The Contribution of Lower Limbs to Pelvic Tilt:

A Baseline and Postoperative Full-Body Analysis

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This study was approved by institutional review board in each of the participating centers (Clinicaltrials.gov identifier: Nct00738439). All included patients provided their informed consent to take part in the study.

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The authors have no conflict of interest to declare relatively to this study.

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ABSTRACT

Background: Pelvic tilt (PT) has been a parameter of interest in biomechanics of spinal deformity for decades. It remains unclear how patients achieve different values of PT pre- and postoperatively.

Research question: This study aimed at assessing the relative contribution of hip extension, knee flexion and ankle extension to PT, factoring malalignment and hip osteoarthritis (OA).

Methods: This retrospective included Adult Spinal Deformity (ASD) patients with preoperative full-body radiographs from a multicenter database, with a sub-analysis of patients with complete 1-year follow-up (1yFU). Age and PI-adjusted normative PT (NormPT) and offset from norm (OffPT) were calculated, as for sacro-femoral angle (SFA), knee flexion angle (KA) and ankle angle (AA). Multivariate linear regression models controlling for age, frailty, severe hip OA, pelvic incidence (PI), SFA, and KA were used to predict PT at baseline, and offset from NormPT. Another model was generated to predict PT change.

Results: 600 patients at baseline and 336 with 1yFU were included. Mean age was 61±15, 70.2% were females and 40% were revision cases. At baseline, regression analysis revealed that 1° increase in hip extension (SFA) amounts to 0.9° increase in PT, and 1° increase in knee flexion (KA) to 0.6° increase in PT.

Knee and ankle contribution to PT significantly increased for while hip extension decreased as TPA augmented (*p<0.001*). Patients with low deformity compensated with hip extension, while knee flexion was the largest contributor of PT in high deformity patients: 70.7% (44.7 – 111.9). Median contribution of knee flexion to PT was larger for patients who presented hip OA.

Significance: This study demonstrated that PT is a phenomenon driven by extension of the hips and flexion of the knees and proposed values to predict PT from those two compensatory mechanisms. Magnitude of spinal deformity and hip OA alters the magnitude of SFA/KA contribution to PT.

KEYWORDS: pelvic tilt; pelvic retroversion; knee flexion; hip extension; lower limb; sagittal malalignment

INTRODUCTION

Adult spinal deformity (ASD) is a frequent condition with a prevalence exceeding 60% in patients aged above 60 years according to certain authors [1], with an expected ongoing increase with the aging of population. ASD encompasses different patterns of spinal deformity, and when symptomatic causes a major impact on health-related quality of life (HRQoL) [2]. Global malalignment is commonly associated with ASD, and is a main driver for pain and disability [3]. In order to maintain an aligned posture, several compensatory mechanisms can be recruited in standing position and while walking [4,5]. The first mechanisms to be activated are the spinopelvic ones adjacent to the kyphotic spine such as cervical hyperlordosis, thoracic kyphosis flattening, lumbar hyperextension and retrolisthesis, and pelvic retroversion [6]. After exhaustion of spino-pelvic mechanisms in case of worsening alignment, compensation through hip extension, knee flexion and ankle flexion to increase pelvic retroversion and pelvic shift becomes essential [7,8]. Indeed, it has been demonstrated that removal of lower limb compensation in malaligned patients was associated with a two-fold greater sagittal vertical axis (SVA) [9].

Previous studies have reported the correlation between sagittal malalignment and lower limb mechanisms [8,10]. Other authors have described the evolution of lower limb compensatory mechanisms recruitment according to malalignment, highlighting non-linear relationship [11]. Thus, pelvic retroversion plateaued for most anterior values of SVA while pelvic shift was constantly progressing. The participation of knee and ankle flexions in compensation was minimal in low SVA, increased for more anterior SVA before decreasing for extreme SVA. Lafage et al. also demonstrated that hip osteoarthritis (OA) was significantly associated with spino-pelvic compensatory mechanisms in standing and sitting position, with severe OA patients presenting lower hip range of motion and higher change in pelvic tilt [12].

Although the lower limb compensatory mechanisms have been extensively described in literature, little is known about the relationship between them and the factors influencing their recruitment. The goal of this study was to assess hip extension, knee flexion and ankle flexion contribution to pelvic tilt variation, accounting for hip osteoarthritis. The hypothesis was that pelvic tilt is a multifactorial phenomenon driven by hip extension, knee flexion, ankle flexion and is affected by hip osteoarthritis.

METHODS

Population

This study was a retrospective review of a prospective multicentric database of ASD patients. Patients with pre- and post-operative full-body radiographs were included if they met at least one of the following criteria:

- Severe Radiographic deformity: PI-LL≥25°, TPA≥30°, SVA≥15cm, Thoracic Cobb ≥70°, or Thoraco-lumbar Cobb≥50°
- Complex Surgical procedure: ≥12 levels fused, 3CO or ACR
- Geriatric deformity surgery: >65-year-old and ≥7 levels fused

Exclusion criteria were the following: presence of inflammatory or autoimmune diseases, neuromuscular disorder (such as Parkinson's), active tumor or infection, trauma or syndromic scoliosis. This study was approved by Institutional Review Boards in each site, and all patients provided informed written consent. This study was registered on ClinicalTrials.gov (#NCT04194138).

Parameters

Patients' demographics were collected preoperatively: age, sex, race, education, body mass index (BMI), Charlson comorbidity index (CCI), frailty score, history of lumbar surgery. The following baseline patient reported outcomes were also noted: Oswestry disability index (ODI), PROMIS score, the Veteran's RAND-12 (VR-12) and the Scoliosis Research Society 22 score (SRS-22).

Hip OA was assessed preoperatively by grading left and right hip from 1 to 4 according to Kellgren-Lawrence's classification [13]. Classic spino-pelvic parameters were measured: pelvic incidence (PI), pelvic tilt (PT), L1-S1 lumbar lordosis (LL), PI-LL mismatch, T2-T12 thoracic kyphosis (TK), sagittal vertical axis (SVA), T1 pelvic angle (TPA), thoracic and lumbar Cobb angles as well as SRS-Schwab classification. Lower limb parameters were assessed through sacro-femoral angle (SFA), pelvic shift (P. Shift), knee angle (KA), and ankle angle (AA) (**Figure 1**). Radiographic alignment was measured pre- and postoperatively.

