The treatment of spinal disorders over the past few decades has been increasingly focused on spinal alignment, especially in the sagittal plane. Spinal curvature has evolved to bear axial loads and decrease strain on the axial musculature, allowing us to sit, stand, and walk comfortably for prolonged periods of time. When this alignment is disturbed, the resulting deformity can lead to increased pain, disability, and reduced quality of life.12,17,18,22

A variety of parameters have been proposed to help evaluate patients with spinal deformities as well as serve as important targets when performing spinal deformity surgery. Sagittal alignment parameters such as pelvic incidence, lumbar lordosis, and thoracic kyphosis have been
well studied in the literature. More recently, cervical parameters have been included in the discussion as well to encompass the entire spine and define true global alignment.

When analyzing any of these parameters, the discussion of the “optimal” value quickly becomes the focus. Lumbar lordosis, for instance, has garnered more attention over the recent years as a radiographic parameter that correlates with improved postoperative outcome. But what exactly is optimal?

There have been several studies of sagittal balance in the standing position, using volunteer subjects. However, these studies frequently involve volunteers of only one age group or do not perform between-age-group comparisons. Accordingly, there is no widely accepted normal range of quantitative values for these parameters across all age groups. An increasing body of literature suggests that there most likely is not a singular “ideal” spinal alignment but rather a range within which an individual of a certain age is likely to remain asymptomatic.

Thus, the aim of the present study is to develop a quantitative atlas of the natural history of radiographic spinal parameters as the spine ages. We determined these parameters from asymptomatic patients representing all age groups from 20 to 90 years in order to better elucidate a range of normal values to aid in the diagnosis and treatment of patients with spinal disorders and deformities.

Methods

Patients evaluated between 2013 and 2017 and who had no personal history of a spinal disorder, spinal surgery, or radiographic abnormality were identified retrospectively and included in this study. After institutional review board approval, 210 consecutive patients who were asymptomatic and included in this study. Radiographs were digitized and sagittal spinopelvic parameters were assessed using Surgimap, a computer program (Nemaris Inc.) that enables quantitative measurements of the spine and pelvis. A total of patients with spinal disorders and deformities.

From each lateral radiograph, the following spinopelvic parameters were measured: Cervical lordosis (CL), the angle between the major axis of C1 and the inferior side of the body of C7; thoracic kyphosis (TK), the angle between the line from the superior endplate of T4 and the inferior endplate of T12; lumbar lordosis (LL), the angle between the superior endplate of L1 and the superior endplate of S1; pelvic incidence (PI), the angle between the line perpendicular to the sacral plate and the line connecting the midpoint of the sacral plate to the bicoxofemoral axis; pelvic tilt (PT), the angle between the lines connecting the midpoint of the sacral plate to the bicoxofemoral axis and the vertical plane; sagittal vertical axis (SVA), the distance between the C7 plumb line and the posterosuperior corner of S1 in the sagittal plane; and the truncal inclination or T1-spino-

pelvic inclination (T1-Spi), the angle between the vertical plumb line and the line drawn from the vertebral body center of T1 and the center of the bicoxofemoral axis. Figure 1 shows an example of these measurements. From these measurements, the following relationships were calculated: T1 slope/CL, TK/LL, PI−LL, “ideal” LL (PI + 10°), and absolute LL−PT.

The data were analyzed with the use of Python software (Python Software Foundation). We first subdivided the cohort by age in decades, from the 3rd decade of life through the 9th decade, creating 7 cohorts. We then conducted a descriptive analysis, obtaining the median and interquartile ranges of each parameter. We then conducted a univariate ordinary least-squares regression analysis of the median value of the parameter against the median age of each age group to describe the degree of correlation between each parameter and age.

Results

The main characteristics of the population and the values of the parameters measured and calculated are listed in Table 1. Figure 2 provides box plots of sagittal parameters and subsequent calculations for each decade of life from 20 to 90 years of age. In general, we found that nearly all parameters showed a significant correlation with increasing age. In our regression model, cervical SVA (cSVA) and T1-Spi did not have a significant correlation with age. However, CL (R^2 = 0.61) and TK (R^2 = 0.84) were found to have a significant positive trend with age. SVA (R^2 = 0.88) also showed a significant increase with age, with the increase becoming notably more pronounced in the 6th decade of life (> 5 cm). T1 slope (R^2 = 0.77) also showed a positive trend, with a significant increase occurring after the 6th decade of life. PT (R^2 = 0.92) had a very strong positive trend, with large increases in the 5th and 7th decades of life.

