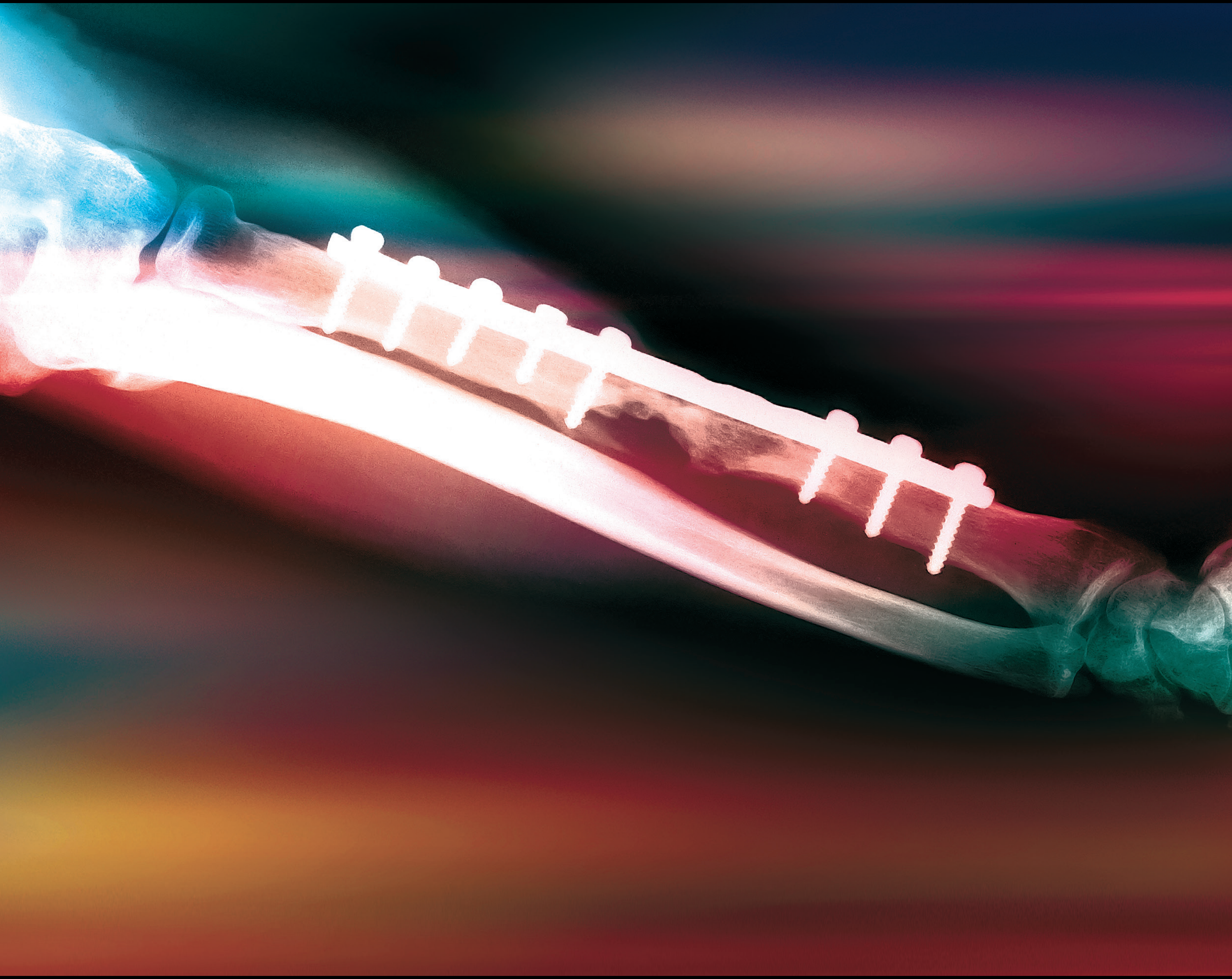
Advances in Orthopedics

Abnormal Posture Relating to the Alignment of Spine and Lower Extremity

Lead Guest Editor: Yasushi Oshima
Guest Editors: Mitsuhiro Kawata, Nobuyoshi Watanabe, and Shinro Takai



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Editorial

Abnormal Posture Relating to the Alignment of Spine and Lower Extremity

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In an aging society with an increase in the average life expectancy, abnormal posture with body balance disorder is a serious issue because it results in the reduction of activities of daily living and health-related quality of life.

Spinal deformity is an essential factor for adult abnormal posture defined as an abnormality in alignment, formation, or curvature of 1 or more portions of the spine [1]. Adult spinal deformity (ASD) reportedly occurs in more than 60% of the older population and develops with multiple conditions, including trunk muscle weakness, disk degeneration, vertebral fracture, and spondylotic changes. ASD is classified into coronal curve types and three sagittal modifiers (the difference between the pelvic incidence and the lumbar lordosis, the global alignment, and the pelvic tilt) [2]. In ASD, sagittal plane deformity is known to be of critical importance for pain and disability; therefore, recently, posterior spinal fusion has been applied for the correction of sagittal spinal malalignment. However, the surgical indication and the target of the alignment for each patient remain controversial. Besides the varying of the thoracic kyphosis and the lumbar lordosis, the spine anatomically connects to the pelvis involving the hip joint; therefore, ASD management is crucial focus for spino-pelvic-hip alignment.

The hip-spine syndrome was first described by C. M. Offierski, wherein the degenerative change of the hip and the lumbar spine are interrelated [3]. It is classified into 4 types: simple, complex, secondary, and misdiagnosed. Thereafter, the deformity of the spine or the hip and the following compensation mechanisms of each other have been investigated. Consequently, spinal surgery is able to reduce low back pain and abnormal posture directly; however, total hip replacement may also have the potential to repair hip disorders and improve posture. Moreover, the pelvis is known as the main regulator of a chain of correlation between the spine and the lower extremities. Thus, the relationship among the spine, the pelvis, and the hip joint for the treatment of the hip-spine syndrome needs further investigations.

Similarly, the knee-spine syndrome demonstrates that the symptoms from the lumbar spine may be caused by osteoarthritis (OA) of the knee and that the limitation of knee extension in turn affects the loss of lumbar lordosis [4]. In the treatment of knee pain, the limitation of the knee range of motion, and the malalignment of the lower extremity in the knee OA, many surgical procedures have been developed, including around knee osteotomies, unicompartmental knee arthroplasty, and total knee arthroplasty. All the surgical techniques have shown promising results with respect to the correction of the malalignment of the lower extremities and clinical outcomes. However, the target of the alignment in the lower extremities is different in each surgical procedure. Moreover, the effect on the corrected alignment following each procedure on the posture in older people remains debatable. At least, knee OA is known to affect spinal alignment; and therefore knee treatments can improve posture.

The feet act as a fulcrum, connecting to the lower extremities, pelvis, and spine, and the head moves like a pendulum. Hence, body balance and posture resemble an inverted pendulum, and the degeneration of these parts could affect the posture. Therefore, all these portions should be ultimately considered for the treatment of abnormal posture together although it is an extremely confusing issue.

With this background, in this special issue, we would like to focus on the principle of abnormal posture as well as the management of the malalignment and optimal alignment of the spine and the lower extremities.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Yasushi Oshima
Nobuyoshi Watanabe
Shinro Takai
Mitsuhiro Kawata

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Review Article

Knee–Hip–Spine Syndrome: Improvement in Preoperative Abnormal Posture following Total Knee Arthroplasty

Yasushi Oshima [1], Nobuyoshi Watanabe [2], Norishige Iizawa [1], Tokifumi Majima [1], Mitsuhiro Kawata [3] and Shinro Takai [1]

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An ergonomic upright body posture is maintained by the alignment of the spine, pelvis, and lower extremities, and the muscle strength of body trunk and lower extremities. The posture varies with age because of the degenerative changes in the involved structures and the weakening of the muscles. The compensatory mechanisms underlying these changes have recently been evaluated, and the loss of lumbar lordosis results in spinal kyphosis, pelvic retroversion, hip extension, knee flexion, and ankle dorsiflexion. These mechanisms are referred to as the hip–spine and knee–spine syndromes. The spine, hip, and knee are anatomically connected, and the pain and discomfort of the lower back, hip, and knee frequently arise due to degenerative changes of these structures. Thus, these mechanisms are considered as the knee–hip–spine syndrome. Spinal fusion, total hip arthroplasty, and total knee arthroplasty are the surgical procedures for severe degeneration, and their clinical outcomes for the affected sites are promising. However, despite surgeries, other structures may degenerate and result in complications, such as proximal junctional kyphosis and hip dislocation, following spinal fusion. Therefore, it is necessary to evaluate each patient under specific conditions and to treat each section while considering associations between the target structure and entire body. The purpose of this article is to introduce postural maintenance, variations with age, and improvements with surgical interventions of spine, hip, and knee as the knee–hip–spine syndrome.

1. Introduction

An ergonomic upright body posture is maintained by the alignment of the spine, pelvis, and lower extremities with the support of the muscles of the body trunk and lower extremities, and this posture varies with age because of degeneration of the involved structures and weakening of the muscles. In the advent of an aging society, abnormal posture with body balance disorders is a serious issue because it leads to decline in activities of daily living and health-related quality of life (QOL).

In the last few decades, treatments involving surgical procedures have been developed as specialized interventions for adult spinal deformity (ASD), osteoarthritis of the hip (hip OA), and osteoarthritis of the knee (knee OA). More recently, mechanisms underlying interactions among the spine, hip, and knee as well as compensatory mechanism underlying their deformities have been elucidated. In addition, similar medical conditions have been speculated to arise from different segments. For instance, spinal deformity results in spinal kyphosis; however, progressions of hip and knee OA may lead to the abnormal global sagittal alignment of the body.

Therefore, the purpose of this article is to summarize the current understanding of associations of the spine, pelvis, hip, and knee with the global and abnormal body postures and to explain postural improvements with surgical interventions, including our clinical outcomes of postural variations following total knee arthroplasty (TKA).

2. Body Posture

In 1994, Dubousset put forth the concept of "the cone of economy," which refers to the upright body posture maintained by the skeletal muscle strength of the body trunk and lower extremities and the alignment of the skeletal structures, including the head, spine, pelvis, and lower extremities. Body posture has been considered the chain of balance, with the body being balanced as an inverted pendulum in the standing position such that both feet on the floor act as the fulcrum connecting the ankles, knees, hips, pelvis, spinal segments, and head. The body sways to maintain balance while standing as the shape of a cone, and the body posture remains stable with minimal energy expenditure when the cone size is narrow. In contrast, the body becomes unstable and the energy expenditure increases when the cone size is large as the body trunk is positioned peripherally of the cone. Thus, when the trunk extends beyond cone, supportive devices, such as cane or crutch, are necessary to prevent fall [1].

3. Global Alignment

Body alignment is an important index of body balance in static and dynamic conditions, and it is known to vary with age. The ideal alignment of the body is considered to match C7 plumb line, which is the center of the gravity of the body trunk, and the center of the sacral vertical line in the coronal plane. C7 plumb line passes thought the posterior of the rotational center of the hip in the sagittal plane [2, 3]. In the previous study, the global sagittal alignment of 40-year-old healthy individuals was extensively investigated using a three-dimensional X-ray device [4]; the authors reported that the head was almost on the gravity line, as determined using a force plate as a vertical line from the center of gravity. Moreover, the cervical, thoracic, and lumbar regions of the spine showed lordosis, kyphosis, and lordosis in the normal adult posture, respectively. T7 was the posterior apex of the spine and was 5.0 cm posterior to the gravity line, while L4 was 0.6 mm anterior to the gravity line. The hip center was 1.4 cm anterior to the gravity line, whereas the knee and ankle centers were 2.4 mm and 4.8 cm posterior to the gravity line, respectively. When the ideal alignment of these segments is disrupted due to degenerative change of the involving structures, the underlying compensatory mechanisms preserve the body balance. Otherwise, the body becomes instable and loses balance.

4. Fall

The frequency of fall increases with age. Approximately 30% of the individuals older than 65 years of age fall more than once a year. Falls were reported to account for 10% of the emergency room visits and 6% of the hospital admissions [5].

Compared with those who did not fall, individuals who suffered falls showed reportedly poorer body balance, spinal sagittal alignment, muscle strength, and gait speed [6]. Falls in older people, especially in those with osteoporosis, may cause fractures, including vertebral compression as well as proximal femoral and distal radius fractures. Majority of these fractures can easily occur as low-energy injuries with fall from standing height. In older individuals who suffered proximal femoral fracture, 1-year incidence of second hip contralateral fractures was 2.7%–9% [7, 8] and 1-year mortality was approximately 10% [9].

Therefore, preventing falls via strategies involving exercises is crucial considering the higher overall 30-day mortality rate of older patients than that of younger patients following bone fractures [10, 11].

5. Sagittal Vertical Axis (SVA) and Sagittal Malalignment

On the contrary to coronal alignment, global sagittal alignment and pelvic version are associated with health-related QOL in terms of pain and disability [12]. Thus, many studies have focused on global sagittal alignment.

SVA, defined as the horizontal distance from the posterosuperior corner of S1 to the plumb line dropped from the center of the body at C7, is one of the indices of the sagittal body balance. A positive SVA indicates a plumb line passing anteriorly to the front of the sacrum, while a negative SVA indicates a plumb line passing through or behind the sacrum.

SVA of adolescents is significantly more negative than that of adults [13]. Thereafter, SVA has been reported to increase with age [2, 4]. Higher SVA values indicate forward bending the body trunk, resulting in low back pain, difficulty in touching the top of the shelf, and performing routine tasks, all of which lead to restricted activities of daily living. Consequently, back muscle strength is reduced, and the vertebral spine motion is limited. The vision is directed downwards, which impairs the ability to grasp the circumstances quickly and may lead to imbalance, walking disturbances, and falls [6, 12, 14].

SVA is an index of a stable standing posture, in which the femur is fixed and the gluteus maximus is contracted such that the pelvis is tilted posteriorly [15]. Thus, SVA is an indicator of changes due to the actions of compensatory mechanisms of the pelvis, hip, and knee [16, 17]. However, in the dynamic status, the femur is not fixed and the pelvis may tilt anteriorly [18]. Therefore, additional indices must be applied to dynamic alignment while performing normal activities.

6. ASD

Degenerative spinal kyphoscoliosis of the coronal and sagittal alignments occurs with degeneration of the facet joints and/or spinal discs, vertebral compression fractures, and weakening of the lumbodorsal muscles. Reduced lumbar lordosis (LL: the sagittal Cobb angle measured between the superior end plate of L1 and the superior end plate of S1) and excessive spinal kyphosis are associated with increased intradiscal pressure, which may cause low back pain [19]. Approximately 60% of the older individuals are considered to present with ASD; however, some patients with abnormal posture do not show any spinal deformities [20].

According to the Scoliosis Research Society-Schwab Classification, ASD is characterized by coronal curves of 4 types: type T, a thoracic major curve of $>30^\circ$ (apical level of T9 or higher); type L, a lumbar or thoracolumbar major curve of $>30^\circ$ (apical level of T10 or lower); type D, a double-major curve, with each curve >30°; and type N (normal), no coronal curve >30° (i.e., no major coronal deformity) [20]. Moreover, sagittal alignment is characterized through 3 modifiers: (1) the difference between the angle of the pelvic incidence (PI: the angle between the line drawn perpendicular to the sacral end plate at its midpoint and the line drawn from the midpoint of the sacral end plate to the midpoint of the bicoxofemoral axis) and LL; (2) the pelvic tilt (PT: the angle between the line connecting the midpoint of the sacral end plate to the midpoint of the bicoxofemoral axis and the vertical); and (3) SVA (SVA > 40 mm indicates poor sagittal alignment).

Variations in the spinal alignment are related to the pelvis position as a compensatory mechanism. When LL increases, the pelvis tilts anteriorly and thoracic kyphosis (TK) increase as a reciprocal change. In contrast when LL decreases, the pelvis tilts posteriorly and TK increase and the knee flexes. However, when this mechanism cannot maintain body posture, the thoracic and lumbar kyphosis increase, the body bends forward, and the gravity line moves forward, giving rise to severe abnormal posture with the stretching of the erector spinae muscles and chronic low back pain [2].

The pelvis has a fundamental role as the main regulator of the chain of correlation between the spine and lower extremities in this compensatory mechanism. Thus, the parameters LL, PT, sacral slope (SS; the tangent line to the superior endplate of S1 and the horizontal plane), and PI (the sum of PT and SS, which does not change with patient position, activity, age, or structural deformity) are important in the evaluation of the relationship between the spine and pelvis [12, 21].

7. Hip and Knee OA

OA is the most common form of arthritis and involves inflammation and major structural changes of the joints, causing pain and functional disabilities.

The risk of knee OA increases with age, with the global prevalence of radiographically confirmed symptomatic knee OA estimated to be 3.8%. In contrast, the incidence of hip OA is less than that of knee OA, with the global age-standardized prevalence of symptomatic radiographically confirming hip OA being 0.85% [22].

Coxitis knee is defined as the secondary knee OA, which occurs due to hip OA. Originally, coxitis knee was believed to be related to hip disease. However, adduction contracture of the hip and discrepancies of leg length have been regarded as the main etiologies of coxitis knee [23]. Of note, although an important symptom of hip and knee OA, coxitis knee affects the coronal alignment of the body posture to a greater extent rather than the sagittal alignment for the body posture.

8. Hip–Spine Syndrome

The concept of hip–spine syndrome, in which the spinal and hip diseases are related and/or concomitant, was first proposed in 1983 [24]. This syndrome was classified into 4 groups: simple, complex, secondary, or misdiagnosed hip–spine syndrome.

Subsequently, the association between spinal alignment and hip was studied. Nonetheless, it is necessary to evaluate hip pathology and spinal alignment in hip OA treatment [25].

In the coronal plane, spinal scoliosis shifts the center of the body gravity line, and the mechanical load increases on one side of the hip and results in hip pain of the affected side. In this situation, the compensatory mechanism of the pelvis is activated, with the gluteus maximus being responsible for the reciprocal movement of the spine and pelvis.

On the other hand, the sagittal alignment progresses to spinal kyphosis and pelvic retroversion with age. In such cases, the loading area of the acetabulum reduces and the load per unit area increases significantly; this is considered to be the mechanism of the progression of primary hip OA. When the hip develops a fixed flexion deformity, there may be an associated loss of LL. Thus, in patients with severe hip OA, the body trunk bends forward, resulting in low back pain and sagittal malalignment. In contrast, in acetabular dysplasia of the hip, which is one of the main causes of secondary hip OA, the front coverage area of the acetabulum remains anatomically small. Thus, the compensatory mechanism activates pelvic anteversion, leading to increased LL and SS [25] and eventually resulting in vertebral disk dislocation, foraminal stenosis, radiculopathy, and low back pain [26]. In this situation, the compensatory mechanism is not activated when the spine too undergoes degenerative changes and the hip OA may thus progress.

Since symptoms of lumbar radiculopathy of L3 root nerve greatly vary from thigh pain to hip and/or knee pain, they may appear similar to pain due to hip or knee OA [27]. Thus, lumbar disease might be mistreated as hip and/or knee diseases. Therefore, lumbar diseases should be considered in nonrespondents of hip and knee OA treatment [28].

9. Knee–Spine Syndrome

In the sagittal alignment, spinal kyphosis induces pelvic retroversion, hip extension, knee flexion, and ankle dorsiflexion as compensation mechanisms [12]. These mechanisms increase the load on the knee joint and lead the progression of knee OA.

