Special Considerations for Orthopedic and Spine Surgeons Treating Hip-Spine Syndrome

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Edited by

Jeffrey K. Lange, Kirkham B. Wood and James D. Kang

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FOREWORD

Drs. Lange, Wood and Kang should be congratulated for tackling this difficult topic in such a comprehensive fashion. Degenerative changes of the hip and spine represent the most common musculoskeletal complaints among the elderly. These changes are often progressive and can become functionally debilitating. When they occur together, they are called hip-spine syndrome (HSS). HSS manifests as concurrent hip and spine arthritis, determining how best to manage overlapping pathologies has been the subject of much research and clinical attention since its initial description in the 1980's.

The hip and spine are biomechanically connected. Pathologic spino-pelvic motion due to spine disease, such as ankylosing spondylarthrosis or spine surgery for degenerative disc disease or deformity, have been identified as risk factors of instability after THA. Acetabular orientation and hip biomechanics are influenced by the arc of movement undertaken by the lumbar spine. Therefore, modifications to the lumbar spine can modify the complex biomechanics that interplays between the spine and hip, thus altering the stability of the hip. Lumbar-sacral fusion reduces the variation in pelvic tilt in functional situations by reducing lumbar spine flexibility, resulting in a narrower range of motion for hip stability that can lead to anterior or posterior impingement and dislocation after total hip replacement.

Special Considerations for Orthopedic and Spine Surgeons Treating Hip-Spine Syndrome provides a thorough overview and clinical description of the definitions, biomechanics, classifications, imaging options, clinical manifestations, and surgical decision-making process related to HSS. The timing and implications for surgery of the hip, spine or both are explored in depth. The intricate interplay between spino-pelvic motion and its influence on surgical outcomes is described. An algorithm based on the numerous parameters to be considered in the timing and order of surgical intervention are explored. Illustrative case studies are used to illustrate these teaching points. This work will serve as a guidebook for how to systematically evaluate patients with pathology of both the hip and spine and prioritize their care. A common language developed for both hip and spine surgeons will serve to improve communication among caregivers for patients with complex musculoskeletal problems.

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PREFACE

The field of Orthopaedic Surgery has become highly subspecialized as academic research and new innovative surgical techniques have greatly advanced the treatment of musculoskeletal conditions. With such specific advancements, there has been a tendency for practicing orthopaedic surgeons to have a narrower focus on their "anatomic" specialty, which for the most part, has been a positive force driving research into the pathophysiology and treatment within their specialty. However, the human body and its manifestations of various disease states, often clinically present to the practitioner with conditions that do not always seem to fit into a convenient anatomic category. Such is the case with Hip-Spine Syndrome. Orthopaedic surgeons who specialize in joint arthroplasty have all had patients who should have seemingly done well with a joint replacement surgery, but unfortunately have had complications with persistent pain or dysfunction. Likewise, spine specialists have also had patients who were treated with the latest innovative surgical techniques, only to have less than ideal patient reported outcomes. Such negative experiences by many practicing surgeons (the authors and editors of this book included), have led to the two specialties taking a renewed and closer look at the significant interplay between the hip and lumbar spine.

Offierski and MacNab (Spine 8(3):316-21, 1983) were the first in the modern era to bring attention to this entity which was coined "Hip-Spine Syndrome." At that time, orthopaedic surgeons were largely "generalists" and the sub-specialization movement had not really begun. As such, their targeted audience was to the entire Orthopaedic community since most surgeons practiced without a focused specialty. Over the past 4 decades, however, there has been an explosion of innovation and specialization within the Orthopaedic community, and specialties such as Arthroplasty and Spine Surgery have diverged into their own communities.

The authors and editors of this book felt that there needed to be a focused re-examination of the Hip-spine syndrome that Offierski and MacNab introduced nearly 40 years ago. Much has changed in the Orthopaedic landscape with a more sophisticated understanding of the pathophysiology and major surgical advancements within each specialty, but a close examination of the intersection of hip and spine pathologies and disorders is seemingly in order. This book attempts to address the many variables involved in patient assessment as well as surgical treatment principles, keeping in mind that the hip and spine are closely interconnected and deserve a careful assessment by both the hip and the spine surgeon. The more specialized and divergent the field of Orthopaedics becomes, the more we will need to refocus on the patient, who often does not present to the clinician with a singular disease. The practicing orthopaedic surgeon and all future trainees will need to hone their skills in evaluating and assessing the anatomic regions outside of their own specialty.

INTRODUCTION

Hip-Spine Syndrome has been well-recognized as a clinical entity for decades, affecting a significant portion of the adult population world-wide. As the practice of medicine has trended toward hyper-specialization, surgeons in particular have often gravitated toward a narrower anatomic focus. While this anatomic focus carries many advantages, it also has the potential to obscure the important interplay between disparate anatomic realms – for instance, the hip and the spine.