The offset between measured PT (OffPT) and age-and-PI adjusted normative value (NormPT) was calculated as per Iyer et al. regressions based on a cohort of 119 asymptomatic volunteers [14]. The same offsets were calculated for SFA, KA and AA:

- PT = -14.088506 + 0.400229 * PI + 0.143222 * Age *(R^2=0.508)*
- SFA = 176.589074 + 0.433317 * PI *(R^2=0.332)*
- KA = -11.778654 + 0.190999 * Age *(R^2=0.247)*
- AA = -0.555636 + 0.071511 * Age *(R^2=0.155)*

Statistical analysis

First, baseline, surgical and in-hospital parameters were described using mean ± standard deviation. The offsets of PT, SFA, KA and AA from age- and PI-adjusted values were investigated with overall description and comparison across hip OA grades. Multilinear regression was performed to evaluate the respective contributions of hip and knee to pelvic compensation, while controlling for age, frailty, PI and OA grade.

Patients were then stratified by deformity severity into four equal groups according to TPA magnitude: “Minimal”, “Low”, “Moderate” and “High”. Percentage of hip and knee compensation contributing to pelvic compensation was compared between the groups. This analysis was further carried out according to Hip OA grade. Patients were labelled as “high-OA” if they had available OA grade data for both hips, with at least one of them graded ≥3, and “low-OA” if ≤2. The patients with total hip replacement or who did not meet these requirements were not included in this analysis.

A sub-analysis was conducted on patients who completed 1-year follow-up at the time of the analysis. Multilinear regression was utilized to evaluate SFA, KA and PT compensation relaxation following ASD surgery, controlling for age, frailty, PI and OA grade.

Statistical analyses were conducted with RStudio (Version 2023.09.1+494) with p-values lower than 0.05 considered significant.

RESULTS

Baseline description

This study included 600 patients with a mean age of 61.1±15.1 years and a mean BMI of 27.3±5.5 kg.m^{-2}. There were 70.2% of females and 39.5% of the cohort had a previous thoracolumbar surgery. Preoperative HRQoL demonstrated moderate to severe pain and disability (**Table 1**). There were 46.6% of patients SRS-Schwab type N, 28.0% type L patients and 23.7% type D. Sagittal alignment was poor, with 45.2% of patients graded as ++ for SRS-Schwab PI-LL modifier, 30.8% of ++ patients for PT modifier and 31.6% for the SVA modifier.

Pelvic and lower limb compensation

Mean preoperative compensation in the lower limbs, measured as the offset from age-and-PI adjusted normative values, were of 8.3±9.2° for PT, 3.8±10.0° for SFA, 5.6 ± 8.7° for KA and 1.2±4.4° for AA. The cohort was equally distributed between hip high-OA and low-OA groups, with respectively 273 and 274 patients.

Patients with greater hip degeneration were older (65.8±11.8 versus 55.2±16.8 years, $p<0.001$), with greater OffPT (9.4±9.2 versus 7.4 ± 9.1°, $p=0.01$), OffKA (7.4±8.9 versus 3.6 ± 7.8°, $p<0.001$), and OffAA (1.7±4.6 versus 0.6±4.1°, $p=0.005$). There were no differences in pelvic incidence ($p=0.56$) nor SFA values ($p=0.79$) between the two groups.

Multilinear regression demonstrated a significant association of hip (SFA) and knee compensation (KA) with pelvic tilt, with a high R-squared value of 0.951 (standard error: 2.5°). This regression highlighted that 1° increase in hip extension amounts to 0.9° increase in PT, while 1° increase in knee flexion was associated with 0.6° increase in PT. Including AA in the regression provided the following geometric formula: PT=SFA-180+KA-AA (**Figure 1**).

Contribution of lower limbs to PT across deformity groups

Patients with poorer alignment were significantly older, with a greater PI as well as pelvic and lower limb compensation: greater PT, SFA, KA and AA (**Table 2**). There were no compensations in the "Minimal" group.

Comparison of relative contribution to PT demonstrated a significant increase of knee and ankle participation while hip extension decreased significantly as TPA augmented ($p<0.001$) (**Figure 2**). Patients compensated first with hip extension (100% for low deformity), then recruited knee flexion that became the largest contributor of pelvic tilt in high deformity patients (**Figure 3**).

Stratification by hip OA grade demonstrated a larger median contribution of knee flexion to pelvic compensation for patients who presented hip degeneration, exceeding hip extension contribution for moderate deformities in hip-OA patients, versus for high deformities in no-OA patients (**Figure 4**).

Postoperative change

In the cohort, 336 patients completed their 1-year follow-up out of 406 eligible patients (83% follow-up rate), of whom 264 had full-body X-rays. There was a significant change in coronal and sagittal alignment postoperatively: maximum Cobb angle decreased by 19.1° (IQR: 9.0 to 33.5°), PI-LL mismatch decreased by 12.7±18.2° ($p<0.001$) and TPA decreased by 6.6±10.1° ($p<0.001$). Consequently, it was noted a 3.0±7.8° decrease in PT ($p<0.001$), 1.4±6.4° decrease in SFA ($p<0.001$) and 1.6±7.0° decrease in KA ($p<0.001$), but no significant change in AA ($p=0.74$).

Pelvic tilt variation between preoperative and 1-year follow-up was correlated with that of SFA (r=0.80, $p<0.001$), KA (r=0.59, $p<0.001$), and AA (r=0.42, $p<0.001$). Multivariate regression, controlling for demographics, hip degeneration and PI demonstrated excellent results with an R-squared of 0.907 (standard error of the estimate = 2.35°). Regression coefficients demonstrated that a 0.9° change in SFA (95%CI: 0.83 to 0.93°) and 0.6° change in KA (95%CI: 0.51 to 0.59°) contributed to 1° change in PT at one year.