A study evaluating compensatory mechanisms of knee OA in older patients reported that knee flexion in mild knee OA was mainly compensated with the lumbar spine to reduce LL and move C7 plumb line forward [29]. Moreover, sagittal balance was not compensated by the lumbar spine only in severe knee OA; the hip was flexed and the pelvis was anteverted with significant forward spinal inclination, resulting in an unbalanced status.

Spinal compensatory abilities are limited for knee flexion because older patients might have spinal deformity, and the flexibility of the spine may be poor [17, 29]. In this condition, the head goes forward, SVA increases, and sagittal malalignment leads to low back pain. Interestingly, knee flexion contracture can lead to loss of LL and anterior sagittal shift in young individuals without any spinal pathology, although it does not influence the pelvis [17].

Tsuji et al. described a correlation between sacral inclination and patella-femoral pain, which is related to changing of lumbar alignment as the knee–spine syndrome [30]. After that, the relationship between the knee and spine involving pelvis has been examined. Murata et al. also evaluated the correlation between the restriction of knee extension and loss of LL [31]. Lumbar malalignment is common in patients older than 70 years of age; however, such restriction of knee extension is predominantly found in patients older than 60 years of age. Therefore, knee OA may occur first, followed by spinal deformity. Harato et al. suggested knee flexion contracture significantly influenced three-dimensional trunk kinematics and would lead to spinal imbalance [32]. Moreover, Tauchi et al. demonstrated the relationship between increased spinal inclination and knee OA as the knee–spine syndrome [33].

10. Spinal Fusion Surgery and Alignment

Loss of LL with age is a common cause of sagittal malalignment of the spine. When the body trunk is located peripherally to the shape of the cone along with markedly increase SVA, surgical interventions with spinal osteotomy and fusion have been applied to improve the abnormal posture. Although the surgical algorithmic approaches for ASD have not been established, a postoperative SVA of <50 mm has been suggested as an optimal target [21, 34]. Aggressive correction of the malignment in older patients increases the risk of proximal junctional kyphosis and treatment failure. However, inflexible deformities generally require more aggressive approaches to achieve adequate correction. Thus, careful planning with operative alignment target and determining spinal flexibility are important to obtain successful outcomes [21].

11. THA and Alignment

Implantation of the acetabular cup in the ideal orientation is necessary to reduce edge loading and to avoid articular impingent; the malposition of prostheses in THA accelerates polyethylene wear and increases risk of hip dislocation. Traditionally, the anteroposterior view of the radiography has been applied to evaluate the cup positioning and implantation of the prosthesis within the safe zone. However, patients with normal standing cup orientation occasionally experience dislocation. Therefore, a new idea of the functional orientation of the acetabular cup has been developed recently, wherein the sagittal pelvic kinematics is involved [35, 36].

Pelvic retroversion progresses with age regardless of THA, and the risk of superior edge loading and anterior hip dislocation increases with hip extension. Patients with sagittal deformities are at an increased relative risk of dislocation and THA revision [37]. Moreover, spinal fusion following THA increases the risk of hip dislocation, particularly involving the fusion of the sacrum. Anterior impingement of the hip in deep hip flexion may be the risk factor for posterior THA dislocation while in stand up from the chair because the pelvis is surgically fixed [38–40]. Moreover, THA following spinal fusion is associated with a high risk of hip posterior dislocation because the pelvis is not posteriorly tilted, which may occur even in the sitting position [35].

Therefore, different reactions of the pelvis in individual patients need to be carefully considered during THA to prevent postoperative hip dislocation. More studies regarding cup positioning are necessary; however, restoration of normal sagittal balance and consideration of patient-specific pelvic kinematics are speculated to be critical [14, 36].

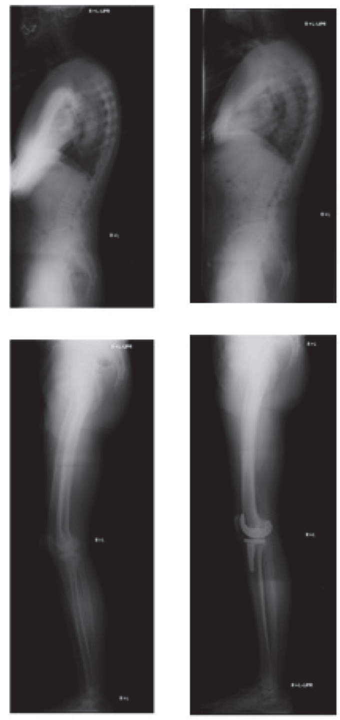
12. TKA and the Alignment

Muscle weakness of the lower extremities and restriction of knee extension in knee OA have been considered to be associated with loss of LL and abnormal posture [31]. However, malalignment of the lower extremities and limited range of motion of the knee, particularly extension, can be improved by TKA. Thus, effects of the spinopelvic alignment following TKA were evaluated, and SS was reported to increase postoperatively in the preoperative knee contracture of >10° [41].

Recently, effects of TKA on sagittal malalignment and variations in the alignment of the spine, pelvis, and lower extremity following TKA were assessed prospectively in our institution [42]. In the present study, the hip flexion was defined as the angle between the femoral shaft and vertical line in the standing position, and SVA ≤ 40 mm was considered normal. Patients with primary knee OA, who were scheduled to undergo primary TKA, were enrolled. However, patients with arthritis secondary to another etiology, such as rheumatoid arthritis, trauma, and previous surgical interventions to the knee, were excluded. Moreover, patients with hip and ankle OA, cranial nerve diseases, and severe spinal deformity were excluded. The study was approved by an institutional review board, and informed consent for participation was obtained from all patients. We observed different patterns of postural changes as well as hip and knee angles following TKA. Three typical cases are presented.

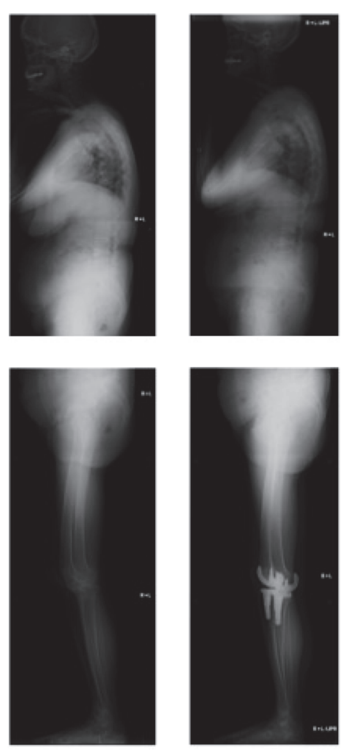
Maintained Normal SVA with the Extension of the Hip and Knee Joints. A case of 69-year-old man who underwent right TKA: the preoperative roentgenographic parameters of SVA, TK, LL, PI, PT, SS, hip flexion, and knee flexion were 14.8 mm, 34°, 40°, 52°, 20°, 32°, 7°, and 18°, respectively (Figure 1(a)). Preoperative SVA was normal and hip and knee joints were flexed while standing. At 12 months after TKA, the parameters of SVA, TK, LL, PI, PT, SS, hip flexion, and knee flexion became 0 mm, 35°, 45°, 55°, 23°, 32°, 1°, and 8°, respectively (Figure 1(b)). These results indicated that SVA remained normal with the extension of hip and knee joints. Some of the patients with the preoperative normal SVA showed that the hip and knee positions tended to extend, lumbar lordosis was decreased, and SVA was increased; however, SVA was still almost within the normal range after TKA.

Abnormal SVA in spite of the Extension of the Hip and Knee Joints. A case of 72-year-old woman who underwent bilateral TKA as a two-stage surgery: the preoperative parameters of SVA, TK, LL, PI, PT, SS, hip flexion, and knee flexion were 75.0 mm, 23°, 23°, 58°, 35°, 23°, 6°, and 17°, respectively (Figure 2(a)). Postoperative evaluations were performed after



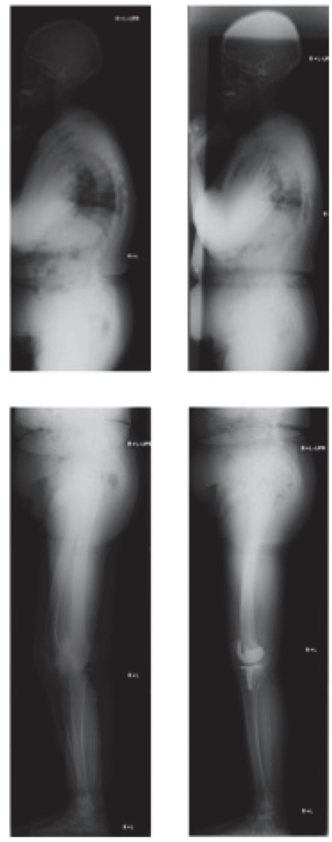
(a) (b)

Figure 1: A case of normal SVA with the extension of knee joint (a) before and (b) after the surgery.



(a) (b)

Figure 2: A case of improved abnormal SVA with the extension of knee joint (a) before and (b) after the surgery.



(a) (b)

Figure 3: A case of the improved SVA with the extension of hip and knee joints (a) before and (b) after the surgery.

19 and 6 months of right and left TKA, respectively. Postoperative parameters of SVA, TK, LL, PI, PT, SS, hip flexion, and knee flexion became 49.7 mm, 21°, 25°, 54°, 35°, 19°, 5°, and 10°, respectively (Figure 2(b)). Some of the patients with the preoperative abnormal SVA showed that the hip and knee tended to extend; however, pelvic posterior tilt was not improved and SVA was increased, or PT and SVA were increased.

Decreased SVA with the Extension of the Hip and Knee Joints. A case of 74-year-old woman who underwent left TKA: preoperative parameters of SVA, TK, LL, PI, PT, SS, hip flexion, and knee flexion were 70.5 mm, 58°, 57°, 58°, 25°, 33°, 8°, and 17°, respectively (Figure 3(a)). At 12 months after TKA, the parameters of SVA, TK, LL, PI, PT, SS, hip flexion, and knee flexion became 28.4 mm, 50°, 55°, 57°, 23°, 34, 4°, and 7°, respectively (Figure 3(b)). Thus, most patients with the preoperative abnormal SVA showed that the hip and knee became extended, lumbar lordosis increased, and pelvic posterior tilt decreased even after the short-time period of TKA.

Together, these data suggest that knee OA results in the knee flexion while standing. With the progress of knee OA, hip is flexed, pelvis is posteriorly tilted, and the spine is bent forward. However, once the restriction of knee extension is corrected and lower extremity alignment is improved following TKA, lumbar and pelvic parameters are affected even in patients with normal SVA before surgery. Moreover, preoperative abnormal SVA tends to decrease with changes in knee flexion and lumbar parameters as knee–hip–spine syndrome (Figure 4). Therefore, TKA may help recovered knee function and correct lower extremity alignment in severe knee OA as well as improving posture to prevent falls.

13. Knee–Hip–Spine Syndrome

The current THA and TKA strategies have been developing since 1960s. At that time, the longevities of the artificial prostheses were much shorter than those in recent years. However, there were surgeries indicated for older patients and the mean lifespan was much shorter than the present years. Thus, the surgeons only needed a short observation period of the affected site.

Recently, the longevities of prostheses and surgical procedures have dramatically improved. These surgeries have also been performed in younger patients, and generally the mean lifespan has become longer than before. Therefore, long-term follow-up is indispensable after the primary surgery. During this longer period, additional concomitant symptoms may occur with age followed by the original pathology. In

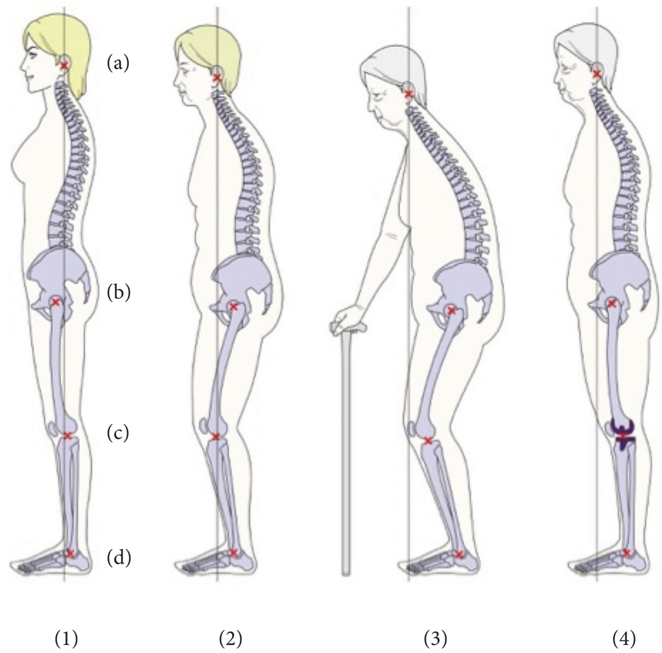


Figure 4: Age-related global postural changes. (a) The center of the acoustic meati, (b) the center of the hip, (c) the center of the knee, and (d) the center of the ankle. The vertical line shows the plumb line from the center of the acoustic meati. (1) The global alignment of the healthy subject. The plumb line from the center of the acoustic meati is close to the gravity line. The cervical and thoracic vertebrae are posterior to the gravity line. The lumbar vertebrae show lordosis, and L4 is anterior to the gravity line. The sacrum is posterior, and the hip center is anterior to the gravity line. The knee joint and ankle joint are posterior to the gravity line. (2) TK increases, LL decreases, and the pelvis tilts posteriorly while the hip, knee, and ankle flex. Consequently, the sagittal balance sifts anteriorly with age. (3) Older subjects show spinal kyphosis with the severe anterior shift of the sagittal balance. Consequently, the body balance is better maintained with support. (4) As the knee becomes extended and the lower extremity alignment is corrected with TKA, the global alignment and the sagittal balance can be improved.

addition to THA and TKA, reconstruction of the spinal alignment with the spinal long fusion has emerged as a new approach. Therefore, long-term follow-up after surgeries as well as additional treatments is essential for older patients with complex deformities of multiple structures to improve their QOL.

The spine, hip, and knee are anatomically connected, and all these structures undergo degenerative changes with age as ASD, hip OA, and knee OA. Clinically, pain and discomfort of the low back, hip, and knee are commonly occurring simultaneously, which are referred to as the knee–hip–spine syndrome. Occasionally, physicians misdiagnose and treat the wrong structures. The pendulum test is recommended to detect hip pathology from these symptoms to prevent misdiagnosis [43]. In addition, the abnormal posture occurs with ASD, hip OA, and knee OA. Treatments for the spine, hip, and knee are separated and specialized; however, physicians often carefully examine patients under the consideration with the knee–hip–spine syndrome as differential diagnosis.

At present, physicians often face new challenges of treating the complex multiple degenerative structures or additional degenerative changes following the changes to the primary affected structure. Thus, it is necessary to understand the knee–hip–spine syndrome and to elucidate the etiologies and compensatory mechanisms of the spine, hip, and knee, individually.

14. Conclusion

Musculoskeletal structures are interconnected, and pathologies of these structures are collectively referred to as the knee–hip–spine syndrome. Thus, when each structure is treated, its effect on the entire body must be considered. In this article, we reviewed the association between knee, hip, and spine, and our findings may be helpful for orthopaedic surgeons to bridge the gap between the treatments of these structures.

Abbreviations

QOL:	Quality of life
ASD:	Adult spinal deformity
hip OA:	Osteoarthritis of the hip
THA:	Total hip arthroplasty
knee OA:	Osteoarthritis of the knee
TKA:	Total knee arthroplasty
SVA:	Sagittal vertical axis
TK:	Thoracic kyphosis
LL:	Lumbar lordosis
PI:	Pelvic incidence
PT:	Pelvic tilt
SS:	Sacral slope.

Data Availability

Aggregate data are included in the results section. Please contact the corresponding author for raw data, including individual ratings.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Research Article

A Preoperative Analytical Model for Patient-Specific Impingement Analysis in Total Hip Arthroplasty

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Prosthetic impingement is important to consider during total hip arthroplasty planning to minimise the risk of joint instability. Modelling impingement preoperatively can assist in defining the required component alignment for each individual. We developed an analytical impingement model utilising a combination of mathematical calculations and an automated computational simulation to determine the risk of prosthetic impingement. The model assesses cup inclination and anteversion angles that are associated with prosthetic impingement using patient-specific inputs, such as stem anteversion, planned implant types, and target Range of Motion (ROM). The analysed results are presented as a range of cup inclination and anteversion angles over which a colour map indicates an impingement-free safe zone in green and impingement risk zones in red. A validation of the model demonstrates accuracy within +/- 1.4° of cup inclination and anteversion. The study further investigated the impact of changes in stem anteversion, femoral head size, and head offset on prosthetic impingement, as an example of the application of the model.

1. Introduction

Dislocation is one of the most common complications leading to revision surgery after Total Hip Arthroplasty (THA), accounting for almost one-quarter (21%) of all revision procedures [1]. Component mal-positioning has long been recognised as a major cause of dislocation [2–5]. Although spontaneous dislocation can occur due to poor soft tissue balance, prosthetic impingement, due to mal-positioned components, commonly precedes dislocation.

In a cup retrieval study performed by Marchetti et al., 80% of cups revised due to dislocation showed evidence of prosthetic impingement [6]. Recurrent prosthetic impingement between the femoral neck and acetabular liner can cause severe component wear due to the high stress concentration at the impingement site, producing wear debris [7]. This wear debris may result in an increased risk of osteolysis [8]. In Marchetti et al.'s study, prosthetic impingement was observed in all retrieval groups including loosening, infection, osteolysis and miscellaneous cases, highlighting the importance of an impingement-free motion to the clinical outcome of THA. Due to the numerous undesirable effects of early impingement on the stability and longevity of the prosthetic hip, it is deemed necessary to place the components in a position that avoids prosthetic impingement whilst allowing maximum hip range of motion (ROM).

Acetabular "safe zones" have been introduced by various authors to assist with cup alignment and to minimise postoperative complications. Well-known safe zones, such as those published by Lewinnek [4], Esposito et al. [9], and Callanan et al. [10] are often used as gold standard in THA. However, despite the implementation of these "safe zones", postoperative dislocation rates remain the same [11]. In contemporary clinical studies, combined anteversion of the acetabular and femoral components, and not cup orientation alone, has been correlated with dislocation [12–15]. These more recent investigations have emphasised a need for an individualised target for cup orientation rather than a generic range applicable to all patients.

Motion capture, laboratorial simulators, and computational models are common methods of measuring range of motion of the hip [16–18]. These traditional methods can provide accurate analyses of the ROM of the hip with live subjects, generic bone models, or patient-specific bone models. However, these analyses are resource- and time-consuming and require significant setup. It is for these reasons that the above-mentioned methods are unviable for preoperative or intraoperative investigation on a large scale.

An analytical ROM model has been proposed by Yoshimine et.al. [19] and Hisatome & Doi [2] to calculate theoretical prosthetic impingement of the hip. Analytical models are faster to run and require less prework compared to traditional methods. However, analytical models are limited by their simplicity and key assumptions limit the accuracy of the model. The ROM model described in this study utilises a combination of computational simulations and analytical methods, which are accurate and efficient to run.

The aim of this study is to develop and validate a robust and accurate analytical model to assess the cup inclination and anteversion angles that are associated with prosthetic impingement using patient-specific inputs.