In recent years, renewed interest has emerged with regard to Hip-Spine Syndrome and its implications for diagnosis and treatment outcomes. The purpose of this book is to present a clear picture of where we are today in terms of our understanding of Hip-Spine Syndrome, to provide a comprehensive and succinct review of this topic, and to inspire further work aimed at optimizing outcomes for our patients who suffer from this condition.

This book is divided into four sections: 1) Basic Considerations, 2) Hip Surgery, 3) Spine Surgery, and 4) Special Considerations. Section 1 reviews Hip-Spine Syndrome in general and provides a basis for understanding this clinical entity in a practical context. Section 2 reviews knowledge of the hip-spine relationship as it relates to performing hip surgery, with the major focus on hip replacement surgery. Section 3 reviews the hip-spine relationship from a spine surgeon's perspective, with special focus on spinal surgeries and hip-related considerations. Section 4 reviews considerations with regard to surgical timing when both spine and hip surgery are required, and reviews clinical cases and evidence-based decision-making. In addition, Section 4 introduces the knee-spine relationship, opening the door for further exploration of this and other manifestations of non-adjacent segment diseases.

Although this book has two distinct audiences – hip surgeons and spine surgeons, we organized the sections as noted above so that it would be easily digestible for any reader. Although hip surgeons may gravitate most toward section 2, and spine surgeons may gravitate most toward section 3, we think that each section is accessible to all, and we hope this will encourage interdisciplinary conversation and collaboration on this important cross-over topic.

We cannot thank the chapter authors enough – all recognized experts in their fields – whose outstanding contributions elevate our understanding of this complex topic. Without their efforts, this work would not be possible.

It was our great pleasure to prepare this book. We hope that the reader will enjoy reading as much as we enjoyed preparing.

CHAPTER 1

OVERVIEW AND CLINICAL DESCRIPTION

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Introduction

Hip-Spine Syndrome (HSS) was described in the early 1980s as clinicians began to appreciate overlapping symptomatology between degenerative hip and spine pathologies. At that time, the importance of a clear clinical history, targeted physical exam, and thoughtful utilization of ancillary tests was emphasized in the proper diagnosis and management of this condition. Over the last 40 years, these central tenets have held true. While the realm of orthopedic and neurosurgical care has advanced, in particular our understanding of spinopelvic dynamics and surgical techniques, HSS remains an enigmatic entity that significantly affects lower extremity and core function. In this chapter, we provide an overview of HSS, offering a brief historical perspective, highlighting its definitions and classification schemes, and introducing key considerations that will be expounded upon in the chapters that follow.

Prevalence and Impact

Degenerative pathology in the form of hip and spine arthritis represent the most common musculoskeletal complaints among the elderly[1,2]. These changes are often progressive and can become functionally debilitating. Fortunately, conservative and operative interventions exist that are successful in addressing the pain, weakness, and associated symptoms that characterize these conditions. HSS usually manifests as concurrent hip and spine arthritis, and determining how to best manage coexisting pathology with overlapping symptomatology has been the subject of much research and clinical attention since its initial description.

Historical Perspective

Formal naming and classification of HSS is attributed to Offierski and MacNab[3]. In 1983, they published a retrospective review in which 35 patients were separated into three categories that constituted a novel classification scheme. Fifty-four percent of patients presented with symptoms that were clearly attributable to either the hip or the spine and were deemed to have simple HSS. While concurrent disease was present, the primary symptom generator was evident. In the remaining patients, nonspecific symptoms obscured the clinical picture and precluded ready diagnosis. These patients were divided into two groups: complex HSS and secondary HSS. In complex HSS, coexisting pathologies manifested in a constellation of complaints that could be attributable to either pathology or to a synergistic effect. In this scenario, Offierski and MacNab highlighted the utility of ancillary tests, including intraarticular blocks and epidural steroid injections, in discerning the primary symptom generator. In secondary HSS, coexisting processes were interrelated, with one exacerbating the other. In this clinical situation, addressing the primary pathology often led to improvement of secondary symptoms and avoidance unnecessary procedures. Ultimately, Offierski and MacNab's insight into the pathogenesis of HSS promoted the development of a treatment algorithm that in turn shaped the path for improved understanding and care of HSS patients in the decades that followed.

Present-day Approach

Advances in understanding spinopelvic biomechanics, in utilizing novel, low radiation imaging modalities, and in designing prostheses with enhanced stability and longevity have changed the management and improved the outcomes for HSS patients. However, as clinicians and surgeons, the importance of the history and physical exam, as detailed by Offierski and MacNab, cannot be overlooked. In meeting and examining the patient, our aim is to more completely appreciate the relative contribution of hip and spine pathology within the overall presentation. Accordingly, we may optimize care by targeting the primary symptom generator. While conclusive histories and examinations often elude practitioners, certain symptoms and tests have greater correlations with specific pathologies and are explored further in the ensuing chapter. Importantly, as diagnostic ambiguity within the spectrum of HSS persists, clear communication employing transparent terminology and practical classification schemes is invaluable. In this way, we promote continuity of care within care teams and facilitate coordinated interdisciplinary efforts across care teams.

