjlighet är långvarig stående ställning, som utsätter ryggen för hög belastning. En sådan ställning återfinns ofta inom vissa idrottsgrenar. Under de senaste 20 åren har flera studier rapporterat om betydelsen av den så-kallade ”spino-pelvis” sagitella hållningens hos både unga och vuxna populationer. Medan specifika ryggåkommor har visat sig vara korrelerade till viss typ av ryggform (sagitell hållning) enligt Roussouly och medarbetare (2003), är kunskapen avseende hur bäcken- eller höftmorfologi kan påverka ryggens form begränsad. Trots att den anatomiska närheten mellan dessa båda regioner d.v.s. ländrygg och bäcken/höft till följd av deras anatomiska, moforlogiska och funktionella närhet är det inte helt belagt hur patologi eller överbelastning i höftleden, såm cam eller femuro-acetabulär impingement (FAI) och idrottsaktiviteter, kan påverka ”spino-pelvis” sagitella hållning hos unga elitidrottare.

Syftet med denna avhandling är att beskriva resultaten från kliniska och radiologiska studier som jämför ”spino-pelvis” sagitella hållning hos unga idrottare, jämfört med en åldersmatchad population av icke-idrottare. Idrottsgruppen består av unga elitskidåkare (n=75) samtliga gymnasieelever (årskurs 1-4, mellan 16 och 20 års ålder) på Åre Skidgymnasium, Åre, Sverige. Kontrollgruppen (n=27) var förstaårselever på en gymnasieskola i Östersund, Sverige. Samtliga deltagare erbjöds delta i denna prospektiva studie efter en muntlig presentation av två av medförfattarna. Deltagare erhöll även skriftlig information.

Studie I är en valideringsstudie av ryggens sagitella hållning, som undersöktes med slätröntgenundersökning och Debrunner´s kyfometer. Studien jämför skidåkare och icke-idrottare. Mätning av den thorakala kyfosen visade god samstämmighet mellan de båda metoderna. Dock visade mätningar av ländryggslordos endast en svag korrelation mellan metoderna.

Studie II är en radiologisk studie som jämför spino-pelvis sagitella parametrar mellan elitskidåkare och icke-idrottare. Elitskidåkare visade sig ha en högre prevalens av Roussouly typ 1 spinala kurvor vilket innebär en lång toraco-lumbar kyfos som kan orsaka specifika ryggpatologier, tex diskbråck.

Studie III är en klinisk studie som jämför spino-pelvis parametrar i stående och sittande mellan unga elitskidåkare och icke-idrottare. Elitskidåkare visade sig ha signifikant lägre spino-pelvis-sagitella värden i sittande och stående jämfört med den icke-idrottande kontollgruppen. Detta innebär att skidåkare har hypolordos (låg PI eller ”flat back”) och med ökad belastning övergången bröst- och ländrygg samt nedre ländrygg. Detta innebär att individer med låg PI har en större benägenhet att utveckla cam-FAI, pga oförmåga att kompsera med pelvis retroversion och som konsekvens kan leda till Rousslouly typ 2 ryggar (”flat back”).

Studie IV är en radiologisk studie, som jämför spino-pelvis sagitell hållning i relation till höftledens femoroacetabular cam-impingement hos elitskidåkare och icke-idrottare. Pelvic tilt var signifikant högre hos en blandad grupp av elitskidåkare och icke-idrottare vid förekomst av cam-impingement i höften. Elitskidåkare hade också en högre prevalens av typ 2 sagitell rygghållning enligt Roussouly’s klassifikation hos de med samtidig cam-typ FAI i höftleden.

Studie V undersökte prevalensen och korrelationen av rygg- och höftsmärta hos idrottare, undersökta med rygg- och höftsmärtenkäter, Oswestry disability index samt EuroQol. Unga elitskidåkare visade sig inte ha t högre frekvens av rygg- och höftsmärta, mätt med VAS, jämfört med icke-idrottare. Skidåkarna hade doch högre frekvens av lång duration av ryggsmärta.

Sammanfattningsvis har Debrunner´s kyfometer begränsat värde för mätning av ländryggslordosen, jämfört med radiologisk mätning. Unga elitskidåkare visar sig ha en förändrad spino-pelvis-sagitell hållning, vilket resulterar i retroverterad bäcken och låggradig ländryggslordos (”flat back”), i synnerhet vid samtidig förekomst av morfologisk cam-typ FAI. Unga elitskidåkare visade sig inte ha högre livstidsprevalens och duration av rygg- och höftsmärta, minskad livskvalité eller handikapp samt ingen korrelation mellan rygg och höft smärta jämfört med icke-idrottande population.

List of papers

This thesis is based on the following studies, referred to in the text by their Roman numerals.

I. Cecilia Agnvall PT, Carl Todd MSc DO, Peter Kovac MD, Anna Swärd MD, Christer Johansson MSc, Leif Swärd MD PhD, Jon Karlsson MD PhD, Adad Baranto MD PhD.

Validation of spinal sagittal alignment with plain radiographs and the Debrunner Kyphometer

Medical Research Archives. 2015: 1. DOI: http://dx.doi.org/10.18103/mra.v2i1.319.

II. Carl Todd MSc DO, Peter Kovac MD, Anna Swärd MD, Cecilia Agnvall PT, Leif Swärd MD PhD, Jon Karlsson MD PhD, Adad Baranto MD PhD.

Comparison of radiological spino-pelvic sagittal alignment in skiers and non-athletes

Journal of Orthopaedic Surgery and Research. 2015: 10:162, DOI: 10.1186/s13018-015-0305-6.

III. Carl Todd MSc DO, Anna Swärd MD, Cecilia Agnvall PT, Leif Swärd MD PhD, Jon Karlsson MD PhD, Adad Baranto MD PhD.

Clinical spino-pelvic parameters in skiers and non-athletes

Jacobs Journal of Sports Medicine. 2016: 3(3): 022.

IV. Carl Todd MSc DO, Wisam Witwit MD, Peter Kovac MD, Anna Swärd MD, Cecilia Agnvall PT, Páll Jonasson MD PhD, Olof Thoreson MD PhD, Leif Swärd MD PhD, Jon Karlsson MD PhD, Adad Baranto MD PhD.

Pelvic retroversion is associated with flat back and cam type Femoro-acetabular impingement in young elite skiers

Journal of Spine. 5: 326. DOI:10.4172/2165-7939.1000326

V. Carl Todd MSc DO, Anna Swärd MD, Cecilia Agnvall PT, Olof Thoreson MD PhD, Leif Swärd MD PhD, Jon Karlsson MD PhD, Adad Baranto MD PhD.

An investigation into the prevalence of spine and hip pain in young elite skiers

Submitted October 2016.

Additional papers

Olof Thoreson MD PhD, Peter Kovac MD, Anna Swärd MD, Cecilia Agnvall PT, Carl Todd MSc DO, Adad Baranto MD PhD.

Back pain and MRI changes in the thoraco-lumbar spine of young elite Mogul skiers

Scandinavian Journal of Medicine and Science in Sport. 2016: DOI: 10.1111/sms.1270.

Contents

Abbreviations

AF	Annulus Fibrosis
CT	Computerised Tomography
EP	End Plate
EQ-5D	Euro Qol-5 Dimensions
FABER	Flexion Abduction External Rotation
FADDIR	Flexion Adduction Internal Rotation
FAI	Femoro-acetabular Impingement
FSU	Functional spinal unit
ICC	Intraclass Correlation Coefficient
IVD	Intervertebral Disc
LBP	Low Back Pain
LE	Lumbar Extension
LF	Lumbar Flexion
LL	Lumbar Lordosis
OA	Osteoarthritis
PI	Pelvic Incidence
PT	Pelvic Tilt
PROM	Patient Reported Outcome Measures
MRI	Magnetic Resonance Imaging
NP	Nucleus Pulposus
ROM	Range of Motion
SD	Standard Deviation
SI	Sacroiliac
SS	Sacral Slope
sLE	Sitting Lumbar Extension
sLF	Sitting Lumbar Flexion
SVA	Sagittal Vertical Axis
TK	Thoracic Kyphosis
VAS	Visual Analogue Scale

Brief Definitions

Alpha angle	The angle between a line from the centre of the femoral head through the middle of the femoral neck and a line through a point where the contour of the femoral head-neck junction exceeds the radius of the femoral head. A radiographic measurement describing the extent of a cam lesion.
Anteversion	A forward rotation of an entire organ or part, such as the pelvis rotating forwards around the hip joints.
Cam-type impingement	A type of femoro-acetabular impingement where asphericity of the femoral head-neck junction results in the abutment of the aspherical head-neck junction on and under the acetabular rim during movement of the hip joint.
Ceiling effect	When a significant number of subjects obtain the highest score, an instrument is able to measure and the instrument is thus unable to detect an upward change.
Construct	A subjective phenomenon such as pain, function or quality of life. A construct is frequently measured with multiple items.
Construct validity	The degree to which the scores of an instrument are consistent with hypotheses (for instance, with regard to internal relationships, relationships to scores of other instruments, or differences between relevant groups) based on the assumption that the HR-PRO instrument validly measures the construct to be measured.
Content validity	The degree to which the content of an instrument is an adequate reflection of the construct to be measured.

Criterion validity	The degree to which the scores of an HR-PRO instrument are an adequate reflection of a 'gold standard'.
Femoroacetabular impingement	A syndrome of symptoms caused by the impingement of the femoral head-neck junction on and/or under the acetabular rim.
Floor effect	When a significant number of subjects obtain the lowest score, an instrument is able to measure and the instrument is thus unable to detect a downward change.
Pelvic Incidence	A morphological parameter and relates to the angle measured from a perpendicular line to the mid-point of the sacral plate and extended to the centre of the femoral head.
Pelvic Tilt	A positional parameter and is the angle measured from a perpendicular line starting at the centre of the femoral head and extended to the mid-point of the sacral plate.
Range of motion	The measured movement over a joint in degrees.
Retroversion	A backward rotation of an entire organ, such as the pelvis rotationg backwards around the hip joints.
Sacral Slope	A positional parameter and is the angle measured from the superior endplate of S1 and a horizontal axis.
Visual Analogue Scale	A measurement instrument for subjective phenomena that cannot be directly measure. Agreement level with a statement is indicated by a mark on a continuous line between two endpoints.

Introduction

"Yet all experience is an arch where through gleams that untraveled world whose margin fades, Forever and forever when I move."

LORD ALFRED TENNYSSON

1.1 Spinal alignment

The ability to maintain a vertical posture in humans is a result of bipedal locomotion that involves simultaneous extension of the vertebral column, pelvis, hips and lower extremities. The vertebral column viewed from the side, is comprised of a number of curvatures, the cranial cervical and caudal lumbar lordotic curves that are separated by the kyphotic thoracic curve [1]. These curvatures are intrinsically related and assist with maintenance of spinal sagittal alignment [2-4].

The degrees of curvatures vary between individuals and have been shown to influence the form and function of the pelvis and hip joints [4]. Spinal alignment may not be a static entity but rather the result of a dynamic evolution to mechanical loads. Moreover, sporting participation has also been shown to influence the development of spinal curvatures [5-7]. Spinal curvatures have also been categorized by morphological and positional measurements that help to determine the pelvic parameters [8].

A well-balanced spino-pelvic-hip complex assists humans to maintain an upright posture, forward gaze and to minimize energy expenditure [1, 2, 9, 10]. In order to achieve a well-balanced spino-pelvic sagittal alignment, the pelvic girdle must facilitate the lumbar lordosis curvature with hip joint extension [1-3, 9-12]. Therefore, the pelvic girdle becomes a mobile platform through which the spinal column communicates with the lower extremity.

1.2 Anatomy of the spinal column

The vertebral column (*Figure 1*) has several curvatures in the sagittal plane, cranial and caudal lordotic curves that are separated by the thoracic kyphotic curve [1, 13]. The curvatures must be capable of ensuring two mechanical requirements, rigidity and plasticity [14]. Extending from the base of the skull to the pelvis, the column consists of a series of vertebral bodies that increase in size from the cervical to the lumbar region. Seven vertebrae are found in the cervical region, compared with twelve vertebrae in the thoracic region, and five vertebrae in the lumbar region. The sacral region has five vertebrae and is fused. Intervertebral discs form the anterior pillar of the vertebral column whilst paired facet joints, and a vertebral arch form the posterior pillar and separate the vertebral bodies [15].

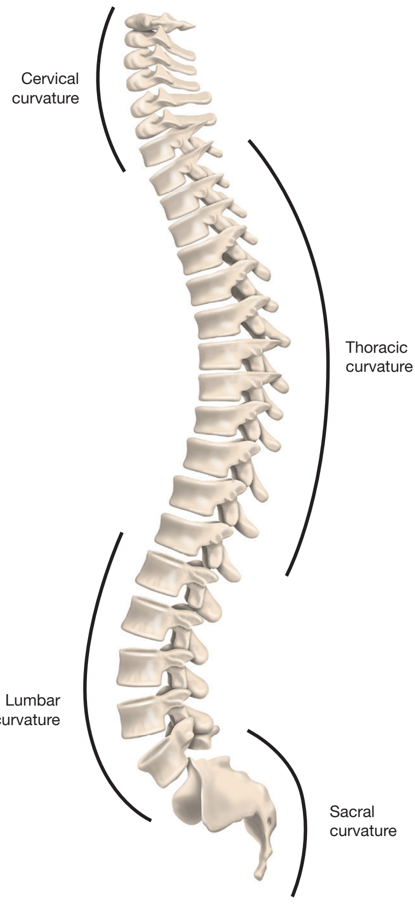


Figure 1: Vertebral column with spinal curvatures.

The vertebral motion segment (vertebra-disc-vertebra) (*Figure 2*) or functional spinal unit (FSU) consists of a superior and adjacent inferior vertebra with their intervening disc, facet joints and ligamentous attachments. The intervertebral disc (IVD) is comprised of the central nucleus pulposus (NP), the circumferential annulus fibrosis (AF) and two hyaline cartilage endplates (EP) that connect to the superior and inferior vertebral bodies [16, 17]. The different tensile properties of the IVD enable it to withstand and transfer heavy spinal loads and to accommodate spinal motion [18]. The shape and orientation of the facet joints, largely determines the range and type of movement possible between two vertebrae [15]. Moreover, the vertebral column is capable of flexion, extension, lateral flexion and rotation however; movement within the column varies between regions. The anterior pillar has a static role whilst the posterior pillar has a dynamic role. There appears to be a functional link between the anterior and posterior pillars aiding in the absorption of compression from both passive and active stresses. Plasticity of the spinal column is achieved through the multiple components of the anterior and posterior pillars that are interlinked by the complex attachments of ligaments and muscles [14].

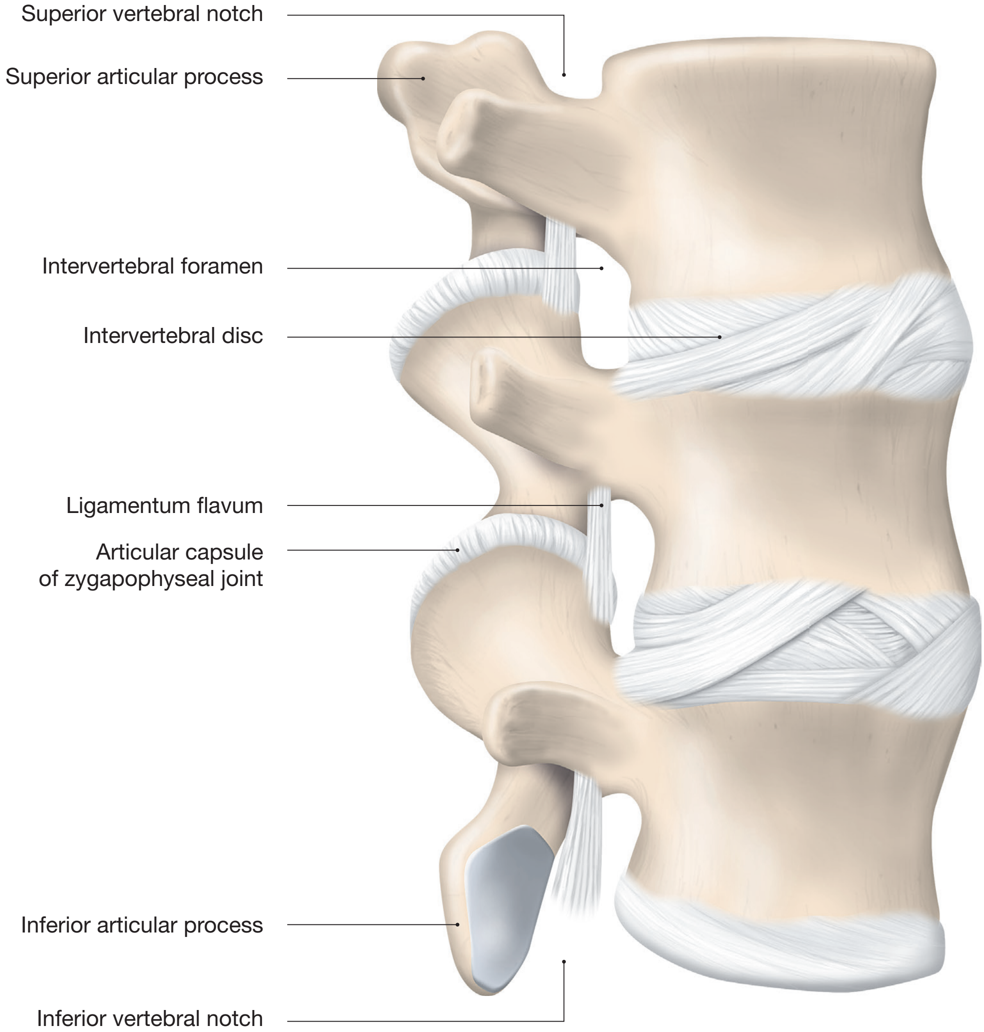


Figure 2: Vertebral motion segment.

1.2.1 Development of spinal morphology

The thoracic kyphosis (TK) curvature is viewed as a primary curve and is due to fetal development, whilst the cervical and lumbar lordotic curvatures develop during infancy [19]. Development of the cervical lordotic curve occurs as a result of an infant beginning to hold the head upright, whilst the lumbar lordosis (LL) curvature develops as a result of an infant being able to sit upright and walk (*Figures 3 & 4*). Therefore, the ability to maintain a vertical posture and bipedal locomotion in humans involves simultaneous extension of the vertebral column, hips, thighs and legs [3].

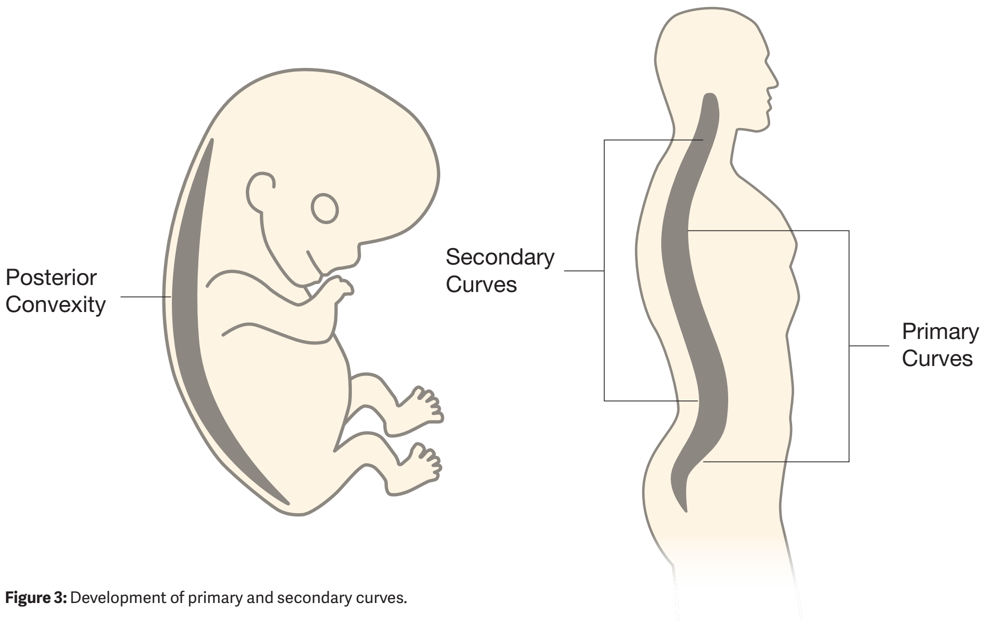


Figure 3: Development of primary and secondary curves.

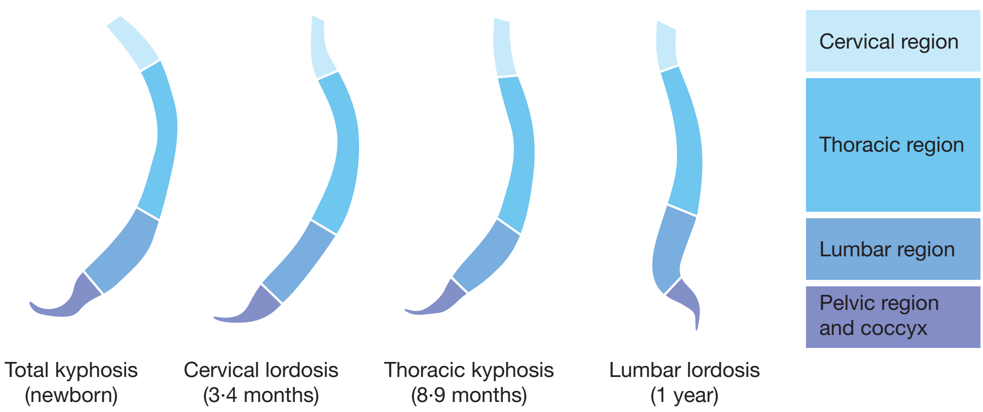


Figure 4: Development of spinal curavtures.

1.2.2 Descriptive spinal parameters

Spinal alignment is the integration of anatomical regions that provide shape, position, form and function between the spine, pelvis and hips [4, 20]. Such integration helps humans to maintain an upright posture, forward gaze, and bipedal locomotion and minimizes energy expenditure [1, 9, 10, 20]. Maintaining spinal alignment is achieved regionally by the cranial and caudal lordotic curves that are separated by the thoracic kyphotic curve [1].

To maintain sagittal spinal balance the cervical lordosis, TK and LL are intrinsically related and therefore both lordosis and kyphosis must be analyzed. The superior arc of LL is equal to the inferior arc of the TK.

Each curve may react to compensate for degenerative changes in the other therefore, to allow humans to maintain a forward gaze (*Figure 5*). Moreover, spinal alignment may not be a static entity but rather the result of a dynamic evolution to mechanical loads.

Previous studies have shown conflicting levels of evidence for normal values for spinal curvatures [21, 22]. It appears that difficulties occur with obtaining suitable levels of exposure in the upper thoracic and thoracolumbar spine; therefore inaccuracies may result with measuring spinal curvatures. In spite of this, it has been shown that the TK mean values are (49.3° ± 9.2 ranging from 33° to 71°) and LL mean values are (63.5° ± 10.9 ranging from 45° to 87°) [3, 23].