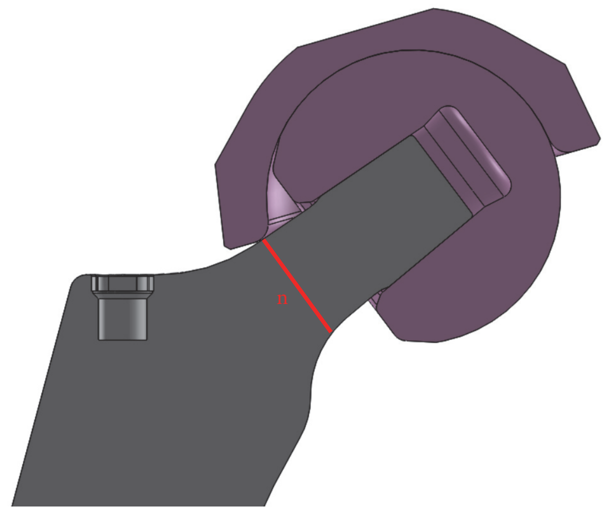

Figure 1: Stem neck width (n) at the impingement level.

2. Method

2.1. Model Development. Hisatome and Doi proposed a mathematical formula to calculate the theoretical range of motion using seven factors including head radius (r), cup depth (d), cup inclination (α) and anteversion (β), stem neck angle from the transverse plane (a), stem anteversion (b), and neck width at the impingement level (n) [2]. The first six factors are defined from implant design drawings and measurements. The last factor, neck width at the impingement level, varies for different stems and at different impingement positions. Hisatome and Doi assume all stem necks are cylindrical in shape, i.e., that neck width is a constant value at all stem positions. However, the neck width varies significantly in modern trapezoidal stem designs, and the assumption of a constant neck width will significantly affect the model accuracy. The model presented in this study improves on Hisatome and Doi's work by considering neck width as a variable that differs for different stem types and impingement positions.

Hisatome provided a mathematical formula to calculate the prosthetic hip range of motion in certain activities, i.e., pure flexion, extension, internal rotation at 90° flexion, and external rotation. The impingement model in this study allows for customised inputs to define the target ROM test conditions. The proposed model offers two combined target ROM conditions: (1) user-defined degree of Internal Rotation (IR) at any Flexion (FL) and (2) user-defined degree of External Rotation (ER) at any Extension (EX). The IR_FL test is associated with anterior prosthetic impingement in flexion, and the ER_EX test is associated with posterior prosthetic impingement in extension. The derivation of how to calculate the cup orientations that satisfy the user-defined target ROM (IR_FL and ER_EX) is detailed in the Appendix.

An automated computational simulation is used to calculate the stem neck width (n) at the impingement level (Figure 1) in Solidworks (Dassault Systèmes, US). The 3D geometry of the acetabular and stem components are imported into Solidworks. The centre of rotation of the acetabular and stem components are placed at the origin of the assembly. The stem component is placed at −40° to 60° of anteversion in 20° increments and 6° of natural femur adduction. The stem component is simulated to perform flexion/extension and then internal rotation/external rotation. The acetabular component can rotate about the stem component in a range of 0° to 60° inclination and anteversion. The cup orientation is measured using Murray's radiographic definitions [20]. The automated simulation records the cup inclination and anteversion angles, and the stem neck width when any collision is detected. The results are saved in a database for use in the proposed model.

Even with an automated simulation, and running only discrete values of stem anteversion, this is a time-consuming process. In order to run the impingement analysis at any stem anteversion, 'Thin Plate Spline Interpolation' was used to calculate the neck width at all cup and stem positions, utilising the simulated neck width values. The simulated data was plotted with cup inclination and anteversion on the X and Y axes, and neck width on the Z axis in Matlab (Mathworks, US) (Figure 2). Through the interpolated surface, the stem neck width can be calculated for any given cup and stem position in all cases with the same implant type. By utilising the neck width simulator and surface interpolation combined, the neck width at any given cup and stem position can be simulated robustly and accurately. The simulated neck width can then be placed in the formula given in the Appendix and cup orientations that satisfy the target ROM conditions can be calculated. The cup inclination and anteversion which fulfil the target ROM conditions are plotted as impingement boundaries. For ease of visualisation, the area that satisfies the ROM conditions is displayed in green and the area that does not satisfy the ROM conditions is displayed in red.

The proposed impingement model generates two impingement boundaries for any given set of target ROM conditions (IR@FL and ER@EX). Figure 3 illustrates an example of the output of the model with impingement

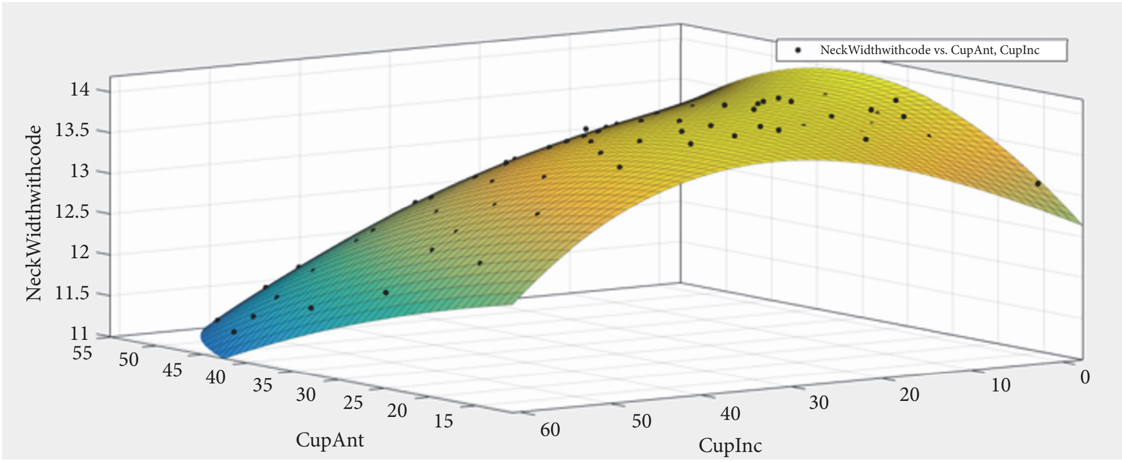

Figure 2: Surface interpolation of stem neck width.

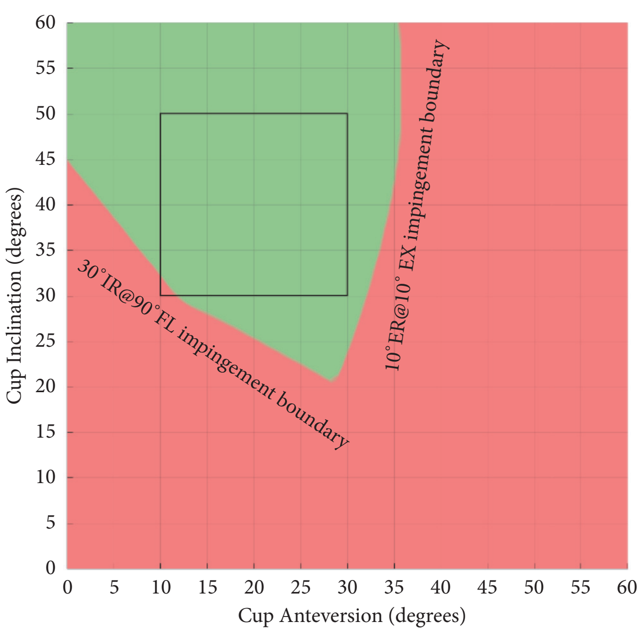

Figure 3: Impingement plot at 30° IR @ 90° FL and 10° ER @ 10° EX.

testing condition of 30°IR@90°FL and 10°ER@10°EX. The diagonal curve represents the 30°IR@90°FL impingement boundary. Cup orientations on the left-hand side of this boundary are at risk of prosthetic impingement in flexion. The vertical curve represents the 10°ER@10°EX impingement boundary. Cup orientations on the right-hand side of this boundary are at risk of prosthetic impingement in extension. The green cup orientations between these two boundaries satisfy the impingement conditions tested, and no impingement is detected. The cup orientations in red do not satisfy the impingement testing conditions as impingement is detected. A square black box is drawn on the graph for ease of comparison to the coloured area. The box highlights an area with 10° to 30° of cup anteversion and 30° to 50° of cup inclination which overlaps with commonly accepted cup positions [4, 10, 21].

Using the formula proposed in the Appendix, the cup orientations that satisfy any target ROM conditions can be calculated. The proposed model was investigated with the target ROM of 30°IR@90°FL and 10°ER@10°EX as an example. In order to test the application of the model in preoperative planning scenarios, three parameters (stem anteversion, femoral head size, and femoral head offset) were investigated to see how each parameter affects the prosthetic ROM. All other input parameters were set to the default values: neck-shaft angle = 125°, stem flexion = 0°, and stem adduction = 6°.

2.2. Model Validation. An alternative CAD model was used to verify that the proposed analytical model can accurately calculate the cup inclination and anteversion at impingement. The worst-case implant combinations that would provide the least accurate results were selected to validate the proposed model.

The worst-case implant size was determined with a combination of maximum head size which engaged with the shortest head offset. This resulted in the impingement to occur at the most lateral position of the stem (i.e., closer to the stem shoulder and therefore with the greatest difference in stem neck geometry (Figure 4)). This gives results furthest from the simulated impingement boundaries and therefore is the worst case for the accuracy test. The proposed model utilises the impingement boundaries in the neck width database, which was generated using 20° increments of stem anteversion, and then interpolated the impingement boundaries for other stem anteversions using the Thin Plate Spline Interpolation. Stem anteversions which would result in maximum deviation on the interpolated solution were selected for testing. It was hypothesised that the maximum deviation on the interpolated solution lies at the point which is the maximum distance away from any two exact solutions from the interpolation. The stem anteversion was placed at −40°, −20°, 0°, 20°, 40°, and 60° in the neck width database,

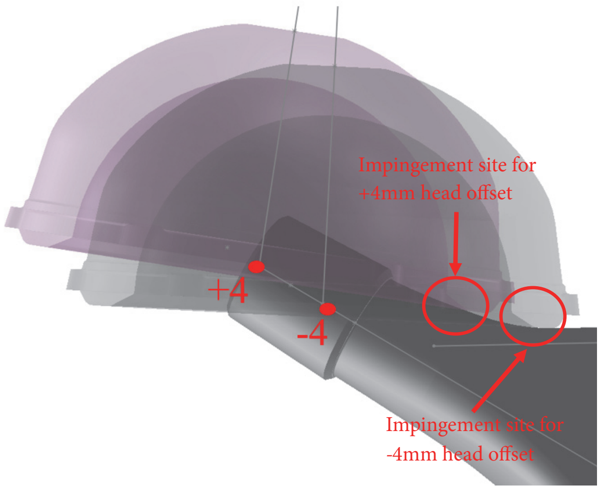

Figure 4: 40mm polyethylene liner engaging at -4mm head offset compares to engaging at +4mm offset.

Table 1: Maximum difference in cup orientation, at impingement in flexion and impingement in extension, between the proposed impingement model and an independent CAD model.

	Cup Anteversion	Cup Inclination
Maximum difference in flexion	1.1°	1.4°
Maximum difference in extension	1.4°	1.0°

Table 2: Neck width range for four stems investigated in this study.

Stems	Neck width range in mm (Avg)
Stem 1	11.3 – 22.2 (14.7)
Stem 2	10.9 – 17.3 (13.5)
Stem 3	11.0 – 18.2 (13.7)
Stem 4	10.9 – 20.3 (13.7)

and thus stem anteversions −30°, −10°, 10°, 30°, and 50° were selected for the accuracy test.

The implant geometries were imported into Solidworks and placed at the positions defined above. The liner was free to rotate about its centre of rotation. Using the interference detection function in Solidworks, the cup inclination and anteversion at which the acetabular component impinges with the stem can be recorded. The recorded cup inclination and anteversion in Solidworks were compared with the simulated results to determine the accuracy of the proposed model.

3. Results

The accuracy of the analytical model was assessed against the CAD model with worst case implant combinations. The cup orientation boundaries that were created by the proposed model and the CAD model were compared. The results show the maximum difference between the two models is 1.4° in both cup inclination and anteversion (Table 1).

In order to show how the neck width can vary at different impingement levels on the neck, four different stems were analysed within the neck width database. As shown in Table 2, the stem neck width varies significantly with different impingement locations. This suggests that using a constant neck width value is too simplistic to provide an accurate impingement analysis. The proposed model utilised a combination of an automated simulator and surface interpolation to create a database containing the neck width of the stem. Substituting the neck width database into the mathematical formula allowed the quick analysis of the prosthetic impingement model. By gaining computational efficiency in this way, the model can be used as an accurate preoperative planning tool or as a general tool to study how implant parameters impact the prosthetic ROM.

Figures 5–7 demonstrate how the prosthetic impingement can be impacted by stem anteversion, femoral head size, and femoral head offset using Stem 2 from Table 2 as an example. Similar trends can be observed with other types of stems which have a trapezoidal neck design.

As can been seen from Figure 5, as the stem anteversion increases, the impingement-free (green) zone shifts towards the low cup anteversion area, suggesting high stem anteversion must be combined with low cup anteversion in order to reduce the risk of prosthetic impingement, and vice versa. There is no significant difference in the area of the green zone at each stem anteversion. This finding agrees with the combined anteversion concept which states radiographic cup anteversion and stem anteversion are linearly correlate [2, 22, 23]. This further highlights the point that an acetabular safe zone should not be considered independent of stem anteversion.

The impingement safe zone generated by the proposed model is also affected by femoral head size. As the femoral head increases, the green zone gets larger, suggesting that a larger femoral head results in more cup component positions which satisfy the impingement testing condition (Figure 6), when all other parameters are kept constant. This agrees with previous studies that suggest that larger femoral head sizes allow for a wider range of acceptable implant orientations [24]. With a 40 mm head, the impingement-free area increases significantly compared to smaller heads. Other factors, such as wear rate and trunnionosis, should also be taken into account when selecting head sizes. Based on the implants assessed in this study, a 28 mm head should be avoided where possible as the impingement-free area decreases significantly.

Femoral head offset is a common parameter to consider when planning patient's leg length, offset, or soft tissue tension during THA. However, it can be overlooked during impingement analysis. The proposed model allows the impact of different head offsets on the prosthetic impingement to be considered. In the case of the stem tested (Stem 2), short (-4mm) and extra-long (+8mm) head offsets showed a smaller impingement-free zone (green area) compared to neutral (+0mm) and long (+4mm) head offsets (Figure 7), especially in the common cup orientation range (highlighted in black

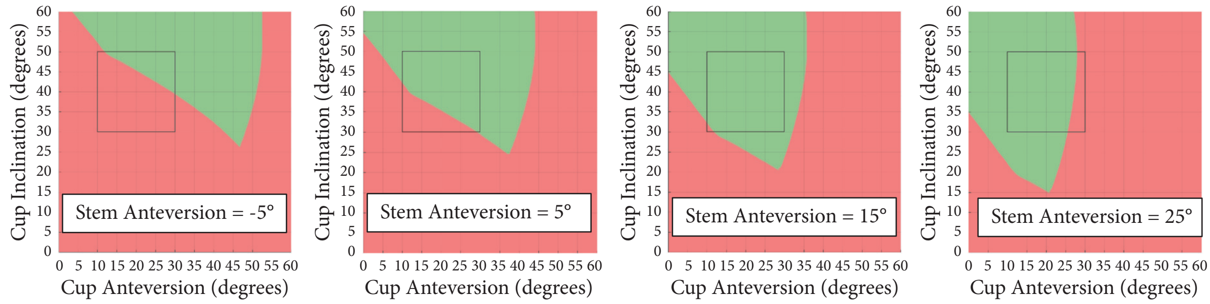

Figure 5: Impingement with different stem anteversion for Stem 2.

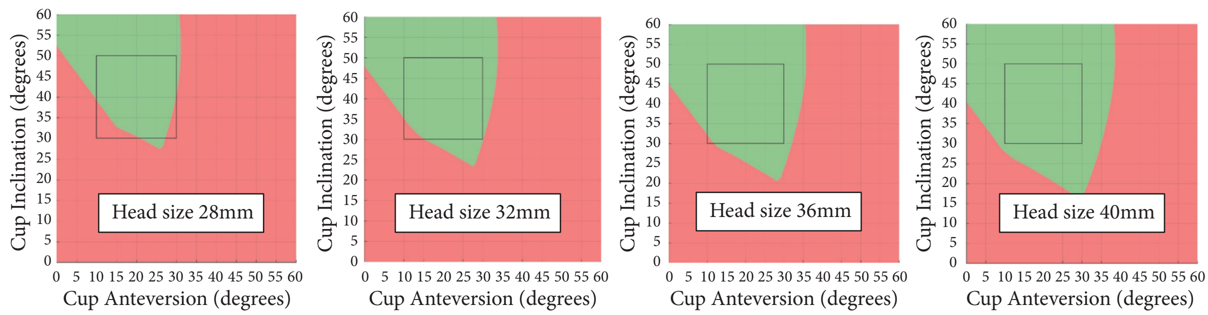

Figure 6: Impingement with different head sizes. At stem anteversion of 10° for stem 2.

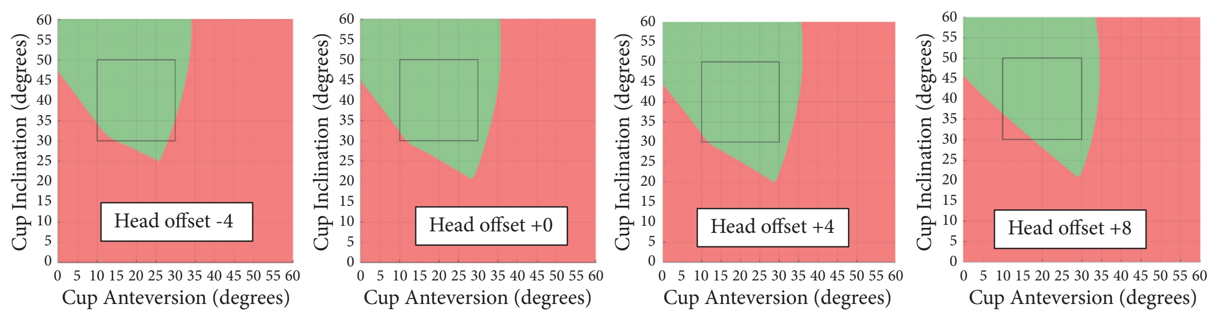

Figure 7: Impingement with different head offset for stem 2.

box). The femoral head offset is related to the stem neck width at the impingement level. Generally speaking, the shorter the offset, the wider the neck width at the impingement site, and consequently the smaller the hip range of motion (earlier impingement). However, in the case of extra-long (+8) head offset, impingement occurs at the level of the stem trunnion, which is usually wider than the stem neck. This results in extra-long head offset being less favourable than standard or long head options when trying to maximise prosthetic ROM (Figure 8).

4. Discussion

The present study introduced an analytical model for analysing prosthetic impingement in THA. The model involves a mathematical formula in combination with an automated neck width simulator which allows the model to take into account implant-specific neck width variations to accurately determine optimal cup orientations that are free from risk of prosthetic impingement. The model requires a one-off pre-generation of the neck width profile database for the stem of interest using the automated neck width simulator prior to the use of the model. Combined with the pre-generated neck width database and the proposed formula, the model is able to provide a zone of cup orientations that satisfy any user defined flexion and extension testing conditions, combined with any internal rotation or external rotation. The output of the model is presented as a colour map for ease of visualisation.