Review of Terms

An important first step in beginning to understand HSS is clarifying clinical terminology as it pertains to the spine and pelvis. Following the American Academy of Orthopedic Surgeons (AAOS) 2018 annual meeting, a hip-spine working group was formed and was tasked with creating a common vocabulary intended for use across specialties[4]. A review of their terminology follows, accompanied by radiographs depicting the included parameters (Figure 1):

Anterior Pelvic Plane (APP): The plane between the anterior superior iliac spines and the pubis on a lateral pelvic X-ray.

Functional Pelvic Plane (FPP): The plane passing through the pubic tubercle and remaining parallel to the coronal plane of the body when standing or supine[5].

Anterior Pelvic Plane Tilt (APPt): The angle formed between the APP and a vertical reference line, analogous to pelvic tilt. APPt is often referred to as neutral, anterior, or posterior relative to the coronal plane.

Pelvic Tilt (PT): The angle formed by a line originating from the center of the femoral heads and intersecting the midpoint of the superior S1 endplate and a vertical reference line.

Sacral Slope (SS): The angle formed by a line parallel to the superior S1 endplate and a horizontal reference line.

Pelvic Incidence (PI): The angle formed by a line extended from the center of the femoral heads to the midpoint of the superior S1 endplate and a second line perpendicular to the superior S1 endplate. PI is an intrinsic pelvic parameter and does not change with position. It is the sum of PT and SS, two variables that change reciprocally with position.

Lumbar Lordosis (LL): The angle formed between lines subtended from the superior endplate of L1 and the superior S1 endplate. The relationship between PI and LL is used to characterize sagittal deformity; PI-LL mismatch >10° is referred to as flatback deformity and can be congenital, degenerative, or iatrogenic in origin.

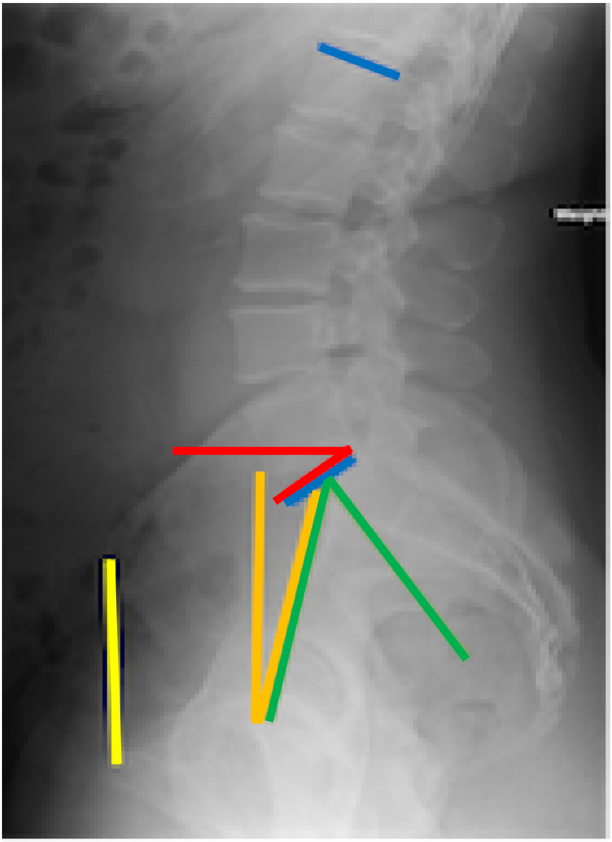

Figure 1. Pertinent pelvic parameters. Anterior pelvic plane (APP, yellow), pelvic tilt (PT, orange), sacral slope (SS, red), pelvic incidence (PI, green), lumbar lordosis (LL, blue).

Spinopelvic Kinematics

The biomechanics of the spine and pelvis are integrally related. Understanding physiologic motion provides insight as to how dysfunction and disability can arise.

Normally, there is slight anterior APPt with corresponding LL to achieve sagittal balance. Upon transitioning from standing to sitting, the pelvis tilts posteriorly, increasing the APPt, PT, and functional acetabular anteversion to allow for hip flexion without anterior impingement (Figure 2). In accordance with the formula, PI = PT + SS, as PT increases, SS decreases by the same amount. This decrease in SS results in lumbar spine flexion, decreasing LL to maintain sagittal balance and an upright posture.