DISCUSSION

The major role of lower limb compensation in spinal sagittal malalignment in order to maintain whole-body balance has been demonstrated in literature [9]. Lower limbs also reflect post-operative global alignment as lower limb pathologic compensatory mechanisms should be restored in case of appropriate spinal alignment correction [15]. Persistent lower limb compensation postoperatively may indicate under-correction of malalignment [16]. The results of this study allow to further understand the relationships between the different compensatory mechanisms in the lower limbs and the factors influencing their recruitment. Thus, the magnitude of sagittal malalignment significantly impacted proportion of hip extension and knee flexion to pelvic retroversion. In moderate deformities, all patients used hip extension and started recruiting knee flexion for poorer alignment, until the proportion of knee flexion surpassed hip participation in pelvic retroversion. Hip degeneration was another significant factor differentiating several patterns in high-PT patients. Indeed, patients with major hip OA used more knee flexion while patients without hip degeneration recruited hip extension in order to increase pelvic tilt. After ASD correction surgery, hip contribution to PT decrease was greater than the knee's.

Pelvic retroversion is a major compensatory mechanism for sagittal malalignment and is correlated with patients' HRQoL [17]. Two main independent phenomena can lead to an increased pelvic tilt: hip extension and knee flexion. The latter phenomenon is associated with an augmentation in posterior translation of pelvis (pelvic shift). This study highlighted that hip extension was used at early-stage deformities, while knee flexion participation to pelvic tilt outweighed hip extension in major deformities, according to TPA groups. Similarly, Cheng et al. demonstrated that for larger PI-LL mismatches, relative importance of hip extension decreases in favor of knee flexion by providing greater femoral incline [18]. Shimizu et al. also demonstrated a higher prevalence in lower limb compensation in ASD patients with increased cranial SVA, especially knee flexion [19]. These authors also concluded that as all lower limb compensatory mechanisms resulted in pelvic retroversion, lower-extremity compensation can be estimated without obtaining a full-body radiograph, using PT cutoff values determined in their study. However, other authors have demonstrated that sagittal malalignment of the spine did not only induce change in the sagittal plane at the lower limb level. Indeed, Sato et al. noted a 3D alignment improvement of lower limbs after ASD correction surgery, with significant impact on knee flexion and hip-knee-ankle angle, measured in the coronal plane [20].

This study exhibited a significant impact of hip osteoarthritis on lower limb compensation for sagittal spinal malalignment, underlining once more the central relationship between hip and spine. Patients with major hip degeneration used more knee flexion than hip extension to increase their pelvic retroversion. These findings are in line with a recent study from the International Spine Study Group, highlighting that patients with severe hip and knee OA exhibited decreased SFA and PT, but increased KA [21]. Day et al.'s study results in 136 patients, noting that patients with severe hip osteoarthritis rather utilized pelvic shift and thoracic kyphosis flattening than pelvic retroversion to compensate for sagittal malalignment [22]. Other authors have demonstrated that patients with severe hip osteoarthritis exhibited limited ranges of coordinated motion of pelvis, femur and hips in daily life movements [23]. Moreover, patients with severe hip osteoarthritis present a poorer global alignment than patients with no degeneration in hips [24]. After total hip replacement, these patients presented significant improvement in thoracic kyphosis, sacral slope and knee flexion angle. These phenomena emphasize the need to evaluate hip osteoarthritis while assessing ASD patient as it may alter alignment and its compensatory mechanisms, especially since it has been demonstrated that hip osteoarthritis was independently associated with the severity of disc degeneration in the lumbar spine [25]. Further, mobility of the hips should always be assessed before undertaking long spinal fusion to the pelvis as they will have to compensate for lost motion in the fused spine.

Limitations

This study presents several limitations, including its retrospective nature. First, the knee osteoarthritis grade was not assessed in this study. Similarly to hip OA, knee OA could have an impact on the recruitment of knee flexion. Second, a longer duration of follow-up would be required to assess long-term variation of compensatory mechanisms after ASD correction. In this study, the whole cohort did not complete the one-year follow-up.

CONCLUSION

This study demonstrated that pelvic tilt is a phenomenon driven by extension of the hips, flexion of the knees and ankle flexion, and proposed values to predict PT from those two compensatory mechanisms of the lower limbs. The recruitment of theses mechanisms is regulated by sagittal malalignment magnitude and hip degeneration. Patients use first hip extension to compensate in low deformities then recruit knee flexion and ankle flexion as sagittal malalignment increases. In patients with hip osteoarthritis, knee flexion contribution to pelvic retroversion is larger.

REFERENCES

[1] F. Schwab, A. Dubey, L. Gamez, A.B. El Fegoun, K. Hwang, M. Pagala, J.P. Farcy, Adult scoliosis: prevalence, SF-36, and nutritional parameters in an elderly volunteer population., Spine (Phila. Pa. 1976). 30 (2005) 1082–1085. https://doi.org/10.1097/01.brs.0000160842.43482.cd.

[2] F. Pellisé, A. Vila-Casademunt, M. Ferrer, M. Domingo-Sàbat, J. Bagó, F.J.S. Pérez-Grueso, A. Alanay, A.F. Mannion, E. Acaroglu, Impact on health related quality of life of adult spinal deformity (ASD) compared with other chronic conditions, Eur. Spine J. Off. Publ. Eur. Spine Soc. Eur. Spinal Deform. Soc. Eur. Sect. Cerv. Spine Res. Soc. 24 (2015) 3–11. https://doi.org/10.1007/s00586-014-3542-1.

[3] M. Takemoto, L. Boissière, J.-M. Vital, F. Pellisé, F.J.S. Perez-Grueso, F. Kleinstück, E.R. Acaroglu, A. Alanay, I. Obeid, Are sagittal spinopelvic radiographic parameters significantly associated with quality of life of adult spinal deformity patients? Multivariate linear regression analyses for pre-operative and short-term post-operative health-related quality of life., Eur. Spine J. 26 (2017) 2176–2186. https://doi.org/10.1007/s00586-016-4872-y.

[4] C. Barrey, P. Roussouly, G. Perrin, J.C. Le Huec, Sagittal balance disorders in severe degenerative spine. Can we identify the compensatory mechanisms?, Eur. Spine J. 20 (2011) 1–8. https://doi.org/10.1007/s00586-011-1930-3.

[5] P. Severijns, L. Moke, T. Overbergh, E. Beaucage-Gauvreau, T. Ackermans, K. Desloovere, L. Scheys, Dynamic sagittal alignment and compensation strategies in adult spinal deformity during walking, Spine J. 21 (2021) 1059–1071. https://doi.org/10.1016/j.spinee.2021.02.017.