The ratio between T1 slope and cervical lordosis remained stable across all age groups. TK and LL remained relatively stable until a marked increase in the 7th decade of life—from 0.55 to 0.84. The calculated difference between ideal LL and observed LL became significantly greater over time. The ratio between LL and PI also became more positive over time. The difference between LL and PI was positive in the 2nd decade of life but then followed a downward trend (R^2 = 0.96), until the 5th decade of life, where the 2 values appeared to equal each other. Subsequently, PI became larger than LL.

PT had a strong positive correlation with age (R^2 = 0.92), with a large increase after the 4th decade of life. When considering the absolute value of the combination of PT+LL there was a downward trend (R^2 = 0.76).

Discussion

The current study serves to provide a natural history of radiographic spinal alignment parameters in normal, asymptomatic patients across all age groups from 20 to 90. This study also serves to elucidate how changes in some spinopelvic parameters may interact with others in either synergistic or compensatory capacities. For example, TK appears to increase with age. CL also appears to increase

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FIG. 1. Measurements of sagittal parameters on a representative sagittal radiograph. TPA = T1 pelvic angle; T1S = T1 slope. Figure is available in color online only.

TABLE 1. Sagittal parameter measurements: median values by age for all measured and calculated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>20–30</th>
<th>30–40</th>
<th>40–50</th>
<th>50–60</th>
<th>60–70</th>
<th>70–80</th>
<th>80–90</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 13)</td>
<td>(n = 26)</td>
<td>(n = 44)</td>
<td>(n = 28)</td>
<td>(n = 53)</td>
<td>(n = 30)</td>
<td>(n = 16)</td>
</tr>
<tr>
<td>CL (°)</td>
<td>5.0</td>
<td>5.5</td>
<td>15.0</td>
<td>18.5</td>
<td>9.0</td>
<td>19.0</td>
<td>20.0</td>
</tr>
<tr>
<td>C2–7 SVA (mm)</td>
<td>21.9</td>
<td>23.2</td>
<td>17.7</td>
<td>18.9</td>
<td>29.1</td>
<td>36.5</td>
<td>30.4</td>
</tr>
<tr>
<td>C7–S1 SVA (mm)</td>
<td>1.7</td>
<td>4.20</td>
<td>9.30</td>
<td>3.8</td>
<td>28.1</td>
<td>36.4</td>
<td>52.5</td>
</tr>
<tr>
<td>T1 slope (°)</td>
<td>23.0</td>
<td>23.0</td>
<td>22.5</td>
<td>25.0</td>
<td>26.0</td>
<td>36.0</td>
<td>36.0</td>
</tr>
<tr>
<td>TK (°)</td>
<td>24.0</td>
<td>26.0</td>
<td>24.5</td>
<td>29.5</td>
<td>29.0</td>
<td>36.5</td>
<td>35.0</td>
</tr>
<tr>
<td>T1-SPi</td>
<td>−4.0</td>
<td>−5.0</td>
<td>−3.0</td>
<td>−4.5</td>
<td>−3.0</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>LL (°)</td>
<td>−57</td>
<td>−55</td>
<td>−57</td>
<td>−57</td>
<td>−51</td>
<td>−47</td>
<td>46.5</td>
</tr>
<tr>
<td>PT (°)</td>
<td>9.0</td>
<td>10.5</td>
<td>12.0</td>
<td>18.5</td>
<td>18.0</td>
<td>24.0</td>
<td>22.5</td>
</tr>
<tr>
<td>T1 slope/CL</td>
<td>−2.5</td>
<td>−1.1</td>
<td>−1.2</td>
<td>−1.0</td>
<td>−1.6</td>
<td>−1.6</td>
<td>−1.9</td>
</tr>
<tr>
<td>TK/LL</td>
<td>0.44</td>
<td>0.47</td>
<td>0.44</td>
<td>0.53</td>
<td>0.55</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>LL/PI</td>
<td>−1.2</td>
<td>−1.2</td>
<td>−1.1</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>PI–LL (°)</td>
<td>9.0</td>
<td>6.5</td>
<td>4.5</td>
<td>−0.5</td>
<td>−4.0</td>
<td>−5.5</td>
<td>−13.5</td>
</tr>
</tbody>
</table>