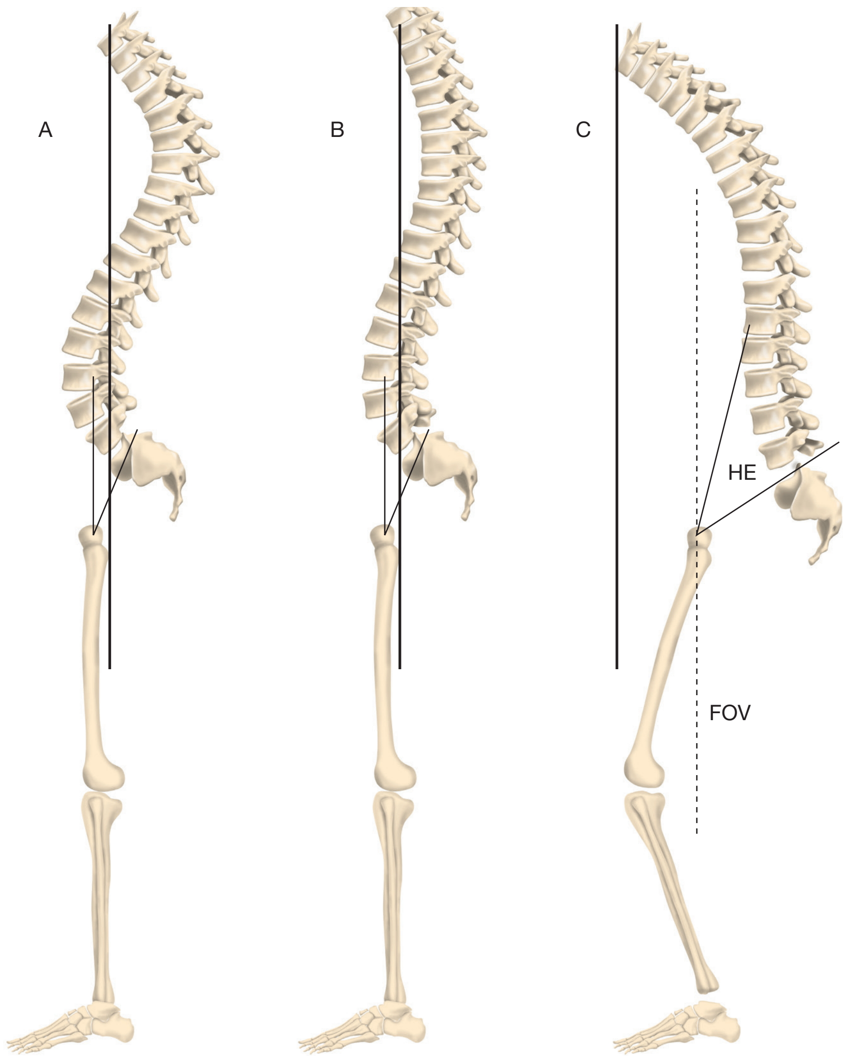


Figure 5: Spinal curvatures compensatory patterns. A. Balanced spine with slight pelvic retroversion and C7 plumb line (PL) over the sacral endplate behind femoral heads. B. Reduced lumbar lordosis, pelvic retroversion maintains C7 PL behind femoral heads. C. Thoracic kyphosis, hip extension (HE) limits pelvic retroversion. Compensations occur with knee flexion, as C7 PL passes forward to femoral heads.

Evaluation of spino-pelvic alignment has been shown to be useful for determining the characteristics of the spinal curvatures, global spinal orientation and pelvic parameters [24] (*Figure 5*). Previous studies have suggested spinal curvatures to assist with force distribution throughout the spinal column [21, 22, 24, 25]. The curvatures are intrinsically related and have been shown to influence the form and function of the pelvis and hips [3, 4, 20]. For example, a loss of LL may result in pelvic retroversion with subsequent hip joint extension. Compared with an increased LL, which may result in pelvic anteversion and subsequent hip joint flexion. Or an increase in TK which may result with an insufficient LL therefore increasing pelvic retroversion and hip joint flexion [23]. Spinal curvatures have also been categorized by morphological and positional measurements that help to determine the pelvic parameters. Other variables such as growth, balance, posture, heavy loads and sporting activities are all associated with the development and changes within these curves [7, 26]. It is possible that this may be related to spinal axial loading and development of muscular imbalances due to intense training regimes [5, 7].

Global spinal orientation provides evidence towards the overall spinal alignment. The centre of the C7 vertebral body is used as a reference point alongside other respective anatomical landmarks on the sacral-pelvic region. The Sagittal Vertical Axis (SVA) can be viewed as a measurement of global spinal orientation (*Figure 6*). The SVA assesses if an individual is in neutral, positive or negative alignment by comparing the head position relative to the sacral promontory [27]. Clinically using the SVA for global spinal orientation may be used as a means to evaluate individuals with sagittal imbalance, spinal pathology and progressive deformities [28].

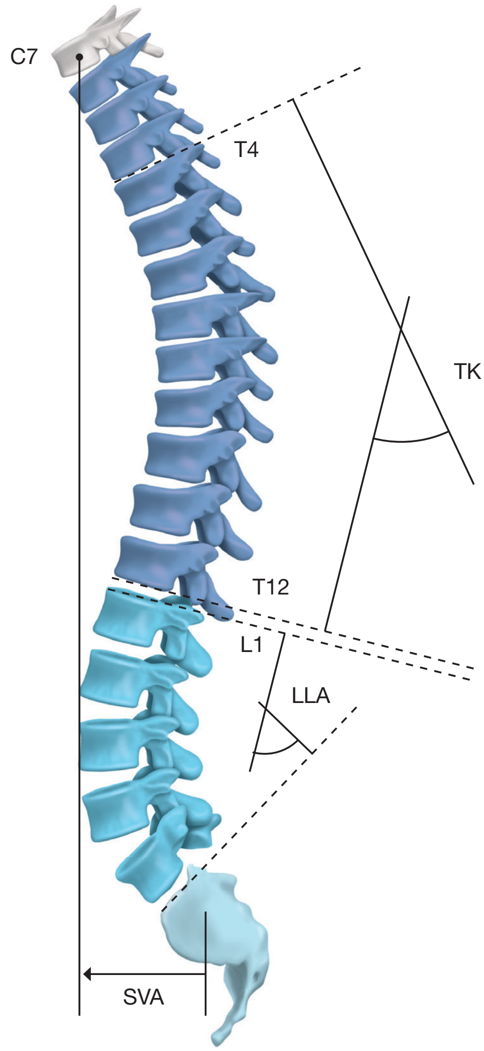


Figure 6: Geometrical evaluation of spinal parameters.

1.2.3 Anatomy of the pelvic girdle

The pelvic girdle constitutes the base of the trunk, supports the abdomen and links the vertebral column to the lower limbs. Described by Kapandji [14] as; “A closed osteo-articular ring made up of three bony parts and three joints”. The paired innominate bones formed by fusion between the ilium, ischium and pubic bones. Anteriorly, the symphysis pubis forms the articulation between the innominate bones. Posteriorly, the sacroiliac (SI) joints form the articulation with the vertebral column (*Figures 7 & 8*).

As with all joints stability is provided by the congruity of articular surfaces, the joint caspule and the ligaments that bind the joints together combined with the muscles that act around them [15]. Functionally, the innominate bone should be viewed as a lower extremity bone and the two SI joints as the junction of the vertebral axis and the lower extremities. Palastanga [15] suggests one key role of the pelvis during the walking cycle is the translation from side-to-side by a rotatory movement at the lumbosacral articulation.

Figure 7: Anterior view of the pelvic girdle.

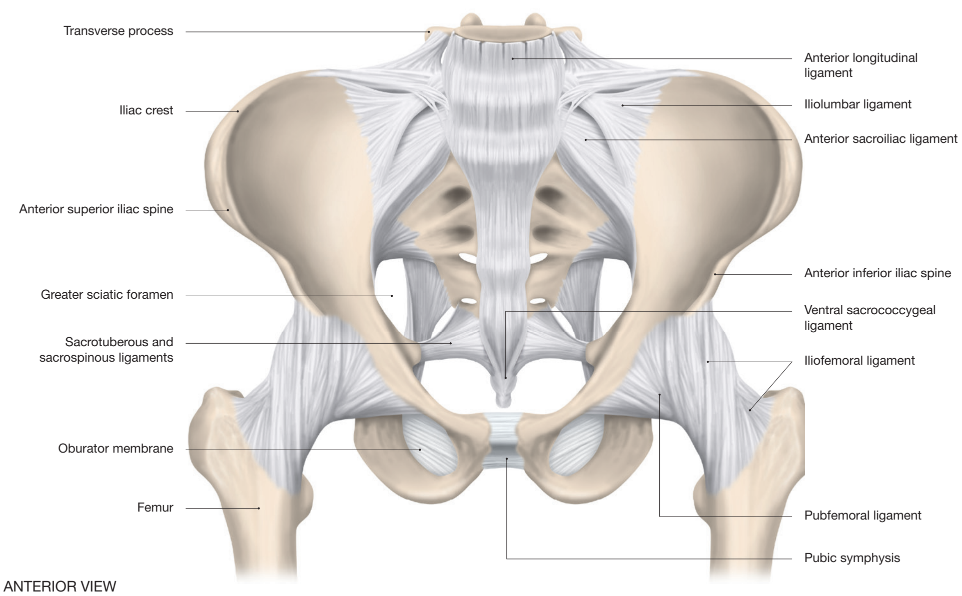
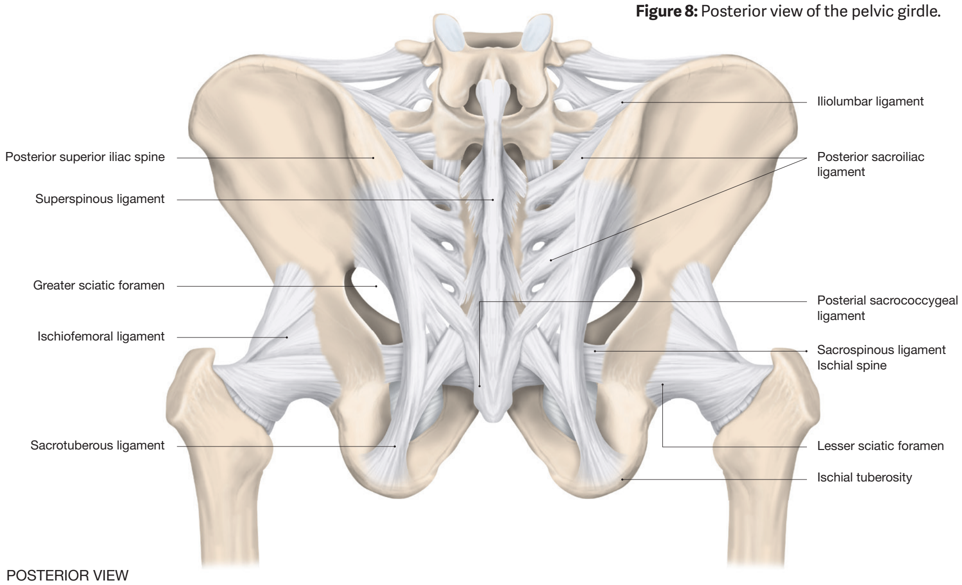


Figure 8: Posterior view of the pelvic girdle.



1.2.4 Descriptive pelvic parameters

Pelvic parameters have been shown to place significant emphasis on maintaining spinal sagittal balance [3, 10, 29]. The anatomical relationship between the spine and the pelvis helps with modulating an erect posture through the pelvic girdle balancing lumbar lordosis with hip joint extension [3]. Moreover, it has been suggested that the angle of Pelvic Incidence (PI) is an essential anatomical pelvic parameter that can be used as a means to classify both the morphology and functionality of the pelvis [10, 30]. A low PI angle is associated with a reduced LL and a high PI angle is associated with an increased LL [29, 31-34].

Pelvic parameters (*Figure 9*) are a concept of comparing three parameters by means of pelvic geometry, Pelvic Incidence (PI), Pelvic Tilt (PT) and Sacral Slope (SS). PI is a morphological parameter and relates to the angle measured from a perpendicular line to the mid-point of the sacral plate and extended to the centre of the femoral head. PT is the angle measured from a perpendicular line starting at the centre of the femoral head and extended to the mid-point of the sacral plate and is a positional (functional) parameter. SS is a positional parameter and is the angle measured from the superior endplate of S1 and a horizontal axis [8, 31].

I. 1.1.1 Pelvic Incidence (PI)

The PI angle provides information pertaining to pelvic compensation such as an individual's ability to perform pelvic retroversion in relation to the femoral heads [3]. Previous studies have shown that PI values within an asymptomatic population range from 35° to 85° with an approximate mean PI value being 52° [24]. Moreover, this angle becomes fixed after skeletal maturity. Individuals with a low PI angle are shown to have a short pelvic ring on anterior-posterior (AP) axis resulting in a more vertical shaped pelvis that has a lower tolerance for pelvic retroversion (pelvis rotates backwards). Conversely individuals with a high PI angle have been shown to have a larger AP axis resulting in a more horizontally shaped pelvis and therefore, have a greater ability for pelvic retroversion [3]. A low PI angle (<44°) has been shown to correlate with a low SS angle and reduced LL as a high PI (>62°) correlates with a high SS angle and an increased LL [31]. PI values <35° are seen in Scheurmann's disease and PI angles >85° are seen in patients with isthmic spondylolisthesis [35].

I. 1.1.2 Pelvic Tilt (PT)

The mean value of the PT angle is approximately 12° ranging from 5° to 30° [27]. Moreover, this is a compensatory angle and changes with posture. PT decreases when the pelvis rotates forwards (anteversion) and PT increases when the pelvis rotates backwards (retroversion).

I. 1.1.3 Sacral Slope (SS)

The mean value for the SS angle is approximately 40° ranging from 20° to 65° [27, 36]. Similarly to PT, the SS is also a compensatory angle and adapts to posture. A geometrical relationship exists between the morphological PI angle and functional parameters PT and SS resulting in the equation PI=PT+SS [8].

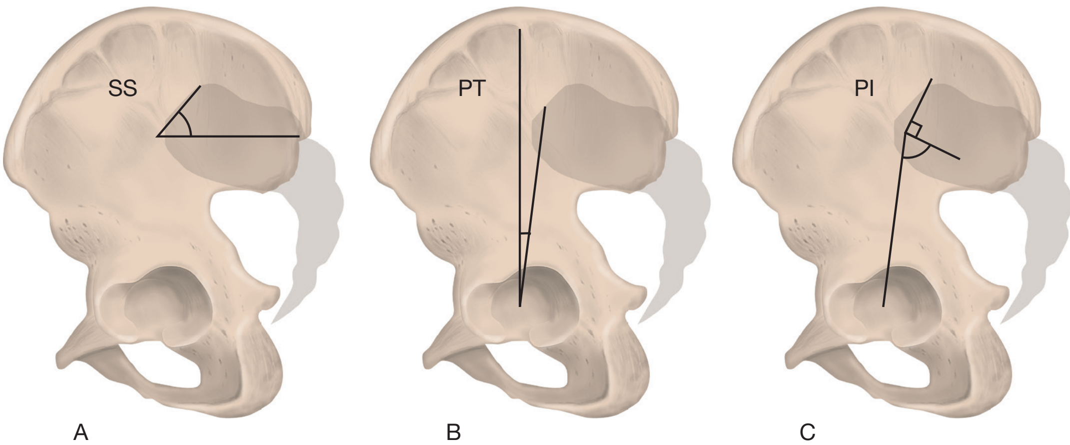


Figure 9: Geometrical evalutaion of pelvic parameters.

1.2.5 Roussouly spinal classifications

Alongside PI, the SS helps to determine the type of specific lordosis an individual may have. Stagnara et al. [37] proposed a correlation between LL and the SS. The greater the SS, the greater the LL, conversely, when SS was horizontal, lumbar kyphosis (flat back) was noted. Other studies have proposed such a correlation between SS and LL [38, 39]. The inferior arc of LL corresponds to the SS and Roussouly et al. [8] demonstrated the importance of this in determining global lordosis. Moreover, four types of spinal curvatures correlating to the angle of the SS were defined according to Roussouly et al. [8]. Types 1 and 2 are generally being more conducive to a low PI angle as Types 3 and 4 have a high PI angle *(Figure 10)*.

Roussouly et al. [24] further established such a classification model of spinal types *(Figure 10)* within a normal variation using a sample of 160 asymptomatic LBP participants (mean age 30.8 years). Within this sample, 34 (21%) had characteristics of a Type I spine, compared with 18 (11%) that had a Type II spine, 60 (38%) had a Type III spine and 48 (30%) a Type IV spine.

Type I: Low SS angle <35° and a low PI angle. A long thoracolumbar curve and short lordotic curve is noted resulting in a thoracic/lordosis ratio of 80:20 *(Figure 10)*. The point at which the vertebral bodies change their orientation in relation to this long thoracic curve occurs at the segmental levels of L3-4. The apex of the LL is low at the level of L5-S1.

Type II: Low SS angle <35° and a low PI angle. A shorter kyphotic curve and a longer lordotic curve are noted resulting in a thoracic/lordosis ratio of 60:40 *(Figure 10)*. Moreover, in spite of this appearance, the end result is a thoracolumbar flat back. The point at which the vertebral bodies change their orientation in relation to this thoracolumbar ‘flat back’ occurs at the segmental levels of L1-2. The apex of the LL appears to be slightly higher at the L4-5 level.

Type III: High SS angle >35° <45° and a greater PI angle. The kyphotic and lordotic curvatures result in an equal thoracolumbar curve with a ratio of 50:50 *(Figure 10)*. The point at which the vertebral bodies change their orientation in relation to this equal thoracolumbar split occurs at the segmental levels of T12-L1.

Type IV: High SS angle >45° and a high PI angle. A reversed thoracolumbar curvature results in a longer lordotic curve and a shorter kyphotic curve with a ratio of 20:80 *(Figure 10)*. The point at which the vertebral bodies change their orientation in relation to this reversed thoracolumbar split occurs at the segmental levels of T9-10. The LL is greater and therefore an increased contact point of load is exhibited posteriorly upon the L4 and L5 facet joints.

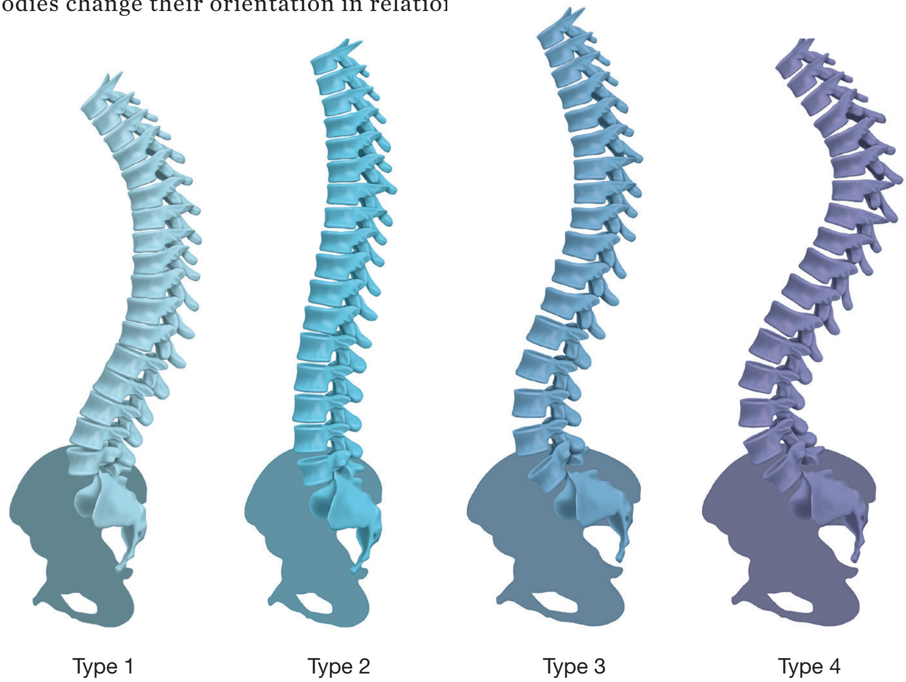


Figure 10: Spinal classifications according to Roussouly et al. **Type I:** Low sacral slope <35° and a low PI with a long thoracolumbar curve and short lordotic curve resulting in a thoracic/lordosis ratio of 80:20. **Type II:** Low sacral slope <35° and a low PI with a shorter kyphotic curve and a longer lordotic curve resulting in a thoracic/lordosis ratio of 60:40. **Type III:** High sacral slope >35 ° <45 o and a greater PI. The kyphotic and lordotic curvatures result in an equal thoracolumbar curve with a ratio of 50:50. **Type IV:** High sacral slope >45 ° and a high PI with a reversed thoracolumbar curve resulting in a long lordotic curve and short kyphotic curve with a ratio of 20:80.

Spinal pathologies correlated to spinal curves

Specific spinal pathologies *(Table 1)* have been attributed to three of the four types of spinal curvatures according to Roussouly & Pinheiro-Franco [3]. These range from increased disc degeneration in the thoraco-lumbar region with Type I, to central disc herniation in Type II, a well-balanced spine with Type III and an increased risk of spondylolisthesis in Type IV [32, 39-41].

Table 1: Spinal pathology associated with Roussouly Type spines.

Spinal type	Segmental contact points	Spinal pathology
Type I	L4-5, L5-S1	Disc degeneration/ retrolisthesis
Type II	Flatback- multiple levels	Multiple disc herniation
Type III	Balanced spine	
Type IV	L4-5, L5-S1	Spondylolisthesis

The spino-pelvic alignment differs between the spinal curvatures and it has been shown that the increased stress between the contact points effect the degenerative evolution and pathology related to sagittal balance [3]. A previous study highlighted a reduced LL and SS to be shown in patients who underwent disc herniation surgery compared to a control group of healthy participants [40]. This suggests that Type I and II spines may be more prone to disc herniation.

In the thoracolumbar junction of a Type I spinal classification *(Figure 10)*, the intervertebral discs are tilted with an increased risk of retrolisthesis. This may be due to a low PI and short LL limiting the range of pelvic retroversion and therefore, creating spinal compensatory patterns. Due to the short lordosis, in a younger population, hyperextension of the L4-5 and L5-S1 segments may induce a nutcracker spondylolysis.

Type II spinal classification 'flat back' *(Figure 10)*, according to Roussouly et al. [8] have been shown to have an increased disc pressure and a higher risk of early central disc herniations. The risk of early disc degeneration at multiple levels has been shown to increase in patients with a low PI and 'flat back' [39]. Moreover, bio-mechanically due to increased disc degeneration a Type II spine is not conducive to high intensity sporting activities that place increased loading upon the lumbar spine [3].

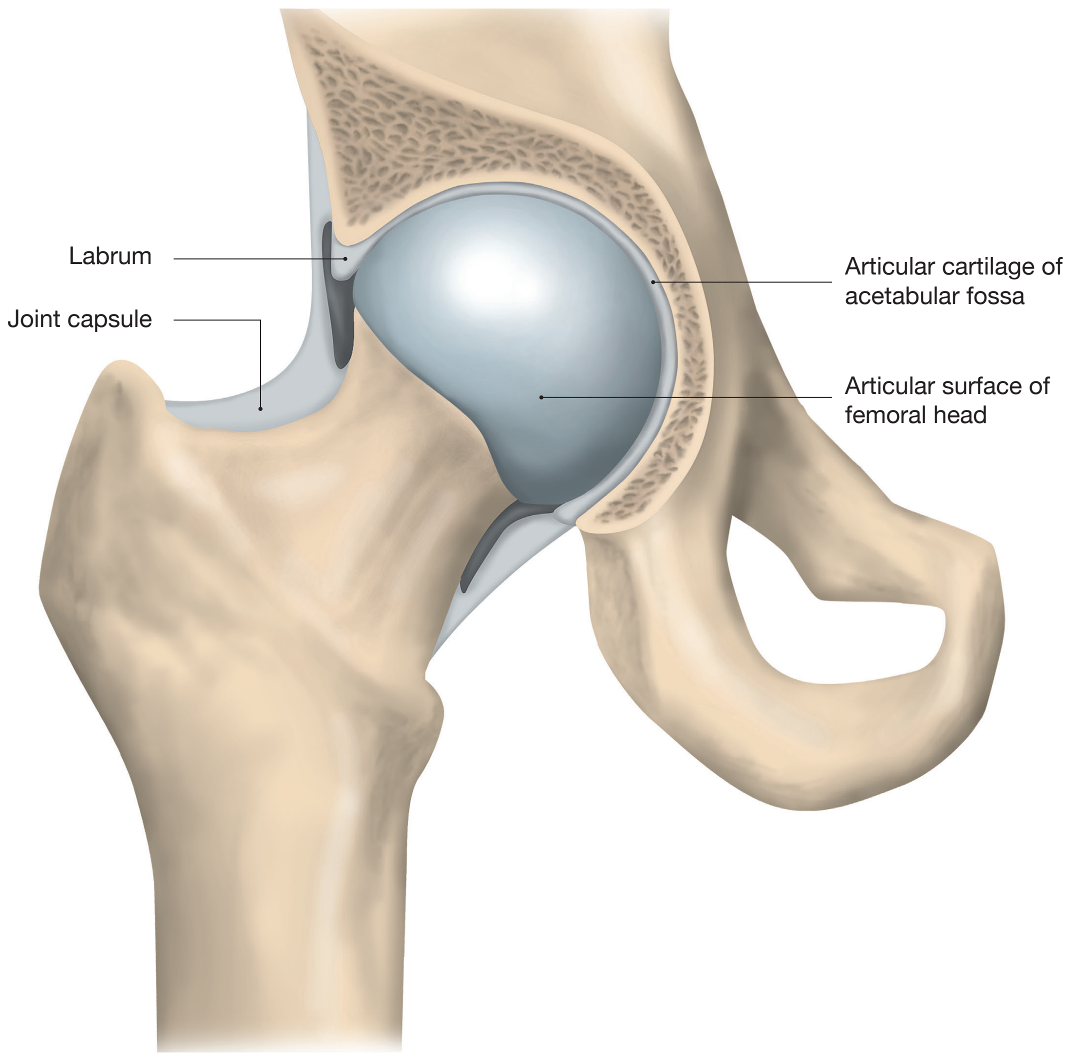
Type III spinal classifications *(Figure 10)* exhibit a well-balanced spine and are shown not to be correlated with any specific spinal pathology. However, Type IV spinal classifications *(Figure 10)*, have a higher PI angle and SS angle therefore, develop a greater hyperlordotic lumbar curve increasing the risk of the contact force upon the posterior segments of the lumbar spine. In this instance, in the younger population, a higher PI angle leads to an increased SS angle and therefore, greater stresses are exhibited upon the L4 and L5 facet joints with an increased risk of fracture or elongation of the par interarticularis resulting in spondylolysis/olisthesis. This has been suggested in a previous study by Marty et al. [32]. Moreover, Swärd et al. [42] found a similar correlation between an increased SS angle, spondylolysis and the degree of elongation in an identical population of spondylolisthesis patients. In the older population, and if LL has been maintained, degeneration of the L4-5 posterior facet joints may result in a degenerative L4-L5 spondylolisthesis.