[6] C. Barrey, P. Roussouly, J.-C. Le Huec, G. D'Acunzi, G. Perrin, Compensatory

mechanisms contributing to keep the sagittal balance of the spine., Eur. Spine J. 22 Suppl 6 (2013) S834-41. https://doi.org/10.1007/s00586-013-3030-z.

[7] B.G. Diebo, E. Ferrero, R. Lafage, V. Challier, B. Liabaud, S. Liu, J.-M. Vital, T.J. Errico, F.J. Schwab, V. Lafage, Recruitment of Compensatory Mechanisms in Sagittal Spinal Malalignment Is Age and Regional Deformity Dependent, Spine (Phila. Pa. 1976). 40 (2015) 642–649. https://doi.org/10.1097/BRS.0000000000000844.

[8] E. Ferrero, B. Liabaud, V. Challier, R. Lafage, B.G. Diebo, S. Vira, S. Liu, J.M. Vital, B. Ilharreborde, T.S. Protopsaltis, T.J. Errico, F.J. Schwab, V. Lafage, Role of pelvic translation and lower-extremity compensation to maintain gravity line position in spinal deformity., J. Neurosurg. Spine. 24 (2016) 436–46. https://doi.org/10.3171/2015.5.SPINE14989.

[9] R. Lafage, P. Duvvuri, J. Elysee, B. Diebo, S. Bess, D. Burton, A. Daniels, M. Gupta, R. Hostin, K. Kebaish, M. Kelly, H.J. Kim, E. Klineberg, L. Lenke, S. Lewis, C. Ames, P. Passias, T. Protopsaltis, C. Shaffrey, J.S. Smith, F. Schwab, V. Lafage, Quantifying the Contribution of Lower Limb Compensation to Upright Posture, Spine (Phila. Pa. 1976). 48 (2023) 1082–1088. https://doi.org/10.1097/BRS.0000000000004646.

[10] A. Yucekul, A. Ozpinar, F.D.B. Kilickan, M. Dalla, N. Muthiah, T. Zulemyan, Y. Yavuz, J. Pizones, I. Obeid, F. Kleinstück, F.J.S. Pérez-Grueso, F. Pellisé, C. Yilgor, A. Alanay, European Spine Study Group (ESSG), Relationship between pelvic incidence-adjusted relative spinopelvic parameters, global sagittal alignment and lower extremity compensations., Eur. Spine J. 32 (2023) 3599–3607. https://doi.org/10.1007/s00586-023-07677-6.

[11] R. Lafage, B. Liabaud, B.G. Diebo, J.H. Oren, S. Vira, S. Pesenti, T.S. Protopsaltis, T.J. Errico, F.J. Schwab, V. Lafage, Defining the Role of the Lower Limbs in Compensating for Sagittal Malalignment., Spine (Phila. Pa. 1976). 42 (2017) E1282–E1288.

https://doi.org/10.1097/BRS.0000000000002157.
[12] A.J. Buckland, L. Steinmetz, P. Zhou, D. Vasquez-Montes, M. Kingery, N.D. Stekas, E.W. Ayres, C.G. Varlotta, V. Lafage, R. Lafage, T. Errico, P.G. Passias, T.S. Protopsaltis, J. Vigdorchik, Spinopelvic Compensatory Mechanisms for Reduced Hip Motion (ROM) in the Setting of Hip Osteoarthritis, Spine Deform. 7 (2019) 923–928. https://doi.org/10.1016/j.jspd.2019.03.007.
[13] J.H. Kellgren, J.S. Lawrence, Radiological Assessment of Osteo-Arthrosis, Ann. Rheum. Dis. 16 (1957) 494–502. https://doi.org/10.1136/ard.16.4.494.
[14] S. Iyer, L.G. Lenke, V.M. Nemani, T.J. Albert, B.A. Sides, L.N. Metz, M.E. Cunningham, H.J. Kim, Variations in sagittal alignment parameters based on age: A prospective study of asymptomatic volunteers using full-body radiographs, Spine (Phila. Pa. 1976). 41 (2016) 1826–1836. https://doi.org/10.1097/BRS.0000000000001642.
[15] T. Shimizu, R.A. Lehman, J.A. Sielatycki, S. Pongmanee, M. Cerpa, M. Takemoto, L.G. Lenke, Reciprocal change of sagittal profile in unfused spinal segments and lower extremities after complex adult spinal deformity surgery including spinopelvic fixation: a full-body X-ray analysis., Spine J. 20 (2020) 380–390. https://doi.org/10.1016/j.spinee.2019.09.012.
[16] W.-S. Ha, M.-H. Shin, Postoperative lower limb compensation in patient with adult spinal deformity., J. Clin. Neurosci. 59 (2019) 106–111. https://doi.org/10.1016/j.jocn.2018.10.119.
[17] 2009 Lafage et al., Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity., Spine (Phila. Pa. 1976). 34 (2009) E599--606. https://doi.org/10.1097/BRS.0b013e3181aad219.
[18] X. Cheng, K. Zhang, X. Sun, C. Zhao, H. Li, J. Zhao, Analysis of compensatory mechanisms in the pelvis and lower extremities in patients with pelvic incidence and

lumbar lordosis mismatch., Gait Posture. 56 (2017) 14–18. https://doi.org/10.1016/j.gaitpost.2017.04.041.

[19] T. Shimizu, M. Cerpa, L.G. Lenke, Understanding sagittal compensation in adult spinal deformity patients: relationship between pelvic tilt and lower-extremity position., J. Neurosurg. Spine. (2021) 1–8. https://doi.org/10.3171/2021.1.SPINE201660.

[20] Y. Sato, K. Hasegawa, M. Okamoto, S. Hatsushikano, Y. Ishii, K. Watanabe, Y. Oshima, H. Shimoda, T. Homma, Correction surgery for adult spinal deformity improves not only spinopelvic alignment but also the three-dimensional alignment of the lower extremities., J. Orthop. Sci. 25 (2020) 946–952. https://doi.org/10.1016/j.jos.2019.12.002.