Negative measurements indicate lordosis while positive measurements indicate kyphosis. Boldface type indicates statistical significance.
in parallel as a compensatory mechanism to maintain the position of the cranium over the pelvis. However, it appears that this compensation is only partial, leading SVA to increase as a counterbalance. This is particularly noticeable in patients in their 70s, 80s, and 90s.

Sagittal parameters have been demonstrated in several studies to strongly affect patient-reported quality of life scores, and the studies have shown similar improvement in those same scores after surgical correction. At the same time, other studies have investigated various spinal parameters that influence sagittal balance. Combined, these studies have led to static assumptions about the ideal values for these parameters for adult patients of all age groups. Our study suggests that these “ideal” parameters are dynamic over the course of life.

The well-known but poorly understood CL, as measured between C2 and C7, was shown in our study to, predictably, increase over time. However, a minority of individuals did have a slightly kyphotic cervical curvature, in line with recent studies by Le Huec et al., underscoring that although cervical lordosis is widely prevalent, it should not be considered the biomechanical norm. Notably, cSVA did not show a significant increase with age. T1 slope also showed a strong positive trend with age. This has been shown to correlate with CL and SVA and likely determines the amount of subaxial cervical lordosis necessary to maintain the head in a balanced position. With this in mind, one would assume that the ratio of T1 slope to CL should remain constant with age, which is indeed what was found. In fact, the ratio had remarkably little variation both within and between age groups, suggesting that this ratio may be a superior alternative to either T1 slope or CL individually when planning surgical deformity correction in the cervical spine.

Thoracic kyphosis has been reported to have a wide range in asymptomatic subjects. We found that this ky-
Degenerative pathology of the spine. In particular, PI, unique to each individual, has a strong positive correlation with LL. Recently, the parameter PI−LL has been used to characterize mismatch between pelvic morphology and the lumbar curvature. From this, an "ideal" sagittal alignment goal for LL was identified by Schwab et al. as PI + 10°. However, our study shows that the difference between this calculated "ideal" LL and actual observed values tended to increase with age from a median difference of 1° during the 2nd decade of life to a median of 23.5° in the 8th decade, suggesting that older individuals, particularly those beyond the 8th decade, would need less LL than expected from what the PI + 10° rule of thumb would have indicated. This may at least partially explain the occurrence of proximal junctional kyphosis (PJK) in those older individuals after deformity correction surgery. Over-correction to the ideal LL likely adds more stress to the proximal junctional level and may contribute to the development of PJK. Although multiple studies have validated the relationship between PI and LL in the context of patient-reported quality of life measures, the universally adapted equation of LL = PI + 10° may be an oversimplification that may not hold true for older populations. Surgeons planning deformity correction must also consider the patient’s age and curvature of the thoracic spine.

PT has been understood to act in a compensatory manner and has been used as an indicator of sagittal imbalance when significantly increased. In one study, Lazennec et al. demonstrated postoperative increases in this parameter to be associated with more residual pain. Lafage et al. also found an association with the Oswestry Disability Index walking and SF-12 PCS (physical component summary) outcome measures, suggesting that an increase is a result of malalignment elsewhere and can prevent effective amelioration. Simply restoring this value to "normal" belies the fact that it increases with age, considerably so between the 4th and 5th decades and again between the 6th and 7th decades.