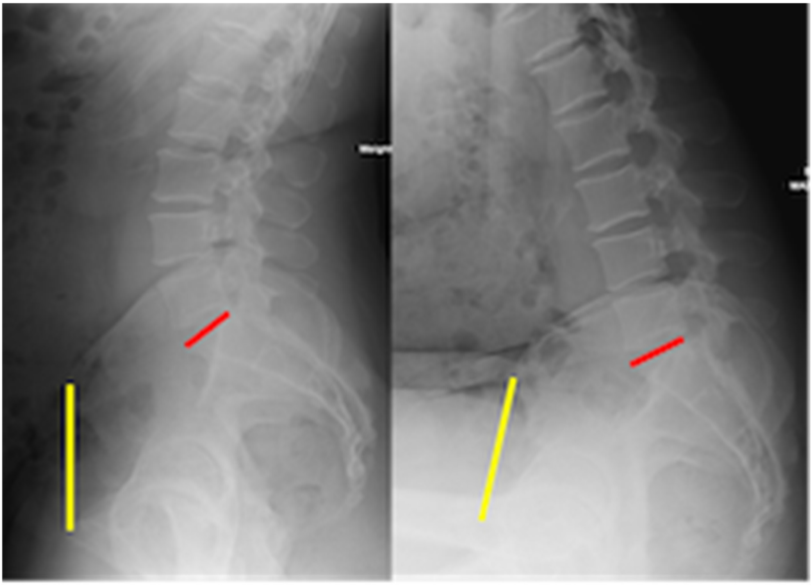

Figure 2. Standing and seated radiographs of the lumbar spine and pelvis depicting pelvic rollback during sitting as compared to standing, with increased APPt and PT and decreased SS upon sitting.

Abnormal spinopelvic motion is often the result of sagittal malalignment, spinal stiffness, or both. Sagittal imbalance occurs with aging with a tendency for the spine to become more kyphotic. In an effort to restore sagittal balance, there is compensatory posterior pelvic tilt. Maximum attainable posterior pelvic tilt depends on an individual's PI and their hip extension reserve[6]. With increased posterior pelvic tilt, the acetabula are functionally anteverted, increasing the risk of posterior impingement and anterior dislocation.

Spinal stiffness also contributes to abnormal spinopelvic kinematics and, similar to sagittal malalignment, is associated with degenerative changes. Spinal stiffness can by assessed through the change in sacral slope between standing and sitting, with a change <10° denoting spinal stiffness[4]. Patients with stiff spines are unable to substantially modify pelvic tilt to increase functional acetabular anteversion. Accordingly, when the hip flexes upon sitting, these patients are at risk of anterior impingement and posterior dislocation.

Classification Schemes

While our understanding of HSS has evolved, the original classification system proposed by Offierski and McNab remains relevant and informative. More recent classification schemes have incorporated radiographic parameters delineating HSS subtypes. Diebo et al. utilized PI-LL mismatch and Kellgren-Lawrence grades of the hip joint to define non HSS patients (PI-LL ≤ 10°/Grade 0), hip type HSS patients (PI-LL ≤ 10°/Grade 3-4), spine type HSS patients (PI-LL > 10°/Grade 0), and hip spine type HSS patients (PI-LL > 10°/Grade 3-4)[7].

Some authors have described classification schemes aimed at aiding in component placement during THA[8-10]. Luthringer and Vigdorchik's HSS classification system incorporated determinations of spinal deformity and spinal stiffness using standing and seated radiographs[4]. Patients were divided into four groups depending on the presence or absence of spinal deformity and spinal stiffness with accompanying treatment recommendations (see below and Chapter 8 for full discussion). Utilizing this algorithm, the authors decreased their primary THA dislocation rate from 3.1% to 0.5%[11].

Within this system, Group 1A patients have normal sagittal alignment and normal spinopelvic mobility; accordingly, traditional cup positioning in 20° to 25° of anteversion is appropriate. Group 1B patients also have normal sagittal alignment but have limited pelvic rollback when transitioning to from standing to sitting. To avoid impingement of the proximal femur on the anterior acetabulum, increased cup anteversion is recommended.

Group 2 patients have flatback deformity and often stand with natural posterior pelvic tilt, increasing functional acetabular anteversion. These patients are at risk of anterior dislocation with overly anteverted cups. Group 2B individuals have flatback deformity and stiff spines; these patients have the highest risk for instability due to a narrow safe zone of cup position and should be considered for high stability prostheses[4].

Pelvic and Hip Pain		**Low Back and Knee Pain**	
Intra-articular Pathology	Extra-articular Pathology	Spinal Pathology	Extra-spinal Pathology
Arthritis Osteoarthritis Inflammatory Labral tears Articular cartilage injuries Osteonecrosis Loose bodies Synovial Diseases Pigmented Villonodular Synovitis Synovial Chondromatosis Gout Pseudogout Fractures Traumatic Pathologic Stress Infection Septic arthritis Osteomyelitis Psoas abscess Neoplasm Primary Metastatic Adhesive capsulitis Transient Osteoporosis of the Hip	Bursitis Trochanteric Ischial Psoas Tendinitis Hip flexor Adductor/abductor Snapping hip Internal External Muscle tears Gluteus medius Gluteus minimus Adductor Hamstring Syndromes Piriformis Deep gluteal Osteitis pubis Sacroiliac joint pain Genitourinary issues Endometriosis Ovarian Cyst Degenerative lumbar spine stenosis	Degenerative spinal stenosis Vertebral body fractures Insufficiency Traumatic Isthmic spondylolisthesis Herniated nucleus pulposis Inflammatory arthritis Rheumatoid arthritis Spondyloarthropathies	Hip osteoarthritis Peripheral vascular disease Knee osteoarthritis Neoplasm Primary Metastatic Fibromyalgia Meralgia paresthetica Shingles

Table 1. The differential diagnosis for pelvic and hip pain as well as low back and knee pain is broad. The nonexhaustive lists above demonstrate how hip pain can be due to both intraarticular and extraarticular pathology; similarly, various extra-spinal pathologies can produce low back pain.