1.2.6 Anatomy of the hip joint

The hip joint is a synovial ball and socket joint. The architecture of the hip joint allows for the round femoral head to articulate with the concave acetabulum of the pelvis *(Figure 11)*. Triplanar movement in all three planes is possible at the hip joint, sagittal (flexion and extension), frontal (abduction and adduction) combined with transverse (internal and external rotation). These movements are similar to the glenohumeral joint but due to the larger loads imposed upon the hip joint; there is a greater demand for stability. Microinstability may occur from subtle anatomical abnormalities of the acetabular labrum or from ligamentous laxity and weaknening of the joint capsule and surrounding muscles [43, 44]. The joint capsule is reinforced with strong ligaments to enhance stability but also functions to influence the range of motion (ROM) within the joint. Anteriorly, the iliofemoral ligament limits extension, inferiorly; the pubofemoral ligament limits abduction as posteriorly, the ischiofemoral ligaments limit internal rotation.

The joint capsule is further reinforced posteriorly by the annular ligament that attaches into the greater trochanter of the femur and runs circumferentially around the neck of the femur, assisting with resisting distractive forces on the joint [45]. The labrum is a fibrocartilagenous structure and is located along the bony circumference of the acetabulum. Superiorly it runs continuous with the acetabular cartilage as inferior; the transverse ligament connects the anterior and posterior portions. The labrum functions to increase joint depth therefore influencing joint stability [46]. An intra-articular connection between the pelvis and femur occurs thorough the ligamentum teres. This arises from the transverse ligament and inferior aspect of the acetabulum and inserts into the fovea capitis on the head of the femur functioning as an intrinsic hip joint stabilizer [47].

Figure 11: The architecture of the hip joint.



1.2.7 Development of increased hip joint morphology and FAI

Femoroacetabular Impingement (FAI) consists of two types known as cam (osteophytes in the femoral head-neck junction zone) and "pincer" (osteophytes at the acetabular edges), or by a combination of both [48-55]. Clinically both cam and pincer impingement can be observed individually or together. Hip joint cam-type FAI *(Figure 12)* has been shown to be common in young athletes [56], result in suboptimal hip function [57] and may affect spino-pelvic motion [58]. In cam-type FAI impingement there is a non-spherical femoral head or an insufficient offset between the femoral head and neck [59]. Such abnormal joint morphology combined with repetitive loading from the proximal femoral head abutting against the acetabulum [48-55], may cause increased stress and damage to the articular cartilage, during repetitive hip flexion and internal rotation [60, 61].

A recent consensus statement on FAI highlight the primary symptom to be motion-related or position-related pain in the hip or groin [62]. In athletes, the most common complaint relating to FAI is groin pain that has been exacerbated by intense activity including repetitive hip flexion movements. Moreover, symptoms may be vague and diffuse with pain often being referred medially towards the pubic symphysis, laterally towards the greater trochanter or dorsally towards the gluteal muscles. The C sign is often used by individuals to describe the location of their pain by placing their hand in a C shape around the hip [63]. Clinically the most common finding with FAI examination relates to reduced ROM especially flexion and internal rotation [64-66].

FAI diagnosis is based upon clinical history, physical examination and investigations using plain radiographs, Computerized Tomography (CT) or Magnetic Resonance Imaging (MRI) [60]. The reliability of clinical tests such as the Flexion Abduction External Rotation (FABER) *(Figure 12)* and Flexion Adduction Internal Rotation (FADDIR) *(Figure 13)* tests for FAI vary in many studies. However, both tests have been shown to be sensitive but lack specificity [65, 67]. Moreover, the FABER test also shows good reliability as the FADDIR test appears to be widely reported in studies regarding FAI [66, 68-71]. Jónasson et al. [72] found in a clinical and radiological study that athletes had higher Tönnis grade, more pain on FADDIR test and significantly lower ROM in internal and external rotation.

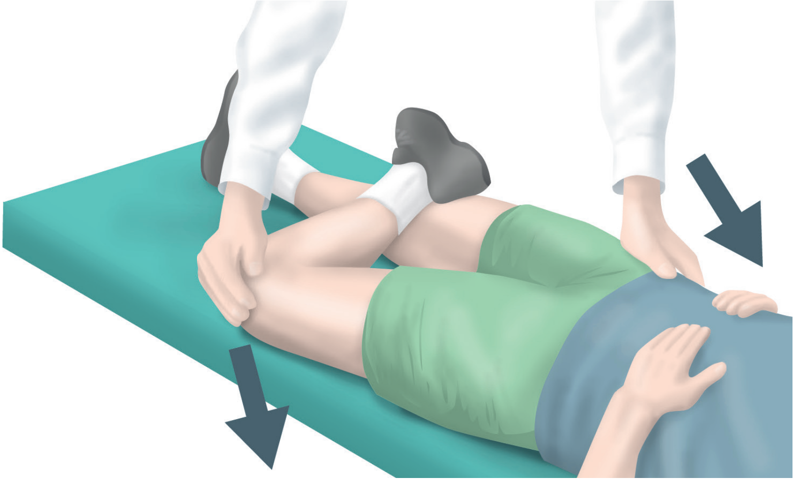


Figure 12: The FABER test is performed with the patient in supine. The lateral malleolus of the examined hip is placed superiorly to the patella of the contralateral knee. The hip is then abducted with one hand, while the pelvis is stabilised with the other hand. Reproduction of symptoms means the test is positive. The angle between the examination table and the lower leg of the examined extremity can be registered as an indication of ROM.

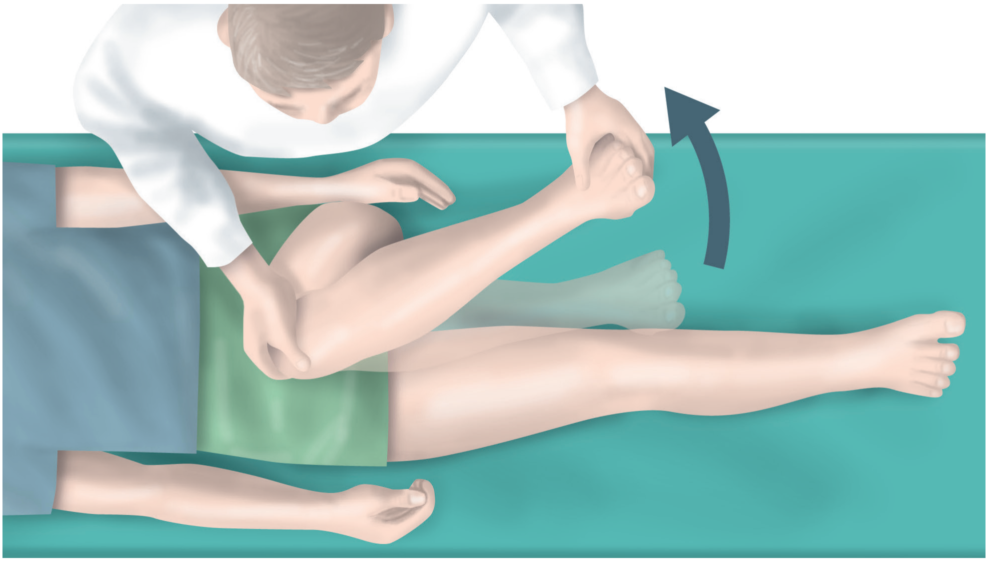


Figure 13: The FADDIR test is performed with the patient supine. The hip is flexed to 90°, adducted and rotated at the same time. The reproduction of patient symptoms means the test is positive.

FAI diagnosis cannot be made without radiographic investigation. A plain radiograph with an AP and lateral view is often sufficient; however, cam deformities are best visualized using the Dunn's view, with the patient supine and the hip flexed and abducted 20° or using the Lauenstein view with the hip flexed and abducted 45° *(Figure 14)* [73, 74]. Measurement of the alpha angle quantifies the extent of the cam deformity and is used to determine the prominence of the anterior femoral head-neck junction [60].

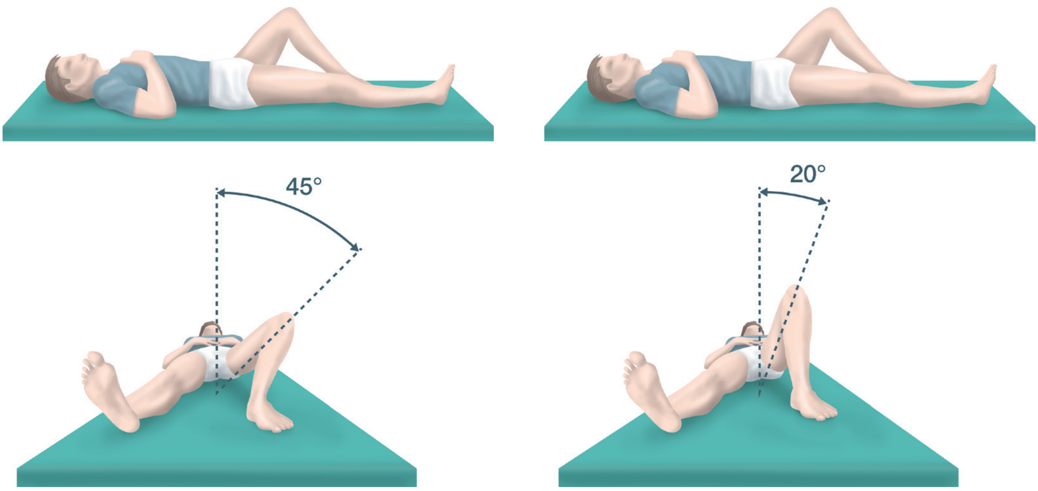


Figure 14: The Dunn view (right) or the modified Lauenstein view (right) are often used to visualise the cam deformity. Both tests are performed with the patient supine and knee flexed to 45°. The Dunn view is acquired with 20° abduction and the modified Launstein with 45° abduction.

Recent studies have shown that the cam-type deformity may be linked to a mechanical etiology, emerging from the physeal scar of the proximal femoral physis [52]. It has been suggested that this may have developed during adolescence as a response to vigorous sporting activity [76-78] *(Figure 15)*. Similar growth disturbances and chronic physeal damage has also been reported to occur in other regions such as the spine in adolescent elite athletes [79-82].

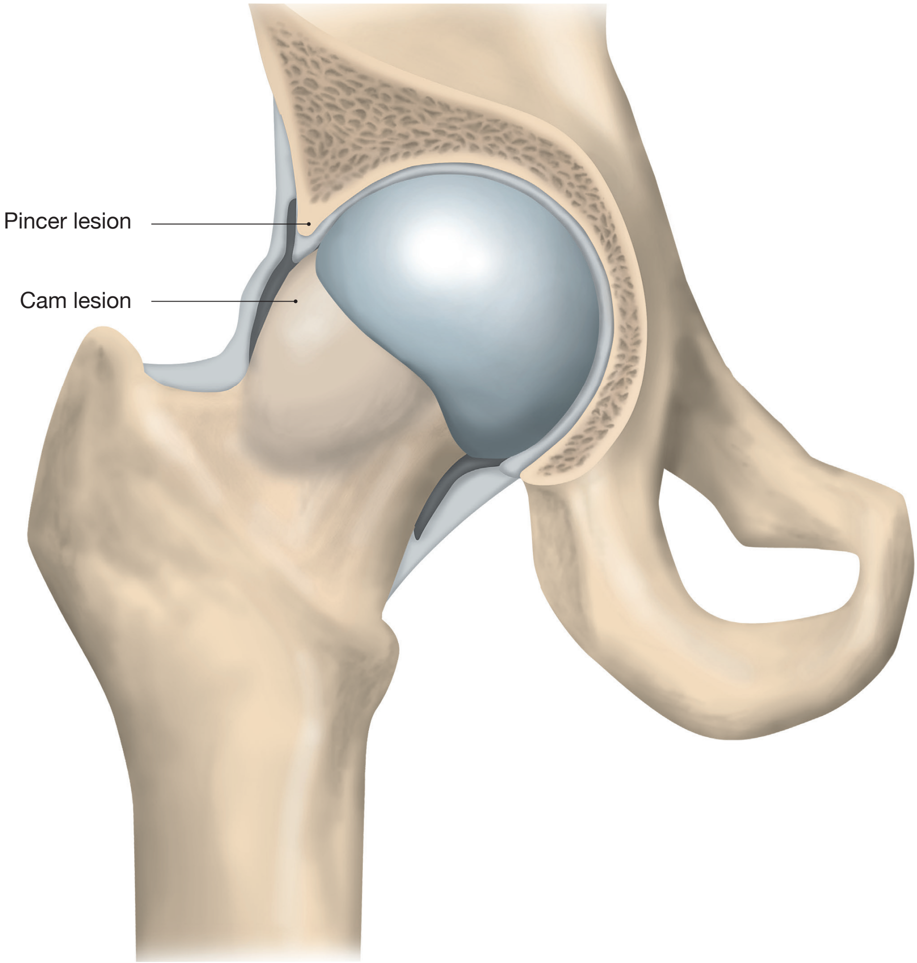


Figure 15: Effects of hip joint cam and pincer impingement.

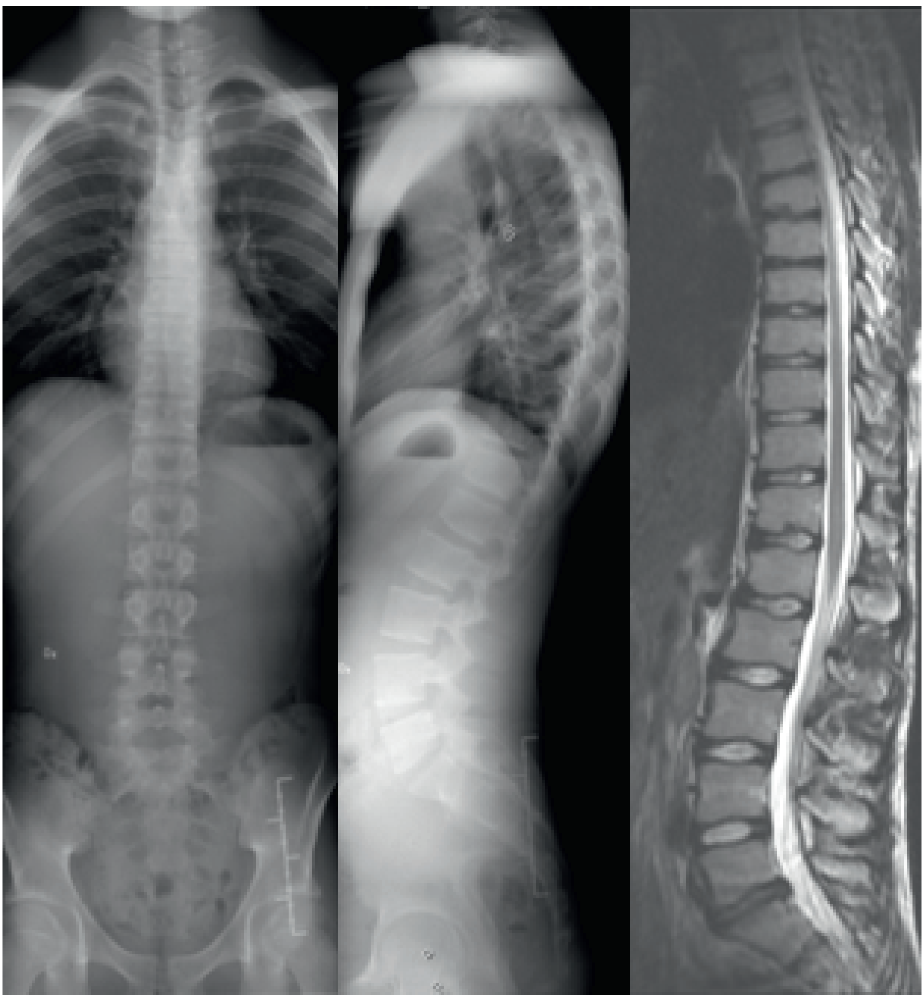
1.2.8 Imaging methods

Standing plain radiographic evaluation of spinal sagittal alignment *(Figure 16, 17, 18)* can be used in the assessment of local, regional and global spinal orientation [83]. Such an evaluation may provide objective information on many variables including the characteristics of the spinal morphology, overall spinal alignment and malalignment, standing posture, progressive spinal deformities and pathological processes [1, 3, 21, 22, 24, 25, 83].

Spinal posture has been described

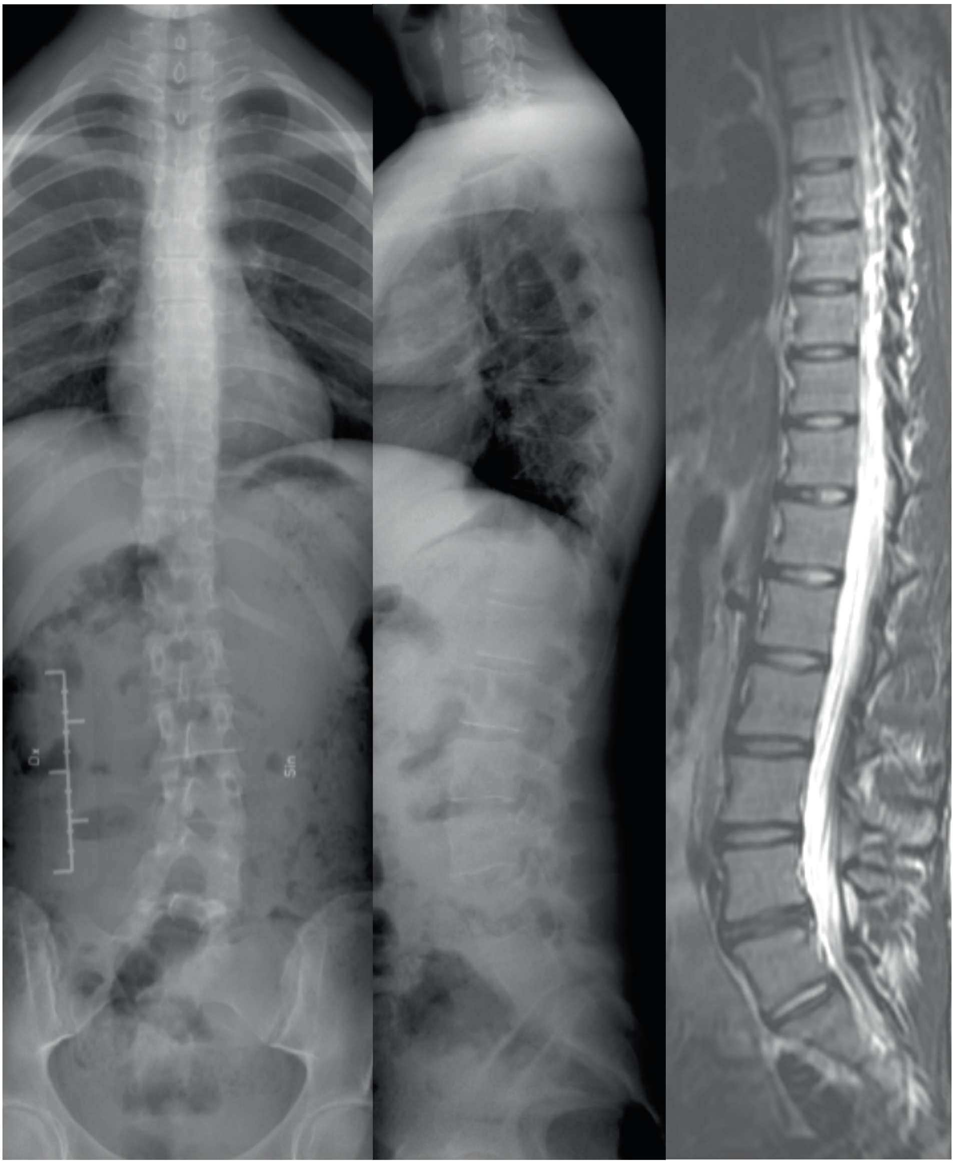
differently in many studies, according to the morphology of the spinal curve (normal, kyphosis, lordosis, kypho-lordosis) [37]. Moreover, the angle of LL in relation to the sagittal tilt of the sacral plate has also been used to define spinal curvatures [10, 30, 33, 34, 84]. The LL being defined as either the angle between the upper plate of the L1 vertebra and the upper plate of the first sacral vertebra or the lower vertebral plate of L5. The mean values for spinal parameters also appear to vary between studies. Moreover, this may due to the variable ranges observed amongst individuals and differences in measuring techniques *(Table 2)*.

Quantifying pelvic parameters may be defined through pelvic geometry [10]. Geometrical measurements taken from plain lateral radiographs can be used to describe the form (PI) and function (PT and SS) of the pelvis in relation to the values of PI, PT and SS. Similar values have previously been shown in studies *(Figure 19)* when describing pelvic parameters [10, 33, 34].



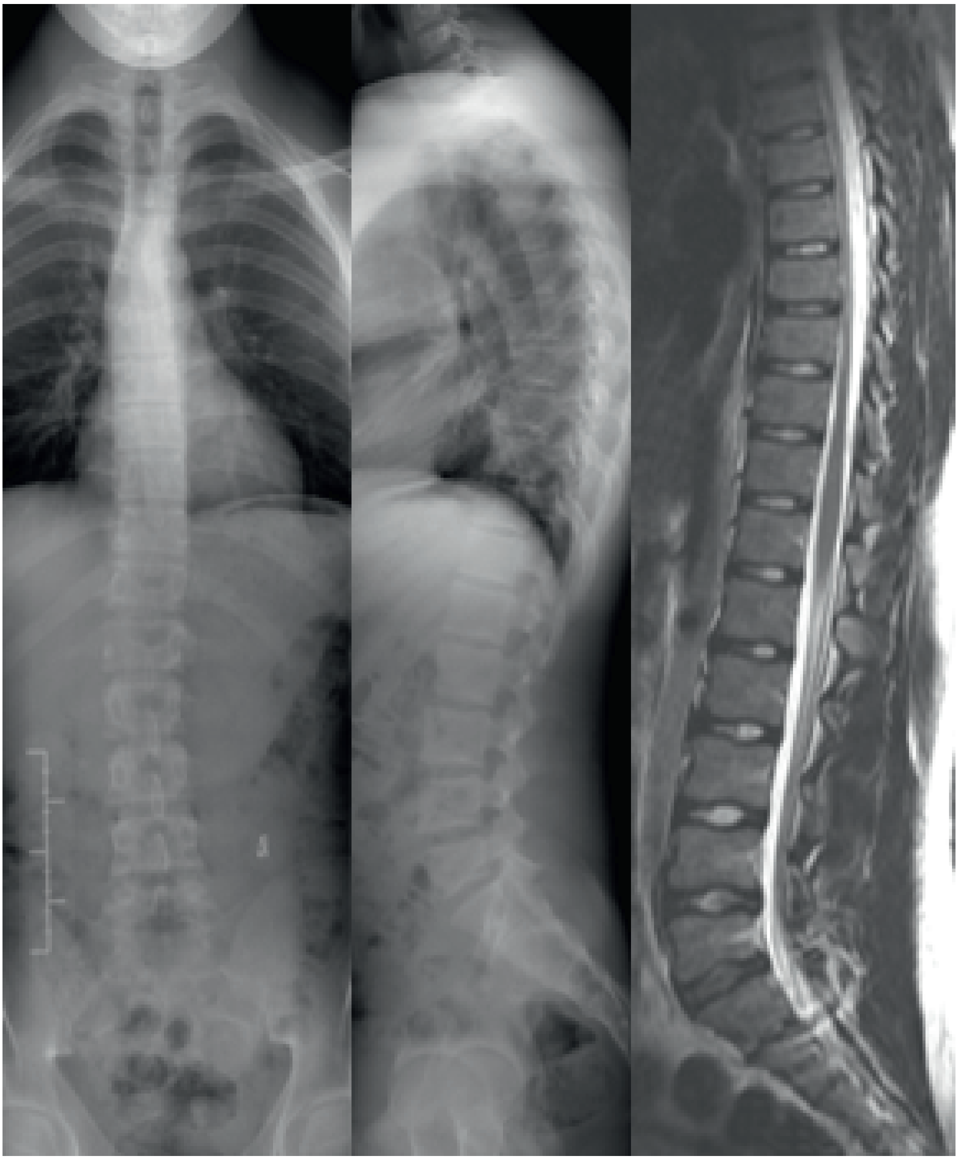
A. B. C.