Even though the proposed model is capable of testing the prosthetic impingement at any user defined target ROM conditions, the question of which target ROM suits each individual patient is yet to be solved. Different target ROMs have been suggested by different groups. Incavo et al. studied passive ROM of eight cadaveric hips and suggested subjects can reach an average of 20° in extension and 24° in external

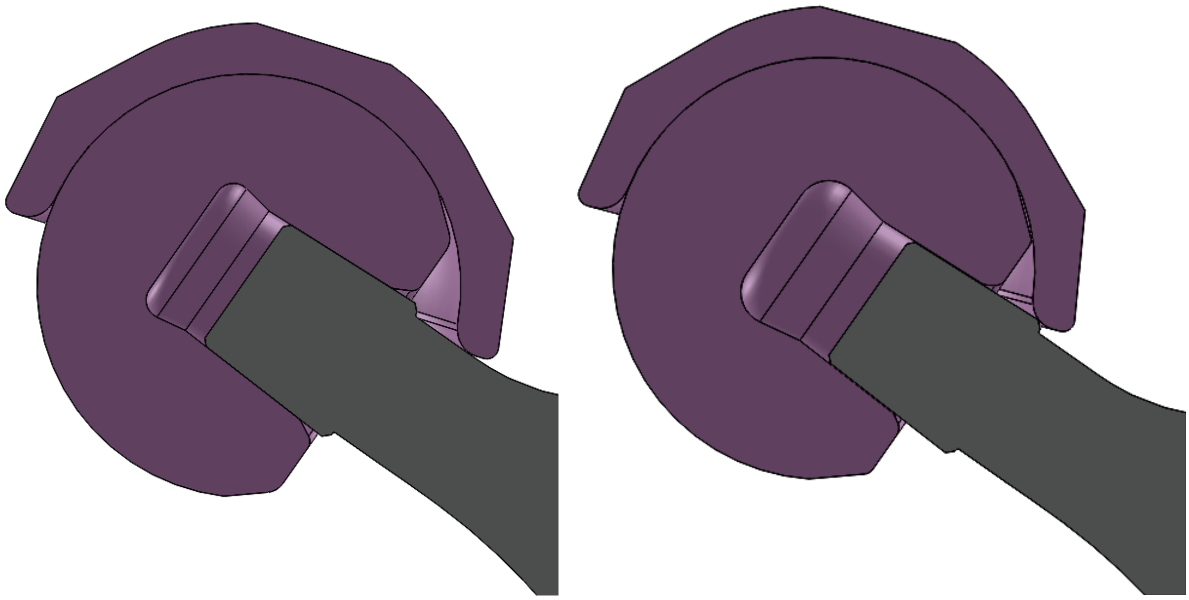

Figure 8: (Left) Liner impinges at stem neck with a +4mm offset head. (Right) Liner impinges at stem trunnion with a +8mm offset head.

rotation [25]. Similar cadaveric studies conducted by Miki et al. reported passive movement of the femur can reach up to 113° in flexion, 75° of internal rotation, 34° in extension and 36° of external rotation [26]. Only single movement and no combined movement of the femoral component were conducted in both studies. Yoshimine et al. [19] provided their combined motion ROM formula with 45° of internal rotation at 90° flexion, and Hisatome & Doi's [2] model is built based on 60° of internal rotation at 90° flexion. Both models use 30° of extension for their posterior impingement test; no combined extension and external rotation was tested. The combined motion tested in this study (30°IR@90°FL and 10°ER@10°EX) is smaller than suggested by previous authors for the following two reasons: (1) the neck width simulated from the actual stem geometry in our model is much larger than 10 mm (used in both Hisatome and Yoshimine's model). This results in fewer cup orientations that can satisfy the target ROM in our model. This also highlights the sensitivity of the stem neck width on the available ROM. The neck width of the actual stem should be used for more accurate results. (2) The previous studies suggested target ROMs were based on the results from cadaveric hips or intraoperative navigation data which did not isolate the femoral movement; i.e., pelvic movement was not taken into account during measurement of the femoral ROM. This results in overestimation of the femur movement as some of the movement observed should be attributed to the pelvis. The proposed model can accommodate different combined target ROM and was tested with 30° IR @ 90° FL, 10° ER @ 10° EX. Having customisable target ROM conditions enables the tool to accommodate inputs and test conditions on a patient-specific basis.

Similar to findings from previous studies, our model also highlights the importance of considering combined anteversion of the acetabular and femoral components. Widmer provided a simplified formula to achieve optimal ROM which suggests the sum of cup anteversion and 0.7 times the stem anteversion should be equal to 37° [22]. Similarly, Hisatome and Doi used their model and suggested cup anteversion and 0.7 times the stem anteversion should equal to 42° [2]. Other authors such as Jolles et al. and Dorr et al. suggested target ranges for combined anteversion which are 40°-60° and 25°-50°, respectively [12, 23]. Despite the various mathematical formulae or guidelines recommended in these studies, there is still a lack of general consensus of an optimal combined version. This is because the optimal combined version is multifactorial. As suggested in this study, stem version, head size, neck offset, and stem types (specifically neck width and neck angle) can all impact which cup orientations satisfy the targeted ROM. The impingement-free cup orientations determined by this model are customised for each individual and for the implant types/sizes modelled. The proposed analytical model allows different implants and positions to be input into the model and robustly calculates the range of impingement-free cup orientations.

There are a few limitations to the proposed model. First, the neck width simulator requires the specific implant geometry to be analysed prior to use. This limits the model to be used only with the implants available in the pregenerated database. More implants can be added into the database upon availability of the implant geometry. Secondly, the combined motion provided in this model is limited to the two mentioned above (IR@FL and ER@EX). Abduction and adduction of the femur were not considered in this model as it was believed that the amount of abduction and adduction was small during daily activities such as sitting and walking, in comparison to the other movements. Lastly, it is acknowledged that the functional outcome of a THA is multi-factorial and not only based on risk of

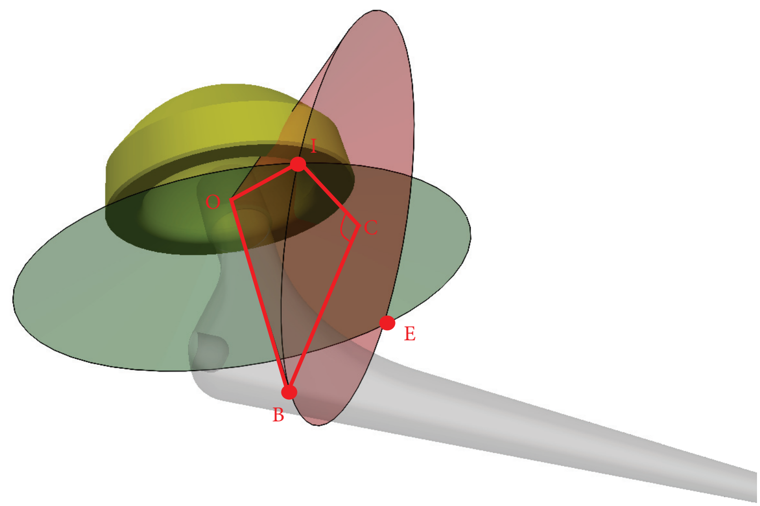

FIGURE 9: Cup cone and stem cone overlap. ∠BCI is the maximum internal rotation angle at the defined flexion angle.

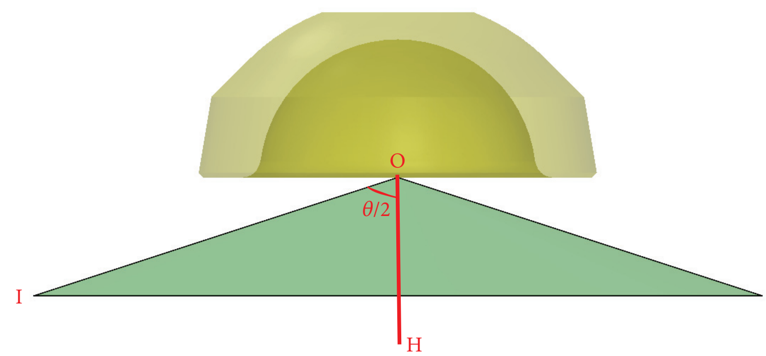

FIGURE 10: Cup cone.

prosthetic impingement. The cause of other phenomena, such as bony impingement, contact joint force, and component wear, will also significantly impact the functional outcome and longevity of the THA [9, 15, 27]. The proposed model should not be used in isolation, but rather, it should be used in combination with other analysis tools for preoperative THA planning.

This study describes an analytical model that determines a cup orientation "safe zone" for avoiding prosthetic impingement, based on accurately derived implant parameters. The model tests combined rotations of flexion/internal rotation and extension/external rotation, the limits of which can be customised. The model has demonstrated improved accuracy over other published impingement models and can be used as an investigational tool to assess the impact of varying implant parameters, in additon to preoperative planning in THA.

Appendix

The concept of creating the IR_FL formula is to calculate the maximum rotation of the stem at a defined degree of flexion via finding the intersection point I (INTRflx, INTRfly, INTRflz) of the cup rotation cone and stem rotation cone (Figure 9). The cup rotation cone is a right circular cone with a unit generatrix which is formed by rotating the stem component inside the cup. The orientation of the cup cone changes with changes in cup inclination and anteversion angle (Figure 10). By applying vector analysis to the cup cone, we can get the following two equations:

$$|I| = \mathrm{INTRflx}^2 + \mathrm{INTRfly}^2 + \mathrm{INTRflz}^2 = 1 \tag{A.1}$$

$$\begin{aligned}&\mathrm{INTRflx} * \sin(\beta) + \mathrm{INTRfly} * \sin(\alpha) * \cos(\beta)\\&\quad - \mathrm{INTRflz} * \cos(\alpha) * \cos(\beta) = \cos\left(\frac{\theta}{2}\right)\end{aligned} \tag{A.2}$$

where α and β are cup inclination and anteversion, respectively. θ is the oscillation angle which can be calculated by $\theta = 360^\circ - 2*\sin^{-1}(\mathrm{n}/2\mathrm{r}) - (180^\circ - 2*\sin^{-1}((\mathrm{r}-\mathrm{d})*\mathrm{r}))$, where n is the neck width, r is the head radius, and d is the head centre offset from the liner centre.

The stem rotation cone is another right circular cone with a unit generatrix formed by rotating the stem at defined

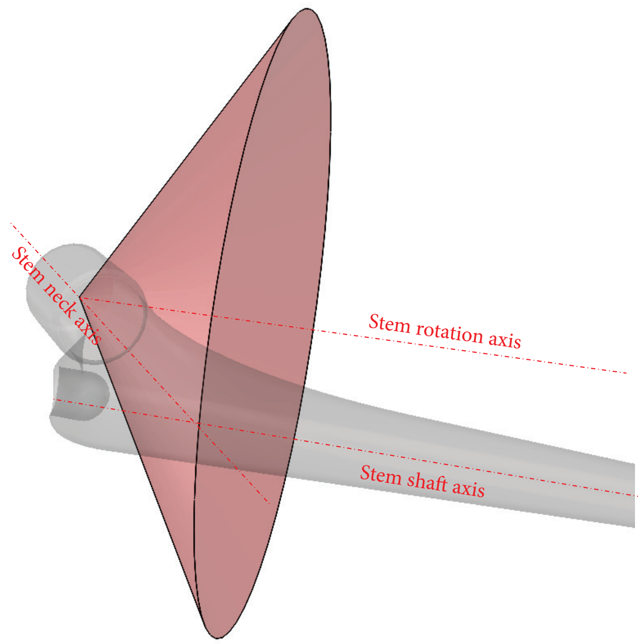

Figure 11: Stem cone.

flexion angle (Figure 11). By applying vector analysis to the stem cone, we can get the following equation:

$$\mathrm{INTRflx} * \sin(\mathrm{FL}) - \mathrm{INTRflz} * \cos(\mathrm{FL}) = \sin(a) \quad (A.3)$$

where a is the angle between stem neck axis to transverse plane.

The maximum internal rotation angle is equal to $\angle BCI$, where B is the initial position of the stem and C is the base centre of the stem cone (Figure 9). By solving (A.1), (A.2), and (A.3) simultaneously, the coordinates of I (INTRflx, INTRfly, INTRflz) can be solved. Subsequently, $\angle BCI$ can be calculated and this is the maximum internal rotation (Max_IR) of the stem before impingement occurs.

$$\begin{aligned}\mathrm{Max\_IR} &= \angle \mathrm{BCI} \\ &= \operatorname{acos}\Big(\big((\mathrm{INTRflx} - \sin(a) * \sin(\mathrm{FL})) * (\sin(a) * \sin(\mathrm{FL}) - \cos(a) * \sin(b) * \cos(\mathrm{FL}) - \sin(a) * \sin(\mathrm{FL})) \\ &\quad + \mathrm{INTRfly} * \cos(a) * \cos(b) + (\mathrm{INTRflz} + \sin(a) * \cos(\mathrm{FL})) * (-\cos(\mathrm{FL}) * \sin(a) - \sin(\mathrm{FL}) * \cos(a) * \sin(b) + \sin(a) * \cos(\mathrm{FL}))\big) \times \big((\cos(a))\ \hat{}\,2\big)^{-1}\Big)\end{aligned} \quad (A.4)$$

where a is the angle between stem neck axis to transverse plane and b is the angle between stem neck axis to coronal plane which projected onto transverse plane (stem anteversion).

The same concept can be applied to calculate the maximum external rotation of the stem at any defined extension angle.

$$\begin{aligned}&\mathrm{Max\_ER} \\ &= \operatorname{acos}\Big(\big((\mathrm{EXTRexx} + \sin(a) * \sin(\mathrm{EX})) * (-\sin(a) * \sin(\mathrm{EX}) - \cos(\mathrm{EX}) * \sin(b) * \cos(a) + \sin(a) * \sin(\mathrm{EX})) \\ &\quad + \mathrm{EXTRexy} * \cos(a) * \cos(b) + (\mathrm{EXTRexz} + \sin(a) * \cos(\mathrm{EX})) * (-\cos(\mathrm{EX}) * \sin(a) + \sin(\mathrm{EX}) * \sin(b) * \cos(a) + \sin(a) * \cos(\mathrm{EX}))\big) \times \big((\cos(a))\ \hat{}\,2\big)^{-1}\Big)\end{aligned} \quad (A.5)$$

where Max_ER is the target maximum external rotation defined by the user and EX is the target extension angle defined by the user. EXTRexx, EXTRexy, and EXTRexz are the coordinates of intersection point of the cup rotation cone and stem rotation cone when stem is in extension, a is the angle between stem neck axis to transverse plane, and b is the angle between stem neck axis to coronal plane which projected onto transverse plane (stem anteversion).

Data Availability

The data used to support the findings is contained within the article.

Conflicts of Interest

The author or one or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article.

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Review Article

A Dynamic Model of Hip Joint Biomechanics: The Contribution of Soft Tissues

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Guest Editor: Nobuyoshi Watanabe

Before recent advances in computer modeling technology, it has been nearly impossible to define the contribution of soft tissue structures when constructing models of the body, and in particular the lower extremity. For almost 100 years, the design and fixation of femoral components for total hip arthroplasty (THA), whether cemented or press fit, have been predicated on the Koch model of hip biomechanics. A more comprehensive model, which includes the dynamic contribution of soft tissues, has expanded the Koch's static model. This new model has led to a more complete representation of reality and has become the basis for the inclusion of a new stem design element (a lateral flare), a new concept of implant fixation (rest fit), and consequent significant increase in bone preservation and implant stability.

1. Introduction

It has been long recognized that soft tissues, such as ligaments and muscle-tendon units, are important stabilizing structures of articulations. However, the exact magnitude and character of their contribution have been the subject of much controversy. Historically, paradoxes have been recognized in the articulations of the lower extremity which have dramatized this issue. For example, if osteoarthritis (OA) is considered to be a "wear and tear" process, the incidence of OA in the joints of the lower extremity should be proportional to load/unit area (L/A) over time. Since the hip, knee, and ankle are exposed to an identical number of cycles of load and carry approximately the same body mass, the relative incidence of OA in each of these articulations, over time, should be proportional to their relative size. However, it has been universally recognized that the knee, the largest of these articulations, is the most frequently undergoing arthroplasty; and the ankle appears, unless its architecture has been disrupted, virtually immune to OA over a lifetime of use. Implicit in this reality is the conclusion that OA is more than a L/A phenomenon.

In its most basic form OA is the consequence of compromise of the integrity of the surface layer of the articular cartilage. This leads to a loss of the unique hydrostatic, frictionless nature of intact articular movement. Stability of an articulation protects an articular surface from excessive frictional wear. As such the incidence of OA will be inversely proportional to the stability of a given articulation, with stability being provided by a combination of geometry and soft tissue stabilizers crossing a given joint.

In this manner, it is predictable that the incidence of OA occurring in the geometrically unstable knee joint consisting of two large round condyles of the distal femur resting on a flat tibial plateau knee joint will be greater over time than that in the very geometrically stable ankle, where the talus is keystoned into the mortise of the ankle.

In addition to bony geometry, articulations are also stabilized by the soft tissues crossing that joint. For each plane of movement, these soft tissue structures can be subdivided into couples composed of a static (ligamentous) component and a dynamic (muscle-tendon) component. In this fashion it is apparent that the knee is much more dependent upon soft tissues for stability than is the ankle. It further explains why the relatively smaller ankle becomes so rapidly compromised and arthritic following unrepaired disruption of the syndesmosis ligament.

This importance of soft tissue stabilizers and their consequence for the loading of the lower extremity articulations have been of great consequence in the understanding and treatment of many conditions of the hip joint. In 1917, John Koch published his model of hip biomechanics [1]. It was to become accepted as the definitive model of the hip and lower extremity, for the next century. This model became the basis for the design of femoral implants employed in millions of hip arthroplasty surgeries performed around the world. Although intuitively attractive, this static model was plagued with many internal contractions and paradoxes.

It correctly assumed that the body's center of gravity (COG) was located in the midline of the body, 1 cm anterior to the first sacral segment. From this point the effect of gravity on the lower extremity was represented by a vertically oriented, downward directed vector. From these assumptions, it was proposed that during *unilateral stance* the weight of the body (B) would create both a compressive and varus load on points along the entire lower extremity. It further suggested that the magnitude of this varus deforming force acting at any point along the lower extremity could be calculated by multiplying the vector force created by gravity (body's weight) by its perpendicular medial displacement from that point along the lower limb (b), or B x b. It further hypothesized that this destabilizing torque must be counterbalanced by an equally strong valgus torque in order to maintain a stable equilibrium state during the gait cycle.

When Koch applied this analysis to the hip joint, he assumed the counterbalancing valgus torque would be supplied by isometric contraction of an abductor muscle (A), specifically the gluteus medius. He further assumed that the average length of the body's lever arm (b) from the center of the hip's rotation was approximately twice that of the length of the abductor's insertion on the lateral aspect of the greater trochanter to the center of hip rotation (a), b = 2a.

From these assumptions, Koch wrote the equation for hip stability as B x b = A x a. And since b = 2a, he concluded that the gluteus medius must generate twice the weight of the body force, 2 x B, in order to maintain a stable equilibrium during unilateral stance. (Figure 1).

However, a more critical examination of Koch's assumptions must be undertaken before accepting his model as an accurate depiction of reality and in particular events occurring during gait.

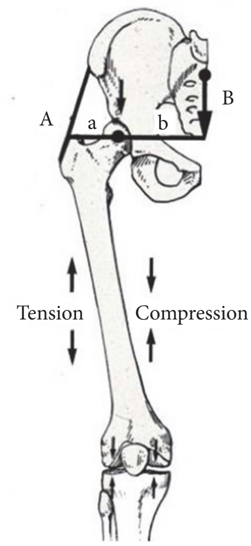


Figure 1: The Koch model of hip biomechanics (1) is static cadaveric model, (2) demonstrates his hypothesis of hip loading, and (3) requires the gluteus medius to exert a force twice that of the body's weight in order to maintain equilibrium during single stance.