Differential Diagnosis

Maintaining a differential diagnosis in the workup of HSS is important. Various pathologies can produce pelvic and hip pain as well as low back and knee pain. A directed approach can elucidate distinct clinical entities within the complex patient (Table 1).

Summary

As a condition first reported in the literature in the early 1980's, HSS remains a complex condition necessitating thoughtful workup and management. Its original description and treatment approach remain valid. The diagnostic and therapeutic difficulties in some ways represent an incomplete understanding of spinopelvic dynamics. This also represents the challenges of a diagnosis that crosses specialties which, until recently, lacked a clear, shared vocabulary. However, efforts in the domain have drastically improved interdisciplinary care. Thus, while keeping close the pillars of care that have held true over time, the future of HSS care lies in: 1. Increased understanding of both spinopelvic physiology and pathology to inform technical and technological advancements and 2. Disseminating this knowledge across hip and spine providers to promote effective, efficient, and economical interdisciplinary care.

Take-home pearls

- Concomitant hip and spine disease is common and coexisting pathology can create a confounding clinical picture
- Awareness of HSS is the first step in avoiding misdiagnosis and mistreatment; understanding how a targeted history, physical exam, and use of ancillary tests can be leveraged in the diagnostic workup is important for providers caring for HSS patients
- Increasingly, our understanding of the complexities of spinopelvic dynamics is informing clinical care; in this effort, communication across specialties using a common, clear vocabulary is paramount
- Treatment considerations in HSS are evolving with exciting developments in imaging technology, surgical techniques, and implant innovations
- As value-based and evidence-based care is presented in this book, physicians can sort through the complexities of HSS to assure proper diagnosis and treatment while optimizing patient outcomes

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CHAPTER 2

BIOMECHANICS

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Introduction

The spine-pelvis-hip complex is a complex biomechanical system representing the confluence of three separate joints. The spine is composed of cervical, thoracic, and lumbosacral regions with alternating convex and concave sagittal curvatures and cartilaginous discs between vertebrae. This composition serves to anchor and stabilize the head, neck, and trunk, and absorb shock and attenuate dynamic compressive forces via the intervertebral discs. The pelvis forms at the base of the spine (*i.e.*, the sacrum), through which loads are distributed from the upper body bilaterally to the left and right hip joints. The hip joint is a ball-and-socket articulation composed of the acetabulum of the pelvis and the femoral head on the most proximal end of the femur bone. In a healthy adult, the normal spine-pelvis-hip complex combined with surrounding musculature synergistically attenuates and distributes the physiological loads to maintain the normal function of the body.

When a patient suffers from spine or hip diseases, native alignment, anatomy, and soft tissue function may be altered[1,2]. This creates an imbalance in posture and movement of the body as these components of the musculoskeletal system are dependent on each other and integrated into a complicated physiological, functional system. Pelvic disorders may result in an alteration in the alignment of spinal columns and spinal deformity (*e.g.*, scoliosis) may induce an imbalance in the force distribution between the hip joints. Therefore, an in-depth understanding of the interactions of these anatomic components of the spine-pelvis-hip system can help improve treatments of diseases related to these components, restore the function of the entire system, and reduce postoperative complications in patients and enhance patient satisfaction.

However, it is technically challenging to investigate the biomechanical function of the spine-pelvis-hip complex in biomechanical engineering. In the early years, most biomechanical analyses of the human musculoskeletal system focused on individual components of the spine-pelvis-hip. For example, native and instrumented lumbar spine computational models have been developed in computational studies, and their simulation results significantly improved our understanding of spine biomechanics[3]. *In vitro* and *in vivo* experiments have also been performed to investigate the kinematic responses of native and instrumented spinal segments and multi-segment spines in various loading conditions[4,5]. Recent studies have attempted to investigate the coupled biomechanical functions of the spine-pelvis-hip complex undergoing surgical treatments using finite element analysis[6] as well as global musculoskeletal models[7,8].