Figure 16: A. 17 years old male control. Standing frontal radiograph. **B.** Standing lateral radiograph shows Roussouly Type III spine. **C.** MRI shows moderate disc degeneration L5-S1 and Schmorls nodes T6-9 and T12-L1.



A. B. C.

Figure 17: 20 years old female skier. **A.** Standing frontal Radiograph shows thoracolumbar scoliosis. **B.** Standing lateral radiograph shows Roussouly Type III spine. **C.** MRI shows mild to moderate disc degeneration L4-5.



A. B. C.

Figure 18: 17 years old male skier. **A.** Standing radiograph shows thoracolumbar scoliosis convex right. **B.** Standing lateral radiograph highlighting evenly balanced spine (50:50 for thoracic and lumbar curve) Roussouly Type III spine. **C.** MRI shows mild to moderate disc degeneration at the L4-5 level.

Table 2: Variable ranges in values for Lumbar Lordosis (LL) and Thoracic Kyphosis (TK).

Spinal parameters (°)	Min.	LL Max.	Range	Min.	TK Max.	Range
Duval-Beaupère et al. (1998)	46	87	41	33	71	38
Guigui et al. (2003)	37	89	52	7	65	58
Vaz et al. (2002)	26	76	50	25	72	47
Gelb et al. (1995)	38	84	46	9	66	57
Jackson et al (2000)	35	90	55	22	75	52

(All values showing mean and SD).

Values for pelvic parameters have also been shown to highlight a correlation with the organization of the spino-pelvic complex [8]. The PI angle has been shown to provide the most substantial values for understanding the possible adaptations relating to pelvic compensation. Moreover, it has been suggested by Roussouly & Pinherio-Franco [3] that an individual's ability to perform pelvic rotation around the axis of the femoral heads may be one of the best mechanisms for regulation of spinal sagittal balance.

Table 3: Variable ranges for spino-pelvic parameters between studies.

	Duval-Beaupère et al. (1998)		Guigui et al (2003)		Vaz et al. (2002)	
Parameters (°)	Mean	SD	Mean	SD	Mean	SD
Pelvic Incidence	52	11	55	11	52	12
Sacral slope	41	9	42	9	39	9
Pelvic Tilt	11	6	13	6	12	6
Lordosis	64	11	61	13	47	11
Kyphosis	49	9	41	9	47	9

(All values showing mean and SD).

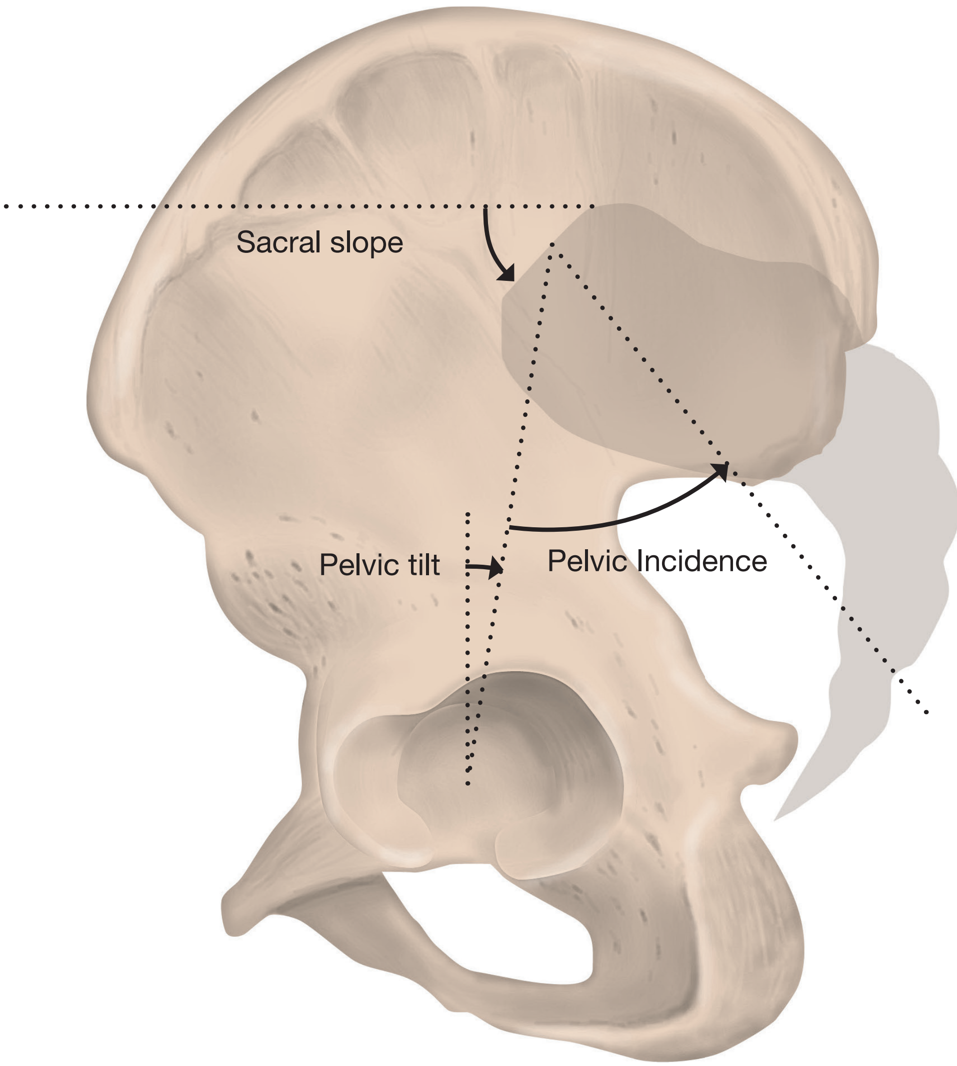


Figure 19: Geometric measurements for pelvic parameters.

Increased morphological hip joint cam-type FAI changes cannot be diagnosed without the use of radiological evaluation such as a plain radiograph with an Anterior/Posterior (AP) and lateral view. Moreover, Magnetic Resonance Imaging (MRI) may also be used to evaluate the morphological changes *(Figures 21-26)*. The benefit of using MRI for evaluation of young athletes is that it reduces any unnecessary exposure to radiation.

Quantifying the shape of the femoral head *(Figure 20 & 21)* on MRI is done by measuring the alpha (α) angle according to Nötzil et al. [85]. The α-angle is measured in all planes from 9 to 3 o'clock. This is the angle between a line drawn along the axis of the femoral neck and a line drawn from the femoral head center to the point where the head extends beyond the margin of a best-fit circle [86]. The α-angle is used to define the presence of a cam deformity and in previous studies a threshold of >55° has been considered pathological [87-90].

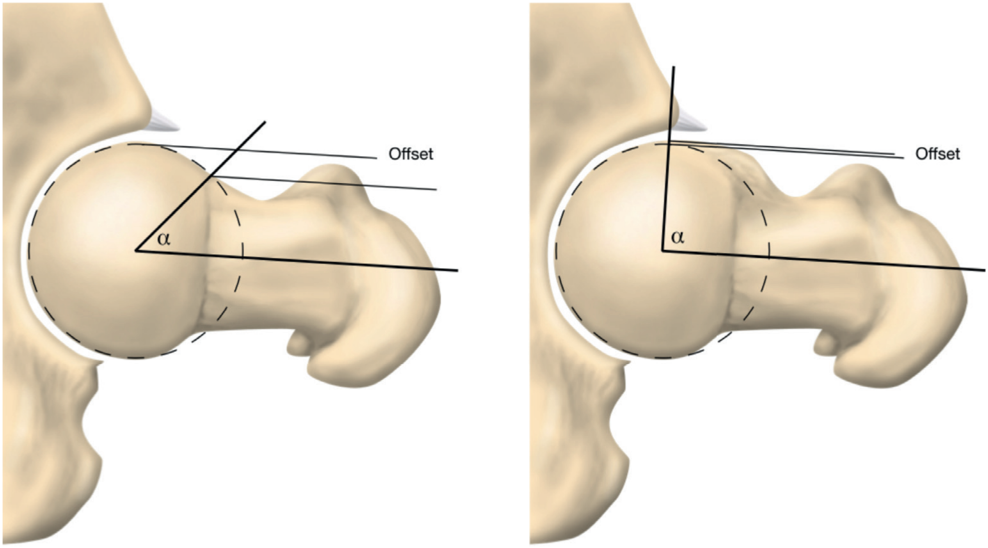


Figure 20: Quantification of the α angle. Measurement of the alpha angle to quantify the cam deformity. The α-angle was set as greater than 55o and measured in all planes from 9 to 3 o'clock. This is the angle between a line drawn along the axis of the femoral neck and a line drawn from the femoral head center to the point where the head extends beyond the margin of a best-fit circle.

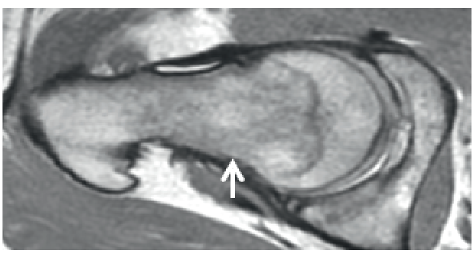


Figure 21: MRI of right hip showing cam FAI 64° α-angle in a 20 years old male skier.

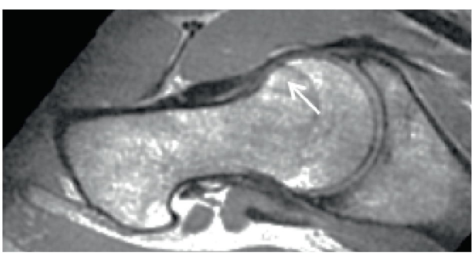


Figure 22: MRI of right hip showing cam FAI 73° α-angle in 20 years old female skier.

Figure 23: MRI of left hip showing cam FAI 67° α-angle in 20 years old female skier.

Figure 24: MRI of left hip showing cam FAI 66° α-angle in 19 years old male skier.

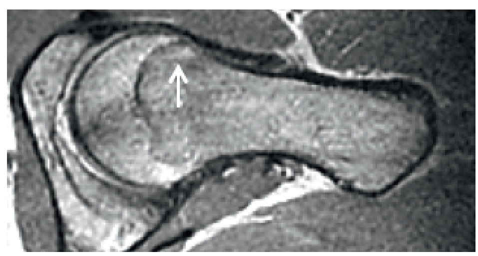


Figure 25: MRI of left hip showing cam FAI 65° α-angle in 20 years old male skier.

Figure 26: MRI of right hip showing cam FAI 66° α-angle in 19 years old female skier.

1.2.9 Clinical methods

Clinical evaluation of spino-pelvic sagittal alignment has been investigated with non-invasive, skin-surface measuring devices [5-7, 91-99]. Benefits of using non-radiological methods such as the Debrunner Kyphometer and Palpation (PALM) meter include low costs combined with ease of ability to perform especially within a short time frame [100]. Both the Debrunner Kyphometer and the Palpation meter are small, portable and relativley safe [101, 102]. Moreover, good reliability and moderate to good levels of validity have been shown with using both clinical methods [96-99, 103].

A recent systematic review of clinical methods highlighted, the Debrunner Kyphometer to show strong levels of evidence for measuring the reliability of TK. However, criticisms for using the Debrunner Kyphometer included inconsistent findings due to marking and palpation of anatomical landmarks and poor levels of validity compared to a radiological standard [100].

1.2.9.1 The Debrunner Kyphometer

The Debrunner's Kyphometer (Protek AG, Bern, Switzerland) *(Figure 27)* is a protractor with two movable arms that can be placed on specific bony landmarks [93]. Each arm is connected together by a block, large enough to span two spinous processes. The Debrunner Kyphometer is capable of providing accuracy of measurement in a 1 degree-scale. The original Kyphometer design measured kyphosis angles up to 52° however, modifications increased the range to 70° and made it suitable for measuring lumbar flexion and extension [94].

It appears that for the mean range *(Table 3)* of TK (23° to 57.7°) and LL (-31° to -36°) varies between studies [93, 94, 97-99]. Moreover, previous studies have shown the Debrunner Kyphometer to be a reliable *(Table 4)* handheld measuring device [97-99]. Validity measurements to compare the Debrunner Kyphometer with a radiological standard, for TK has been shown to be good *(Table 4)* (ICC 0.759) [98] and (ICC 0.656 to 0.758) [97].

Table 3: Mean values for kyphosis and lordosis with the Debrunner Kyphometer.

		Kyphosis*			**Lordosis***	
	Sample	Mean	SD	Sample	Mean	SD
Greendale et al. (2011)	113	57.7	9.6			
Purser et al. (1999)	16	51	19	16	-31	13
Korovessis et al. (2001)	90	49.7	8.7			
Öhlén et al. (1988)	17	23		11	-37	
Öhlén et al. (1989)	31	29	2.4	31	-36	2.7

(All values showing mean and SD).

Table 4: Reliability and validity data using the Debrunner Kyphometer.

	High quality	Reliability (ICC)	Validity (correlation coefficient)
Korovesis et al. (2001)	No	.84 (inter) .92 (intra)	.759
Öhlén et al. (1989)	Yes	.92, .93 (intra) .91, .94 (inter)	N/A
Purser et al. (1999)	Yes	.95-.97 (intra)	N/A
Greendale et al. (2011)	Yes	.96 (intra + inter)	.656-.758

Adapted from Barrett et al. [96].

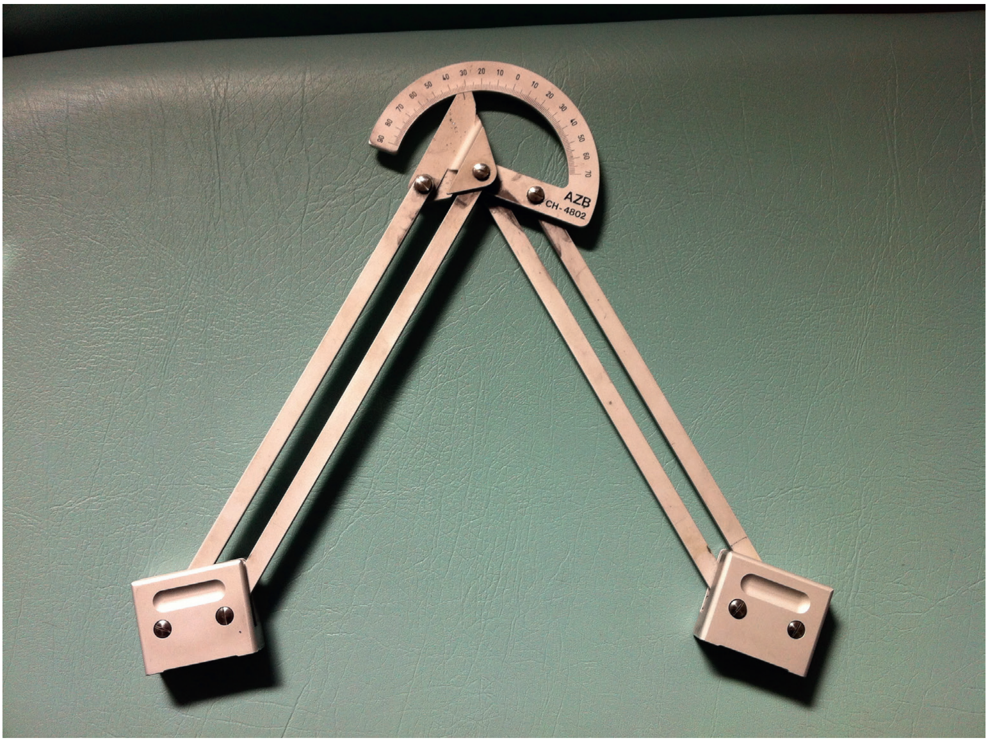


Figure 27: The Debrunner Kyphometer.

The Debrunner Kyphometer can be used as a hand-held skin-surface measuring device by placing the blocks on pre-marked anatomical landmarks for both the thoracic and lumbar spine *(Figure 28)*. Clinical experience and anatomical palpatory awareness ensures that the bony landmarks can be located and marked effectively. Moreover, the use of the Debrunner kyphometer may also be dependent upon extra-articular variables such as muscle bulk and tone and ligamentous tension that act upon the spino-pelvic complex.

Reference points or anatomical landmarks to measure the LL *(Figure 28)* the anatomical landmarks can be palpated and marked between T11-12 spinous processes and between the posterior superior iliac spine (PSIS) on the S1-2 segments. To measure the TK *(Figure 29)* can be used by palpation and marking between T2-3 spinous processes and between T11-12 spinous processes. These angles are then classified as the neutral position measurements for TK and LL according to Öhlén [93].

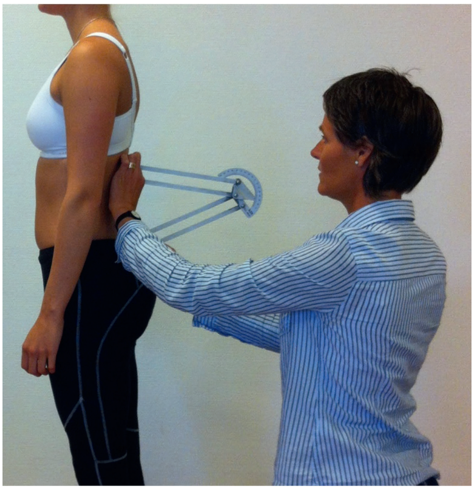


Figure 28: The Debrunner Kyphometer measurement for neutral lumbar lordosis.

Figure 29: The Debrunner Kyphometer measurement for neutral thoracic kyphosis.

Figure 30: Measurement of thoracic extension with the Debrunner Kyphometer.

Figure 31: Measurement of thoracic flexion with the Debrunner Kyphometer.

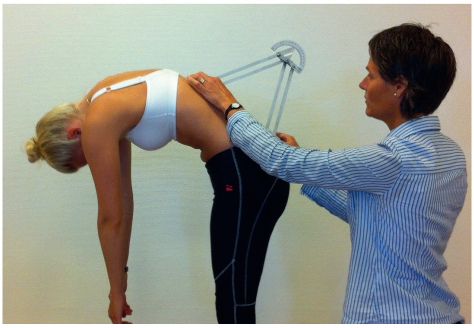


Figure 32: Measurement of lumbar flexion with the Debrunner Kyphometer.

Figure 33: Measurement of lumbar extension with the Debrunner Kyphometer.

Figure 34: Measurement of lumbar lordosis in sitting with the Debrunner Kyphometer.

Figure 35: Measurement of lumbar flexion in sitting with the Debrunner Kyphometer.

Figure 36: Measurement of lumbar extension in sitting with the Debrunner Kyphometer.

1.2.9.2 The PALM Palpation meter

A standardized clinical method of assessing the angle of Pelvic anteversion or retroversion can be depicted by measuring the angle between the horizontal and a line drawn from the anterior superior iliac spine (ASIS) to the posterior superior iliac spine (PSIS). Moreover, although such an angle may be dependent on extra-articular variables such as muscle bulk and tone and ligamentous tension that acts between the spino-pelvic-hip complex, this angle is also dependent on the relative position of the two bony landmarks (ASIS and PSIS) on the separate innominate bones.

1.2.9.3 Pelvic anteversion and retroversion

Pelvic anteversion describes the orientation of the pelvic girdle that has rotated anteriorly in the sagittal plane. Pelvic anteversion is normally accompanied by an increase in LL. Pelvic retroversion describes the orientation of the pelvic girdle that has rotated posteriorly in the sagittal plane and is normally accompanied by lumbar kyphosis.

The Palpation meter (PALM, Performance Attainment, Associates, St Paul Minnesota, USA) is a non-invasive instrument capable of measuring pelvic motion *(Figure 37)*. The Palpation meter (PALM) is essentially a set of hand-held callipers; the tips of the callipers can be placed upon pelvic landmarks, therefore, providing more reliable results compared with visual estimates. With the pelvis fixed in a standardized standing or sitting position, the ASIS-PSIS angles relating to pelvic neutral, pelvic anteversion and pelvic retroversion can be measured and recorded in degrees [95, 96, 103].

Previous studies have shown similar values for the measurement of standing Pelvic motion using the Palpation meter (PALM). Herrington [95] reported 6° to 7° of pelvic anteversion in a sample of 120 young, healthy subjects, similar to Gajdosik et al. [96] who reported 8.5° of pelvic anteversion in a sample of 20 healthy adults and Lee et al. [104] reported 7° to 8° in a sample of 40 healthy adults. In a recent study, a slighty higher mean range of pelvic anteversion (10.5°) has been shown by [102] involving a sample of 18 young, healthy adults.

The Palpation meter has been shown to be reliable (ICC 0.97 and 0.98) and valid (ICC 0.79 and 0.78) instrument to measure pelvic crest height differences compared with radiographic measurements [103].

Figure 37: PALM palpation meter.

Table 3: Reliability and validity data using the Palpation Meter.

	Reliability (ICC)	Validity (Correlation coefficient)
Herrington (2011)	0.87 (intra)	No
Gajdosik et al. (1985)	0.88 (intra)	No
Petrone et al. (2003)	0.97 + 0.98 (intra) 0.88 (inter)	0.90 and 0.92
Beardsley et al. (2016)	0.81-0.88 (inter) 0.88-0.95 (intra)	No

1.3 LBP in young athletes

LBP has been shown to be a common problem among adolescent athletes [105-109]. With athletes being shown to have a greater prevalence of LBP compared with non-athletes [79, 110-112]. The prevalence of LBP appears to differ depending on the type of sporting activity and the duration of sporting participation [113]. Moreover, the incidence of LBP has been well documented in many sports such as *(Table 6)* and has been shown to be correlated with increased spinal loads in up to 89% of elite athletes [79-81, 111, 112, 114]. Athletes, who perform sports requiring greater hip joint rotation, may be at risk of overload and traumatic injuries and might therefore be more susceptible to LBP [115-117].

Table 6: Incidence of LBP in sports.

Sporting discipline	Incidence of LBP (%)
Gymnastics	67
Water-ski jumping	45
Soccer	53
Weight-lifting	71
Wrestling	77
Orienteering	55
Ice-hockey	89
Diving	89
Tennis	50
Alpine & Cross-country skiing	67

1.3.1 Hip pain in young athletes

Hip joint injuries in young athletes appear to be diagnosed with increasing levels of frequency [63]. Athletic hip joint pain may encompass either intra- and extra-articular pathologies or a combination of both. These may be a result from progressive repetitive micro-trauma or as a result of a specific incident. Extra-articular overload injuries around the hip include pathologies such as tendonopathy, bursitis, hernia and muscle strain [63].