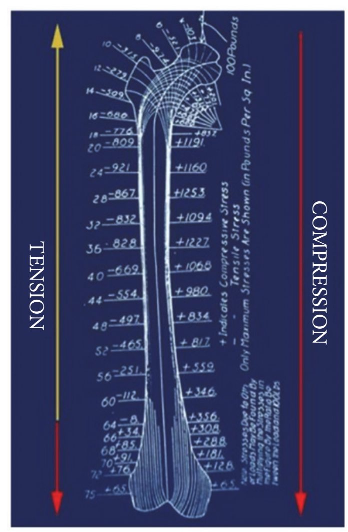


Figure 2: Koch's "quantification" of forces within the femur [1]. According to the Koch Model, during unilateral stance, (1) most of the lateral cortex experiences tensile loading and (2) the distal 1/3 of the lateral cortex and entire medial cortex experiences compression.

2. History of Hip Biomechanics

To begin with, Koch's model is static, unlike the conditions that occur during gait, where the body's center of gravity usually remains medial to the supporting foot in a dynamic equilibrium. Secondly, Koch limits the source of resistance to the body's varus load to a single structure, the gluteus medius. These two factors have dramatic consequences for conclusions drawn from the Koch model. The most important of them is the conclusion that, below the insertion point of the gluteus medius, the entire lateral aspect of the lower extremity experiences a tensile load. Koch went so far, in his original article, as to attempting to qualify the loads experienced by the femur during unilateral support. He used positive integers to represent compressive forces and negative integers to designate areas of tensile loading (Figure 2). Intuitively, it can be understood that he labeled the entire medial aspect of the femur as experiencing compressive loading. However, curiously he does not explain how the lateral femur experiences tension along its lateral proximal 2/3's but coverts to compression along the lateral distal 1/3 of its length. It may be assumed that Koch was attempting to keep his model consistent with the reality, and contemporary belief, that there is compression within the lateral compartment of the knee. It was believed, at that time, to be the explanation for the presence of a lateral meniscus within the knee's

Table 1: Importance of an intact ITB to amputee function.

	Iliotibial band	Gluteus medius	Trendelenburg sign	Energy expenditure
BKA	Intact	+	−	−10%
AKA	Transected	+	+	−40 ~ −70%

lateral compartment. An element intended to buttress against compressive loading.

The static model raised additional paradoxes. For example, at birth the neck-shaft angle of the femur is similar to that of a quadruped, approximately 160-165 degrees. As one assumes, in bipedal gait, by the age of four, the neck-shaft angle reduces to its final value of 130-135 degrees and remains so throughout the remainder of a lifetime. This has been explained as being the result of the upright posture placing a varus load on the young plastic bone. However it is interesting, that in spite of significant time spent in an upright posture and with increasing body mass, the femoral neck-shaft angle remains relatively unchanged throughout the remainder of growth and development of the femur.

It is further interesting to note that in neuromuscular conditions involving spasticity, the valgus deformity of the femoral neck is often corrected with a varus osteotomy. However, if insufficient soft tissue releases are performed at the time of the osteotomy, the valgus deformity will reoccur over time in spite of bipedal stance.

Another paradox of the Koch model occurs among lower extremity amputees. It has been found that below knee amputees (BKA) do not usually exhibit a positive Trendelenburg gait pattern. They only lose about 10% of their metabolic efficiency and with today's technological and material advancements can function at near normal levels of performance, while above knee amputees always exhibit a positive Trendelenburg gait pattern and lose 40-70% of their metabolic efficiency. Yet both the BKA and the AKA have intact abductor, gluteus medius, and musculature. The question is an obvious one. What is lost in an AKA that creates such a significant compromise of the gluteus medius' ability to provide stability against the varus load of the body during gait? (Table 1)

These clinical paradoxes suggest an explanation for why femoral components whose designs are based on the static, flawed, or at least incomplete Koch model of hip loading have provided unintended consequences. They have been plagued with outcomes which have included loss of proximal femoral bone mass termed "stress shielding"; diaphyseal hypertrophy; thigh pain; subsidence due to "poor bone quality"; loosening; and fracture on insertion.

Bone, as all connective tissues, responds to its environment. It hypertrophies and atrophies in response to demand. Also, the quality of bone reflects the type of load it experiences: cortical bone appears in areas of compression and cancellous bone in areas of tensile loading, i.e., apophyses and points of tendon attachment. It would appear that, rather than "reconstruct" damaged hip anatomy, femoral component designs and various methods for their fixation, based on the Koch model, have created nonphysiologic patterns of loading within the femur following hip replacement surgery (Figures 3(a) and 3(b)).

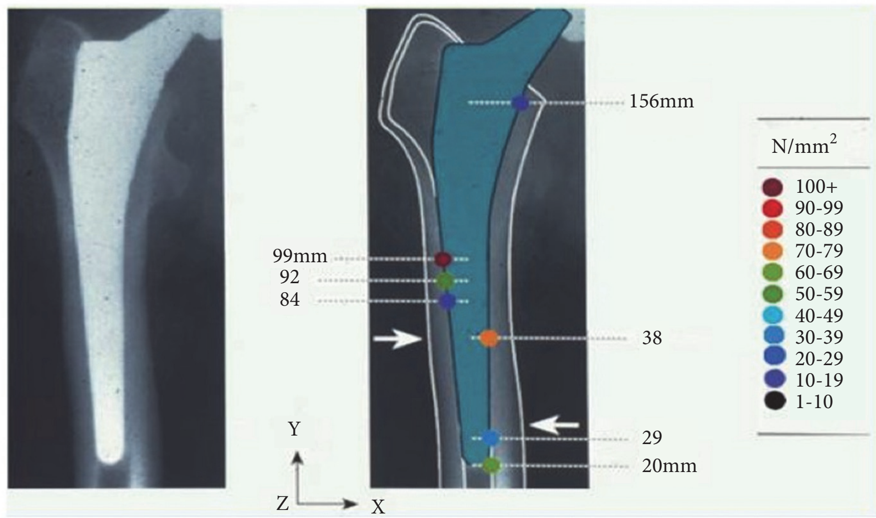
Over the past 150 years, there have been many theories proposed as models of hip biomechanics [2–7]. In efforts to avoid the paradoxes raised by the Koch model, each proposed the inclusion of additional structures to complement and supplement the action of the gluteus medius. However, due to a lack of the necessary means of investigation to prove their theory, all of these alternative models have been unable to displace the accepted model of Koch. This situation changed in the later 20th and early 21st century with the introduction of technological advances such as electromyograhic (EMG) studies, Finite Element Analysis (FEA), and radiologic techniques such as radio-stereotactic analysis (RSA) and DEXA analysis of bone density.

Electromyographic studies of Inman [8] directly challenged the conclusion of the Koch model. He demonstrated that the gluteus medius was most active just before and just after the midstance phase of gait. This implied that some additional factor was acting at midstance phase of gait to reduce the demand on the abductor musculature. The question was, How is this accomplished and what structure(s) is responsible?

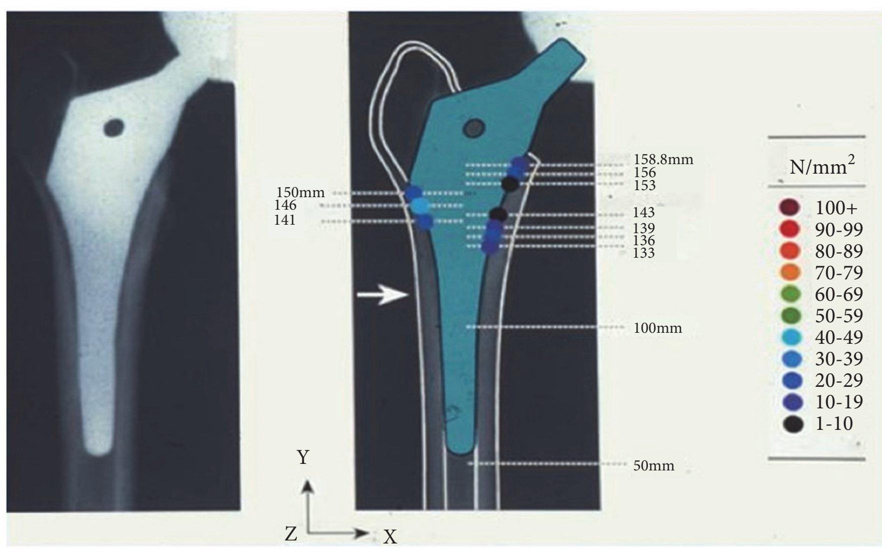
3. Articular Cartilage

Unrelated was the observation that although the knee, hip, and ankle joint go through an equal number of load cycles throughout life and carry a similar load, it remains a fact that the smallest of these joints, the ankle, appears to be the most resistant to mechanical wear and development of osteoarthrosis requiring replacement. An explanation for this phenomenon can be deduced from an understanding of the ultrastructure of articular cartilage.

Articular cartilage is the soft covering at the end of bones and is present in all joints. It is the product of chondrocytes and is an avascular tissue, dependent upon the passive and active diffusion of nutrients and water through a porous surface layer. Chondrocytes produce two critical components of articular cartilage. They are collagen and proteoglycan. Collagen fibers are formed by long linear cross-linked triple helix molecules, specifically designed to resist tensile loading. It is paradoxical that they would be crucial to the integrity of articular cartilage, which is specifically intended to function in a compression environment. The key to the understanding of this paradox is the orientation of the collagen fibers within the cartilage cap. They are parallel at the surface forming a "skin" and dive from the surface into the hyaline cartilage to anchor themselves perpendicularly into the subchondral bone. As such they form an arcade in which the fibers have a



(a) Traditional press fit loading of the femur showing diaphyseal hypertrophy and proximal stress shielding



(b) Proximal femoral loading with a stem design based on the dynamic model of the hip showing bone preservation and no abnormal diaphyseal bone formation

Figure 3: 2-year stress distribution within the femur as a consequence of stem design.

specified orientation. Their orientation is such that as water is drawn into the cartilage tissue by the hydrophilic nature of the proteoglycan molecules, the surface layer of the cartilage structure is tethered to the subchondral bone by the collagen fibers, as it is pushed outward analogous to that of the surface of a stuffed pillow. The integrity of this structure then allows, when a compressive load is applied, water to exude from the cartilage to create a frictionless hydrostatic bearing between the surfaces of any joint. Thus, unless anything occurs to compromise the integrity of the hyaline cartilage surface layer, the cartilage cap is virtually immune to wear over time. From this description it is easy to understand how the demise of articular cartilage and resultant arthrosis can come about: proteolytic enzymatic action from bacteria of synovial inflammation; macrotrauma such as fracture; metabolic abnormalities affecting collagen or proteoglycan synthesis such as vitamin C deficiency and mucopolysaccharidoses; or most importantly microtrauma caused by excessive frictional wear. This last causative etiology is the direct result of joint instability.

Joint stability is a function of two factors: articular geometry and soft tissue integrity. In terms of geometry, it is easy to describe the three major joints of the lower extremity as being either inherently geometrically stable or unstable. The ankle, although the smallest of these three joints, has an extremely stable mortise structure with very limited degrees of freedom, particularly in the dorsiflexed position during weight bearing. As such it suffers minimal frictional wear throughout a lifetime unless the integrity of the mortise is compromised by either a fracture or more subtly disruption of the syndesmosis ligament. In either event, translational movement increases across the articular surfaces and demise of the ankle is rapid. With regard to soft tissues contributing to the stability of a joint, they can be divided into static and dynamic structures. Each plane of movement is stabilized by a couple comprised of a dynamic and a static entity. The dynamic structure is a muscle-tendon unit and the static stabilizer is a ligament. Muscles can adjust their length in response to demand. Ligaments however cannot. Hence since ligaments are critically important at extremes of motion and are lax at mid-range, all ligaments are composed of two parts: one taut in extension, the reciprocal part taut in flexion.

Because joint stability is critical to the preservation of the integrity and functionality of articular cartilage, and the knee joint is an inherently geometrically unstable articulation, it is easy therefore to understand and predict the knee's greater susceptibility to becoming arthritic over time.

4. The ITB Dynamic Tension Band Effect on the Hip Joint Biomechanics

Applying this type of analysis to the hip joint, it is possible to characterize the hip as being more geometrically stable than the knee but less so than the ankle. This is particularly true in the sagittal plane. In this plane the geometry of the hip provides no resistance against the varus deforming force which occurs during midstance phase of gait. The hip therefore must rely on a dynamic stabilizer such as the gluteus medius and some static stabilizer as well in order to maintain equilibrium at this phase of the gait cycle.

Cadaveric studies, in which a weight was suspended from the midline of the sacrum while soft tissue structures were divided into various combinations and permutations, demonstrated that the iliotibial band (ITB) is that static stabilizer of the hip against varus loads [9].

From this observation, it was concluded that the ITB should be included in the analysis of hip biomechanics to produce a more complete, dynamic, and accurate model of hip stability. The inclusion of the ITB served to resolve many of the paradoxes raised by the previous static model. It resolved the seeming contradiction of the gluteus medius being less active at the midstance phase of gait. At that point of the gait cycle the ITB apparently serves as a tension band to relieve the metabolic demand and reduce electrical activity of the gluteus medius (Figure 4). It also provides an explanation for the poorer functioning of an AKA relative to that of a BKA, where loss of the distal attachment of the ITB in an AKA compromises the function of the ITB as a static stabilizer of the hip joint. It further gives rationale to the surgical technique of tenodesis of the ITB and lateral soft tissue structures to the distal femur in the performance of an above-the-knee amputation. This would be similar to the technique of wrapping the posterior calf musculature around the distal end of a below-the-knee amputation.

This more dynamic model, which includes the ITB as a tension band, provides an explanation for the presence of cortical bone along the lateral aspect of the femur as being a predictable consequence of compression loading (Figure 4).

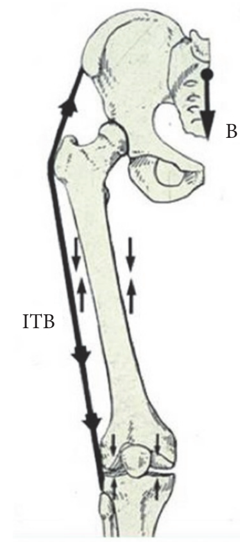


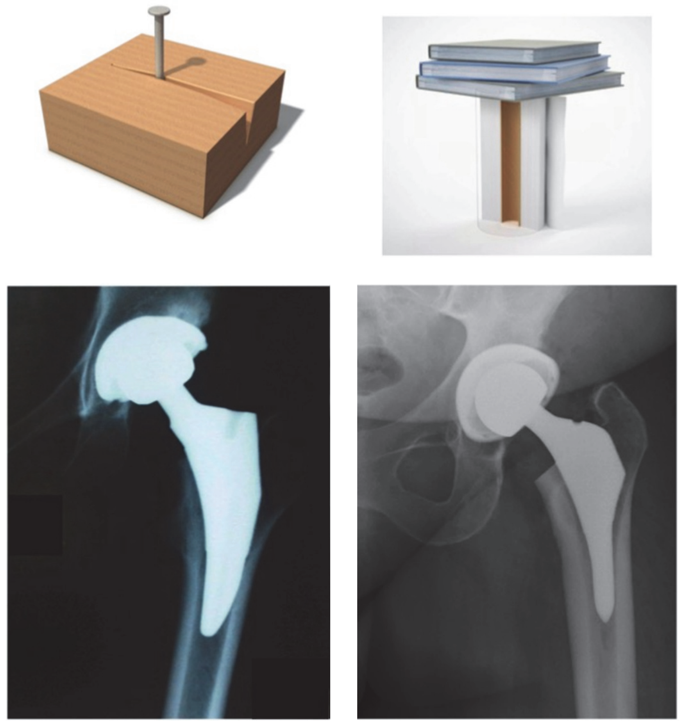
Figure 4: Compression band effect of the ITB. As a "tension band" lateral to the femur, the ITB neutralizes tensile loads and creates compression loading along the lateral aspect of the femur during unilateral stance phase of gait. This explains the presence and distribution of cortical bone in the lateral femur and is consistent with Wolff's Law.

Extending this concept to the knee, it is also possible to predict the actual relative magnitudes of compressive loads in the medial and lateral compartments of that joint, which are 60% and 40%, respectively. Similarly, it explains, as Wolff's Law [9] predicts, the relative growth and dimensions of the medial and lateral femoral condyles being the consequence of the lateral stabilizing and tension band effect of the ITB, LCL, biceps femoris, and popliteus creating gradually increasing compressive loads across the distal femoral growth plate.

5. Femoral Component Design

Returning to femoral component design, it becomes possible, with this expansion of the Koch model to a dynamic model of the hip, to explain the shortcomings of component designs predicated on the 1917 model. Those previous designs treated the femur as a static element. Their placement and stability were analogous to that of a nail in a piece of wood, with the stability of the implant depending on a combination of friction and hoop-stress displacement. Their survival is totally dependent upon the quality of the host bone into which the component is being "pressed". The risk was for subsidence with the choice of an undersized component, insertion into "poor quality bone", or femoral fracture on insertion due to excessive force.

In contrast to traditional means of achieving implant stability whether cemented or noncemented, the dynamic ITB model suggests an alternative method of achieving long term implant survival and superior outcomes for THR. The dynamic ITB model predicts that the lateral femur distal to the greater trochanter experiences compressive loading. Therefore it becomes reasonable to utilize the lateral



(a) (b)

Figure 5: Press fit (a) vs rest fit (b).

endosteal surface of the proximal femur as an additional area to support the femoral component. In this way the entire circumference of the femur would be utilized as a pedestal upon which the body, as well as a femoral component, will be supported. The requirement for the design of a femoral component to achieve this "rest fit" would be to extend the lateral dimension of the component so as to engage the endosteal surface of the femur in the region of Gruen zone 1. This lateral expansion, or "lateral flare", would create an internal collar which would provide the means to transfer load to the entire proximal perimeter of the femur (Gruen zones 1 and 7). As such the component could rest on the entire femur, distributing load both medially and laterally in a more physiologic fashion (Figure 5). This design concept predicts the means to preserve proximal bone stock and avoid transfer of nonphysiologic loading into more distal Gruen zones 2,3,4,5, and 6. It also negates the belief that a long stem design element is required to achieve fixation. Rather the stem portion of a component could simply serve as an alignment device and not a load bearing structure. It would also predict that stem length may be safely reduced without compromising stability or longevity of the construct.

6. Merit of the Lateral Flare and Rest Fit Fixation

The validity of these predictions was evaluated by several means: FEA, in vitro laboratory testing, and finally prospective DEXA and subsidence clinical studies. These published results have shown that, unlike prior stem designs which demonstrate stress shielding, diaphyseal hypertrophy, thigh pain, subsidence, and occasional fracture on insertion, the "lateral flare" stem design has minimized these adverse outcomes. Lateral flare stems have demonstrated preservation of >95% bone stock in proximal Gruen zones 1 and 7; less than 0.5 mm subsidence; no fracture on insertion of the stem when employing a "rest fit" rather than press fit insertion technique; and no thigh pain [10–13].

7. Conclusion

In conclusion, over the past 30 years the application of recent technological advances through laboratory and clinical investigations has led to an expansion of the static Koch model of 1917 to create a more accurate and complete understanding of hip biomechanics. This has produced a more valid dynamic model of the hip. The consequences of this expansion has led to a better explanation of the growth and development of the femur, the functional differences between BKA and AKA patients, suggestions for improved surgical techniques in various clinical situations, and the addition of an important design element to femoral components, specifically the "lateral flare". More importantly this new understanding of hip biomechanics has advanced femoral fixation from a static "nail in a piece of wood" press fit technique to an improved means of femoral fixation termed a "rest fit", which has demonstrated improved outcomes in total hip arthroplasty.