[21] M. Balmaceno-Criss, R. Lafage, D. Alsoof, M. Daher, D.K. Hamilton, J.S. Smith, R.K. Eastlack, R.G. Fessler, J.L. Gum, M.C. Gupta, R. Hostin, K.M. Kebaish, E.O. Klineberg, S.J. Lewis, B.G. Line, P.D. Nunley, G.M. Mundis, P.G. Passias, T.S. Protopsaltis, T. Buell, J.K. Scheer, J.P. Mullin, A. Soroceanu, C.P. Ames, L.G. Lenke, S. Bess, C.I. Shaffrey, F.J. Schwab, V. Lafage, D.C. Burton, B.G. Diebo, A.H. Daniels, International Spine Study Group (ISSG), Impact of Hip and Knee Osteoarthritis on Full Body Sagittal Alignment and Compensation for Sagittal Spinal Deformity., Spine (Phila. Pa. 1976). (2024). https://doi.org/10.1097/BRS.0000000000004957.

[22] L.M. Day, E.M. DelSole, B.M. Beaubrun, P.L. Zhou, J.Y. Moon, J.C. Tishelman, J.M. Vigdorchik, R. Schwarzkopf, R. Lafage, V. Lafage, T. Protopsaltis, A.J. Buckland, Radiological severity of hip osteoarthritis in patients with adult spinal deformity: the effect on spinopelvic and lower extremity compensatory mechanisms., Eur. Spine J. 27 (2018) 2294–2302. https://doi.org/10.1007/s00586-018-5509-0.

[23] D. Hara, Y. Nakashima, S. Hamai, H. Higaki, S. Ikebe, T. Shimoto, K. Yoshimoto, Y. Iwamoto, Dynamic hip kinematics in patients with hip osteoarthritis during weight-bearing activities, Clin. Biomech. 32 (2016) 150–156.

https://doi.org/10.1016/j.clinbiomech.2015.11.019.

[24] J. Ouchida, H. Nakashima, T. Kanemura, K. Satake, K. Ando, K. Ito, M. Tsushima, M. Machino, S. Ito, H. Yamaguchi, N. Segi, H. Koshimizu, H. Tomita, S. Imagama, Impact of the hip joint mobility on whole-body sagittal alignment: prospective analysis in case with hip arthroplasty., Eur. Spine J. 31 (2022) 2399–2407. https://doi.org/10.1007/s00586-022-07251-6.

[25] L. Schönnagel, G. Camino-Willhuber, S. Braun, J. Zhu, S. Tani, A.E. Guven, T. Caffard, E. Chiapparelli, A. Arzani, H. Haffer, M. Muellner, J. Shue, R. Duculan, M. Bendersky, F.P. Cammisa, F.P. Girardi, A.A. Sama, C.A. Mancuso, A.P. Hughes, Association Between Osteoarthritis Burden and Intervertebral Disc Degeneration in Patients Undergoing Lumbar Spine Surgery for Degenerative Lumbar Spondylolisthesis., Spine (Phila. Pa. 1976). (2023). https://doi.org/10.1097/BRS.0000000000004847.

FIGURE LEGENDS

Figure 1: Measurement of pelvic tilt, sacro-femoral angle, knee angle, ankle angle and pelvic shift.

Figure 2: Relative contribution of hip, knee and ankle compensation to pelvic retroversion according to the four groups of sagittal malalignment severity.

Figure 3: Schematic representation of lower limb compensatory mechanisms contribution to pelvic retroversion in each TPA group. Offset values for each lower limb parameter are reported.

Figure 4: Relative contribution of hip, knee and ankle to pelvic retroversion according to sagittal malalignment severity, with respect to hip degeneration.