Intra-articular overload injuries to the hip have also been shown to be common [88] and include FAI as a frequent cause of hip pain [59, 89, 118-120] in young male athletes [56, 59, 121]. A greater prevalence of cam-type FAI impingement has been shown to occur in elite athletes and to range from 60-89% in sports such as basketball, ice hockey, soccer and American football [87-89, 122]. Moreover, intra-articular hip joint symptoms may also be associated with an underlying pediatric issue such as hip joint dysplasia, complex bony deformities or labral and cartilage lesions [63].

1.3.2 Patient recorded outcome measures (PROMs)

Quantitative measurements can be collated objectively through radiographic imaging and clinical methods pertaining to many variables such as; spinal curvatures, global spinal orientation, pelvic parameters, spinal types according to Roussouly et al. [8] and evidence of increased morphological hip joint changes such as cam-related hip pain.

Qualitative methods can also provide a subjective measurement from a patient perspective. Examining ROM may provide objective signs to show differences between groups for joint mobility. However, performing ROM testing, may not necessarily equate to a good subjective outcome. It may be possible that in testing ROM, individuals may develop increased levels of pain. Therefore, qualitative methods have an important clinical relevance and should be used alongside quantitative methods. Examples of qualitative methods used in clinical research are questionnaires.

1.3.3 Back and hip questionnaire

The back and hip questionnaire is one that has been developed and used in several studies by Swärd et al. [80] and Baranto et al. [79] and has also been widely used in other studies [117, 123]. It concentrates on LBP and hip pain relating to previous and present levels of pain. The questions are designed to map out pain characteristics, factors and interventions including levels of general health and sporting activity. LBP and hip questions evaluated the nature, onset and duration of pain, if the pain was correlated to exercise or competition, and if any hip or spine movements aggravated or relieved the pain.

Back and hip pain is self-assessed and graded mild, moderate or severe. Classification of moderate levels were determined if the daily living, work, training or competition was not affected by back pain. Classification of severe levels were determined if the back or hip pain influenced daily living, work, training or competition. Athletic and physical activity was investigated through questions relating to present and previous activity levels. The location and type of pain was investigated by using the Visual Analogue Scale (VAS).

1.3.4 Owestry disability index (ODI)

The Oswestry Disability Index (ODI) questionnaire evaluates levels of back pain in relation to daily life activities where pain intensity and ability is rated subjectively [124, 125]. This ODI includes six answer scores, ranging from 0 to 5 where 5 represents the greatest disability. These are presented to each of the 10 questions that relate to (Pain intensity, personal care, lifting, walking, sitting, standing, sleeping, sex life, social life and travelling). The scores are then summed up, doubled and converted to percentages. The results are interpreted as minimal disability 0-19%, moderate disability 20-39%, severe disability 40-59%, crippling disability 60-79%, and bed bound 80-100%.

1.3.5 EuroQol (EQ-5D)

The EuroQol questionnaire (EQ-5D) is a practical way to measure health of a population and differences within subgroups of the population [126]. Measurement includes assessment of five constructs (daily life activity, mobility, self-care, pain and anxiety levels). The EQ-5D-3L questionnaire is rated levels 1-3, ranging from level 1 indicating no problems, level 2 indicating some problems and level 3 indicating lots of problems. The EQ-5D-5L questionnaire is rated as levels 1-5. Level 1 indicates no problems, level 2 indicates slight problems, level 3 indicates moderate problems, level 4 indicates severe problems and level 5 indicates extreme problems.

The scores range from -0.594 to 1. A score of 1 represents full health and values lower than 0 represents worse than death. EQ VAS records an individual's self-rated health on a 20 cm vertical, VAS. The end-points range from 'the best health you can imagine' to 'the worst health you can imagine' with numerical values of 100 and 0 respectively.

Aims

"Man cannot discover new oceans unless he has the courage to lose sight of the shore."

ANDRÉ GIDE

2.1 Overall Aims

Thoughout the past two decades many radiological and clinical studies have been published relating to the development of spinal morphology, pathology and spino-pelvic alignment or malalignment syndromes. Such an increase in knowledge has helped to correlate many spinal conditions such as disc herniation, disc degeneration and spondylolyarthropathy to specific spinal types according to their postural adaptations or compensations. This has provided a rationale for the subsequent surgical and non-surgical treatment and management options for these conditions.

It is well documented that athletes who repetitively sustain increased axial spinal loading or loading in different positions of the spine, especially at a young age, may also be at risk of developing spinal abnormalities associated with specific spinal conditions. Moreover, athletes have also been shown to have an increased prevalence of LBP compared with non-athletes. Whilst many studies appear to have biased the spine, there appears to be a distinct lack of knowledge relating to how the hip joint may impact the spino-pelvic complex, especially pertaining to variables such as increased hip joint morphological changes and how this may affect the spino-pelvic complex.

Therefore, the overall aims of this thesis was to investigate the spino-pelvic sagittal alignment using both clinical and radiological methods and to investigate what effect hip joint cam-type FAI may have unpon the spino-pelvic sagittal alignment. Moreover, to evaluate, the results of back and hip pain prevalence and their correlation between young Elite skiers and non-athletes of a similar age.

Specific aims of the thesis

"Let fear, then be kind of pain or disturbance resulting from imagination of impending danger, either destructive or painful."

ARISTOTLE

Study I	To investigate if the Debrunner Kyphometer is an effective tool for measuring the spinal curvatures and moreover, if the spinal sagittal alignment of young Elite skiers is different to that of a healthy non-athletic population.
Study II	To investigate with radiological methods the spino-pelvic sagittal alignment of young Elite skiers compared with a healthy non-athletic population.
Study III	To investigate with clinical methods the spino-pelvic sagittal alignment and mobility of young Elite skiers compared with a non-athletic population.
Study IV	To investigate the spino-pelvic sagittal alignment in individuals with increased morphological characteristics of hip joint cam-type FAI and the prevalence of Roussouly Type spines in individuals with increased morphological characteristics of hip joint cam-type FAI.
Study V	To investigate an increased prevalence of back and hip pain in young Elite skiers compared with non-athletes and if a correlation exists between back and hip pain in young Elite skiers compared with non-athletes.

Patients and Methods

"He who studies medicine without books sails an uncharted sea, but he who studies medicine without patients does not go to sea at all."

WILLIAM OSLER

3.0 Study sample

The sample group (n=102) was comprised of young Elite skiers (n=75) and non-athletes (n=27). Stratified by skiing discipline Apline skiers (n=57) and Mogul skiers (n=18).

The skiers in studies I, II, III, IV and V were all High School pupils (grade 1-4, between 16-20 years of age) attending the Åre High School Ski Academy, Sweden. Participants for the control group were first year High School pupils from a class at a High School in Östersund, Sweden. All participants were invited to participate in this prospective study after a short presentation about the project by two of the authors and they also received written information about the project. For all the studies, testing was also carried out at the same school however, in Studies I, II and IV the radiographic and MRI examinations were taken at the Radiographic Department, Östersund Hospital, Sweden. The demographic characteristics of the full sample are presented in *Table 6*.

Figure 38: Female Alpine skier 2014 Sochi Winter Olympics.

Figure 39: Female Mogul skier 2014 Sochi Winter Olympics.

Table 7: Baseline characteristics for all subjects stratified by group.

	All subjects (n=102)	Skiers (n=75)	Controls (n=27)	p-value
Age (years)	18	18.2 (1.1)	16.4 (0.6)	<0.001[b]
Gender Female/Male (%)	52/48	47/53	67/33	0.07[a]
Height (cm)	173	174 (8.2)	172 (8.6)	0.19[b]
Weight (kg)	69	70 (9.1)	67 (17.9)	0.39[b]
BMI (kg/m²)	22.9	22.9 (2.2)	22.7 (5.3)	0.81[b]

Values are mean and (standard deviation; SD) unless specified.
BMI - Body mass index.
[a] Chi-square Test.
[b] Independent sample t-test.

Inclusion criteria for the Elite skiers group was training and competing at an elite level, High School grade 1-4, between 16-20 years of age and recruited from the Åre High School Ski Academy, Sweden.

Inclusion criteria for the control group was first year high school pupils from a class at a High School in Östersund, Sweden, that have not previously or at present participated in any organised sporting activities or exercised for more than 2 hours per week.

Exclusion criteria were if they had history of previous surgery to the lumbar spine, pelvis or hip joint or a history of systemic pathology including inflammatory arthritis or pelvic inflammatory disorders or if they were pregnant.

Ethical approval for the following studies was provided by the Regional Ethical Review Board in Gothenburg at The Sahlgrenska Academy, Gothenburg University, Gothenburg, Sweden (ID number: 692-13).

3.1 Methods in; Study I

This was a cross-sectional descriptive study, using clinical and radiological methods. In this study, clinical methods were compared with radiological methods for measuring the standing spinal sagittal alignment of young athletic Elite Alpine and Mogul skiers skiers (n=75) and a non-athletic population (n=27), mean age was 17.7 (±1.4) years. Radiological data from (n=90) participants and Debrunner Kyphometer data from (n=100) participants was available for analysis due to drop-out and failure to make appointments.

The Debrunner Kyphometer was used to investigate standing spinal sagittal values of TK and LL *(Figures 28 & 29)*. These were calculated and reported in degrees using a standardized protocol [93]. A blinded examiner marked the anatomical landmarks and placed the measuring instrument, therefore, maintaining consistency and avoiding inter-operator reliability. An assistant recorded all measurements, limiting investigation bias. Intra- and inter-observer reliability were tested measuring ten skiers with two examiners (One experienced physical therapist and one physician).

Radiographic values were obtained using a standardized radiographic protocol [83]. A frontal and long-standing lateral radiographs were obtained for each participant recorded from C7 to the femoral head. Geometrical measurements relating to spinal curvatures were obtained from the following; TK as the angle measured from the upper end-plate of T4 to the lower endplate of T12. LL is defined as the angle measured from the upper endplate of L1 to the upper endplate of S1.

The radiographs were measured for sagittal spinal alignment by a single blinded experienced radiologist with the angular parameters reported in degrees. A negative value (-) represented a lordotic alignment whilst a positive value (+) represented a kyphotic alignment.

3.11 Statistical Analysis for Study I

Intraclass correlation coefficients (ICC) were calculated for both the Debrunner Kyphometer and the radiological method. The coefficients was interpreted according to Fleiss [127] Benchmark Scale as Poor <0.40; Good 0.40 to 0.75; Excellent >0.75. Pearson correlation coefficients for TK were calculated for both Elite skiers and non-athletes. The statistical significance for all tests was set as $p<0.05$.

3.2 Methods in Study II

This was a cross-sectional descriptive study, using radiological methods. In this study radiographic methods were used to investigate the spino-pelvic sagittal alignment of young Elite Alpine and Mogul skiers and a non-athletic population.

The radiographic examination protocol was similar to that used in Study I. A frontal and long-standing lateral radiographs were obtained for each participant recorded from C7 to the femoral head. Geometrical measurements were recorded in degrees and included other variables such as the Pelvic parameters, SVA and cateogories of Roussouly Type spines.

The PI angle was measured from a perpendicular line to the mid-point of the sacral plate and extended to the centre of the femoral head. The PT angle was measured from a perpendicular line starting at the centre of the femoral head and extended to the mid-point of the sacral plate. The SS angle was measured from the superior endplate of S1 and a horizontal axis [8, 31].

The SVA was measured and recorded in (mm) and is defined by using the C7 plumb line that intersects the superior corner of the upper sacral endplate. Four types of spinal curvatures defined according to Roussouly et al. [8], were measured correlating to the angle of the sacral slope were. Type I: low SS <35° with an 80:20 thoracolumbar curve. Type II: low SS <35° with a 60-40 thoracolumbar flat back. Type III: SS >35° <45° with a 50:50 thoracolumbar curve. Type IV: high SS >45° with a 20:80 reversed thoracolumbar curve

Baseline characteristics for all subjects stratified by groups is shown in *Table 8*. The mean age for both groups was 17.7 (±1.4) years (Skiers mean age 18.3 SD 1.1 and controls 16.4 SD 0.6). Radiological data from (n=92) participants (Skiers n=66 and controls n=26) was only available for final analysis due to drop-out and failure to make radiology appointments.

Table 8: Baseline characteristics for all subjects and stratified by group.

	All subjects (n=102	Skiers (n=75)	Controls (n=27)	p-value
Age (years)	17.7 (1.4)	18.3 (1.1)	16.4 (0.6)	<0.001
Female sex, n (%)	53 (52%)	35 (47%)	18 (67%)	0.074
Height (cm)	173 (8.3)	174 (8.2)	172 (8.6)	0.19
Weight (kg)	69 (12.2)	70 (9.1)	67 (17.9)	0.39
BMI (kg/m²)	22.9 (3.3)	22.9 (2.2)	22.7 (5.3)	0.81

Values are mean and (standard deviation; SD) unless specified.
BMI – Body mass index.

3.2.1 Statistical Analysis for Study II

An independent t-test was performed to compare variables, (skiers and controls). Fisher's exact test was performed to compare the distribution of spinal curves according to Roussouly et al. [8] between variables. The statistical significance for all tests was set as p<0.05.

3.3 Methods in Study III

This was a cross-sectional descriptive study, using clinical methods. The sample group consisted of young Elite skiers (Alpine and Mogul) mean age 18.3 (SD 1.1) and non-athletes mean age 16.4 (SD 0.6). Data collection encompassed clinical tests in standing and sitting positions for spinal alignment, and mobility, pelvic neutral, anteversion and retroversion. These were calculated and reported in degrees. A blinded examiner marked anatomical landmarks and placed measuring instruments, maintaining consistency and avoiding inter-operator reliability. An assistant recorded all measurements, with the aim of limiting investigation bias.

To measure standing Thoracic extension (TE) *(Figure 30)* participants were instructed to raise their chest without retracting the shoulders, and to arch their thoracic spine independently of their lumbar spine. To measure standing Thoracic flexion (TF) *(Figure 31)* participants were instructed to drop their chin to their chest, roll forward to arch their thoracic spine independently of their lumbar spine. To measure standing Lumbar extension (LE) *(Figure 33)* participants were instructed to arch their lumbar spine to their natural end-point without force and avoiding hip sway. To measure standing Lumbar flexion (LF) *(Figure 32)* participants were instructed to "try to touch the floor with their hands without bending their knees" by rolling their lumbar spine forwards.

To measure sitting lumbar flexion (sLF) *(Figure 35)* participants were instructed to slump their lumbar spine and tilt their pelvis backwards as far as they could, increasing maximum pelvic retroversion. As measurement of sitting lumbar extension (sLE) *(Figure 36)* participants were instructed to arch their lumbar spine and tilt their pelvis forwards as far as they could, increasing maximum sitting pelvic anteversion.

To measure Pelvic anteversion participants were instructed to arch their lumbar spine and tilt their pelvis forward maximally. As Pelvic retroversion was measured with the lumbar spine in maximal flexion, with participants being instructed to slump their lumbar spine and tilt their pelvis backwards maximally *(Figure 37)*.

No participants had to withdraw from the study due to the exclusion criteria; however, due to failure to attend investigations and skiers travelling abroad, data from a sample of (n=98) participants (Skiers n=71 and controls n=27) was available for the final analysis.

3.3.1 Statistical Analysis for Study III

An independent t-test was performed to compare variables, (skiers and controls). The statistical significance for all tests was set as p<0.05.

3.4 Methods in Study IV

This was a cross-sectional descriptive study, using both radiological and Magnetic Resonance Imaging. The sample group consisted of young Elite Alpine and Mogul skiers and a non-athletic population. Standing lateral plain radiographs were taken for measurements of the spino-pelvic sagittal alignment similar to the protocol used in Studies I and II. Measurement of the Pelvic parameters, SVA and Spinal curvatures (Type I-IV) according to Roussouly et al. [8] were also included.

Hip joints were examined for increased morphological cam-type deformity, (alpha angle greater than 55°) using MRI. The MRI equipment GE Optima 450 Wide 1.5T was used for all examinations; a coil surface HD 8ch Cardiac Array by GE was used. Quantifying the shape of the femoral head *(Figure 3)* was by measuring the alpha (α) angle according to [85]. The α-angle was measured in all planes from 9 to 3 o'clock. This is the angle between a line drawn along the axis of the femoral neck and a line drawn from the femoral head center to the point where the head extends beyond the margin of a best-fit circle [86].

Plain radiographs and MRI data from (n=87) participants was available for final analysis. Stratified by cam (n=36) and no cam (n=51). Reasons given for non-attendance were difficulties with timings for radiology and MRI appointments and participant's being worried about claustrophobia.

3.4.1 Statistical Analysis for Study IV

An independent t-test and Pearson Chi-Square test were performed to compare variables, (skiers and controls and cam and no cam). Fisher's exact test was performed to compare the distribution of spinal curves according to Roussouly et al. [8] between variables. The statistical significance for all tests was set as p<0.05.

3.5 Methods in Study V

This was a cross-sectional prospective study, using a three-part questionnaire consisting of a back and hip pain questionnaire, developed by, Swärd et al. [80] and Baranto et al. [79, 128] the Oswestry Disability Index and EuroQoL [129] to evaluate their health, activity level and the prevalence of hip pain and LBP.

The sample group consisted of young athletic Elite Alpine and Mogul skiers and a non-athletic population. Due to drop-out and failure to complete the questionnaires, data from (n=99) participants (Skiers n=74 and controls n=25) was available for final analysis. Reasons for non-attendance were difficulties with timings to attend appointments and athletes travelling. *Table 9* highlights the baseline characteristics for all subjects stratified by group.

Table 9: Baseline characteristics for all subjects stratified by group.

	All subjects (n=102)	Skiers (n=75)	Controls (n=27)	p-value
Age (years)	18	18.2 (1.1)	16.4 (0.6)	<0.001[b]
Gender Female/ Male (%)	52/48	47/53	67/33	0.07[a]
Height (cm)	173	174 (8.2)	172 (8.6)	0.19[b]
Weight (kg)	69	70 (9.1)	67 (17.9)	0.39[b]
BMI (kg/m²)	22.9	22.9 (2.2)	22.7 (5.3)	0.81[b]

Values are mean and (standard deviation; SD) unless specified.
BMI - Body mass index.
[a] Chi-square Test.
[b] Independent sample t-test.

3.5.1 Patient reported outcome measures (PROMs)

The back and hip questionnaire was developed and used by Swärd et al. [80] and Baranto et al. [79, 128] and has been widely used in other studies [123, 130]. This questionnaire measures LBP and hip pain relating to previous and present levels of pain. The questions are designed to map out pain characteristics, factors and interventions including levels of general health and sporting activity. LBP and hip questions evaluated the nature, onset and duration of pain, if the pain was correlated to exercise or competition, and if any movements aggravated or relieved the pain.

Back and hip pain is self-assessed and graded as moderate or severe. Classification of moderate levels were determined if the daily living, work, training or competition was not affected by back pain. Classification of severe levels were determined if the back or hip pain influenced daily living, work, training or competition. Athletic and physical activity was investigated through questions relating to present and previous activity levels.

The location and type of pain was investigated by using the Visual Analogue Scale (VAS). This was self-assessed by the patient on a 20cm vertical scale marked from 0-100, with 0 equating to the worst imaginable health and 100 the best imaginable health.

The Oswestry Disability Index (ODI) questionnaire was first used is used as a PROM to evaluate levels of back pain by Fairbank et al. [124]. This questionnaire measures ten constructs, in relation to pain, lifting, ability to care for oneself, ability to walk, ability to sit, sexual function, ability to stand, social life, sleep quality and ability to travel. Six answer scores, 0-5 where 5 is the greatest disability, are presented to each of the 10 questions. The scores are then summed up, doubled and converted to percentage. The results are interpreted as minimal disability 0-19%, moderate 20-39%, severe 40-59%, crippling 60-79%, and bed bound 80-100%.

The Euroqol questionnaire (EQ-5D) is a standardized PROM to measure the health of a population and differences that may be observed within subgroups of the population [126]. It measures five constructs, which includes assessment of daily life activity, ability to move, self-care, pain/discomfort and anxiety/depression levels. The questionnaire is rated levels 1-3, ranging from level 1 indicating no problems, level 2 indicating some problems and level 3 indicating lots of problems.

3.5.4 Statistical Analysis for Study V

Pearson Chi square test was performed to compare the distribution of back pain between groups, as Fisher's exact test was performed to compare the distribution of hip pain between groups when the expected cell count was less than 5. The statistical significance for all tests was set as $p<0.05$.

Results

"I am merely picking up peebles from the seashore of knowledge."
SIR ISAAC NEWTON

Study I

Validation of spinal sagittal alignment with plain radiographs and the Debrunner Kyphometer

Introduction

Spinal alignment is maintained regionally by the cranial cervical and caudal lumbar lordotic curves that are separated by the kyphotic curve [1]. Radiographic evaluation of spinal sagittal alignment can be used in the assessment of local, regional and global spinal orientation [83]. However, radiographic evaluation unfortunately can be expensive, time consuming and risk an exposure to radiation, especially in young individuals [97]. Exploring a non-radiological method may provide an alternative option for use in the clinical environment.

Methods

The sample group consisted of Elite Alpine and Mogul skiers (n=75) and a non-athletic population (n=27), mean age was 17.7 (±1.4) years. Non-radiological and radiological measurements of the spinal sagittal kyphosis and lordosis range of motion were carried out in the erect standing position.

The Debrunner Kyphometer was used to measure the standing spinal sagittal values of TK and LL. These were calculated and reported in degrees. Geometrical measurements recorded in degrees were extracted from frontal and long-standing lateral radiographs that were obtained for each participant. These were recorded from C7 to the femoral head. Radiological data from (n=90) participants and Debrunner Kyphometer data from (n=100) participants was available for the final analysis due to drop-out and failure to make appointments.

Results

TK measurements comparing the Debrunner Kyphometer with a radiological standard, showed a good level of agreement and a statistical significance (ICC 0.67, 95% CI: 0.26 to 0.83, p<0.001). LL measurements showed poor levels of agreement in spite of being statistically significant (ICC 0.33, 95% CI: 0.13 to 0.50, p=0.001).

Table 10: Measurements stratified by group mean and standard deviation.

	Skiers	Controls
Thoracic kyphosis° (Radiological)	35.2 (7.4)	37.4 (6.7)
Thoracic kyphosis° (Debrunner Kyphometer)	30.5 (6.5)	32.9 (6.4)
Lumbar lordosis° (Radiological)	-58.4 (9.3)	-60.9 (11)
Lumbar Lordosis° (Debrunner Kyphometer)	-27.2 (6.8)	-30.4 (7.3)

Values are mean and (standard deviation; SD) unless specified.

Table 11: Reliability of the Debrunner Kyphometer compared to radiological measurements.

	Intraclass correlation coefficient	95% Confidence interval	p-value
Intra-rater reliability			
Debrunner Thoracic kyphosis°	0.83	0.30 to 0.96	0.008
Debrunner Lumbar lordosis°	0.71	0.16 to 0.93	0.039
Inter-rater reliability			
Debrunner Thoracic kyphosis°	0.96	0.85 to 0.99	<0.001
Debrunner Lumbar lordosis°	0.79	0.15 to 0.95	0.015

Values are mean and (standard deviation; SD) unless specified.

Table 12: Validity of the Debrunner kyphometer compared to the radiological measurement.

	Intraclass correlation coefficient	95% Confidence interval	p-value
Thoracic kyphosis°	0.67	0.26 to 0.83	<0.001
Lumbar lordosis°	0.33	0.33 to 0.50	0.001

Values are mean and (standard deviation; SD) unless specified.

Figure 41: Bland Altman plot highlighting bivariate analysis for ranges of lumbar lordosis between Radiological and Debrunner Kyphometer.