Conflicts of Interest

The author declares no conflicts of interest.

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Review Article

Possible Improvement of the Sagittal Spinopelvic Alignment and Balance through "Locomotion Training" Exercises in Patients with "Locomotive Syndrome": A Literature Review

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On the basis of rapid population aging, in 2007, the Japanese Orthopaedic Association (JOA) proposed a new disease concept "locomotive syndrome" as a degenerative condition of reduced mobility due to the impairment of the musculoskeletal system. Worsened locomotive components, which consist of bones, joints, and intervertebral discs, and muscles and nerves, can lead to symptoms such as pain, limited range of motion, malalignment, impaired balance, and difficulty in walking, ultimately resulting in the requirement of nursing care. "Locomotive syndrome" has gained increased interest in Japan but still not worldwide. Hence, in this brief review, we summarize an updated definition, assessment, and management of "locomotive syndrome". The JOA recommends "locomotion training" exercise intervention to be effective in maintaining motor function that comprises two simple exercises—squatting and single-leg standing. However, the extent to which exercises affect "locomotive syndrome" is unknown. Here, we further report hypothesis-generating patient cases who presented the improved sagittal spinopelvic alignment in standing radiographs and postural stability in piezoelectric force-plate measurements through our 6-month "locomotion training" outpatient rehabilitation program. It is noteworthy that "locomotion training" facilitated these improvements despite the presence of specific disorders including thoracic kyphosis and symptomatic lumbar spinal canal stenosis. This raises the need for further investigations to clarify effects of "locomotion training" exercises on the spinal alignment, global balance, and quality of life in patients with "locomotive syndrome".

1. Introduction

In 2016, the total population of Japan was 127 million, which was the 10th grade ranking country in the world [1]. However, the number of Japanese people in ages of 65 or more (recognized as the old age in Japan) was approximately 35 million, which was 27.3% of the entire population and the highest percentage of the aging rate in the world [2]. Hence, Japan has the most aged society.

In the aged Japanese population, a big issue is the gap between the increased actual life span and the healthy life expectancy. In 2013, this gap was approximately 9 years in Japanese men and 12 years in Japanese women [3]. Furthermore, the primary cause of the requirement of nursing care in elderly Japanese persons was musculoskeletal disorders (24.6% in 2016), which was higher than cerebrovascular disease and dementia [3]. Actually in persons with any subjective symptoms, low back pain, stiff neck and shoulder, and peripheral joint pain occupied the 1st, 2nd, and 5th and 1st, 2nd, and 3rd most frequent complaints in Japanese men and women, respectively [3]. Therefore, the maintenance of healthy musculoskeletal functions is an urgent national concern in Japan.

On the basis of this accelerated population aging, in 2007, the Japanese Orthopaedic Association (JOA) determined a new disease concept "locomotive syndrome" as a condition being restricted in the ability to walk and have a normal life owing to a degenerative dysfunction in one or more of the parts of the musculoskeletal system [4, 5]. The musculoskeletal system which can cause "locomotive syndrome" consists of three major components: (1) bones, (2) joints and intervertebral discs, and (3) muscles and nerves. The age-related impairment of these organs causes (1) osteoporosis and related fragile fractures, (2) osteoarthritis and spondylosis, and (3) sarcopenia and neural disorders. These diseases can lead to symptoms of pain, limited range of joint motion, malalignment, imbalance, and then difficulty in standing-up and walking, finally resulting in reduced activities of daily living (ADL), lower quality of life (QOL), and required nursing care. "Locomotive syndrome" is the basis of musculoskeletal healthcare problems in the present Japanese society.

Degenerative changes in the musculoskeletal system appear before middle ages. The intervertebral disc is one of the earliest organs to develop degeneration in the body [6]. The first unequivocal findings of degeneration in the lumbar discs are seen in the age group 11–16 years [7]. Then, ~40% of people in ages under 30 years and 90% of those in ages over 55 years present lumbar disc degeneration [8]. Furthermore, a Japanese cohort study found that the estimated number of patients with radiographic knee osteoarthritis, lumbar spondylosis, lumbar osteoporosis, and femoral neck osteoporosis were 25, 38, 6.4, and 11 million of 128 million (Japan's 2005 population) [9]. The prevalence of these disorders is quite high, requiring heavy socioeconomic burden. Therefore, health promotion to prevent "locomotive syndrome" is essential.

2. Assessment of "Locomotive Syndrome"

Early diagnosis and recognition are important. To identify people at risk of "locomotive syndrome" and also raise the public interest in the importance of "locomotive syndrome", JOA developed "loco-check" self-completed questionnaire [10]. Although self-assessment by using "loco-check" is not a mandatory step toward the diagnosis with "locomotive syndrome", "loco-check" is a useful self-assessment tool to detect early stages of "locomotive syndrome" and initiate preventive measures. In fact, statistical correlation between the number of positive "loco-check" items and the incidence of falling in the previous year was found [11].

Many functional assessments, such as the hand-grip strength, one-leg standing time, and 6 m walking time, were proposed to evaluate "locomotive syndrome" [12, 13]. These measurements are useful; however, further validations are required. Currently, the stand-up test, two-step test, and 25-question geriatric locomotive function scale (GLFS-25) have been officially introduced for the diagnosis with "locomotive syndrome" [10, 14]. In these assessments, two risk levels of "locomotive syndrome" have been categorized to assess the severity. To determine "locomotive syndrome risk level", all these three tests (stand-up test, two-step test, and GLFS-25) have to be completed. Recent literature has often recognized "locomotive syndrome risk level 2" as patients who have positive "locomotive syndrome" [15].

2.1. Loco-Check. "Loco-check" consists of the following seven statements regarding daily activities: (1) you cannot put your sock on standing on one leg; (2) you often trip up or slip around the house; (3) you need to hold on to the handrail when climbing the stairs; (4) you have difficulty in doing moderately heavy housework; (5) you have difficulty in carrying home 2 kg of shopping; (6) you cannot walk for a quarter of an hour nonstop; and (7) you cannot make it across the road before the light turns red. Persons who meet one or more statements are suspected of having "locomotive syndrome" [10, 11].

2.2. Stand-Up Test. Subjects are asked to stand from stools of varying heights (10, 20, 30, and 40 cm) with a single leg and both legs [16]. First, the trial using the 40 cm stool is performed with both legs. When completed, the 40 cm stool is tried with a single leg, followed by the 30 cm, 20 cm, and then 10 cm stools. When the 40 cm stool with a single leg is not completed in both right and left legs, the 30 cm, 20 cm, and then 10 cm stools are tried with both legs. Consequently, subjects who fail to stand from the 40 cm stool with a single leg in either of bilateral legs are regarded as "locomotive syndrome risk level 1". Then, subjects who fail to stand from the 20 cm stool with both legs are regarded as "locomotive syndrome risk level 2" [10, 14].

2.3. Two-Step Test. Subjects begin the two-step test in an upright posture and move forward for a maximum of two strides without losing his or her balance [16]. The better result after two trials is recorded. The two-slide distance is subsequently standardized according to the subjects' height. Consequently, subjects with the value less than 1.3 and 1.1 are regarded as "locomotive syndrome risk level 1" and "locomotive syndrome risk level 2", respectively [10, 14].

2.4. Twenty-Five-Question Geriatric Locomotive Function Scale. The GLFS-25 is a self-reported tool to assess difficulty and disability in daily activities related to locomotive organs [17]. This questionnaire consists of total 25 questions (4 questions regarding pain, 16 questions regarding ADL, 3 questions regarding social functions, and 2 questions regarding mental health status) that refer to experiences in the preceding month. The answer of each question is rated on a scale of 0–4 points, indicating higher scores as the presence of symptoms and medical conditions resulting from a greater severity of "locomotive syndrome" (total minimum 0–maximum 100). After careful statistical analysis and evaluation [17], patients with 7 or more points of the GLFS-25 score and those with 16 or more points are regarded as "locomotive syndrome risk level 1" and "locomotive syndrome risk level 2", respectively [10, 14].

3. Prevalence of "Locomotive Syndrome"

Nationwide surveys reported the prevalence of "locomotive syndrome (risk level 2 by the GLFS-25 score $\geq$16)" in Japanese people in ages of 40 years or more as 10.2% (men, 7.9%; women, 12.3%) in 2010 [18] and 11.9% (men, 10.8%; women, 12.9%) in 2014 [19]. The age-specific mean values for GLFS-25 were 5.8, 6.0, 5.9, and 8.8 of 100 points in the 40s, 50s, 60s, and 70s, respectively [18]. The mean value for GLFS-25 was higher in the 70s than in the other age groups and in women than in men [18]. Then, the longitudinal 7-year follow-up survey of the Research on Osteoarthritis/Osteoporosis Against Disability study found the estimated 2013 prevalence in Japan of the indices in "locomotive syndrome risk level 2" including the two-step test score <1.1, difficulty in standing from a 20 cm height using both legs in the stand-up test, and GLFS-25 score ≥16 as 21.1% (men, 20.1%; women, 21.6%), 7.9% (men, 4.9%; women, 9.4% [statistically higher than men]), and 10.6% (men, 9.0%; women, 11.4%), respectively [14]. After the calculation, the estimated Japan's 2013 prevalence of "locomotive syndrome (risk level 2)" was 25.1% (men, 22.7%; women, 26.3%) [20]. This prevalence was significantly higher with aging, although there was no statistical sex difference [20]. Hence, the prevalence of "locomotive syndrome" primarily increases by aging, especially in patients in ages of 70 years or more, which is more likely to develop in women.

4. Intervention in "Locomotive Syndrome"

"Locomotive syndrome risk level 1" indicates that the impairment of locomotive functions has already begun. As muscle strength and posture balance may be deteriorating, JOA recommends to perform daily physical exercises such as "locomotion training" in subjects with "locomotive syndrome risk level 1". In addition, it is recommended to take care to eat a balanced diet with plenty of protein and calcium [10, 21].

"Locomotive syndrome risk level 2" indicates that the impairment of locomotive functions has already progressed. Subjects with "locomotive syndrome risk level 2" are at high risk of having the difficulty in keeping an independent life style. As the subjects may have locomotive organ disorders, JOA recommends to continue exercise training and also medical consultation to orthopaedic clinics [10].

5. "Locomotion Training"

Many studies have reported effectiveness of physical intervention in preventing the loss of mobility, balance, and gait in the geriatric population [22–32], while exercises are generally effective in subjects with mild to moderate disability [24, 33] but not so much in subjects with severe disability [26]. Thus, early detection of "locomotive syndrome" is desirable.

Physical intervention is based on the principles of exercise [34]. First, it is known that the particular body components and skills, which are involved in a given exercise, will demonstrate the improvement (principle of specificity). Second, a high load is required for any functional improvement (principle of overload). Third, it is important to gradually increase the exercise load (principle of progression) with consideration for safety since the majority of people in middle to old ages have chronic degeneration of lumbar spine discs and lower limb cartilages [9].

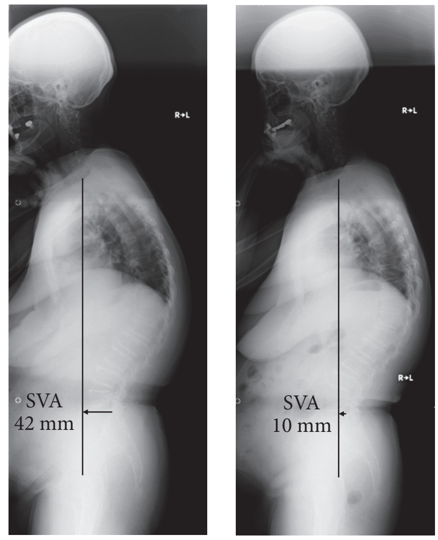
Therefore, JOA recommends "locomotion training" to improve and sustain standing and gait functions in middle-aged and old-aged subjects [5, 10]. The basic protocol of "locomotion training" just consists of two simple exercises directly related to standing—squatting and single-leg standing [35]. Then, in patients who get used to the basic "locomotion training" exercises, other exercises such as heel raises and front lunges are recommended to be added [10]. Walking is generally recommended [36–38]. However, persons with the GLFS-25 score ≥16 are expected to have trouble in walking and going out [17]. Three "locomotive syndrome risk level" indices—the stand-up test, two-step test, and GLFS-25—all predict immobility significantly and independently, and the accumulation of these indices indicates substantial increases in the risk of immobility [14]. Therefore, overload is unfavourable. The JOA recommends just additional 10-minute mild physical activities which can support the prevention of "locomotive syndrome", e.g., bicycling or walking to work, taking the stairs instead of the elevator or escalator, cleaning, and laundering with zest in addition to stretching when you have a moment, doing "locomotion training" or stretching while watching TV, taking a walk during breaks at the office, walking to a supermarket further away than usual for your shopping, using your local park or sports center, taking part in community sports events, going out to have fun with family or friends on days off, and walking briskly with long strides [5, 10].

5.1. Single-Leg Standing Exercise. The single-leg standing exercise is designed to improve posture balance. This exercise can be done alone [39] or combined with other muscle power training (like chair-rising training) [40]. This test has been demonstrated to be effective in preventing falls [39, 40]. Subjects are instructed to stand on one leg with their eyes open and adjacent to a stable chair or desk for arm support to prevent from falling. Performing one minute for each leg, three times a day (morning, noon, and evening), every day is advised.

5.2. Squatting. The squatting exercise is designed to strengthen leg muscles. Previous studies have demonstrated effectiveness of squatting in reducing bone loss and improving muscle strength and balance in the lower extremities [41, 42]. Subjects slowly move the torso down from the standing position as is done during stand–sit movement. In addition, subjects are instructed to maintain the position of the patella over the toes to prevent overload on the knee. The knee flexion angle should not exceed 90°. Performing slow squats five to six times as one set, three times a day, every day is recommended.

6. Effect of "Locomotion Training"

Only a few English reports describing the improvement of physical function tests (visual analog scale scores of low back pain, single-leg standing time, and 6 m walking time) by "locomotion training" intervention have been published [43]. A prior study demonstrated that "locomotion training" monitored by using serial telephone contacts



At baseline (a) At 6-month follow-up (b)

Figure 1: A 70-year-old woman with "locomotive syndrome risk level 2" from lumbar spondylosis. Standing whole-spine radiographs showed the sagittal vertical axis (SVA) of 42 mm with thoracic kyphosis (a). After our 6-month "locomotion training" outpatient rehabilitation program, she showed the improvement to "locomotive syndrome risk level 1" with the improved SVA up to 10 mm (<40 mm, normal range) and decreased thoracic kyphosis in radiographs (b).

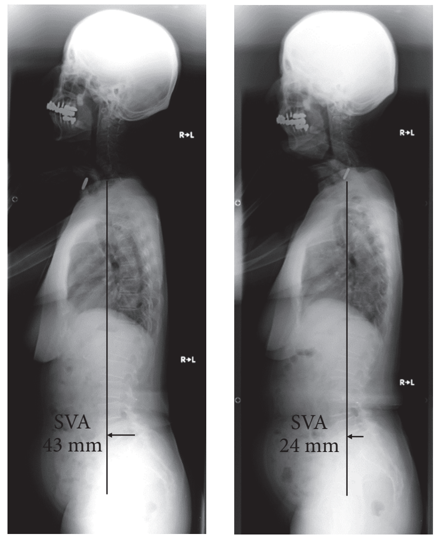
improved physical function test scores and seven of eight SF-8 subscales [44]. Low back pain decreased in 12.6% of the subjects while it increased only in 2.3%. Knee pain decreased in 17.2% of the participants while it increased only in 1.1%. Hence, evidence is accumulating regarding subjective improvements of physical functions, ADL, and QOL through "locomotion training" exercises. However, multidisciplinary studies regarding objective improvements, e.g., radiography, magnetic resonance imaging, electromyography, and bone densitometry, still need to be conducted. These measurements provide useful information to elucidate effects of "locomotion training" on the spinal and upper and lower extremities' alignment, muscle size and quality, and respective disease severity including osteoarthritis, spinal canal stenosis, sarcopenia, and osteoporosis, as the progress of degenerative disorders is not always symptomatic.

7. Future Directions

In age-related changes in the musculoskeletal system, adult deformity of the spine gains increased attention [45]. Particularly, the loss of lumbar lordosis was associated with increased pain and disability and lower QOL scores [46]. The stronger the back extensors, the smaller the thoracic kyphosis and the larger the lumbar lordosis and sacral inclination [47]. In prior reports studying "Pilates"-based exercises, significant improvement in the sagittal alignment of the head was observed after 6-month exercises; however, this was not the report of radiographic measurements [48].

Based on literature evidence, a prospective cohort study was designed and conducted to assess effects of "locomotion training"-based exercises on the sagittal alignment of the spinopelvic axis in standing radiographs and postural balance in piezoelectric force-plate measurements. All experimental procedures were performed under the approval and guidance of the Institutional Review Board at Kyoto Kujo Hospital (Kyoto, Japan). Written informed consent was obtained from each patient in accordance with the principles of the Declaration of Helsinki and the laws and regulations of Japan. In this paper, we would like to show representative patient cases with varying pathologies who underwent our 6-month "locomotion training" outpatient rehabilitation program.

A 70-year-old woman experienced low back pain lasting over 2 months and then visited our orthopaedic clinic. Her diagnosis was lumbar spondylosis. At baseline, she showed standing-up from a 40 cm height on both legs at her best on the stand-up test (risk level 2), 1.05 on the two-step test (risk level 2), and 14 points on the GLFS-25 score (risk level 1), resulting in the categorization into "locomotive syndrome risk level 2". Then, in standing whole-spine radiographs with the clavicle position, baseline sagittal vertical axis (SVA) was 42 mm, indicating mild sagittal deformity [49]. The lumbar lordosis between L1 and S1 (LL) and pelvic incidence (PI) were 38° and 37°, respectively, causing no mismatch of the PI–LL [49]. The pelvic tilt and sacral slope were 16° and 21°, respectively. Furthermore, C2–C7 angle, T1 slope, and thoracic kyphosis between T5 and T12 (TK) were 16°, 40°, and 51°, respectively, thus suggesting that her sagittal deformity primarily resulted from thoracic kyphosis despite no vertebral fractures (Figure 1(a)). She attended our "locomotion training" outpatient rehabilitation program for 20 minutes, once a week, 6 months to confirm the achievement of exercises and add stretching. At endpoint, she improved "locomotive syndrome" scores to complete standing-up from



At baseline (a)

At 6-month follow-up (b)

Figure 2: A 72-year-old woman with "locomotive syndrome risk level 2" from lumbar spinal canal stenosis. Standing whole-spine radiographs showed the sagittal vertical axis (SVA) of 43 mm with decreased thoracic kyphosis (a). After our 6-month "locomotion training" outpatient rehabilitation program, she showed the improvement to "locomotive syndrome risk level 1" with the improved SVA up to 24 mm (<40 mm, normal range) and increased thoracic kyphosis in radiographs (b).

a 20 cm height on both legs on the stand-up test (risk level 1), 1.2 on the two-step test (risk level 1), and 9 points on the GLFS-25 score (risk level 1), corresponding to "risk level 1". The SVA improved up to 10 mm (<40 mm, normal range) [49] with the LL of 42°. Notably, C2–C7 angle, T1 slope, and TK improved to 4°, 29°, and 47°, respectively (Figure 1(b)). The Oswestry Disability Index (ODI) to assess low back pain and related QOL improved from 10 (22.2%, moderate disability) to 7 (15.6%, minimal disability). In piezoelectric force-plate measurements, baseline and endpoint areas of the pressure center, speed, and distance were 7.90 cm^2 and 6.79 cm^2, 3.18 cm/s and 2.00 cm/s, and 190.60 cm and 119.75 cm, respectively, all of which were improved.