Finally, SVA, as a measure of global sagittal balance, has been shown to correlate with quality of life measures in symptomatic patients and has been established as a key parameter in the deformity classification proposed by Schwab et al. In our study, this parameter understandably increases with age. Interestingly, the median measurement’s transition from negative to positive occurs in the 4th decade and increases considerably in the 6th decade. Truncal inclination, as measured by T1-SPI, was found by Lafage et al. to have a more significant correlation with clinical outcomes than SVA in deformity patients. However, we found that T1-SPI did not have a significant correlation with age, thereby rendering this measure an attractive option as a parameter for planning surgical correction. Because T1-SPI is an angular measurement rather than a distance, it does not suffer as much from measurement error when compared to SVA. Furthermore, by definition, T1-SPI takes into account the position of T1 in relation to the pelvis through the hips, allowing one to differentiate between a person in a compensated state with low T1-SPI and compensatory high pelvic tilt and another person with a similar pelvic tilt and more positive T1-SPI. SVA does not take this offset into account. The compensatory nature of PT suggests that an increased PT compensates for a loss of LL. In our study, we note that there is a decreasing trend of absolute PT+LL. This suggests that loss of LL may occur faster than PT can compensate, especially around the 6th decade. However, this decrease may not be symptomatic, and care must be taken to assess other compensatory mechanisms along with PT.

This cross-sectional study demonstrates that the previously proposed ideal spinal balance of LL = PI + 10° and SVA < 5 cm are appropriate targets for patients 50 years of age and younger. In older individuals, however, those relationships may not be as straightforward. We demonstrate that asymptomatic individuals showed a significant increase in SVA with aging, particularly after the 6th decade of life, whereas LL decreased over time. Given those observed changes, it is more appropriate, in our opinion, to use more constant parameters, such as T1/CL, TK/LL, and T1-SPI, when planning surgical correction for older patients. Those parameters, by nature, take into account the harmonious relationship between cervical lordosis, thoracic kyphosis, and lumbar lordosis.

The main limitation of our study is the small sample size in each age group. Future studies with much larger sample sizes, likely in the form of prospective multicenter studies, will be needed in order to obtain more stable estimates of the above-mentioned constant parameters. This study did not include a reliability analysis between the 2 trained observers who performed the measurement of the spinopelvic parameters, but they were supervised by a trained clinician, as stated in Methods. In the elderly population, osteoporosis and osteopenia are prevalent, although we did not take those into account in this cross-sectional study. Likewise, sex was not accounted or controlled for in this study. Future studies would do well to include regression analyses that include sex and bone densities as covariates. Nonetheless, our study here is the first cross-sectional study to assess multiple spinal parameters and relationships in asymptomatic patients across the adult age range through age 90.

Conclusions

To our knowledge, this is the only study that compares radiographic sagittal alignment parameters in asymptomatic patients across the adult age range through 90 years. This may help inform future studies as to the use of more age-appropriate surgical correction targets.
bility over various age groups, the ratio of T1 slope/CL is an important relationship to maintain/target when performing cervical spine surgery, especially fusion across the cervicothoracic junction. Likewise, the harmonious relationship between TK and LL should be considered when correcting sagittal imbalance. Finally, in support of previous literature, this cross-sectional study demonstrates the proposed ideal spinal balance of LL = PI + 10° and SVA < 5 cm are appropriate targets for patients 50 years of age and younger.

References

Disclosures
Dr. Ames reports consultant relationships with DePuy Synthes, Medtronic, Stryker, Medirecra, K2M, and Biomet Zimmer; receipt of royalties from Stryker, Biomet Zimmer Spine, DePuy Synthes, NuVasive, Next Orthosurgical, K2M, and Medicrea; receipt of research support from Titan Spine, DePuy Synthes, and ISSG; being on the editorial board of Operative Neurosurgery; receipt of grant funding from ISSG; and being on the executive committee of Global Spinal Analytics.

Author Contributions
Conception and design: Macyszyn, Gaonkar, Alkhalid. Acquisition of data: Macyszyn, Alkhalid, Villaroman, Medina, Ahn. Analysis and interpretation of data: Macyszyn, Attiah, Gaonkar, Villaroman, Medina, Niu. Critically revising the article: Macyszyn, Attiah, Gaonkar, Niu, Beckett, Ames. Reviewed submitted version of manuscript: Villaroman. Approved the final version of the manuscript on behalf of all authors: Macyszyn. Statistical analysis: Gaonkar. Administrative/technical/material support: Macyszyn, Gaonkar. Study supervision: Macyszyn, Gaonkar.

Supplemental Information
Previous Presentations
Portions of this work were presented as an oral presentation and winner of the Kuntz Award at the AANS/CNS joint spine section meeting, Orlando, Florida, March 14–17, 2018.

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