TABLES

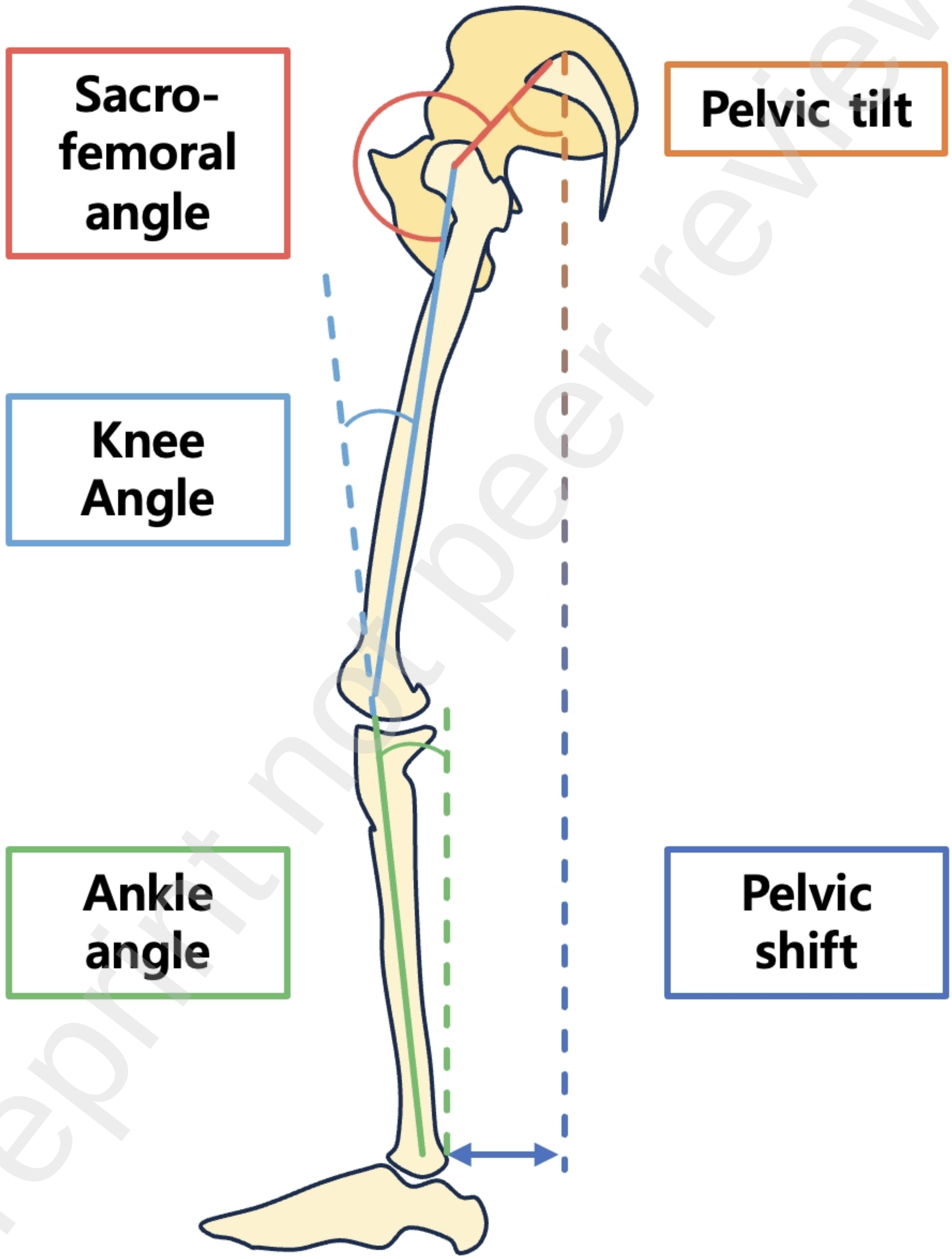
Demographics, Comorbidities and Past Medical History			
Age (years)	65.7 (55.4 – 71.5)	**Sex** (Female)	70.2%
BMI (kg/m2)	26.9 (23.4 – 30.7)	**Race** (White)	91.2%
CCI	0 (0 – 2)	**Education** (College or higher)	67.3%
Frailty Score	3 (2 – 4)	**Previous thoracolumbar surgery** (Yes)	43.5%
Patient Reported Outcomes (PRO)			
NRS Back	7 (6 – 9)	**NRS Leg**	4 (0 – 7)
PROMIS - Anxiety	56.0 (50.6 – 62.0)	**PROMIS - Physical Function**	34.2 (29.3 – 39.0)
PROMIS - Depression	51.2 (46.1 to 57.6)	**PROMIS - Social DSA**	41.7 (36.1 – 47.7)
PROMIS - Pain Interference	64.2 (59.9 – 69.1)	**PROMIS - Social Role**	39.5 (34.7 – 44.7)
ODI	44 (32 – 58)	**VR12 PCS**	28.0 (21.0 – 35.9)
VR12 MCS	49.0 (38.3 – 58.5)	**SRS22 Mental**	3.6 (3.0 – 4.2)
SRS22 Activity	2.8 (2.2 – 3.4)	**SRS22 Appearance**	2.4 (1.8 – 3.0)
SRS22 Pain	2.4 (1.8 – 3.2)	**SRS22 Total**	2.84 (2.4 – 3.3)
Coronal and Sagittal Spinal Alignment			
Lumbar Cobb (°)	27.6 (14.2 – 41.4)	**Thoracic Cobb** (°)	20.8 (11.9 – 39.0)
Pelvic Incidence (°)	54.6 ± 13.4	**Lumbar Lordosis** (°)	37.6 ± 23.7
PI-LL (°)	16.9 ± 22.7	**Thoracic Kyphosis** (°)	-38.1 (-53.4 – -25.8)
T1-Pelvic-Angle (°)	24.3 ± 13.6	**SVA** (mm)	54.6 (13.7 – 111.0)
Pelvic and Lower Limbs Compensation			
Pelvic Tilt (°)	24.7 ± 11.0	**Sacro-Femoral Angle** (°)	204.9 (197.5 to 211.5)
Knee Angle (°)	4.6 (-1.8 – 11.8)	**Ankle angle** (°)	4.7 (1.7 – 8.2)

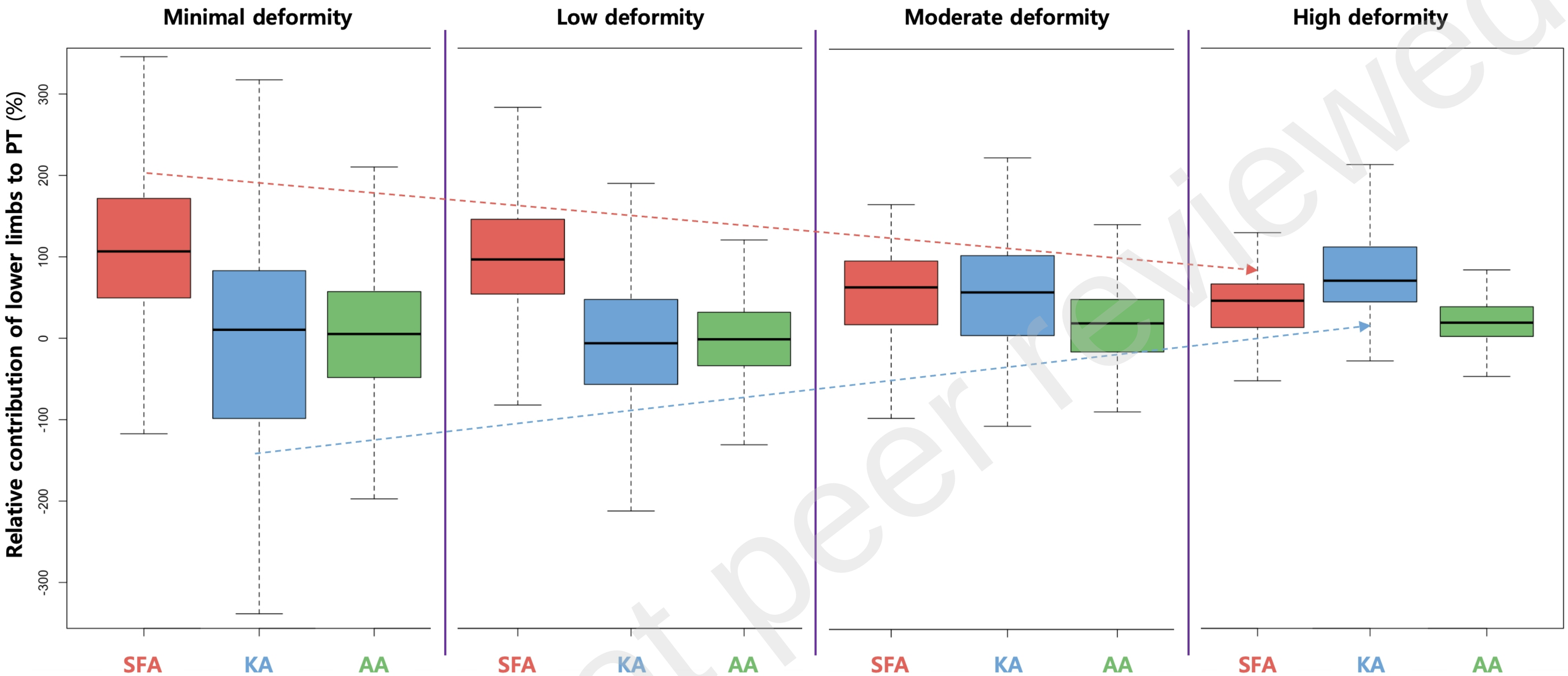
Table 1: Preoperative data for the entire cohort. Values are reported as mean ± standard deviation, median (Q1 – Q3) or percentage as appropriate.

