Development of Pelvic Incidence, Sacral Slope, and Pelvic Tilt and the Effect of Age, Sex, and Obesity: A 3D-CT Study of 10,969 Children and Adolescents

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INTRODUCTION: Spinal deformity in the sagittal plane, which is correlated to sagittal imbalance, is one of the main causes of disability. Therefore, many studies have been conducted to explore the effects of sacropelvic parameters on spinal conditions. However, some of the results are contradictory for different cohorts. “Non-significant” and “significant” differences in sacral slope (SS), pelvic tilt (PT), or pelvic incidence (PI) have been reported between males and females. Furthermore, higher BMI, lower PI and SS were found to be correlated with a higher risk of lumbar disc degeneration (LDD). Here we aimed to conduct an in-depth analysis of how the development of spinopelvic sagittal parameters would be affected by sex and obesity in a large cohort of asymptomatic hips.

METHODS: Following IRB approval, a validated natural language processing pipeline was used to process the clinical notes and radiology reports of all the patients (2-19 years of age) undergoing pelvic CT scans from 2012-2022 in our institute (accuracy of 0.98). We identified a total of 10,969 CT scans that had no documented bone or joint conditions and adequate CT quality for 3D segmentation (Age: 11.4 ± 4.8 years; 48% females; 12.5% obese). A validated custom software (VirtualHip, Boston Children’s Hospital) was used to automatically segment the femur, pelvis, and sacrum, and to measure PI, SS, and PT. We modeled the association between age and each of the spinopelvic measurements using linear models. All models were adjusted for sex and BMI percentile. We further included interactions between age and sex to assess whether the associations between age and spinopelvic measurements differed by sex. We also investigated the effect of obesity (BMI>95th percentile) compared to normal weight (5th < BMI <85th percentile) before and after adjusting the analysis by age and sex.

RESULTS: PI and PT decreased by age (up to 8 years of age), plateaued between ages 8 and 12, and followed by a slight increase in the mid-to-late teens ($p<0.001$). Males showed higher PI and PT than females up to 8 years of age ($P<0.05$). The sex difference in PT diminished over time after 8 years of age, whereas males showed lower PI values between ages 9 and 12, and higher after the age of 12 ($P<0.05$). SS showed no clear age trend from early childhood to late adolescence and remained relatively stable with slight fluctuations. Females had both higher (between 8 and 11 years of age) and lower (13 to 15 years of age) mean SS than males ($p<0.05$). Multivariable analysis revealed significant age-related decreases in PI and PT after adjusting for sex and BMI ($P<0.001$). Females had lower PI compared to males after adjusting for age and BMI ($P=0.006$). SS also demonstrated a small but significant decrease with age ($p<0.001$) which plateaued at older ages. Sex was not a significant predictor of SS after adjusting for age and BMI ($p=0.5$). Obese children (ages 3, 4, 10, and 15 years) had smaller PT compared to those with normal BMI (differences 2.1°-4.8°, $p < 0.05$). There were no other differences in PT, PI or SS between obese and those with normal BMI. In the multivariable analysis, after adjusting for age and sex, obesity was not a significant predictor of PI ($p=0.07$) or SS ($P=0.4$). However, PT was lower in obese vs normal BMI subjects ($p < 0.001$).

DISCUSSION: We used automatic 3D analysis to measure PI, PT, and SS in a large cohort of healthy children and adolescents. The current large-scale study confirms age-related changes in PI and PT which are affected by sex and BMI, however, the influence of age was stronger than sex and BMI. In contrast to PI and PT, sex was not a significant predictor of SS after adjusting for age and BMI. The significant interaction between age and BMI group was found for PT, indicating associations between age and PT differed between obese and healthy weight patients, after controlling for sex. Lower PT in patients with higher BMI is related to a higher risk of spinal injuries such as lower back pain and lumbar disc degeneration. Our findings may help the orthopedic surgeon design the appropriate correction of the sagittal spinopelvic balance when planning for the surgery of children and adolescents with spine deformities.

CLINICAL RELEVANCE: Since patient-specific instrumentation and planning become the norm in spine and hip surgery, in-depth understanding of sacropelvic parameters development will provide better insight in evaluation and controlling of spinal deformities. Our study provides such data on the spinopelvic sagittal alignment during growth which may help the pediatric orthopedic surgeon design the appropriate correction of the sagittal spinopelvic balance when planning for the surgery of children and adolescents with spine deformities.

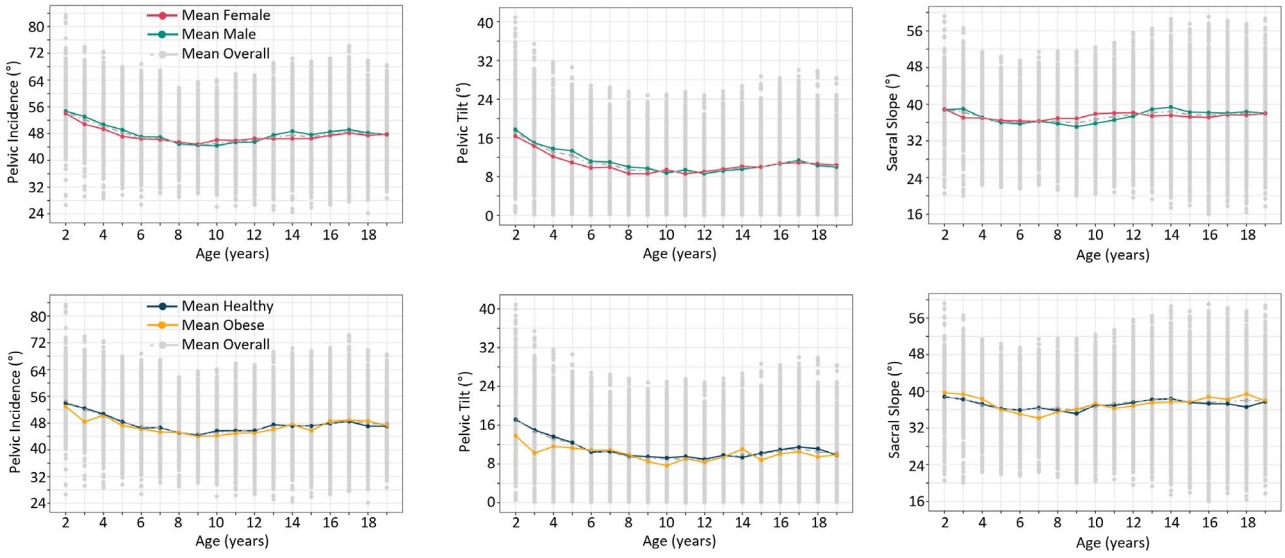

Figure 1. Sex (top row) and obesity (bottom row) related differences in PI, PT, and SS during skeletal growth and maturation.