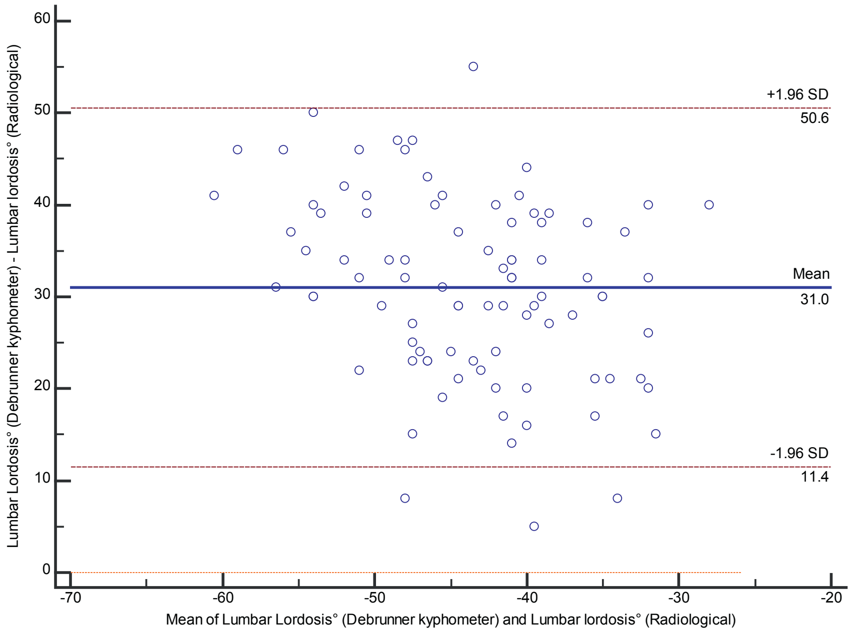
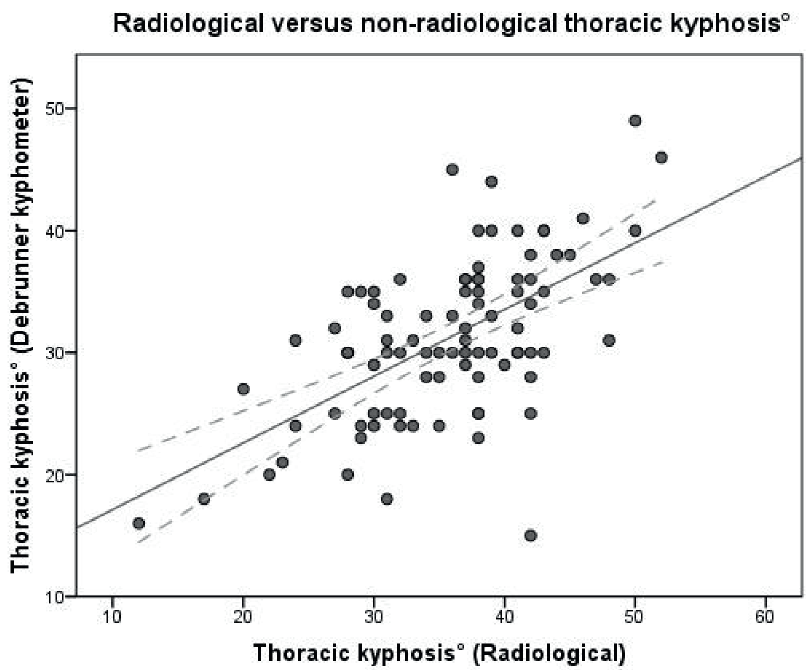


Figure 42: Correlation with bivariate analysis between the measured Cobb angle and the measured Debrunner kyphometer (Pearson's r = 0.605, p < 0.001).



Conclusion

There were no significant differences in the spinal alignment between skiers and controls using both radiological and non-radiological methods. It is suggested that the sample included in this study may have been too young and/or the young Elite skiers may have not trained or competed for a long enough duration to show any difference in their spinal sagittal alignment compared with the control group.

The clinical relevance of this study highlights the Debrunner Kyphometer to show good levels of agreement to measure TK compared with plain radiographs and therefore may be a useful clinical tool for this purpose. Moreover, due to the large variation in ranges between both methods to measure LL, there is a limited value in using the Debrunner Kyphometer as a non-invasive method for the evaluation of LL spinal sagittal alignment.

Study II

Comparison of radiological spino-pelvic parameters in skiers and non-athletes

Introduction

It has been proposed that radiographic evaluation of pelvic parameters, spinal curvatures and global balance, may help to characterize the morphology and functionality of the spine and pelvis. Such an evaluation may provide objective information on several variables including the characteristics of the spinal morphology, overall spinal alignment and malalignment, standing posture, progressive spinal deformities and pathological processes. Moreover, a correlation has also been shown to exist between the pelvic parameters and the four types of spinal curvatures according to Roussouly et al. [8]. Likewise, sporting participation has also been shown to be associated with changes in the spino-pelvic sagittal alignment of athletes.

Methods

The sample group (n=102) consisted of Elite Alpine and Mogul skiers (n=75) and a non-athletic population (n=27), mean age for both groups was 17.7 (±1.4) years (Skiers mean age was 18.3 SD 1.1 and controls 16.4 SD 0.6). Radiological data from (n=92) participants (Skiers n=66 and controls n=26) was only available for the final analysis due to drop-out and failure to make radiology appointments.

Frontal and long-standing lateral radiographs were obtained for each participant recorded from C7 to the femoral head. Geometrical measurements were recorded in degrees and included other variables such as the Pelvic parameters, SVA and cateogories of Roussouly Type spines.

Results

Type I spinal curves according to Roussouly were shown to be more prevalent in the skiers (18.2%) compared with the control group (0.0%, p=0.03). There were no significant differences reported in the pelvic parameters between both groups. A difference was reported in the SVA between skiers (8mm SD 46.0) and the control group (-2mm SD 39.0), which may be of clinical significance, in spite of being statistically non-significant.

Table 13: Comparison between skiers and controls for pelvic parameters and spinal curvature.

	Group	N	Mean	SD	p-value
PI°	Skiers	66	50.9	12	0.794
	Controls	26	50.2	9.8	
PT°	Skiers	66	10.9	9.2	0.139
	Controls	26	7.9	6.3	
SS°	Skiers	66	41.2	9.1	0.587
	Controls	26	42.3	8.1	
SVA (mm)	Skiers	66	8	46	0.361
	Controls	26	-2	39	
TK°	Skiers	66	35	7	0.197
	Controls	26	37	7	
LL°	Skiers	66	-58.4	9.3	0.283
	Controls	26	-60.9	11	

Values are mean, median and (standard deviation; SD) unless specified otherwise.
Pelvic Incidence (PI), Pelvic Tilt (PT), Sacral Slope (SS), Sagittal Vertebral Axis (SVA), Thoracic Kyphosis (TK), Lumbar Lordosis (LL).

Table 14: Distribution of Roussouly type for skiers and controls.

Roussouly type	Skiers	Controls	p=value
I	12 (18.2)	0 (0.0)	0.030
II	3 (4.5)	4 (15.4)	
III	39 (59.1)	18 (65.4)	
IV	12 (18.2)	5 (19.2)	

Number with column percentage in parenthesis.
* Fishers Exact Test (38% of cells analyzed have expected cell counts less than 5).

Table 15: Distribution between genders for spinal curve type according to Roussouly et al. (2003).

Spinal type curve	Female (n and %)	Male (n and %)	Total (n and %)
I	6 (12.8%)	6 (13.3%)	12 (13%)
II	4 (8.5%)	3 (6.7%)	7 (7.6%)
III	25 (53.2%)	31 (68.9%)	56 (60.9%)
IV	12 (25.5%)	5 (11.1%)	17 (18.5%)

Values are mean and (standard deviation; SD) unless specified.

Conclusion

Young Elite skiers were shown to have a more prevalent Type I spine and a different spino-pelvic sagittal alignment compared with a healthy non-sporting population of a similar age. Moreover, due to the limitations in the cohort size in this study, it is proposed that further larger scale investigations may be required.

Study III

Clinical spino-pelvic parameters in skiers and non-athletes

Introduction

Athletes that perform sports requiring repetitive sagittal spinal motion have been shown to develop increased spinal curvatures suggested as a result of postural adaptations from exercise loading. Alpine and Mogul skiing both requires variable levels of spinal and pelvic loading, placing athletes at risk of developing spinal malalignment and back pain. Mogul skiing is freestyle in nature, requires a more upright spinal posture, as Alpine skiing requires a greater level of spinal and hip joint flexion. It could be suggested that the development of sagittal spino-pelvic malalignment may be related to postures associated with specific sports and therefore, the influence of Alpine and Mogul skiing on spino-pelvic alignment and posture requires further investigation.

Methods

The sample group (n=102) consisted of young Elite skiers (Alpine and Mogul, n=75) mean age 18.3 (SD 1.1) and non-athletes (n=27) mean age 16.4 (SD 0.6). Examination with clinical methods using the Debrunner Kyphometer and Palpation meter were used to measure the spino-pelvic parameters in standing and sitting positions. Data collection encompassed clinical tests in standing and sitting positions for spinal alignment, and mobility, pelvic neutral, anteversion and retroversion. These were calculated and reported in degrees. A blinded examiner marked the anatomical landmarks and placed measuring instruments, therefore, maintaining consistency and improving inter-operator reliability. An assistant recorded all measurements, with the aim of limiting investigation bias. No participants had to withdraw from the study due to the exclusion criteria; however, failure to attend investigations and skiers travelling abroad, data from a sample of (n=98) participants (Skiers n=71 and controls n=27) was available for the final analysis.

Results

A significant difference was shown for the mean age of the skiers 18.3 (SD 1.1) and the controls 16.4 (SD 0.6, p=0.001). Significant differences were shown for standing LL of the skiers -27.2° (SD 6.8) compared with controls -30.4° (SD 7.3, p=0.04), sitting LL of the skiers -2.5° (SD 9.5) compared with controls -7.4° (SD 9.9, p=0.027) and standing lumbar flexion of the skiers; 61.5° (SD 9.5) compared with controls; 67.6° (SD 7.4, p=0.004). Significant differences were shown in sitting pelvic neutral of the skier's -3.6° (SD 3.1) compared with controls; -1.8° (SD 2.8, p=0.007), and pelvic anteversion of the skiers 7.1° (SD 4.0) compared with controls; 11.8° (SD 3.0, p=0.001).

Table 16: Standing spinal sagittal alignment stratified by group.

Parameter	Skiers	Controls	p-value
Thoracic kyphosis°	30.5 (6.5)	32.9 (6.4)	0.109
Lumbar lordosis°	-27.2 (6.8)	-30.4 (7.3)	0.040

Values are mean, median and (standard deviation; SD) unless specified otherwise.

Table 17: Standing spinal sagittal mobility stratified by group.

Parameter	Skiers	Controls	p-value
Thoracic flexion°	24.9 (6.5)	24.6 (7.9)	0.82
Thoracic extension°	22.2 (7.7)	21.2 (8.4)	0.56
Lumbar flexion°	61.5 (9.5)	67.6 (7.4)	0.004
Lumbar extension°	28.5 (10.6	27.2 (8.8)	0.57

Values are mean, median and (standard deviation; SD) unless specified otherwise.

Table 18: Sitting neutral lumbar lordosis, lumbar flexion/extension and combined lumbar mobility stratified by group.

Parameter	Skiers	Controls	p-value
Sitting neutral lumbar lordosis°	-2.5 (9.5)	-7.4 (9.9)	0.027
Sitting lumbar flexion°	24.1 (10.8)	27.9 (13.4)	0.15
Sitting lumbar extension°	29.2 (10.7)	27.3 (12.0)	0.47
Combined sitting lumbar mobility°	53.3 (12.8)	55.1 (14.9)	0.56

Values are mean, median and (standard deviation; SD).

Table 19: Sitting pelvic neutral, anteversion and retroversion stratified by group.

	Skiers	Controls	p-value
Pelvic neutral°			
Right	-3.6 (3.1)	-1.8 (2.8)	0.007
Left	-3.6 (3.1)	-1.9 (2.8)	0.012
Pelvic anteversion°			
Right	7.1 (4.0)	11.8 (3.0)	<0.001
Left	7.2 (4.3)	11.8 (3.3)	<0.001
Pelvic retroversion°			
Right	-13.6 (4.7)	-12.7 (6.2)	0.42
Left	-14.0 (4.5)	-13.0 (6.2)	0.35

Values are mean, median and (standard deviation; SD).

Conclusion

Clinical methods show young Elite skiers to have significantly less standing and sitting lumbar and pelvic values for spino-pelvic sagittal alignment compared to an age-matched non-sporting population. This is suggested to be due to adaptation from heavy loads on the spine, pelvis and hips from skiing and training activities. The clinical relevance of this study may assist clinicans and researchers to use non-radiological clinical methods for interpreting the spino-pelvic values of young Elite athletes.

Study IV

Pelvic retroversion is associated with flat back and cam-type Femoro-acetabular impingement in young Elite skiers

Introduction

The spino-pelvic complex in humans helps to maintain an upright posture, by balancing the spinal sagittal alignment with the hip joints and pelvic girdle. However, the extent of how the hip joint may influence the spino-pelvic alignment is not fully understood. Moreover, Roussouly & Pinherio-Franco, [3] suggest that, to maintain such a balanced upright spine, rotation of the pelvis around the femoral head must occur. Therefore, in the presence of increased hip joint morphological changes, the spino-pelvic alignment may change. The aim of this study was to compare the radiological parameters of spino-pelvic sagittal alignment and spinal types according to Roussouly's classification in relation to hip joint cam-type FAI.

Methods

The sample group (n=102) consisted of young Elite Alpine and Mogul skiers (n=75) and a non-athletic population (n=27). Hip joints were examined for increased morphological cam deformity, (α-angle greater than 55°) with MRI and standing lateral plain radiographs were taken for measurements of the spino-pelvic sagittal alignment. Plain radiographs and MRI data from (n=89) participants was available for final analysis. Stratified by cam (n=36) and no cam (n=53). Moreover, two participants from the no cam group failed to have radiological measurements. Therefore, the final value for the no cam (n=51) group was reduced. Reasons for non-attendance were difficulties with timings for radiology and MRI appointments and participant's being worried about claustrophobia.

Results

A significant difference was shown in a mixed population (skiers and controls) in terms of an increased PT angle (13°, SD 10.2) in the presence of morphological hip joint cam-type deformity compared with the PT angle (8.5°, SD 7.1, p=0.036) of participants without cam-type deformity. Type II Roussouly spines occurred more frequently with skiers in the presence of increased cam (67%) compared with no cam (33%), however, this was not significant (p=0.19).

Secondary findings highlighted significant differences were shown for the prevalence of cam in a mixed-population for gender; males 60% (n=26) shown to have significantly more cam compared with females 22% (n=10, p=0.001). This was similar for height with taller participants being shown to have significantly more cam 177cm (SD 7.6) compared with no cam 170cm (SD 7.5, p=0.001).

Table 20: Baseline characteristics for all subjects and stratified by cam and no cam.

	All subjects (n=102)	Cam (n=36)	No cam (n=53)	p-value
Age (years)	17.7 (1.4)	18.0 (1.2)	17.4 (1.2)	0.021
Female sex, n (%)	53 (52)	10 (22)	36 (78)	<0.001a
Male sex, n (%)	51 (48)	26 (60)	17 (40)	
Height (cm)	173 (8.3)	177 (7.6)	170 (7.5)	<0.001
Weight (kg)	69 (12.2)	72 (9.9)	68 (13.7)	0.14
BMI (kg/m2)	22.9 (3.3)	22.7 (2.5)	23.1 (3.8)	0.55

Values are mean and (standard deviation; SD).
[a] Pearson Chi-Square Test.
BMI – Body mass index.

Table 21: Spino-pelvic measurements stratified by cam and no cam for all subjects (n=87).

Parameter	No Cam (n=51)	Cam (n=36)	p-value
Pelvic incidence°	50.1 (11.1)	52.2 (12.1)	0.38
Pelvic tilt°	8.5 (7.1)	13.0 (10.2)	0.036
Sacral slope°	42.0 (8.1)	40.8 (10.2)	0.54
Sagittal vertical axis (mm)	6.0 (43.5)	11.7 (40.1)	0.54
Thoracic kyphosis°	35.9 (7.3)	34.8 (7.6)	0.52
Lumbar lordosis°	-59.5 (10.0)	-58.3 (9.7)	0.60

Values are mean, median and (standard deviation; SD).

Table 22: Spino-pelvic measurements stratified by cam and no cam for Skiers (n=61).

Parameter	No Cam (n=30)	Cam (n=31)	p-value
Pelvic incidence°	49.8 (11.9)	52.7 (12.4)	0.36
Pelvic tilt°	9.4 (7.6)	12.9 (10.8)	0.15
Sacral slope°	41.5 (8.2)	41.2 (10.4)	0.90
Sagittal vertical axis (mm)	9.9 (43.4)	15.2 (42.5)	0.64
Thoracic kyphosis°	34.5 (7.6)	34.4 (7.4)	0.87
Lumbar lordosis°	-57.4 (9.2)	-58.9 (9.6)	0.53

Values are mean, median and (standard deviation; SD).

Table 23: Cam and no cam in categories of Roussouly for all subjects (n=87).

Roussouly type	I	II	III	IV
Cam	2 (20%)	3 (43%)	25 (46%)	6 (38%)
No Cam	8 (80%)	4 (57%)	29 (54%)	10 (62%)

Values are mean and (standard deviation; SD).
Fisher's Exact Test, **P=0.51**.

Table 24: Cam and no cam in categories of Roussouly for all subjects (n=87).

Roussouly type	I	II	III	IV
Cam	2 (20%)	2 (67%)	21 (57%)	6 (55%)
No Cam	8 (80%)	1 (33%)	16 (43%)	5 (45%)

Values are mean and (standard deviation; SD).
Fisher's Exact Test, **P=0.19**.

Table 25: Frequencies of cam lesions in groups.

	Skiers (n=63)	Controls (n=26)	p-value
Cam	31 (49%)	5 (19%)	0.009
No cam	32 (51%)	21 (81%)	

Values are mean and (standard deviation; SD).
[A] Chi-Square Test.

Conclusion

A significant difference was shown with an increased PT value for a mixed-group of young Elite skiers and non-athletes in the presence of increased morphological hip joint cam-type FAI. Moreover, young Elite skiers were shown to have an altered spino-pelvic sagittal alignment resulting in a retroverted pelvis and low LL Type II spinal classification (flat back) according to Roussouly in the presence of an increased frequency of cam-type FAI.

The clinical relevance of this study highlights that increased levels of pelvic retroversion, lumbar kyphosis and other lumbar pathologies may be found in individuals who also have increased hip joint morphological cam-type deformities. It is suggested that other studies involving larger samples of athletes and non-athletes and also adult athletes should be considered to quantify further the relationship between PT and the prevalence of Type I and II Roussouly spines (low Pelvic Incidence) in the presence of increased morphological hip joint cam-type femoro-acetabular impingement and pincer lesions.

Study V

An investigation into the prevalence of spine and hip pain in young Elite skiers

Introduction

The close anatomical relationship between the hip joint and lumbo-pelvic region has been proposed as a possibility for LBP in athletes. Moreover, it has been suggested that athletes who perform sports that require an increased degree of hip joint rotation, are at risk of overload and traumatic injuries and therefore might be more susceptible to LBP. A previous study by Jónasson et al. [117] has shown a significant correlation of back pain and hip pain to in athletes. Whilst, young Elite skiers have previously been shown to develop different spinal sagittal alignments compared with non-athletes [131] resulting in a more forward flexion posture. Moreover, a greater number of spinal abnormalities and increased hip joint morphological abnormalities have also previously been reported in young Elite skiers [72, 123]. Therefore, as a result of heavy loading in different planes to the spine at a young age it may be reasonable to suggest that young Elite skiers may be suitable candidates for investigating the prevalence of back and hip pain. Moreover, the prevalence of back and hip pain and especially the correlation between these two variables has not previously been reported.

The purpose of this study was to evaluate the prevalence of low back pain and hip pain in young Elite skiers and also correlate the findings to a non-athletic control group.

Methods

Sample group (n=102), young Elite Alpine and Mogul skiers (n=75) and non-athletes (n=27) completed a three-part back and hip pain questionnaire, Oswestry Disability Index and EuroQoL to evaluate general health, activity level, hip and back pain prevalence. Due to drop-out and failure to complete the questionnaires, data from (n=99) participants (Skiers n=74 and controls n=25) was available for final analysis. Reasons for non-attendance were difficulties with timings to attend appointments and athletes travelling.

Results

There was no significant difference (p=0.174) for the lifetime prevalence of back pain for the skiers (50%, n=37) compared with the controls (44%, n=11). *Table 3* shows the duration and onset of back pain stratified by group. There were no significant differences for comparison for the duration of back pain between groups (p=0.21). The greatest difference was shown in the skiers (46%, n=17) for a duration of back pain >5 years compared with the controls (9%, n=1). There was no significant difference (p=0.16) shown in years for the onset of back pain between groups, with onset for the skiers (14, SD 1.96) being similar compared with the controls (13, SD 4.43). A significant difference was shown for the greatest level of pain VAS 5.3 (SD 3.06) recorded during the past 6 months in the skiers compared with the controls VAS 2.4 (SD 1.98, p=0.025).

There were no significant differences (p=0.127) shown for the lifetime prevalence of hip for the skiers (22%, n=16) compared with the controls (8%, n=2). *Table 3* shows the values for the duration and onset of hip pain between groups. The greatest percentage of skiers (58%, n=7) were shown to have a duration of hip pain >1 year. The skiers (29%, n=4) were first shown to report an onset of hip pain at 11-13 years of age, whilst the greatest number of skiers (42%, n=6) reported an onset of 17-19 years of age. No statistical comparison between groups was performed due to the low number of controls (n=2) reporting hip pain.

There were no significant differences in Quality of life disability stratified by group for back pain using the EQ-5D with the skiers scoring 0.85 (SD 0.14) compared with the controls 0.88 (SD 0.13, p=0.68), this was similar for the ODI with the skiers scoring 9.4 (SD 8.36) compared with the controls 7.5 (SD 4.43, p=0.66). No statistical analysis could be performed for the Quality of life disability stratified by groups for hip pain using the EQ-5D and ODI due having such few numbers.

Table 26: Lifetime prevalence of back and hip pain stratified by group.

	Skiers (N=74)	Controls (n=25)	Total (n=99)	p-value
Back pain	37 (50%)	11 (44%)	48 (48%)	0.174
Hip pain	16 (22%)	2 (8%)	18 (18%)	0.127

Values are expressed as proportion and percentages in each category unless specified otherwise.

Table 27: Lifetime prevalence of back and hip pain stratified by skiing discipline.

	Moguls (n=17)	Alpine (n=57)	Total (n=74)	p-value
Back pain	9 (53%)	28 (49%)	37 (50%)	0.782
Hip pain	6 (35%)	10 (18%)	16 (22%)	0.119

Values are expressed as proportion and percentages in each category unless specified otherwise.

Table 28: Duration and onset of back pain in years.

	Skiers (n=37)	Controls (n=11)	p-value
Duration of Back pain			0.21
6-12 months	4 (11%)	2 (18%)	
>1 year	11 (30%)	2 (18%)	
>5 years	17 (46%)	1 (9%)	
Onset of Back pain (years)	14 (1.96)	13 (4.43)	0.16

Duration of pain expressed as proportions and percentage in each category.
For first episode values are years and standard deviation.

Table 29: Visual analogue scale for back pain.

	Skiers (n=37)	Controls (n=11)	p-value
VAS Back pain at present	2.3 (2.29)	1.7 (2.37)	0.55
VAS Back pain in last 6 months (worst)	5.3 (3.06)	2.4 (1.98)	0.025
VAS Back pain in last 6 months (usual)	2.4 (2.28)	1.7 (2.28)	0.49

Values are mean and (standard deviation; SD) unless specified.

Table 30: Point prevalence of duration and onset of hip pain stratified by group.

		Skiers (n=16)	Controls (n=2)
Duration of Hip pain	6-12 months	2 (17%)	0 (0)%
	>1 year	7 (58%)	1 (50%)
	>5 years	2 (17%)	1 (50%)
Onset of Hip pain	0-10 years	0 (0%)	0 (0%)
	11-13 years	4 (29%)	2 (100%)
	14-16 years	4 (29%)	0 (0%)
	17-19 years	6 (42%)	0 (0%)

Values are expressed as a proportion and percentage in each category.
Comparison of both groups, only 11 of subjects in the skiers group had data on hip pain and 14 of 16 for onset of hip pain.

Table 31: Number of weekly training sessions stratified by groups.

Training hours per week	Skiers (%)
3-5	6
6-8	21
9-11	25
>11	38

Values are expressed as a proportion and percentage in each category.

Table 32: Lifetime prevalence of training hinderance for skiers.

	Percentage (%) Of back pain	Pertcentage (%) Of hip pain
No	22	25
Yes, once	19	19
2-10 times	29	38
>10 times	22	6

Values are expressed as a proportion and percentage in each category.

Table 33: Baseline characteristics for skiers' age of starting training and competing.