TPA groups	Minimal	Low	Moderate	High	*p-value*
TPA (°)	7.6 ± 6.1	20.1 ± 2.4	28.3 ± 2.6	41.7 ± 7.7	-
Demographics					
PI (°)	48.5 ± 11.2	52.5 ± 11.0	55.7 ± 12.3	61.4 ± 15.5	*<0.001*
Age (years)	49.1 (30.6 – 66.1)	66.0 (57.5 – 71.9)	67.1 (59.6 – 71.9)	68.5 (62.4 – 73.5)	*<0.001*
Compensation					
PT (°)	12.5 ± 7.5	22.8 ± 5.5	28.0 ± 6.5	36.0 ± 7.5	*<0.001*
SFA (°)	196.4 ± 8.6	204.6 ± 8.8	206.4 ± 10.5	209.8 ± 9.3	*<0.001*
KA (°)	-0.9 ± 6.7	1.8 ± 6.9	7.6 ± 8.5	13.6 ± 8.2	*<0.001*
AA (°)	3.0 ± 3.7	3.6 ± 3.9	6.0 ± 4.5	7.5 ± 4.6	*<0.001*
Offset with age-and-PI adjusted normative values					
OffPT (°)	0.2 ± 6.5	6.8 ± 6.3	10.3 ± 7.3	15.9 ± 8.0	*<0.001*
OffSFA (°)	-1.2 ± 8.2	5.1 ± 8.9	5.4 ± 10.3	6.3 ± 10.0	*<0.001*
OffKA (°)	1.6 ± 6.1	1.4 ± 6.4	6.8 ± 8.4	12.7 ± 8.4	*<0.001*
OffAA (°)	0.1 ± 3.4	-0.4 ± 3.7	1.9 ± 4.5	3.3 ± 4.7	*<0.001*
Percentage of contribution to PT					
SFA	106.7 % (49.6 – 171.8)	96.8 % (54.5 – 146.0)	63.8 % (17.9 – 96.2)	46.1 % (13.2 – 66.7)	*<0.001*
KA	10.4 % (-98.6 – 83.0)	-6.1 % (-56.3 – 47.4)	57.6 % (4.6 – 102.8)	70.7 % (44.7 – [illegible]	*<0.001*
AA	5.2 % (-48.3 – 57.3)	-1.3% (-33.6 – 31.5)	19.6% (-15.5 – 49.0)	19.1% (2.3 – 38.6)	*0.001*

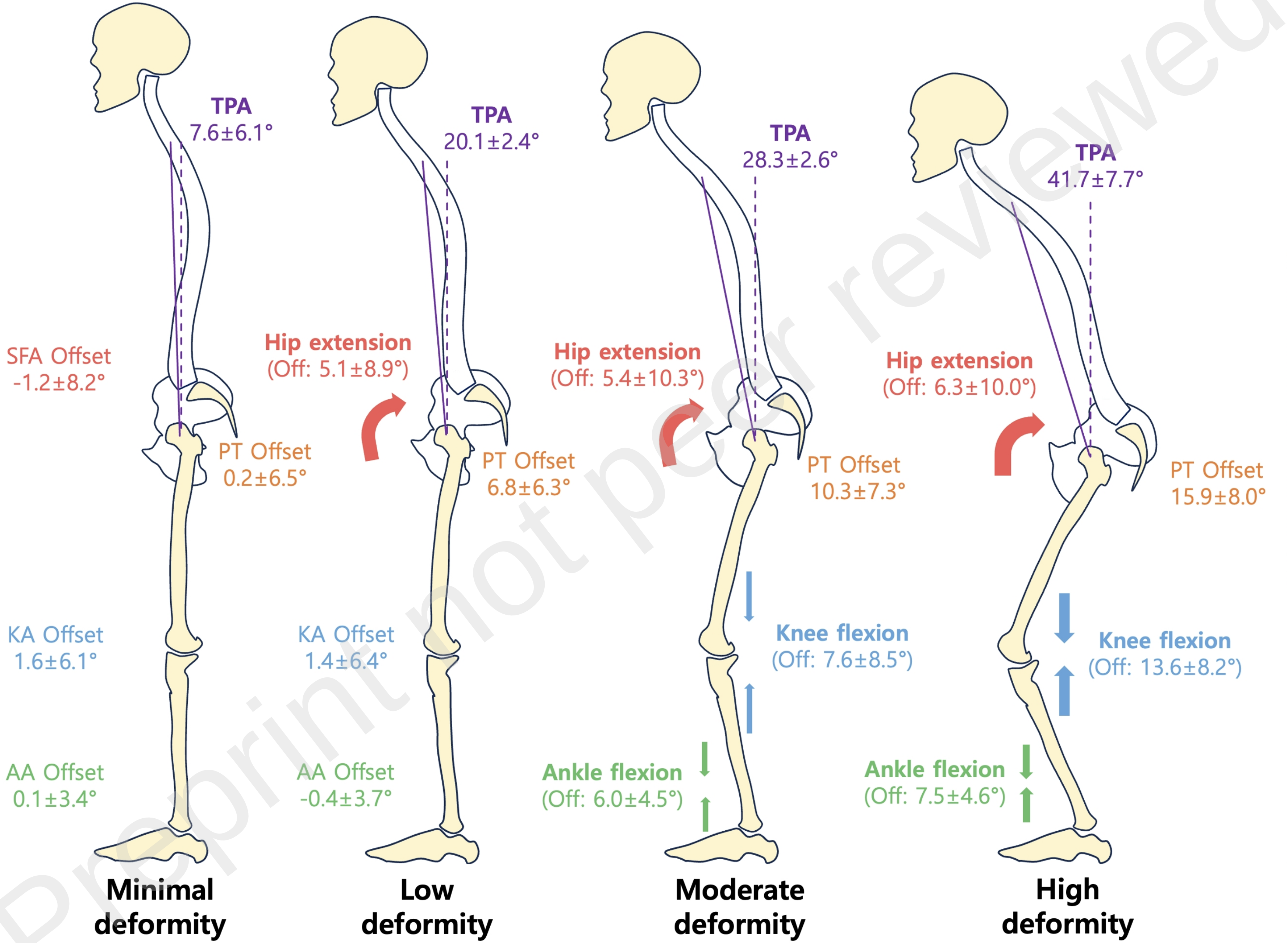
Table 2: Comparison of Age, Pelvic Incidence (PI), Pelvic Tilt (PT), Sacro-femoral angle (SFA), Knee Angle (KA) and Ankle Angle (AA) across global deformity (TPA) groups. Offsets for PT, SFA, KA and AA are provided per group and percentages of contribution to PT for SFA and KA. Values are reported as mean ± standard deviation, median (Q1 to Q3) or percentage as appropriate.