In this chapter, we will discuss current concepts in biomechanical analysis of the spine-pelvis-hip complex with a focus on alignment and balance analysis and the biomechanical understanding of the compensatory mechanisms in the spine-pelvis-hip complex. This chapter is organized into the following sections. We will first overview the anatomy and function of the spine-pelvis-hip complex, including major joints, soft tissue constraints, and physiological range of motion. Next, we will introduce spine-pelvis-hip biomechanics in the coronal plane, including the measurements of coronal alignment and balance, and the potential pathomechanics of neuromuscular scoliosis caused by local muscle imbalance. Next, we will introduce spine-pelvis-hip biomechanics in the sagittal plane, including the radiographic evaluation of global sagittal balance, muscle recruitment in pelvic motion, as well as biomechanical compensatory mechanisms and clinical findings of adverse compensations. Lastly, we will make a summary of the current studies of spine-pelvis-hip biomechanics, and discuss future visions and feasible technologies in the investigation of 3D spinal deformity and physiological loading conditions.

Anatomy and function of the spine-pelvis-hip complex

Spine and functional spine unit

The human spinal column consists of a series of vertebrae (segmented bone), which are connected by intervertebral discs while articulating through two facet joints[9]. Adjacent vertebrae constitute a functional spine unit (FSU) or a motion segment that allows spinal motion (Figure 1A).

The intervertebral disc is a sophisticated soft tissue structure (Figure 1B) that consists of a gel-like center, the nucleus pulposus (NP), and an outer fibrous ring, the annulus fibrosus (AF). The AF is reinforced by collagen fiber lamellae, with a crossing pattern of collagen fiber bundles with fiber orientations alternating in adjacent lamellae[10] (Figure 1C). The NP mainly contains glycosaminoglycan capable of trapping ions to generate an osmotic pressure causing nucleus swelling[11,12]; therefore, high water content is commonly observed in the NP of the healthy disc[13]. As a result of the disc structure, incompressible disc tissue is pressurized in dynamic compression, while AF lamellae resist disc bulging to avoid disc collapse[14]. In spinal rotational motion, the disc is significantly stiffened beyond an initial laxity, as crimped collagen fibers are stretched and reoriented toward the loading axis[10,15]. Such behavior determines the physiological segmental range of motion (ROM)[16].

As shown in Figure 1A, the FSU has seven major ligaments which provide stability, including anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligamentum flavum (LF), intertransverse ligament (ITL), capsular ligament (CL), interspinous ligament (ISL) and supraspinous ligament (SSL). Like the annular lamellae, the behavior of spinal ligaments can be described as a tension-only, nonlinear stress-stretch or force-deflection curve, with an effect of tissue stiffening. In addition, there are two facet joints, each of which is a synovial plane joint between the articular processes covered by cartilage and encapsulated by capsular ligaments between adjacent vertebrae (Figure 1A). According to *in vitro* experiments[16,17], the dissection of the facet joints caused distinct changes in kinematic responses in both flexion and extension, indicating their capability of resisting both tension and compression[18].

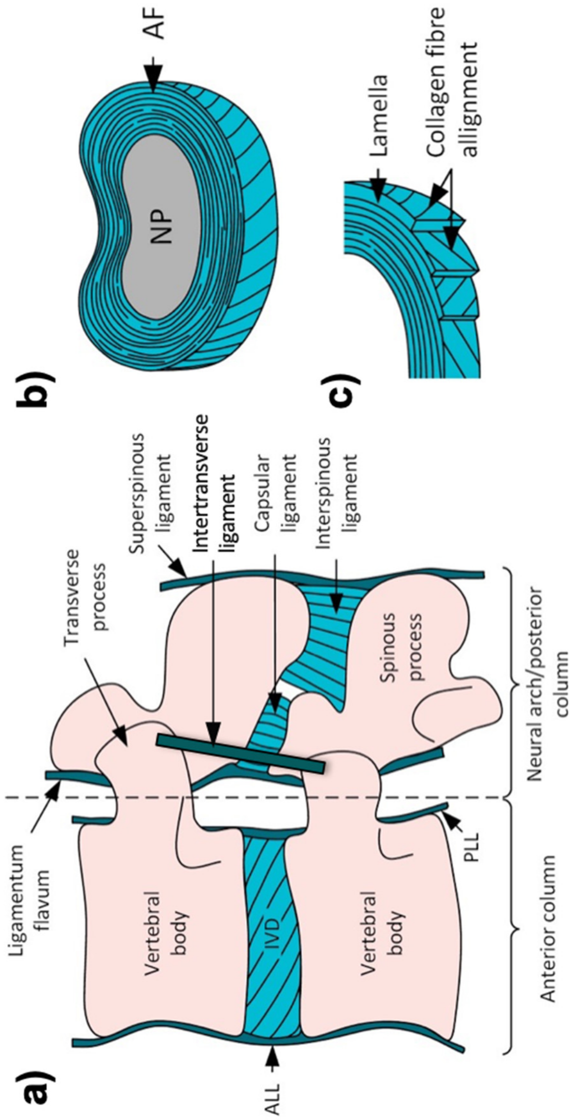

Figure 1. Illustration of a functional spine unit (A) separated by an intervertebral disc (B) which is embedded with crossing-patterned collagen fiber lamellae (C). Adopted from Newell et al. [9] under the terms of the Creative Commons CC-BY 4.0 license (https://creativecommons.org/licenses/by/4.0/).