	Age started training (years)	Age started competing (years)
Sample	73	73
Mean age (years)	6.9	8.6
Median	6	8
Std. Devation	2.9	2.8
Range	2	5
Minimum	2	5
Maximum	16	16

Values are mean and (standard deviation; SD) unless specified.

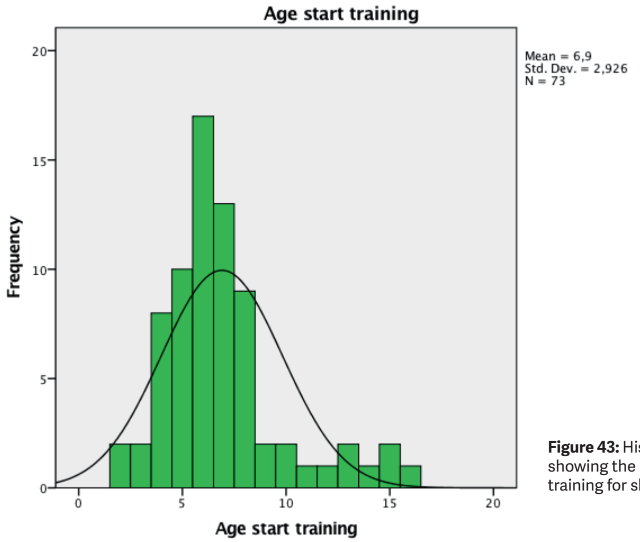


Figure 43: Histogram showing the age of starting training for skiers

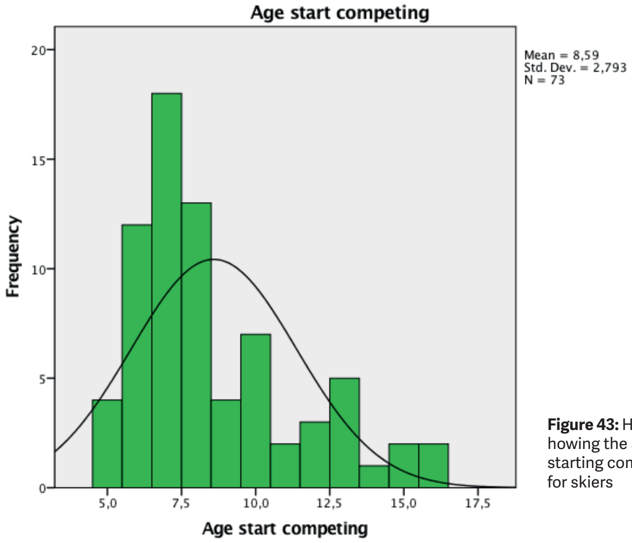


Figure 43: Histogram howing the age of starting competition for skiers

Conclusion

Young Elite skiers are not shown to have increased lifetime prevalence for back and hip pain compared with a non-athletic control group. In spite of this a high percentage of skiers reported a duration of back pain prevalence >5 years, however, this was not statistically significant.

The clinical perspective of these findings may suggest that many skiers continue to train and compete regularly with LBP or hip pain. Therefore, preventative measures should be taken to educate coaches, monitor training loads and intensities to reduce the prevalence of LBP and hip pain in young Elite skiers.

Coaches should encourage good technique and educate athletes to improve trunk and lower limb strength, flexibility and proprioception exercises to reduce levels of back and hip pain. Future studies should include larger sample cohorts with more sensitive, validated questionnaires to increase the possibility for a more in depth investigation for the lifetime prevalence and correlation of back and hip pain in young Elite skiers.

Discussions

"Let us hold our discussion together in our own persons, making trial of the truth and of ourselves."
PROTAGORAS

Clinical and Radiographic Study I

The findings in Study I show that comparison of the Debrunner Kyphometer with a radiological standard was shown to be good for measuring values of TK. However, is questionable for measuring values of LL due to the large variations and poor levels of agreement that exist between the methods. Therefore, there is a clinical value for using the Debrunner Kyphometer for evaluation of TK but limited value in using the Debrunner Kyphometer as a clinical method for the evaluation of LL. Moreover, no significant difference was reported in the spinal alignment between Elite skiers and controls using both radiological and non-radiological methods. Therefore, it is suggested that for the clinical evaluation of TK spinal sagittal alignment, the Debrunner Kyphometer may be a reasonable option to use. In doing so, patients would avoid the risk of any unnecessary exposure to radiation from plain radiographs.

The mean values of TK measured using radiological methods (35.8°) and the Debrunner Kyphometer (31.2°) appears similar to those previously reported within a normal asymptomatic population [8, 94, 97-99, 132]. The mean values for radiological measurement of LL (-59.1°) also appear to be similar to those previously reported within a normal asymptomatic population [3, 4, 8, 21, 22, 24-26, 133]. However, the mean values for the Debrunner Kyphometer measurement of LL (-28.0°) showed a lack of sensitivity and challenge the Debrunner Kyphometer as an effective clinical tool.

No significant differences were noted for comparison of both methods stratified by groups, i.e. skiers versus controls. This was similar for both methods. Radiological values for TK of skiers (35.2°) and controls (37.4°) compared with LL of skiers (-58.4°) and controls (-60.9°), appeared similar to the Debrunner Kyphometer values for TK of skiers (30.5°) and controls (32.9°) compared with LL of skiers (-27.2°) and controls (-30.4°). It could be suggested that early participation in sport does not affect sagittal spinal alignment in a young population. Measurements were recorded in the erect standing and sagittal plane only, which is a limitation to this study. Standing sagittal plane does not reflect the multi-directional dynamic movement patterns required to perform sporting activities especially those movements involved in elite level skiing.

Previous studies report strong reliability using the Debrunner Kyphometer [93, 94, 97-99, 134]. This was similar to the present study, where reliability of the Debrunner Kyphometer showed excellent levels for both intra-tester (ICC 0.83) and inter-tester (ICC 0.96) measurement of TK and good levels in terms of intra-tester (ICC 0.71) and inter-tester (ICC 0.79) reliability measuring LL.

Validating the Debrunner Kyphometer with radiological methods for TK showed a good level of agreement (ICC 0.67) between both measures. Poor levels of agreement (ICC 0.33) were shown between both measures for measuring LL. This was similar to Greendale et al. [97] and Korovessis et al. [98] who both showed moderate to good levels of validity for using the Debrunner Kyphometer to measure TK. Moreover, it appears that inadequacies of both studies methodologies and statistical analysis exist [100]. The limits of agreement for LL in the present study ranged from 11° to 51° implying the Debrunner Kyphometer could show a reading as high as 11° above or 51° below that of a radiological method. Such a large variation between both methods questions the Debrunner Kyphometer's validity to measure LL and appears similar to what has been reported in other studies [97, 98, 100].

Radiographic Study II

In Study II the most important finding was the greater difference in Type I spinal curvatures according to Roussouly et al. [8] in young Elite skiers compared with controls of a similar age. Type I spinal curves were shown to be more prominent for the skiers (18.2%) compared with the control group (0%). Type II spinal curvatures were shown to be more common in the control group (15.4%) compared with the skiers (4.5%). Type III and IV spines were common between both groups and moreover, no differences were reported between the genders of both groups.

The significant difference in Type 1 spinal curvatures that were mentioned by Roussouly et al. [8] might suggest an association with the biomechanics and the muscular development required for function in sports [5-7]. Therefore, it could be hypothesised from the reults of this study that a lack of abdominal, lumbar, pelvic and hip musculature tone within the control group might be a reason for their association with a 'flat back' Type II spine.

Spino-pelvic mean values of all participants for radiology pertaining to pelvic parameters have shown the PI (50.7°), PT (10°), SS (41.9°) and SVA (5.2mm) to be similar to those previously reported within a normal asymptomatic population [8, 10, 27, 31-34, 135-137]. This was similar for the radiological measurements of TK (35.8°) and LL (-59.1°) previously reported in a normal asymptomatic population [1, 3, 4, 21, 22, 24-26, 132, 133].

No significant differences were noted for radiological comparison of skiers versus controls. Radiological values were similar for, the PI of the skiers (50.9°) and controls (50.2°), the PT of the skiers (10.9°) and controls (7.9°) and the SS of the skiers (41.7°) and controls (42.3°). A difference was noted with the radiological value for the SVA of the skiers (8mm) compared with the controls (-2mm).

This may be of clinical relevance, in spite of being statistically non-significant. Moreover, this may suggest that, sports such as skiing require a predominance of forward-bending postures may be associated with functional changes that affect the global spinal balance rather than a specific structural issue. The skiers in the present study comprised of both Alpine (n=57) and Moguls (n=17). Alpine skiing requires a more forward flexed posture compared with Mogul skiing which requires a more upright spinal posture combined with greater hip and knee joint flexion. Nonetheless, functional changes may have occurred in both skiing disciplines due to the development of anterior muscular stiffness affecting the global spinal balance.

Muyor et al. [13] showed no increment in the sagittal curvatures of adolescent tennis players. This was similar with the present study, where radiographic values for the TK of the skiers (35.2°) and controls (37.4°) and LL of the skiers (-58.4°) and controls (-60.9°) were both similar. However, methods with this study utlized radiological parameters to compare the spino-pelvic sagittal alignment, however, Uetake et al. [7], Alricsson & Werner, [5], Rajabi et al. [6] and Muyor et al. [13] all used non-radiological methods. There were no significant differences between genders for the values of pelvic parameters and spinal curvatures, which is similar to previous studies [28, 31]. Therefore, this might suggest that although differences may exist in the morphology between genders. Clinical evaluation of the spino-pelvic parameters using non-radiological measuring devices may not highlight any such differences. This may be due in part to the young age of the sample used in this study.

Clinical Study III

The findings from Study III show significant differences for the clinical values of the skiers neutral LL in standing and sitting and for standing LF mobility compared with the controls. A significant difference was also shown for comparison in sitting of pelvic neutral and pelvic anteversion for the skiers compared with the control group.

Comparison of LL between both groups for standing and sitting highlighted a significant difference. The mean values for standing LL of the skiers (-27.2°) was shown to be 3.2° less and significantly different compared with the controls (-30.4°). This was similar for the mean values for sitting LL of the skiers (-2.5°), which, were also shown to be 4.9° less, and significantly different compared to the controls (-7.4°). Comparison of standing spinal sagittal mobility between groups showed a significant difference for the mean value of LF for the skiers (61.5°) compared with the controls (67.6°). Therefore, the results of the present study highlight that the skiers were unable to flex their lumbar spine 6.1° less than the controls. The clinical relevance of this might suggest that the skiers may have had developed more muscle bulk and tone which may have actually limited their lumbar mobility. Moreover, a reduction in lumbar mobility may have been shown with the skiers as they may have already been standing in a more forward flexion posture as a postural adaptation from sports specific training or from the development of specific spinal types according to Roussouly et al. [8].

It could be hypothesized that hamstring flexibility [138, 139] and hip joint growth disturbances [75] may have decreased LL and LF values for the skiers. Moreover, spinal pathologies [140], early sporting participation and development of hip joint muscle dominance and stiffness from adaptation to exercise loading [5-7] may have reduced the LL values in standing and sitting and LF mobility in the skiers compared with the control group.

No significant differences were noted for the comparison of TK between groups with the mean values being shown for the skiers

(30.5°) and controls (32.9°), similar to those previously reported [94, 97]. Moreover, this conflicts with other studies that have shown sports such as canoeing, cycling, cross-country skiing, freestyle and Greco-Roman wrestling all to increase the curvature of TK [5, 6, 13, 138, 139, 141, 142]. Likewise, similar values were also shown for the LE of the skiers (28.5°) and controls (27.2°) the TF of the skiers (24.9°) and controls (24.6°), and TE of the skiers (22.2°) and controls (21.2°). Moreover, these results appear to be similar to those previously reported within an asymptomatic population [94]. However, there were no differences for the combined standing sagittal spinal mobility between skiers and controls

The skiers were shown to have significantly lower values in sitting for the measurement of pelvic neutral compared with the controls. Mean values in sitting for pelvic neutral of the skiers (-3.6°) were shown to be 1.8° less compared with the control group (-1.8°). This was similar for the values in sitting for pelvic anteversion of the skiers (7.1°), which, were shown to be 4.7° less compared with the controls (11.8°). No significant differences were noted for the values in sitting for pelvic retroversion between groups. This may, suggest that in sitting, Elite skiers show reduced values for both pelvic neutral and pelvic anteversion compared to non-athletes. One explanation may be that the skiers' values for pelvic anteversion was lower compared with the controls may be related to them having a lower pelvic neutral value. Therefore, such differences may be due to the skier's finding it more difficult to sit in pelvic neutral and anteversion, perhaps adapting a more comfortable sitting pelvic retroversion and lumbar kyphosis position.

Therefore, it could be hypothesized that such differences in pelvic values may be related to other factors such as hamstring flexibility [13, 139], hip joint growth disturbances and the development of cam or pincer type FAI [75], pathology in the lumbar spine [140]. Other factors that may have affected pelvic values are muscular development from skiing in forward flexed postures and sustained spinal loading [5-7]. Moreover, it was hypothesized in Study II that sports specific adaptations might affect the values for spino-pelvic parameters.

Previous studies have shown athletes to develop an increase in spinal curvature due to specific load demands and sports-related biomechanics [5-7, 141, 142]. However, participants in other sports such as tennis, volleyball and soccer have shown no increment in spinal curvatures [13, 143]. Moreover, these studies hypothesised that triplanar spinal motion occurred more frequently with these sports and therefore, specific spinal curvatures were less likely to develop. No increase in spinal curvatures was shown between groups for the measurement of TK of the skiers (30.5°) and controls (32.9°). However, a significant difference was shown for the LL of the skiers (-27.2°) compared with the controls (-30.4°) and it may be possible that such a difference may be related to increased muscular development of the anterior hip musculature such as a shortened iliopsoas muscle. It is possible this may be a postural adaptation from specific sports biomechanics [5, 7, 141]. The iliopsoas muscle comprises of the psoas major/minor and iliacus and originates from the T12-L4/5 anterior vertebral bodies, transverse processes and lumbar discs with the exception of the L5 disc and share a common insertion onto the lesser trochanter of the femur [144, 145]. Nachemson [146, 147] has previously shown the psoas major muscle to be active during upright standing and forward flexion of the trunk. Whilst, Swärd et al. [148] have suggested a lack of passive hip and spinal mobility to be a source of LBP. This could be of clinical relevance as shortening of the iliopsoas muscle may have led to a reduction in LL, increased pelvic retroversion and limitions in active lumbar mobility with the skiers. Such an hypothesis has previously been reported as a source of LBP in athletes [145, 149].

Radiographic Study IV

The findings in Study IV highlight a significant difference for an increased spino-pelvic PT (13°) value in the presence of increased cam-type FAI in a mixed-population compared with the no cam PT value (8.5°). The greatest distribution of cam-type FAI (67%) was shown to occur in the Type II spinal category according to Roussouly et al. [8] for the skiers compared with no cam FAI (33%).

Measurement of the spino-pelvic parameters in the present study highlighted a significant difference for the values of PT in a mixed-population. Individual's diagnosed with increased morphological hip joint cam showed PT (13°) values to be significantly greater compared with those PT (8.5°) values with no cam. The PT angle describes the orientation of the pelvis, a greater PT angle correlates with a greater degree of pelvic retroversion; therefore, in the present study pelvic retroversion may have occurred in individuals with an increased PT in the presence of morphological hip joint cam-type deformity. Perhaps such an increment in PT may be seen as compensatory mechanism for individuals to cope with an increased morphological hip joint cam-type FAI. Moreover, pelvic retroversion may have occured as a result of increased PT therefore, affecting spinal sagittal alignment values. This may have resulted in Type I and II spines according to Roussouly et al. [8] being more common in the skiers.

An important point needs to be addressed in terms of the geometrical relationship that occurs between the morphological (PI) and the functional parameters (PT, SS). According to Roussouly et al. [8] this relationship results in the equation PI=PT+SS. Accordingly, this would imply that if an increase PT value occured, then a decrease in the SS value would also be noted. The reason for this relates to the angle of PI remaining constant after skeletal maturity. With the present study all participants were shown to have closed physis on plain radiographs. Moreover, the value for SS (40.8°) in the cam group was lower compared with the value for SS (42°) in the no cam group, however, without statistical difference. Therefore, caution would have to be taken with intepreting these results. Although the present study was able to show a difference in the PT angle between the cam and no cam groups such a limited sample in this study, would question any such significance. Moreover, it is possible that such limited sample numbers may have impacted the statistical analysis and therefore, the significance shown may have purely been due to an error in measurement.

However, PT has been shown to be a functional parameter [8] and therefore; it is possible that an increased PT may have increased pelvic retroversion as means to regulate the spino-pelvic sagittal balance to accommodate increased morphological changes associated with hip joint cam-type FAI. One explanation may be that the spino-pelvic complex may have attempted to rotate around the hip [3] to maintain a balanced spine. However, this conflicts with the clinical results from Study III that have shown limitations in pelvic mobility. Moreover, pelvic mobility has also been shown to be limited in the presence of hip joint cam-type FAI [58]. However, the spino-pelvic parameters were measured with radiology in the present study compared with previous studies that measured only sagittal range of motion with clinical methods and motion camera analysis [57, 58].

A difference was noted with the spino-pelvic SVA measurement for comparison between cam (11.7mm) and no cam (6mm) for all participants, this was also similar for cam

(15.2mm) and no cam (9.9mm) for the skiers group. These values were not statistically significantly different. Moreover, this may still have a clinical relevance as it highlights those individuals with increased morphological hip joint cam-type FAI may stand in a more forward flexion posture compared with individuals with no cam.

Similar values were also previously reported for the measurement of SVA in Study II. It was hypothesized that such a change in global spinal positioning may have been related to the skier's heavy training load. However, Study IV showed that a difference in SVA values also occurred within a mixed-population therefore, it may be possible that a increase in SVA value might be related to increased morphological hip joint cam-type FAI rather than any particular training or sports specific activity.

Measurement of the spino-pelvic parameters PI, SS, TK, LL between groups appears to be similar. Moreover, the spino-pelvic parameters do not appear to be significantly affected by an increased prevalence of morphological hip joint cam-type FAI. Study II reported similar values for the spino-pelvic parameters in skiers and controls without considering the influence of increased morphological hip joint cam-type FAI. Accordingly, this might suggest that an increased prevalence of hip joint cam-type FAI may not actually affect PI, SS, TK and LL parameters. Major limitations with this study relate to the limited cohort size and the subgroup statistical analysis. Moreover, the participants may have been too young and therefore, not yet developed any significant changes to alter their spino-pelvic sagittal alignment.

There were no significant differences in terms of the prevalence of cam-type FAI for the classification of spinal types according to Roussouly et al. [8]. The presence of increased morphological hip joint cam-type FAI was shown to occur in all four spinal classifications for a mixed-population, which was similar for the skiers, but only for Types II and III compared with the control group. Moreover, Type II Roussouly spines were shown to occur more frequently with the skiers in the presence of an increased prevalence of cam (67%) compared with no cam (33%). However, this did not show any level of significance due to such small numbers within this group. One explanation may be that Roussouly's spinal classifications might be a more holistic and sensitive method for analyzing spinal types compared with the measurement of spinal parameters. Roussouly's spinal classification model includes the entire spine rather than specific spinal curvatures. Therefore, it may be possible that in the presence of increased morphological hip joint cam-type FAI, classifying Elite skiers with a Roussouly spinal type may be a more appropriate method rather than using spino-pelvic parameters. However, this must be viewed cautiously as errors in measurement may occur with using such a holistic spinal classification model due to an overlap between Roussouly type spines and therefore, this would make it more difficult to quantify such a small sample.

Moreover, it may also be possible that the development of spinal types according to Roussouly et al. [8] may be due to a small angle of PI and/or growth-related hip joint disturbances [75]. A small PI angle may restrict pelvic retroversion therefore, the spine would have to compensate by reducing the LL and increasing the TK. Similarily, a small PI may also limit hip flexion ROM and therefore, young Elite athletes that perform repetitive hip flexion movements, may become more susceptible to growth-related disturbances and the development of hip joint morphological cam-type FAI. However, this would require further investigation in a much greater scale.

Evaluation of increased hip joint morphological cam-type FAI changes in this study were done using the α-angle measurement; this is seen as a quantitative way of evaluation an increment in prominence of the femoral head-neck junction [60]. In the present study, the α-angle was set as greater than 55° [85, 150], however, some studies have shown a huge variability with the α-angle ranging from 32° to 62° within a mixed-gender population. Moreover, Pollard et al. [151] and Agricola et al. [77] both suggest increasing the α-angle cut off to 78°. Golfam et al. [152] suggest using a threshold angle of 63° (in the oblique axial view) and 66° (in the radial view) at the 1:30 clockface position for the diagnosis of a cam-type deformity. It must be highligted that the α-angle provides only an indication of the size of the cam, and therefore, in the presence of clinical symptoms related to pathology, clinical examination should also be included [153]. However, in the present study only the increased morphological characteristics of hip joint cam-type FAI and not hip joint pathology were evaluated with MRI, moreover, no clinical evaluations were performed.

The mean value in years for the age of the mixed-population (skiers and controls) (17.7) was shown to be significantly greater for the cam-type FAI (18) group compared with the no cam (17.4) group. The intentions of this study were to have age-matched groups; however, some of the skiers were from High School grades 1-4 as the controls were from the first grade. Moreover, all participants were shown to have a closed spinal physis on plain radiographs and closed growth plate on hip joint MRI therefore, limiting the possibility of growth-related spurts [154] or a higher prevalence of cam-type deformity [121] between groups.

A significant difference was shown in terms of the prevalence of increased morphological hip joint cam-type FAI within the mixed-population group (skiers and controls), with males (60%) showing an increased frequency compared with females (22%), which appears to be similar to previous studies [48, 56, 59, 89, 121, 155]. Likewise, a significant difference was also shown for the height variable of a mixed population with taller individuals being shown to have a significantly increased prevalence of cam-type FAI (177cm) compared with the no cam (170cm) group.

Patient reported outcome measures Study V

The most important findings in Study V show that young Elite skiers do not have increased lifetime prevalence for back pain (50%) and hip pain (22%) compared with a non-athletic control group. Moreover, a high percentage of skiers (46%) reported a duration of back pain prevalence >5 years however, this was not statistically significant. A significant increment in back pain measured using the VAS was shown for the skiers (5.3) compared with the controls (2.4). Moreover, there was no correlation between back and hip pain in the skiers compared with a non-athletic population.

The clinical relevance of this study highlights, that a high percentage of young elite skiers train and compete regularly with back pain and hip pain. Moreover, a high percentage of skiers report duration of back pain prevalence >5 years. It could be suggested that education of coaches and preventative measures such as monitoring the loading of young Elite skiers should be taken to reduce the prevalence of back pain and hip pain. Moreoever, it is also suggested that due to the poor correlation between these variables, pain in the hip joint may not actually affect the back and vice-versa. However, this should be viewed with caution, as the size of the cohort may have been a limitation with this study.

The present study also highligted that there were no significant differences shown for the lifetime prevalence of back pain between the skiers (50%) and the controls (44%), or between the Mogul skiers (53%) compared with the Alpine Skiers (49%), with both values appearing to be similar to a previous study [130]. Other studies have shown a higher prevalence of LBP in athletes. A 5-year follow-up study of 20 elite divers highlighted 89% to report previous or present LBP [79]. Whilst a 15-year follow-up of 71 elite athletes highlighted 78% to report previous or present levels of LBP [114]. Moreover, it could be suggested that if 50% of the young Elite skiers are experiencing a higher prevalence of back pain, then this may be related to the intense training and loading upon the young athletic spine, which has been shown to be more vulnerable during growth-related spurts [156, 157]. This suggests that objectively measuring training load may be an important tool for reducing the prevalence of back pain in young Elite skiers [158, 159].

There were no significant differences in the comparison of onset and duration of back pain between groups. The onset of back pain appeared similar between groups with the skiers reporting their first episode at 14 years and the controls at 13 years of age. This is in spite of the skiers reporting a mean age (6.9 years) for starting training and a mean age (8.6 years) for starting competitions. The greatest range for the duration of back pain occurred within the category of >5 years, highlighting (46%) of the skiers to have back pain compared with (9%) of the controls. This may suggest that a high number of skiers continue to train and compete regularly with some degree of back pain and this may be a cause of concern in terms of the longevity of their athletic career.