$$PT = (SFA - 180) + KA - AA$$

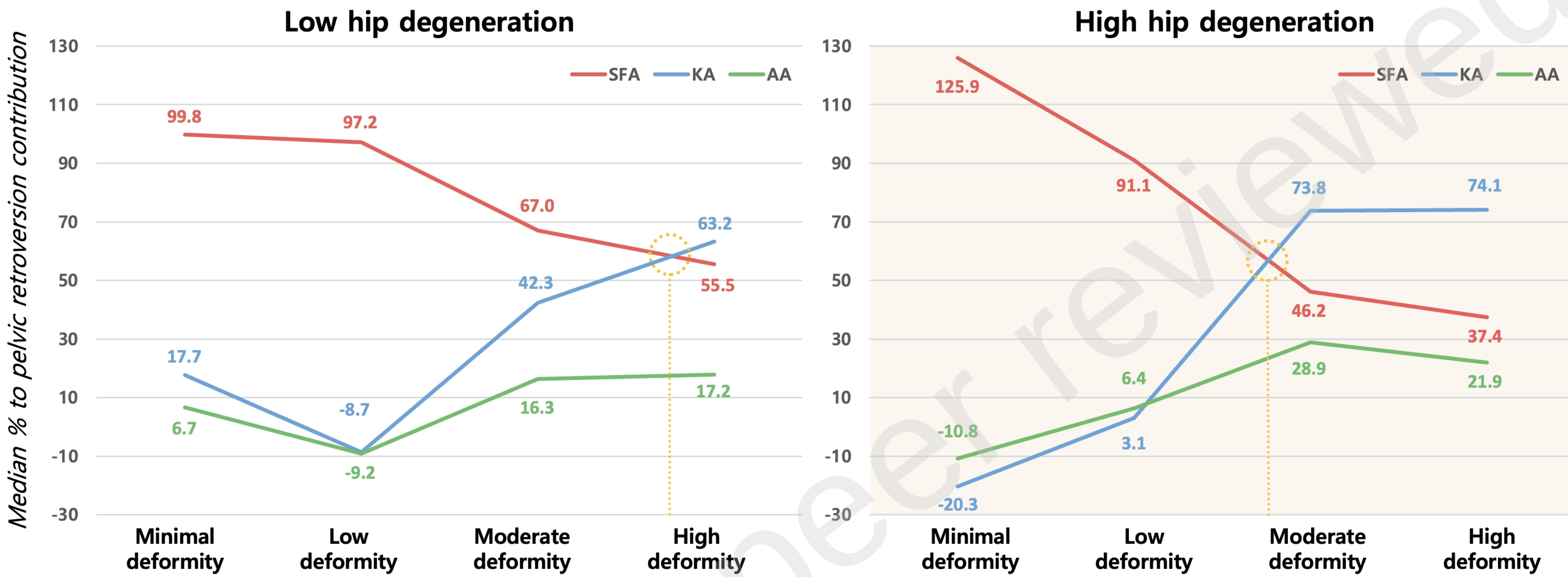




Minimal deformity
Low deformity
Moderate deformity
High deformity
Relative contribution of lower limbs to PT (%)
300
200
100
0
-100
-200
-300
SFA
KA
AA
SFA
KA
AA
SFA
KA
AA
SFA
KA
AA



TPA
7.6±6.1°
TPA
20.1±2.4°
TPA
28.3±2.6°
TPA
41.7±7.7°
SFA Offset
-1.2±8.2°
Hip extension
(Off: 5.1±8.9°)
Hip extension
(Off: 5.4±10.3°)
Hip extension
(Off: 6.3±10.0°)
PT Offset
0.2±6.5°
PT Offset
6.8±6.3°
PT Offset
10.3±7.3°
PT Offset
15.9±8.0°
KA Offset
1.6±6.1°
KA Offset
1.4±6.4°
Knee flexion
(Off: 7.6±8.5°)
Knee flexion
(Off: 13.6±8.2°)
AA Offset
0.1±3.4°
AA Offset
-0.4±3.7°
Ankle flexion
(Off: 6.0±4.5°)
Ankle flexion
(Off: 7.5±4.6°)
Minimal deformity
Low deformity
Moderate deformity
High deformity



Low hip degeneration
High hip degeneration
Median % to pelvic retroversion contribution
SFA
KA
AA
130
110
90
70
50
30
10
-10
-30
99.8
97.2
67.0
55.5
17.7
-8.7
42.3
63.2
6.7
-9.2
16.3
17.2
125.9
91.1
46.2
37.4
-20.3
3.1
73.8
74.1
-10.8
6.4
28.9
21.9
Minimal deformity
Low deformity
Moderate deformity
High deformity