Using noninvasive electronic devices, *in vivo* measurement data of asymptomatic subjects showed that the normal lumbar FSU can provide ranges of motion of about 9° in flexion-extension, 6° in lateral bending, and 5° in axial rotation[22]. By stepwise dissection of functional spine structures (ligaments and facet joints), the loading contributions of individual spinal structures during FSU motion, represented by force-displacement curves, have been quantified using cadaveric specimens *in vitro*[16]. Based on these measurements of individual spinal components, model validation or calibration was performed, and the resulting computational models have been used to simulate the kinematic behavior of multi-segment spines[18,19,21]. Well-established computational studies reported that under pure moments, the entire lumbar spine (L1-L5) can move 34° in flexion-extension, 45° in lateral bending, and 17° in axial rotation[3].

Sacroiliac Joint

The sacroiliac joint (SIJ), the largest axial joint in the body, connects the spine to the pelvis, which allows load transfer between the lumbar spine and the lower extremities[23,24]. The SIJ is covered by L-shaped hyaline cartilage and is constrained by interosseous ligaments. Besides, additional ligaments further resist the movement of the SIJ[25]. For example, the long posterior sacroiliac ligament limits sacral counternutation (sacral posterior tilt), the short posterior sacroiliac ligament limits all pelvic and sacral movement, the sacrotuberous ligament constraining sacral nutation (sacral anterior tilt) provides vertical stability, and the iliolumbar ligament stabilizes L5 on the ilium. In addition, the transversus abdominis and the pelvic floor muscles (levatorani and coccygeus muscles) also play a major role in stabilizing the SIJ[26]. As a result, the range of motion of the SIJ in flexion-extension is about 3°, 1.5° in axial rotation, and 0.8° lateral bending[24].

Hip Joint

The hip joint is a ball-in-socket synovial joint, through which the head of the femur articulates with the pelvic acetabulum, as illustrated in[27]. The left and right hip joints transmit the forces between the upper body and the lower limbs during daily activities (*e.g.*, stance and gait). The hip joint capsule is covered by three major ligaments, including the iliofemoral, pubofemoral, and ischiofemoral ligaments, in a spiral fashion[27]. These ligaments constrain the hip joint to prevent excessive motions, especially limiting hip extension[28]. The range of motion of the hip joint is defined as the absolute limits of motion of the hip joint before the occurrence of bony impingement;

typically, the hip joint allows about 120° in flexion, 10° in extension, 45° in abduction, 25° in adduction, 15° in internal rotation, and 35° in external rotation[28].

Spine-pelvis-hip biomechanics in the coronal plane

In the coronal (frontal) plane, the normal spine is vertical and in line with a median axis that passes through the middle of the sacrum and the pubic symphysis. Scoliosis is often defined as an abnormal curvature of the spine in the coronal plane, although it is a complex 3D spinal deformity[2]. The normal pelvis is horizontal, with the corresponding left and right landmarks at the same heights[29]. The coronal balance parameters of the spine are usually used to evaluate spine scoliosis and are important factors for planning surgical treatments to assist surgeons in the decision-making of which segments are treated by osteotomy or spinal fusion[30]. In general, surgical treatment aims to provide optimal balance by correcting the spinal curve through operations of as few spinal segments as possible.

Evaluation of alignment and balance

The coronal balance of the spine can be quantified by the C7 shift or trunk shift[31,32]. As shown in Figure 2A, the C7 plumb line (C7PL) is defined as a vertical line dropping from the center of the C7 vertebra in the direction of gravity (parallel to the vertical edge of a clinical radiograph). For a spine with coronal balance, the C7PL passes through the midpoint of the sacral plateau in the coronal plane[32]. Another line called the center sacral vertical line (CSVL) can be drawn upward from the middle of S1 vertebra (Figure 2A). In a healthy and balanced spine, these two lines coincide. When scoliosis occurs, the induced offset between the C7PL and CSVL is defined as the C7 shift, representing the imbalance in the coronal plane. A shift to the right of the CSVL is marked by convention as a positive value, while a left shift is denoted by a negative value. An imbalance is commonly considered when the absolute offset is more than 2.0 cm[32].