Previous studies [123, 160] have shown similar results but this is in conflict with an earlier study by Bergström et al. [112]. Athletes in the present study comprised of both Elite Alpine and Mogul skiers. This contrasts with the study by Bergström et al. [112], which also included Cross-country skiers and showed a higher prevalence of 67% back pain in adolescent skiers. The outcome of the study by Bergström et al. [112] may have been affected by the inclusion of Cross-country skiers as Alpine and Mogul skiers both have different training regimes [161], different loading on the spine and hips and develop different skiing patterns by increasing variable degrees of knee and hip joint flexion for absorbing the effect of ground reaction forces [162, 163]. Other sports, have shown similar values for the prevalence of LBP such as, water-ski jumping 45%, soccer 53%, orienteering 55% and tennis 50% whilst, a higher prevalence of LBP has been shown in weight-lifting 71%, gymnastics 67%, wrestling 77%, hockey, 89% and diving 89% [79-81, 111]. This suggests certain sports may increase spinal loading therefore, elite athletes who participate in those particular sports, may have a greater prevalence of LBP compared with other sports with less spinal loading. Moreover, due to the anatomical proximity between the spine and hip joint, elite athletes who participate in sports requiring greater levels of hip joint rotation, may be at risk of developing hip joint microinstability [164]. Therefore, athletes that develop hip joint pathology, may become more susceptible to LBP [115, 116, 130] due to their close anatomical relationship.

No significant differences were shown between groups for the prevalence, duration and onset of hip pain, moreover, there were no significant differences shown between skiing disciplines. In spite of this, an increased prevalence of hip pain was shown for the skiers (22%) compared with the controls (8%) and for the Mogul skiers (35%) compared with the Alpine skiers (18%). This appears similar to previous studies comparing elite athletes between sports and non-athletes [130, 165].

The clinical relevance of these findings may suggest that young Elite skiers are more vunerable to developing hip pain compared with non-athletes. Moreover, sports specific biomechanics may also be a relevant factor, as a greater prevelance of hip pain was shown to occur with the Elite Mogul skiers group compared with their Alpine counterparts. One explanation for this may be that Mogul skiing requires a more upright spinal posture combined with greater hip and knee joint flexion. Perhaps a greater range of mobility in the lower extremites might make the hip joint more susceptible to microinstability and pain [164].

Onset of hip pain highlighted the skiers (29%) shown to have their first occurrence between 11-13 years of age; whilst the greatest range of hip pain was shown to occur in the skiers (43%) between the ages of 17-19 years. This might suggest that at a younger age, the Elite skiers may have previously been subjected to hip joint growth-related disturbances [76, 88], which may have contributed to an increased prevalence of hip pain in their later teenage years. Hip pain duration with the skiers (17%) was shown to have the greatest difference for the category 6-12 months compared with the controls (0%).

One explanation may be that the duration of hip pain in the skiers may have coincided with a particular increment in exercise loading intensity [161] such as heavy squatting and weight training. Intense training regimes and early elite sports specialization have both been shown to affect spinal alignment and spino-pelvic parameters [5-7], therefore, it would appear reasonable to hypothesize that such heavy loading may also impact the hip joint. Moreover, the mean age for the onset of training in the skiers group was 6.9 years therefore, due to early sports specialization [166] the skiers may have been at risk of increased loading to their spine and hip joints.

The lifetime prevalence due to training hindrance highlighted the greatest percentage of skiers (29%) to report between 2-10 incidents of back pain during their careers. This appears similar to a previous study that reported a 30% absence from training due to pain [167]. Moreover, the skiers (50%) were shown to have a greater lifetime prevalence of back pain, of which (46%) were shown to have back pain duration >5 years and radiating back pain (24%), this is in spite of the 38% of the skiers training >11 hours per week. Therefore, it could be suggested that a greater number of skiers manage to continue training whilst suffering from long-term back pain and radiating pain and highlights the importance for the possibility of a long-term prevention study within this sporting discipline.

Similar values were also shown for inability to train with the skiers (38%) due to 2-10 incidents of hip pain in spite of accumulating >11 hours training per week. The skiers were also shown to have a lifetime prevalence of hip pain (22%), and showed increased levels for the duration of hip pain (58.3%) >1 year. A greater percentage of the Mogul skiers (35%) were shown to have increased levels of hip pain compared with the Alpine skiers (18%). Mogul skiers have different skiing postures and regimes compared with their Alpine counterparts. Mogul skiers adopt a more upright posture as Alpine skiing involves adopting a more forward flexion posture. Perhaps such a forward flexion posture with the Alpine skiers may have helped reduce the prevalence of hip pain by facilitating the absorption of shock through their knees and hips [162, 163]. Therefore, a more upright stance may actually have contributed to an increased prevalence of hip pain in the Mogul skiers.

There was no correlation for back pain and hip pain between the young Elite skiers and non-athletes. This conflicts with other studies where hip pain and back pain has previously been shown to correlate in athletes [114, 130]. The close anatomical proximity between the hip joint and spino-pelvic region has previously been proposed as one reason for such a coupled pain syndrome [130] and subsequent cause of back pain [57]. However, due to the low numbers of participant's actually reporting back and hip pain in the present study, no correlation statistics of back and hip pain were performed.

There were no significant differences between the young Elite skiers and non-athletes for the ODI and EQ-5D questionnaires. All participants from both groups scored lower than 19% indicating minimal disability with the ODI and had a score of 1 or less for the EQ-5D questionnaires, indicating full health. Moreover, the EQ-5D score for the skiers (0.85) were shown to be slightly less compared with the controls (0.88). A significant difference was shown for the VAS back pain score with the skiers shown to have the greater level of back pain during the past six months VAS 5.3 compared with a VAS 2.4 for the controls. However, although the VAS is a subjective measuring tool, it has shown to be a reliable and valid method designed to measure a change in pain, before and after a particular intervention, [168, 169]. However, the VAS was not designed to measure pain levels between the groups. Therefore, participants may have had difficulties with translating their subjective levels of back or hip pain to correspond with a particular point denoting a quantitative measurement on the scale [170]. It could be suggested that the skiers due to the nature of their training and competing may have developed an increased robustness, stronger personality traits and increased coping mechanisms to deal with pain.

General discussion

In the quest for potential young athletes striving to achieve excellence, the participation and commitment to training and competition remains high. Unfortunatley pain and stiffness appear to be a by-product of overloading the young athletic spine and hip. Symptoms may be attributed to low back and or hip pain and appear to be more common in young athletes compared to the general non-sporting population. Therefore, it is important that a thorough understanding, diagnosis and management of spino-pelvic saggital alignment and its relation to adaptations due to increased hip joint morphological changes are based upon solid scientific evidence.

All studies included in this thesis are either clinical or radiological and moreover, are low in cohort size. Therefore, the studies included may not able to give any true answers but are instead able to highlight some distinct differences, raise new questions and hypotheses for understanding the spino-pelvic alignment in young elite athletes.

In spite of previous studies showing clinical methods to be effective, non-invasive ways to measure changes to the spinal alignment of athletes. The findings from the clinical study highlighted that although changes to the spino-pelvic alignment may occur, this might not actually be so significant in a young athletic population. Perhaps in a younger population, the spino-pelvic complex has not been sustained long enough to increased axial loads for a significant malalignment difference to occur.

Moreover, although the Debrunner Kyphometer was able to show excellent reliability and good validity to measure the thoracic spine, the results pertaining to measuring the validity of the lumbar spine were poor compared with a gold standard such as plain radiograph. An explanation for this may lie within the name of the clinical tool, as the Debrunner Kyphometer was originally designed and used to measure purely TK angles. Therefore, it is suggested that the Debrunner Kyphometer should only be used to measure spinal values for TK.

The findings from the radiological studies have shown that a smaller PI angle and Type I and II Roussouly spines may occur more frequently in young Elite skiers. Moreover, in the presence of increased hip joint morphological changes, an increased value for PT was noted but these results must be viewed with caution as other variables may have affected these results such as an error in measurement and a limited cohort size.

Nonetheless, although it has been hypothesized that the correlation between spine and hip pain may be related to hip joint hypomobility such as cam-type FAI affecting the spino-pelvic alignment. The findings from Study V were unable to substantiate this hypothesis. Fundementally the pelvic morphology categorized by the angle of PI helps to define the thoraco-lumbar curvature. However; the angle of PI may also contribute to increased hip joint morphological changes. Therefore, further larger scale radiological studies are needed to help determine if spino-pelvic morphology is an important factor affecting hip joint morphology or vice-versa.

Clinical relevance

The clinical relevance of this thesis highlights,

- Hand-held measuring devices such as the Debrunner Kyphometer may be used effectively for measuring the thoracic spine; moreover, clinicans should observe caution with using the Debrunner Kyphometer for lumbar spine measurements due to a lack of validity.

- Young Elite skiers were shown to have an altered spino-pelvic sagittal alignment resulting in a low PI angle and Type I and II Roussouly spine resulting in a thoracolumbar kyphosis. Moreover, the spino-pelvic sagittal alignment is different in young Elite skiers compared with a non-athletic population. Therefore, differences in the spino-pelvic sagittal alignment may make young Elite skiers more vunerable to spinal pathologies.

- An increased spino-pelvic sagittal alignment value for PT may be shown in a mixed-population in the presence of increased morphological hip joint cam-type FAI. Moreover, Type II Roussouly spines occur more commonly alongside a smaller PI angle in young Elite skiers in the presence of cam-type FAI. Therefore, individuals with a low PI angle, may be more prone to develop cam-type FAI, this may result from an inability to accomodate pelvic retroversion and subsequently lead to the development of Type II Roussouly spines.

- Young Elite skiers are shown not to have greater lifetime prevalence for LBP compared with non-athletes. In spite of this, a high percentage of skiers reported back pain duration >5 years. Moreover, although young Elite skiers continue to train and compete with back and hip pain, there is no correlation shown between back pain and hip pain for comparison of young Elite skiers with a non-athletic population.

Limitations to the clinical studies

Limitations to Study I and III include, limited sample size and a lack of sample size calculation. Moreover, participant dropout may have biased results as only radiological data from (n=90) and Debrunner Kyphometer data (n=100) was available for final anaylsis. Participant positioning and instructions [98] location and accuracy of palpation, errors in clinical measurement [171-174], and fatigue from repeated measuring

[175-177] are other possible limitations. Other limitations include the positioning of the Debrunner Kyphometer.

The Debrunner Kyphometer was originally designed to measure TK, modifications increased its ability to evaluate LF and LE [94]. Perhaps by modifying this instrument to measure LL, the Debrunner Kyphometer was rendered more susceptible to errors in clinical judgement. The Debrunner Kyphometer is positioned between the spinous processes as radiographic investigations measure from the vertebral bodies [171] and are calculated from standing lateral radiographs using the relevant upper and lower vertebral end plates [1, 178-180]. The limits of agreement for LL ranged from 11° to 51° implying the Debrunner Kyphometer could show a reading as high as 11° above or 51° below that of a radiological method. Such a large variation between both methods questions the Debrunner Kyphometer's validity to measure LL and appears similar to what has been reported in other studies [97, 98, 100].

The mean age of the cohort in Study I was 17.7 years. Perhaps such a young age highlights the lack of excessive sagittal plane curvatures noted. Moreover, a healthy population was selected for validation however; this would have limited the ability to distinguish between alignment and malalignment using this clinical method.

Limitations to Study III include the effectiveness of the skin-surface measuring device, accuracy of palpation and errors in clinical measurement [172]. Poor levels of agreement in terms of validity with plain radiographs have previously been shown as reasons for not using this clinical instrument [100]. This is in spite of the Debrunner Kyphometer showing good reliability [94, 97-99] and strong evidence with comparison of more technical methods such as Rastersterography, 3D ultrasound and sterovideography [100]. Verbal instructions, participant positioning and fatigue from repeated measuring [177] have also been reported as limitations and reasons for making clinical methods less useful compared with plain radiographs.

Measurement of sagittal spino-pelvic alignment and mobility was recorded in the "upright standing" and "sitting" positions. These were chosen as they both reflect postures associated with Alpine and Mogul skiing patterns. However, skiing encompasses triplanar motion, with trunk flexion and extension movements occurring around the long axis of the spine [138].

A significant difference in age was shown between the skiers (18.3) and controls (16.4) and this could be viewed as a major study limitation. It was the intentions of Study III to include aged-matched groups. However, one explanation was that the skiers were from grade 1-4 and the controls from the first grade of High School. All 4 grades of skiers were included to increase the number of participants in this study, however, in doing so, the age span of the skiers group became larger. In spite of this all Study III participants were shown to have a closed spinal physis on plain radiographs and thereby, limiting the possibility of growth-related spurts [154] between groups.

It could be hypothesized that the variability between skiing disciplines may have biased the results. Alpine and Mogul skiers where combined in the same group but both these disciplines have very different skiing patterns. The biomechanics of the spine and lower extremities to absorb the effect of ground reaction forces [162] is very different in each discipline. Therefore, it may be possible that such differences could have reduced the mechanical loading upon the spine and may have affected values for spino-pelvic alignment and mobility.

Lower limb flexibility may have biased the study outcome, even though some studies have reported no association between hamstring flexibility and spinal posture in standing [181, 182]. Hamstring extensibility has been shown to influence spinal and pelvic posture when trunk flexion is performed [138, 139]. Moreover, in the present study, hamstring flexibility may have affected both the lumbar and pelvic posture in sitting. Pelvic posture has previously been shown to be affected by hamstring shortening in highly trained canoeists [139]. The hamstring muscles take their origin from the ischial tuberosity, therefore in the present study, skiers may have developed excessive tension in the hamstring muscles from training that may have influenced both standing and sitting lumbar and pelvic values.

Other postural variances and biomechanical lower limb asymmetries such as hip joint cam-type FAI have been shown to occur in young athletes [51]. Lamontagne et al. [58] have shown limited sagittal spino-pelvic mobility to occur in the presence of hip joint cam-type FAI. Study III showed that the skiers had lower values for sagittal pelvic neutral and pelvic anteversion in a seated position compared with the control group. Moreover, this was also reflected with the values for standing and sitting LL and for standing LF mobility. However, the inclusion criteria did not consider hip joint cam-type FAI. Moreover, the methodology selected only a young healthy population however; this may have limited the ability to distinguish variations in spino-pelvic alignment and mobility between these groups.

Limitations to the radiographic studies
Limitations with Study II include sagittal plane measurements were recorded in the erect standing position. However, this does not reflect the multi-directional patterns of skiing. In sport, repetitive fast trunk flexion and extension movements occur in the sagittal, frontal and transverse planes around the long axis of the spine [13]. A significant difference was shown for the classifications of Type I spinal curvatures according to Roussouly et al. [8] between groups. However, no significant differences were shown for the spino-pelvic parameters between groups.

Roussouly‘s definition and classification of spinal types relates to analysing the entire spine. It may be possible that evaluation of spinal types according to Roussouly et al. [8] may be more sensitive and therefore, show a difference in values compared to the evaluation of the spino-pelvic parameters. However, this must be viewed cautiously as an error in measurement may have occured with using such a holistic spinal classfication model. Moreover, an overlap between the classifications of Roussouly type spines may have occurred and therefore, making it difficult to quantify such a limited cohort.

Such a small control group (n=27) compared with the skiers (n=75) may have biased results perhaps; selection of a larger control group may have shown greater differences in the values of the spino-pelvic parameters. Moreover, there were no sample size calculations carried out prior to Studies II and IV and accordingly, caution must be viewed with interpreting these results.

The intentions with these radiological studies were to find and include aged-matched groups however; a difference in age was shown between the skiers (18.3) and controls (16.4) and moreover, was statistically significant in spite of both groups attending the same first year at Åre High School. Unfortunately, some skiers may have previously lived or studied abroad due to training and competition commitments and would have chosen to attend Åre High School because of the association with the Ski Academy. Spino-pelvic sagittal malalignment may develop during pubertal growth to accommodate postural and physiological changes that alter the spinal morphology [26, 83]. Osseous growth of the sacrum has been shown to occur up to and beyond 20 years of age [9, 183, 184]. Therefore, by selecting a cohort with the mean age of 17.7 years, spino-pelvic alignment differences might have been shown between groups due to postural and physiological changes associated with growth.

Other limitations include accuracy and interpretation of the radiological measurements. A blinded radiologist measured the spinal curvatures which were calculated from measurements taken from the endplates of the vertebral bodies [1, 171, 178-180] whilst the pelvic angles were calculated from measurements taken from the pelvic paramenters [8]. Spinal posture can be affected by lower limb alignment [20, 185-187] therefore; errors may have occurred if the participants were not standing evenly in the same position, fatigued from prolonged periods of standing [175] or postural variance from biomechanical lower limb asymmetries [188]. The inclusion criteria selected only a healthy population and this may have limited the ability to distinguish a greater difference between both groups.

Limitations to Study V

Limitations to Study V include a lack of validation and sensitivity assessment of the questionnaires, which may have affected the outcome. The VAS is a subjective measurement tool and not really designed to measure pain between groups. Errors may have occurred in interpreting and reproducing pain levels with the VAS scale and this may have led to a bias between groups. The skiers due to having been subjected to longer periods of back and hip pain may have actually quantified higher levels of pain as moderate and conversely the controls may have catastrophized their pain and quantified moderate and lower levels of pain as high.

Another study limitation was that the groups (skiers and controls) were not age-matched. The intention was to include aged-matched groups; however, one reason for such a difference may be that the skiers were from grades 1-4 and the controls from the first grade at High School. Unfortunately, some skiers may have previously lived or studied abroad due to training and competition commitments and would have chosen to attend Åre High School because of the association with the Ski Academy. However, age differences and growth-related spurts amongst the skiers may have affected the outcome of the present study.

Recall bias, including interpreting and completing the questionnaires correctly as some participants may have provided incorrect information. Perhaps, by performing a sample size calculation or selection of a larger cohort, Study V might have shown a higher prevalence for the values of back and hip pain. Similarily subgroup analysis reduces numbers and renders statistics unusable. Other limitations may have been related to exercising, the inclusion criteria for the control group was to have exercised less than 2 hours per week; therefore, those individuals may have also been at risk to develop back pain due to reduced activity levels. Some of the young Elite skiers may have had premature career-ending injuries due to back and hip pain and disability therefore; those participants may not have been included and biased the outcome.

Conclusions

“The first duty of the physican is to educate the masses not to take medicine.”
WILLIAM OSLER

All studies included in this thesis are either clinical or radiological. Moreover, the studies are low in sample size and in levels of evidence. Therefore, the studies included in this thesis may not able to give true answers but are instead able to highlight some distinct differences, raise new questions and hypotheses for understanding the spino-pelvic alignment in young elite athletes.

The validity of the Debrunner Kyphometer as an appropriate clinical method for measuring TK values shows good levels of agreement and therefore should be included as a clinical measuring device for evaluation of the thoracic spine.

Moreover, the validity of the Debrunner Kyphometer as an appropriate clinical method to measure LL values is questionable. This is due to the lack of sensitivity and the large range of variations that exist when correlating such a non-radiological method with a radiological standard. Therefore due to the lack of clinical interpretation, there is limited value in using the Debrunner Kyphometer as a clinical method to evaluate of lumbar spinal sagittal alignment.

Young Elite skiers are shown to have a lower PI angle and a more prevalent Type I and II spine and a different spino-pelvic sagittal alignment compared with a healthy non-sporting population of a similar age.

Investigation with clinical methods, young Elite skiers are shown to have significantly less standing and sitting lumbar and pelvic values for spino-pelvic sagittal alignment and mobility compared with a healthy non-sporting population of a similar age. This is suggested to be due to adaptation from heavy loads on the spine, pelvis and hips from skiing and training activities.

A significant increase in the spino-pelvic sagittal alignment values for PT occurs in a mixed-population in the presence of increased morphological hip joint cam-type FAI and that an increased distribution of spinal Type II classification according to Roussouly et al. [8] occurs more frequently alongside a smaller PI angle in young Elite skiers in the presence of cam-type FAI.

Young Elite skiers are shown not to have a significantly greater lifetime prevalence of back or hip pain compared with a non-athletic control group. In spite of this a high percentage of skiers reported duration of back pain prevalence >5 years, however, this was not statistically significant.

Future Perspectives

"As knowledge increases, wonder deepens."
CHARLES MORGAN

Athletes with a more prevalent Type I and II spine according to Roussouly are more likely do develop a thoracolumbar kyphosis, low PI angle and exhibit an increased SVA affecting their spinal global balance compared with a healthy non-sporting population. Such increased levels of pelvic retroversion, lumbar kyphosis and other lumbar pathologies may be found in individuals who are also shown to have increased hip joint morphological cam-type deformities. How these findings influence the short and long term results of evaluating spino-pelvic sagittal alignment in the presence of increased hip joint morphological cam-type impingement remains to be investigated in further radiological studies.

Young Elite skiers are not shown to have significantly greater levels of back pain or hip pain compared with a non-athletic control group. Moreover, a high number of young Elite skiers are shown to have an increased lifetime prevalence of back pain with some skiers reporting back pain duration for more than 5 years. In spite of this, no significant differences could be detected between groups for the prevalence of back and hip pain or for the correlation of back and hip pain.

The potential impact of these findings may suggest that many skiers continue to train and compete regularly in spite of back or hip pain. Therefore, preventative measures should be used to monitor training loads and intensities to reduce the prevalence of back and hip pain in young Elite skiers. Coaches should encourage good technique and educate athletes to improve trunk and lower limb strength, flexibility and proprioception exercises to reduce levels of back and hip pain. It is suggested that future studies should include a larger cohort to investigate further the clinical and radiographic parameters pertaining to spino-pelvic sagittal alignment in athletes.

Acknowledgements

To everybody that in any way have helped me in the process of this thesis. I am extremely grateful for without you this would not have been done.

Adad Baranto, Associate Professor, MD, PhD. The supervisor and co-author. The guide, motivator and foundation to all my work. For your constant support and professionalism for without you, my friend this would not have been able to happen.

Jón Karlsson, Professor, MD, PhD. My co-supervisor and co-author. Thank you for the opportunity to begin this research and for being an inspiration and role model. Your constant support, guidance and professionalism are excemplary.

Leif Swärd, Associate Professor, MD, PhD. My co-supervisor and co-author. Thank you for the opportunity to be able to continue your impressive and groundbreaking research and work. Without your support and belief these studies and this thesis would have never happened. Thank you for great friendship and great memories.

Anna Swärd, MD and co-author. Thank you for your help, guidance and professionalism from my first research steps until the last sentences in this thesis. For great discussions and encouragement and all your assistance with the clinical investigations.

Cecilia Agnvall, PT and co-author. Thank you for your help, guidance and professionalism from my first research steps until the last sentences in this thesis. For great discussions and encouragement and all your assistance with the clinical investigations.

Olof Thoreson, MD, PhD and co-author. Thank you for your help, guidance and professionalism from my first research steps until the last sentences in this thesis.

Páll Jónasson, MD, PhD and co-author. Thank you for great help, co-operation and friendship.

Wisam Witwit, MD and co-author. Thank you for great help with radiological measurements, co-operation and friendship.

Peter Kovac, MD. Thank you for your great help with the radiological measurements.

Christer Johansson, Statistical Consultant, for all statistical and intellectual discussions.

Pontus Andersson, Pontus Art production. For the beautiful illustrations.

Linda Johansson and **Cina Holmer**, Research administrators. For their tireless guidance of my academic cluelessness.

Carl Benett AB for financial support.

Dr Flemming Perdersen and **Dr Zaid Obady** at the Department of Radiology Östersunds Hospital, Sweden for their help with radiological examination.

Helena Brisby, Professor, Chairman of the Department of Orthopeadics, Institute of Clinical Sciences, Sahlgrenska Academy, Gothenburg University for providing the opportunity to do this thesis.

Magnus Karlsson, MD, Chairman of the Department of Orthopeadics, Sahlgrenska University Hospital, for providing the opportunity to do the present research.

The Medical Society of Gothenburg, Sweden, Handlanden Hjalmar Svenssons Research Foundation and Doktor Felix Neuberghs Foundation. For the financial support for this research project.

My parents, **Samuel** and **Elizabeth**. For giving me everything, especially the ambition to succeed in life.

My wife, **Melanie** and my children **Max**, **Callum** and **William**. For their unconditional support, you made this thesis possible and I will never forget that.

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