A 72-year-old woman experienced low back and bilateral buttock to leg pain worsened only during housework and walking. Her symptoms were relieved after sitting. She visited our orthopaedic clinic, and magnetic resonance imaging analysis found lumbar spinal canal stenosis at L4–L5. Baseline and endpoint "locomotive syndrome" scores were 30 cm on both legs (risk level 2) and 20 cm on both legs (risk level 1) on the stand-up test, 1.1 (risk level 1) and 1.3 (risk level not applicable) on the two-step test, and 8 points (risk level 1) and 5 points (risk level not applicable) on the GLFS-25, respectively (overall risk level 2 $\longrightarrow$ 1). Baseline SVA, LL, and PI−LL were 43 mm, 49°, and +4°, respectively (Figure 2(a)). Then, endpoint SVA, LL, and PI−LL were 24 mm, 48°, and +5°, respectively (Figure 2(b)). Thus, SVA improved to the normal range after "locomotion training" exercises. Also in this case, TK decreased to 26° at baseline but increased up to 38° at endpoint. Baseline and endpoint ODI were 8 (17.8%, minimal disability) and 6 (13.3%, minimal disability), no remarkable deterioration of which was observed. However, she recognized substantial improvement of intermittent claudication. Force-plate examination showed the improvement in part of the area, speed, and distance: 4.47 cm^2 and 2.76 cm^2, 1.53 cm/s and 1.54 cm/s, and 91.69 cm and 92.54 cm at baseline and endpoint, respectively.

The first case's woman had the maintained lumbar lordosis and pelvic parameters but increased thoracic kyphosis. This patient case may be a good candidate of "locomotion training" rehabilitation program. Strengthened leg, hip, and back muscles can facilitate the improvement of the sagittal alignment of the spine. Then, the second case's woman suffered from intermittent claudication. The applied "locomotion training" rehabilitation program improved the sagittal alignment and reduced complaints of intermittent claudication. While the first case decreased the patient's own thoracic kyphosis, the second case increased the thoracic kyphosis. Literature evidence reported a normal range of TK (T5–T12) as 34° ± 11° [50]. Improved power and flexibility of the lower limb, hip, and back muscles might contribute to the normalization of the sagittal alignment of the thoracic spine. It is noteworthy that "locomotion training" facilitated these improvements despite the presence of specific disorders including thoracic kyphosis and symptomatic lumbar spinal canal stenosis.

8. Conclusions

The cases shown raised the need for further prospective cohort studies to clarify multidisciplinary effects of "locomotion training" exercises on the spinal alignment, global balance, and quality of life in patients with "locomotive syndrome". Understanding of "locomotive syndrome" is essential for the future of aging care, which is an important health issue not only in Japan but also in the international society.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Effects of Knee Osteoarthritis on Hip and Ankle Gait Mechanics

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Introduction. Knee osteoarthritis (OA) can affect the hip and ankle joints, as these three joints operate as a kinetic/kinematic chain while walking. *Purpose.* This study was performed to compare (1) hip and ankle joint gait mechanics between knee OA and control groups and (2) to investigate the effects of knee gait mechanics on the ipsilateral hip and ankle joint. *Methods.* The study group included 89 patients with end-stage knee OA and 42 age- and sex-matched controls without knee pain or OA. Kinetic and kinematic parameters were evaluated using a commercial optoelectric gait analysis system. Range of motion (ROM) during gait, coronal motion arc, and peak joint moment of hip, knee, and ankle joints were investigated. *Results.* Ankle varus moment was 50% higher in the OA group ($p=0.005$) and was associated with higher knee adduction moment ($p<0.001$). The ROM of the hip and ankle joints were significantly smaller in the OA group and were associated with limited ROM of the knee joint (both $p<0.001$). The coronal motion arc of the hip was smaller in the OA group and was also associated with limited motion arc of the knee ($p<0.001$). *Conclusions.* Knee OA has a negative effect on the ROM, coronal motion arc, and joint moment of the ankle joint and hip joint. As knee OA is associated with increased moment of the ankle joint, attention should be paid to the ankle joint when treating patients with knee OA.

1. Introduction

Knee osteoarthritis (OA) is a leading cause of disability in the elderly population [1]. More than 250 million people suffer from knee OA worldwide, and 1%–2% of the gross national product is spent on OA [2, 3]. Knee OA causes pain and gait disturbances and has a characteristic gait pattern [4, 5].

Knee OA patients have reduced range of motion (ROM) and increased ground reaction force [4, 5]. Stride length and walking speed are decreased in OA [6]. Patients attempt to reduce pain by minimizing the impact on their knees [4, 5]. The gait of knee OA patients is also characterized by higher knee adduction moment (KAM), a marker of medial joint loading and known risk factor for progression of arthritis [7–9]. Such gait changes in knee OA can directly or indirectly affect adjacent weight-bearing joints, i.e., the hip and ankle joints [10–12].

In fact, we often encounter knee OA patients with ankle and hip joint pathology. The joint line orientation angle of the ankle changes and hip arthritis is often observed on X-ray examination [13]. Epidemiological studies also showed that significant numbers of patients have pathologies in more than two of the three weight-bearing joints, which may indicate that problems with one joint are biomechanically related to problems in the others [14, 15]. Many studies have focused on the gait mechanics of the knee in patients with knee arthritis. However, few studies have examined secondary gait changes in adjacent joints, i.e., the hip and ankle joints [10–12]. Theoretically, gait changes in the knee joint can cause gait changes in the hip and ankle joints, as these three joints operate as a kinetic/kinematic chain while walking. Investigation of secondary biomechanical changes in the ankle and hip joints in knee OA patients will provide a better understanding of the gait mechanics of knee OA patients.

In this study, we hypothesized that the gait mechanics of the knee joint would differ between the knee OA group and controls without knee OA, which would have different effects on the hip and ankle joints. This study was performed to compare (1) hip and ankle joint gait mechanics between knee

Table 1: Characteristics of knee OA and control groups.

	Knee OA group (n=89) Mean (SD)	Control group (n=42) Mean (SD)	p-value
Age, yr	65.8 (5.5)	64.5 (2.9)	0.224
Height, cm	151.7 (5.4)	153.7 (5.2)	0.304
Weight, kg	61 (8.6)	58.2 (7.2)	0.004
Body mass index, kg/m2	26.5 (3.5)	24.6 (2.9)	0.002
HKA axis (right side)	5.9 (3.8)	1.7 (1.8)	<0.001
Gait speed (cm/s)	88.7 (17.5)	111.2 (8.4)	<0.001
Stride length (cm)	97.9 (13.7)	115.7 (7)	<0.001
Step width (cm)	10.3 (3.2)	8.5 (1.8)	<0.001

SD: standard deviation, HKA axis: hip-knee-ankle mechanical axis

OA patients and controls and (2) to investigate the effects of knee gait mechanics on the ipsilateral hip and ankle joints.

2. Methods

2.1. Study Subjects. This study was approved by our Institutional Review Board. We retrospectively reviewed 143 patients with three-compartment end-stage OA. End-stage OA was defined as Kellgren–Lawrence (KL) grade 4 in anteroposterior (AP) and lateral knee radiography. We excluded 31 subjects according to the following criteria: (1) aged > 75 or < 55 years ($n = 26$); (2) spine disease, hip or ankle arthritis (KL grade > 2) on X-ray ($n = 15$); (3) male gender (n = 5); (4) inflammatory or traumatic arthritis of the knee ($n = 4$); or (5) any prior bone surgery in the lower extremities ($n = 4$). Consequently, 89 patients with end-stage knee OA were included in the final analysis. The study population had a mean age of 65.8 years, mean height of 151.7 cm, and mean weight of 61.0 kg (Table 1).

The control group consisted of a total of 42 asymptomatic sex- and age-matched volunteers. Gait analysis and X-ray evaluation were performed after receiving informed consent. None of the volunteers experienced concurrent knee pain, had a diagnosis of knee OA, or violated any other exclusion criterion. The controls had a mean age of 64.5 years, mean height of 153.7 cm, and mean weight of 58.2 kg (Table 1).

2.2. Gait Analysis Protocol. Gait data were collected from the Human Motion Analysis Lab at our institution. Participants were asked to perform an gentle 5-minute walk to warm up. After warming up, reflective markers were placed on the subjects [16], and they were asked to walk at a self-selected speed along a 9-m track.

Motion (kinematic) data were acquired at a sample rate of 120 Hz using 12 charge-coupled device cameras equipped with a three-dimensional optical motion capture system (Motion Analysis, Santa Rosa, CA, USA). Ground reaction force (kinetic) data were acquired at a sampling rate of 1,200 Hz using three AMTI (Advanced Mechanical Technology Inc., Watertown, MA, USA) force plates. The kinetic data were then normalized by height and weight (% body weight × height) [17].

We used Eva Real-Time software (Motion Analysis), Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, USA), and MATLAB R2017a (MathWorks, Natick, MA, USA) for real-time motion capture, postprocessing, and marker data tracking. The average of three representative strides from five or six separate trials was used for the analysis of each session. Data for the right side of participants were used in the analysis.

Spatiotemporal data are shown in Table 1. The kinematic parameters investigated were the range of motion (ROM) of the hip, knee, and ankle joints, and the coronal motion arcs of the knee and hip joints. Coronal motion arc was defined as the difference in angle between the maximum valgus (or adduction) angle and the maximum varus (or abduction) angle during a stance phase. For kinetics, the peak moments of the sagittal and coronal planes were evaluated. The sagittal plane moment included internal knee extension moment, hip extension/flexion moment, and ankle plantar flexion moment, and the coronal plane moment included the KAM, hip abduction moment, and ankle varus moment.

2.3. Radiological Measurement. Radiographic evaluations were performed independently by two authors (both trained in arthroplasty) blinded to other patient information. The interobserver reliability of the radiological assessments was satisfactory (intraclass correlation coefficient, 0.87–0.93). The average values measured by the two observers were used in the analysis. Mechanical axis (hip-knee-ankle axis) was measured using standing full-limb radiography. All radiographic images were digitally acquired using a picture archiving and communication system (PACS) (Maroview 5.4; Infinitt, Seoul, Republic of Korea), and assessments were performed using the PACS software.

2.4. Statistical Analysis. Kinetic and kinematic variables were compared using independent Student's t test. The normality of the data was assessed using the Kolmogorov–Smirnov test. Correlations were assessed using Pearson's correlation coefficient. The partial correlation coefficient was calculated to control the effect of gait speed on ROM. For all analyses, $p<0.05$ was taken to indicate statistical significance. Statistical analyses were performed using SPSS® for Windows (ver. 19.0.1; SPSS Inc., Chicago, IL, USA).

Table 2: Range of motion and coronal motion arc of each joint.

		Knee OA group (n=89) Mean	Control group (n=42) Mean	p-value
Range of motion (°)	Knee	51	63	<0.001
	Hip	43	48	<0.001
	Ankle	26	28	0.004
Coronal motion arc (°)	Knee	4	9	<0.001
	Hip	8	12	<0.001

Table 3: Mean peak moment of each joint.

		Knee OA group (n=89) Mean (SD)	Control group (n=42) Mean (SD)	p-value
Sagittal	Knee extension	2.44 (1.16)	3.38 (1.03)	<0.001
	Hip flexion/extension	6.41 (1.19)	6.94 (0.89)	0.010
	Ankle plantar flexion	7.1 (1.15)	7.64 (0.61)	0.005
	Total sagittal moment	15.94 (2.43)	17.97 (1.59)	<0.001
Coronal	Knee adduction	3.27 (0.92)	2.76 (0.65)	0.002
	Hip abduction	4.93 (0.83)	5.34 (0.54)	0.005
	Ankle varus	0.69 (0.44)	0.46 (0.36)	0.005
	Total coronal moment	8.89 (1.58)	8.56 (1.13)	0.239

The unit of moment is %Bw∗Ht. SD: standard deviation

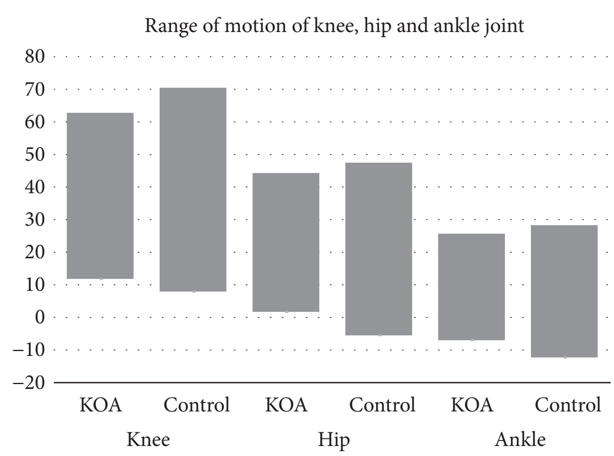

Figure 1: *Range of motion (ROM) of the knee, hip, and ankle joint.* The knee OA (KOA) group showed smaller ROM than the control group. In the knee joint, a negative value indicates hyperextension. In the hip joint, a negative value indicates extension. In the ankle joint, a negative value indicates plantar flexion.

3. Results

The hip and ankle ROM were significantly smaller in the OA group than the control group (Table 2, Figure 1). Knee ROM was also smaller in the OA group ($p<0.001$), and it was correlated with hip and ankle ROM (both $p<0.001$, Figure 2). Controlling the effect on gait speed did not change the fact that knee ROM affected hip and ankle ROM (both $p<0.001$); smaller knee ROM was associated with smaller hip ROM and angle ($r^2 = 0.71$–0.42).

The coronal motion arcs of the hip and knee were also smaller in the OA group than the control group (all $p<0.001$, Figure 3). The coronal motion arc of the knee joint was also correlated with that of the hip joint ($r^2 = 0.36$, $p<0.001$).

The sagittal moments of the hip and ankle were smaller in the OA group compared to the controls (Table 3). Sagittal knee moment was also smaller in the OA group than the control group ($p<0.001$).

The coronal moment of the hip was smaller, but the coronal moment of the ankle joint was higher, in the OA group compared to the control group (both $p=0.005$). The ankle varus moment was 50% higher in the OA group than the control group. KAM was also higher in the OA group than the controls ($p<0.001$). The coronal knee moment (KAM) was correlated with those of the hip ($r^2 = 0.19$, $p=0.032$) and ankle joints ($r^2 = 0.32$, $p<0.001$). Total sagittal moment was smaller in the knee OA group than the control group ($p<0.001$). However, total coronal moment was similar between the two groups ($p=0.239$).

4. Discussion

The results of this study showed that changes in gait mechanics in the knee joint have a strong effect on the ROM, coronal motion arc, and joint moment of the ankle and hip joints. ROM and sagittal moment were significantly limited and gait became stiffer in patients with OA. Interestingly, ankle varus moment was 50% higher and associated with an increase of KAM. Such changes are important as they can be risk factors for the subsequent development of secondary arthritis and result in increased pain [10, 13, 18]. Limited ROM of the lower extremities can cause joint stiffness and may result in significant disability [19]. Clinicians should keep these points in mind when planning treatments or in educating knee OA patients. In our knee OA patients, the ROM of the knee

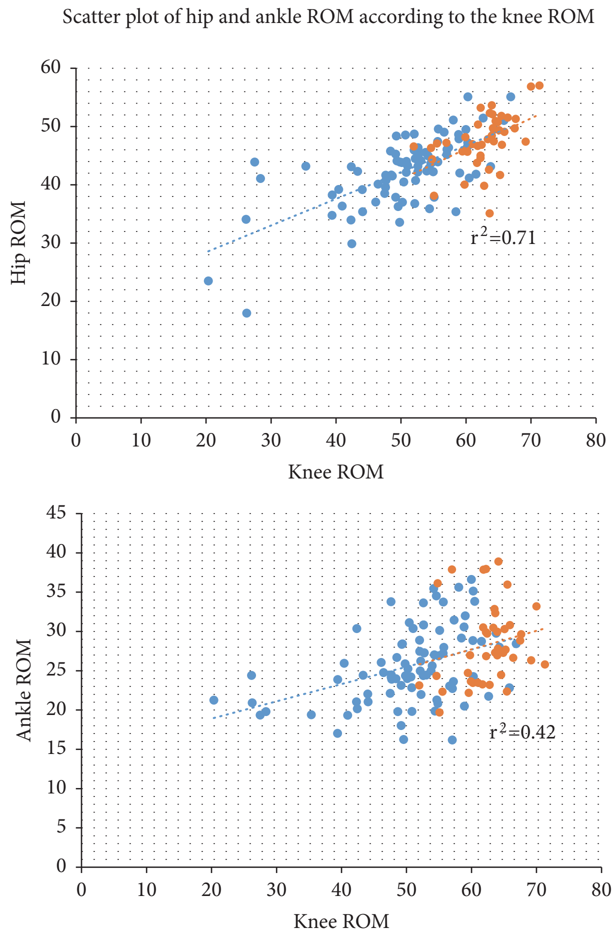

FIGURE 2: *Correlation between knee ROM and hip and ankle ROM.* Strong correlations were observed between knee ROM and the hip and ankle ROM. Blue dots indicate the knee OA group. Orange dots indicate the control group. Dotted lines indicate the trend lines. r^2: Pearson correlation coefficient.

was reduced in both the sagittal and coronal planes and was associated with limited ROM of the hip and ankle joints. The mean knee ROM in the OA group was 51°, which was 19% smaller than the knee ROM of 63° in the control group. This reduced the ROM of the hip and ankle joints by 10.4% and 7.1%, respectively. In the clinic, knee OA patients are often seen to walk with bending and stiffness of the hip, knee, and ankle joints. In particular, the extension angle of the hip joint was about 5° in the control group, but there was 2° of flexion contracture in knee OA patients, and these patients have a bent posture. This pattern was reported previously in knee OA patients [19]. Steultjens et al. measured the ROM using a goniometer and reported close relations between the ROM of the hip and knee joint [19]. Our observations were consistent with their results, and we showed that the relationship still exists during gait. As gait is coordinated by work of the muscle and joint, flexion contracture can cause constant contraction of the quadriceps femoris [20]. Thus, knee OA patients will suffer from pain as well as increased quadriceps load during gait [20]. The gait speed can also be reduced by limited ROM of each joint, similar to that in patients with total knee

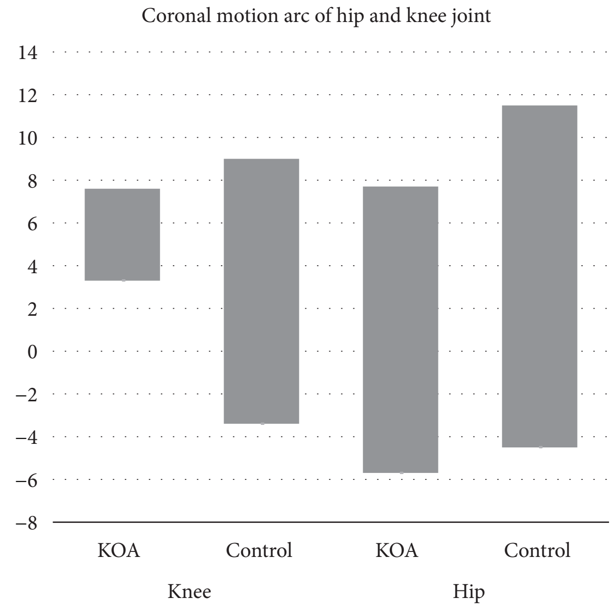

FIGURE 3: *Coronal motion arcs of the hip and knee joints.* The KOA group showed smaller coronal motion arcs compared to the control group. Negative values indicate valgus and abduction in the knee and hip joints, respectively. There was a significant correlation between the hip and knee joints.

arthroplasty [6]. However, after controlling for the effect of gait speed, limited knee ROM significantly affected hip and ankle ROM.