Another parameter to determine the extent of coronal imbalance is the thoracic trunk shift, as shown in Figure 2A[31,32]. First, the thoracic apical vertebra is identified, and its center is marked. A horizontal line is drawn through the center, and the edges of the apical ribs are marked. Then, a vertical line is drawn downward through the midpoint between the two edge

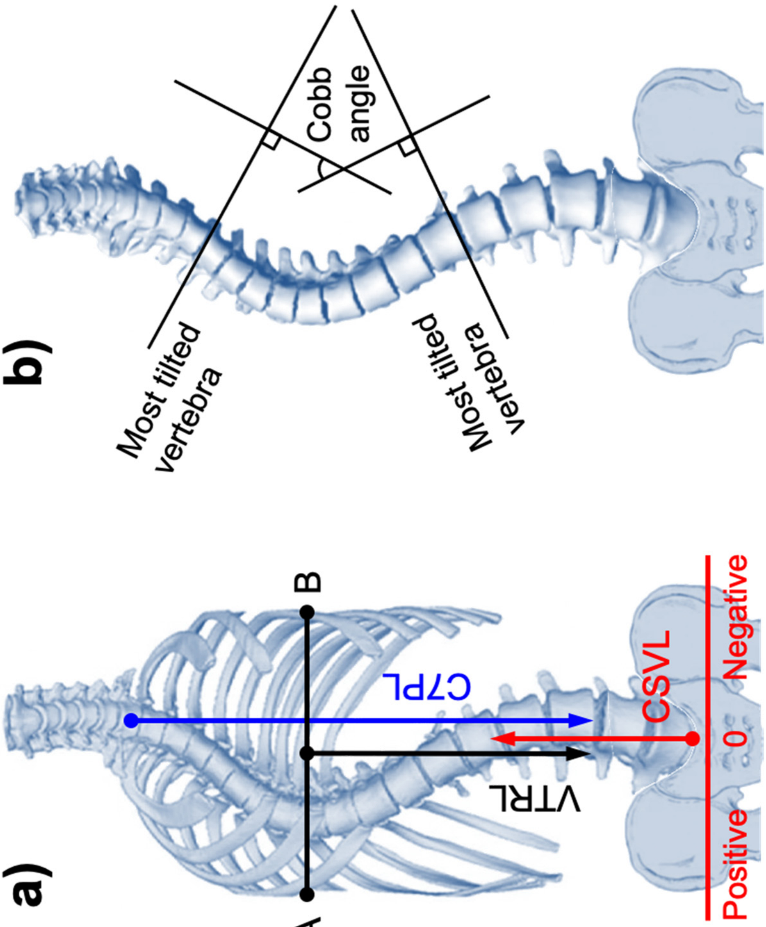

Figure 2. (A) Measurement of the C7 shift (the offset between C7PL and CSVL) and the trunk shift (the offset between VTRL and CSVL) to evaluate coronal balance. (CSVL: center sacral vertical line; C7PL: C7 plumb line; VTRL: vertical trunk reference line). (B) Measurement of the Cobb angle, which is defined as the angle between the upper endplate of the proximal most tilted vertebra and the lower endplate of the distal most tilted vertebra.

points; this line is referred to as the vertical trunk reference line (VTRL). Finally, the trunk shift is measured by the distance between the VTRL and the CSVL. Consistent with the sign convention of the C7 shift, shifts to the right and left of the CSVL are denoted by positive and negative values, respectively.

It should be noted that the trunk shift is more accurate than the C7 shift in the assessment of coronal alignment[33], as demonstrated by Figure 2A. In addition, the lumbar spine frequently undergoes a major loss of balance, which can be measured by the lumbar apical vertebral translation (LAVT), *i.e.*, the distance from the center of the lumbar apical vertebra to the center sacral vertical line[34].

Evaluation of spinal deformity

The Cobb angle is the most important parameter to measure the severity of scoliosis using an anteroposterior radiograph[35], as shown in Figure 2B. The Cobb angle is defined as the angle between the two lines, tangent to the upper and lower endplates of the upper and lower end (most-tilted) vertebra, respectively. A sideways curvature of the spine with a Cobb angle in the range of 10 to 20 degrees is considered as mild scoliosis, 20 to 40 degrees as moderate scoliosis, and greater than 40 degrees as severe scoliosis[36]. In addition to the Cobb angle magnitude, the curves should be noted as right or left, and typically scoliosis is always named for the side of convexity[37]. For the measurement of the Cobb angle, it was required that the standard error is 3 to 5 degrees for the same observer, and 5 to 7 degrees for different observers when the same end vertebrae are used for measurements[38].

There are two general categories of scoliosis, *i.e.*, structural and non-structural scoliosis, depending on whether the deformity in the spine is permanently irreversible[39]. Structural scoliosis, featuring spinal axial rotation in addition to the side-to-side curvature of the spine, is a permanent deformity unless the spine is surgically corrected. Nonstructural scoliosis, also termed functional scoliosis, occurs due to a temporary cause, while the spine's structure is still normal. Commonly, it only involves a side-to-side curvature of the spine, without spinal axial rotation. A nonstructural curve can balance out the structural deformity in the entire spine, but the magnitude of the deformations may increase with time and ultimately the curve progresses to be structural. Lenke et al. introduced a new and reproducible classification system to characterize scoliotic curves[30]. According to their study, a scoliotic curve is considered to be nonstructural, when its Cobb angle can be corrected to less than 25°. Lenke's classification