The limited motion in the coronal plane was also of interest. In this study, the coronal motion arc of the knee in the OA group was 55.6% less than that in the control group. The coronal motion arc was also reduced in the hip joint, which can result in an unstable walking pattern. With limited coronal motion, the patient must balance their body by moving the trunk toward the standing limb. This resembles the Trendelenburg gait and is also a characteristic gait pattern of patients with knee OA [21].

The total sagittal plane moment was reduced in the knee OA group. As the sagittal moment is related to gait speed, it may be related to the slow gait speed of knee OA patients [6]. In contrast, the coronal moment was higher in the knee and ankle joints. Increased KAM has been described in knee OA patients in the literature; it is associated with increased medial joint loading and is a surrogate marker for future progression of arthritis [18]. However, it is interesting that ankle varus moment was increased and associated with KAM. Ankle varus moment was 50% higher in the knee OA group compared to the control group. This can be a risk factor for future progression of arthritis [10, 13, 18]. In fact, we often encounter ankle subluxation in patients with knee OA, and further studies are needed regarding this issue.

This study had some limitations. First, no definitive conclusions on causality can be drawn because of the cross-sectional nature of the study design. A further prospective longitudinal study is warranted to determine the nature of the bidirectional relationship. However, this problem was minimized in this study by excluding patients with KL grade

3 or higher arthritis of the hip and ankle joints. In fact, the incidence rates of hip and ankle joint arthritis are not as high as that for the knee joint, and there is no evidence that hip and ankle arthritis precede knee OA [15]. Therefore, knee OA was thought to influence the mechanics of the hip and ankle joints. Second, generalizability could be limited only to female patients, where this study excluded male patients as there is a significant difference in gait between males and females [22]. However, as only the KAM showed gender differences and there were no differences in joint range of motion or hip angle joint moment, generalization should also be possible to male patients.

5. Conclusions

Knee OA has a negative effect on the ROM, coronal motion arc, and joint moment of the ankle joint and hip joint. As knee OA is associated with increased moment of the ankle joint, attention should be paid to the ankle joint when treating patients with knee OA.

Data Availability

No external data is applicable to this manuscript.

Conflicts of Interest

The authors have no conflicts of interest with regard to this work.

Authors' Contributions

Du Hyun Ro was responsible for design, data acquisition, data interpretation, and manuscript drafting. Joonhee Lee performed data acquisition, analysis, and manuscript drafting. Jangyun Lee and Jae-Young Park contributed to data acquisition, analysis, and interpretation. Hyuk-Soo Han made data acquisition and data interpretation. Myung Chul Lee was responsible for design, data acquisition, data interpretation, and manuscript revision.

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Research Article

Prevalence of Anterior Femoral Neck Osteophyte in a Total Hip Arthroplasty Population: Analysis of Preoperative Surgical Plans

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Despite strongly positive results of total hip arthroplasty (THA), patients remain at risk for complications including dislocation. Spinopelvic motion and the hip-spine relationship have been recognized as important factors in surgical planning and implant positioning in THA. Periarticular osteophytes are one of the hallmark pathoanatomic features of osteoarthritis and may influence implant positioning and joint stability; residual osteophytes at the anterior femoral neck may cause anterior impingement and posterior instability. No studies have been identified which establish the prevalence of anterior femoral neck osteophyte for incorporation into THA planning. 413 consecutive patients scheduled for THA underwent preoperative planning taking into account spinopelvic motion to establish optimal component position. Each surgical plan was reviewed retrospectively by four independent raters who were blinded to other imaging and intraoperative findings. Anterior femoral neck osteophytes were rated as being absent, minor, or extensive for each case. A single outlying rater was excluded. Inter-rater reliability was calculated manually. The patient group comprised 197 male and 216 female hips, with a mean age of 63 years (range 32–91). The presence of anterior femoral neck osteophytes was identified in a mean of 82% of cases (range 78–86%). A significant number of patients were found to have large or extensive osteophytes present in this location (mean 27%; range 23–31%). Inter-rater reliability was 70%. A large majority of our THA patients were found to have anterior femoral neck osteophytes. These must be considered during preoperative planning with respect to the spinopelvic relationship. Failure to identify and address osteophytes intraoperatively may increase the risk of impingement in flexion and/or internal rotation, leading to decreased range of motion, joint instability, and possibly dislocation. Planned future directions include incorporation of an impingement and instability model into preoperative planning for THA.

1. Introduction

Total hip arthroplasty (THA) is a common surgical procedure to treat osteoarthritis (OA) and other hip conditions, with over 91,000 cases reported in the UK in 2017 [1]. Despite significant advances in surgical technique and implant design, patients remain at risk of joint instability and dislocation following THA. Estimates for the rate of dislocation following primary THA have ranged from 0.3 to 10% [2–6]. Numerous patient, surgical, and implant factors may augment the risk of dislocation [2, 3, 6]. Impingement is defined as the abnormal contact between the femoral and acetabular sides during physiologic hip range of motion. Among the multiple causes of dislocation following THA, impingement may be a significant contributing factor [7]. THA impingement may result from contact of the implant, bony, or soft tissue structures. In addition to dislocation, THA impingement may lead to restricted range of motion, subluxation, edge loading, accelerated wear, and increased pain [7]. Impingement may occur at any location around the acetabulum, most commonly at the anterior or posterior walls. Anterior impingement following THA is often caused by residual anterior osteophyte on the femoral or acetabular side. Anterior impingement tends to cause increased edge loading and asymmetric wear at the posterior aspect of the acetabulum, as well as posterior subluxation or dislocation.

Implant positioning is critically important to ensure THA stability [2, 7]. The landmark paper by Lewinnek [8] established the gold standard "safe zone" for acetabular component positioning as $40^{\circ} \pm 10^{\circ}$ abduction (inclination) and $15^{\circ} \pm 10^{\circ}$ anteversion. However, even the Lewinnek cohort included patients within the safe zone who suffered THA dislocation, and other papers have further questioned the presence and location of a true "safe zone" to prevent dislocation [9]. One explanation for this may lie in the spinopelvic relationship. The pelvis is known to tilt forward and backward (flex/extend) with activities of daily living, including climbing stairs, lying, sitting, or rising from a seated position [10]. Further, considerable variation has been demonstrated between individuals including the pattern, direction, and degree of pelvic motion [10]. Differences in spinopelvic motion may significantly impact the instantaneous functional position of a THA acetabular component [11, 12]. For example, anterior rotation (flexion) of the pelvis will lead to an effectively more flat and retroverted cup position, increasing the risk of anterior impingement and posterior instability.

In view of this evolving understanding of the impact of the spinopelvic relationship on THA, numerous techniques and technologies have been developed which accommodate for pelvic motion in the placement of THA implants. One such technology is the Optimized Positioning System (OPS™, Corin Group, Gloucestershire, UK). This system utilizes preoperative lateral pelvic radiographs in multiple functional positions, as well as a low-dose CT scan, to assess patient-specific anatomy and spinopelvic motion and guide THA positioning to maximize range of motion and minimize impingement [13]. A surgical plan is developed for each patient, including 2D imaging and 3D reconstructions of patient anatomy, and planned implant positions.

In spite of the importance of bony anatomy and implant positioning to the stability of THA, no studies have been identified which assess the presence and size of anterior femoral neck osteophytes in patients undergoing THA. The identification of osteophytes in this area may be particularly important in patients with certain patterns of spinopelvic motion, specifically those who display increased pelvic flexion when sitting. This study aimed to use presurgical templating documents to establish the prevalence of anterior femoral neck osteophytes for incorporation into THA planning.

2. Materials and Methods

Surgical plans were retrospectively reviewed for all patients who underwent primary THA using the OPS™ system at a single hospital in Australia between November, 2015, and December, 2016. All patients had previously undergone standardized preoperative assessment including routine radiographs of the pelvis and operative hip, lateral pelvic radiographs in 3 stances (standing, seated, and contralateral leg step-up), and low-dose computerized tomography (CT) scan of the operative hip. Preoperative surgical plans were generated using the OPS™ system, taking into account spinopelvic motion in order to establish the optimal component positions to minimize impingement and maximize range of motion and stability. Each surgical plan includes an AP pelvic radiograph, two CT cuts (coronal plane, central implant axis; axial plane, level of planned femoral neck cut), and three 3D reconstruction images of the proximal femur (coronal, sagittal, and axial views) with the planned femoral implant in situ. An example of the surgical plan generated is shown in Figure 1.

Each planning document was reviewed by four independent assessors (one orthopaedic registrar, one fellow in lower extremity reconstruction, and two fellowship trained arthroplasty surgeons). Assessors were permitted to inspect all images contained within the plan, in the order of their choosing. Assessors were blinded to patient identity, any other imaging which may have been conducted, and any intraoperative findings. Each assessor examined each case to assess the presence and size of osteophytes at the anterior aspect of the femoral neck. In each case, osteophyte was judged to be absent (no bone extending beyond anterior cortex), minor (osteophyte encompassing ≤50% of anterior neck and extending ≤ 5 mm), or extensive (encompassing >50% of anterior neck and/or extending >5 mm). Examples of cases with no, minor, and extensive anterior neck osteophytes are displayed in Figure 2. Scores from each of the four assessors were compiled for each patient case. Descriptive statistics and inter-rater reliability were calculated manually in Apple Numbers [version 5.3 (5989)]. A single assessor was found to be significantly divergent from the other three. Analyses were repeated with all four assessors included and again with the single outlying assessor excluded.

3. Results and Discussion

3.1. Patient Demographics. A total of 413 cases were identified with surgical planning documents available. No patient cases were excluded. The group comprised 197 (48%) male hips and 216 (52%) female hips. Mean age of patients at the time of surgery was 63 years (SD = 10, range 32–91 years). 227 cases (55%) were planned for right THA, compared to 186 cases (45%) on the left hip. Descriptive data on the patient cohort is summarized in Table 1.

3.2. Anterior Femoral Neck Osteophyte. A summary of ratings for all 4 assessors is included in Table 2. All four assessors identified the presence of anterior femoral neck osteophytes in the majority of cases (range 69–86%). After exclusion of Rater #2 as an outlier, a mean of 82% (78-86%) of cases were found to have osteophytes in this location. A significant proportion of patients (mean 27%, range 23–31%) were found to have large or extensive osteophytes there.

3.3. Inter-Rater Reliability (IRR). Inter-rater reliability was calculated manually in Apple Numbers [version 5.3 (5989)].

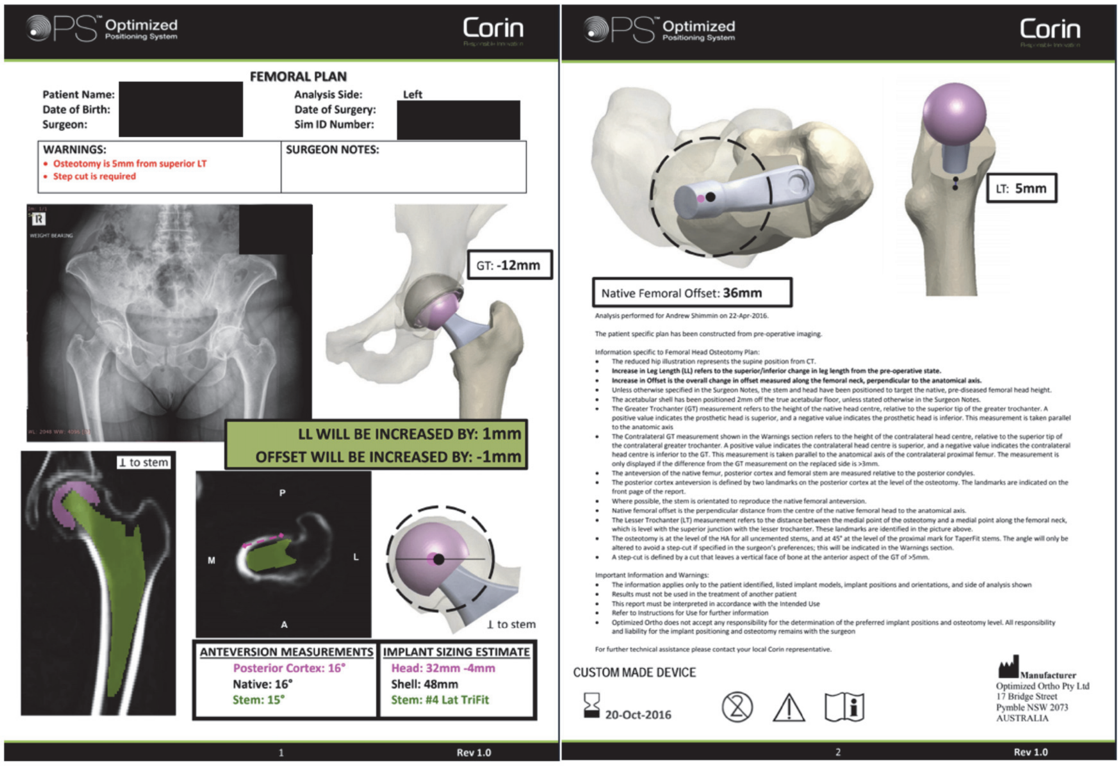

Figure 1: Case example of a presurgical plan developed using the OPS™ system, analyzed to assess the presence and size of anterior femoral neck osteophytes.

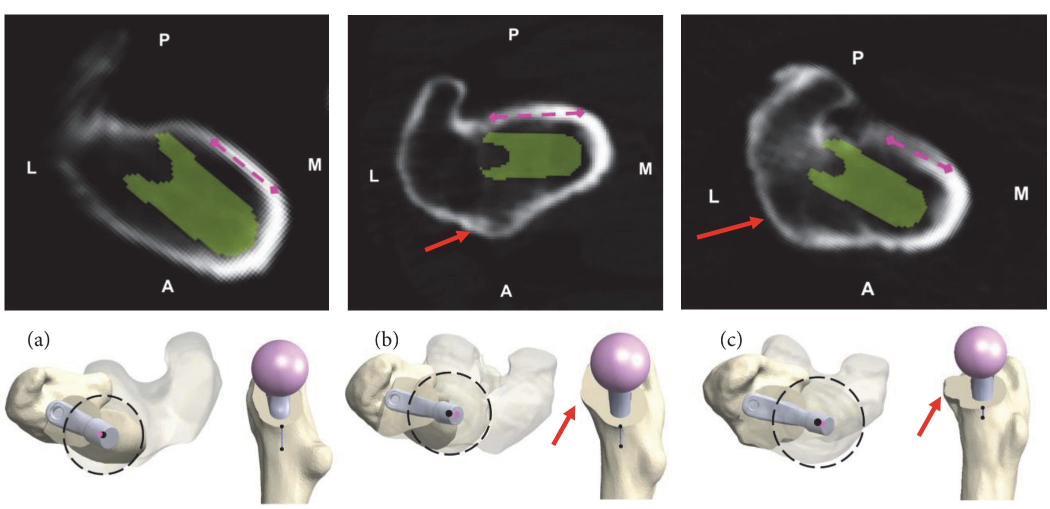

Figure 2: Case examples showing axial CT scan slices in the plane of the planned femoral neck osteotomy, with corresponding 3D reconstructions in the axial and sagittal planes (red arrows indicate anterior femoral neck osteophyte): (a) no anterior femoral neck osteophyte; (b) minor osteophyte; (c) extensive osteophyte.

Table 1: Descriptive statistics of patient cohort.

Patient Parameter	N = 413
Age (years) [mean, range]	63 (32-91)
Gender [n, %]	
Male	216 (52%)
Female	197 (48%)
Laterality [n, %]	
Right	227 (55%)
Left	186 (45%)

With all 4 assessors included, inter-rater reliability was calculated to be 68%. After exclusion of a single divergent assessor, IRR exceeded 70%.

4. Discussion

This study identified the presence of anterior femoral neck osteophyte in the large majority of this Australian cohort of THA patients. This finding was unanimous among all raters who assessed the preoperative plans. This finding is not surprising, given the experience of the authors and the inclusion of periarticular osteophyte formation as one of the hallmark radiographic features of osteoarthritis. If not addressed at the time of surgery, the presence of osteophytes at the anterior aspect of the femoral neck may significantly increase the risk of anterior bony impingement and subsequent posterior instability.

The ability to visualize osteophytes and assess the risk of impingement intraoperatively maybe depends on the choice of surgical approach. In particular, osteophytes at the anterior femoral neck may be more difficult to visualize during cases done via the posterior approach to the hip, when compared to the direct anterior, anterolateral, or direct lateral approaches. In its 2015 annual report, the UK National Joint Registry reported the use of the posterior approach in 62% of all primary total hip arthroplasty cases [14]. Given the commonality of both the posterior approach and anterior femoral neck osteophytes, a significant risk of unaddressed osteophytes remains. Numerous factors may be considered in the selection of a surgical approach, and surgeons may be hesitant to alter their approach in order to facilitate access to anterior osteophytes. Surgeons who utilize the posterior approach may elect to focus specific attention on assessing for and resecting anterior osteophytes during femoral preparation.

The impact of unaddressed anterior neck osteophytes likely also depends on a given patient's pattern of pelvic motion. It has been estimated that 52% of patients experience increased anterior pelvic tilt when sitting compared to standing [15]. These patients would be at particularly high risk of posterior instability in flexion and internal rotation due to the presence of anterior femoral neck osteophytes. A further analysis of this study cohort reveals a similar pattern, in that approximately half of the patients in each group exhibit anterior pelvic tilt with sitting (no osteophyte: 46%; minor: 58%; extensive: 50%) [unpublished data].

One limitation of this study is the utilization of an Australian cohort. This population may not be reflective of other global populations. There were no patient exclusions during analysis of a consecutive series, however, so this cohort is likely to represent the true local population. In addition, the images included in the surgical plans were generated for the purpose of implant positions and sizing and were not optimized for assessment of osteophytes. The relatively low resolution may limit the accuracy of this assessment and may have contributed to the moderate inter-rater reliability. The outlying rater was the most junior member of the research team. Differences in training may have contributed to variability among assessors.

5. Conclusions

A large majority of total hip arthroplasty patients may be expected to exhibit osteophyte formation at the anterior aspect of the femoral neck. Approximately 27% were found to exhibit large or extensive osteophytes in this area. These pathoanatomic variations must be incorporated into surgical planning and addressed intraoperatively in order to mitigate the risk of postoperative impingement and instability. Patients who experience anterior pelvic tilt with sitting will be at particularly high risk. During procedures performed via the posterior approach, focused effort and attention may be required to visualize and resect anterior femoral neck osteophytes. Planned future directions include incorporation of an impingement and instability model into preoperative surgical planning for THA.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

No industry partners were involved in study funding, nor in the preparation or publishing of the manuscript. No specific funding was attributed to this study. Two authors (Adam M. Katchky and Mitchell L. Smith) were paid stipends as clinical fellow and registrar, respectively, by the Melbourne Orthopaedic Group, which included research time to complete this study.

Conflicts of Interest

Adam M. Katchky declares that there are no conflicts of interest regarding the publication of this paper. Mitchell L. Smith declares that there are no conflicts of interest regarding the publication of this paper. Andrew J. Shimmin works for Matortho (royalties; paid consultant), Corin (royalties; paid consultant), Smith & Nephew (paid consultant), and Knee360 (unpaid consultant; shareholder). Stephen McMahon works for Smith & Nephew (unpaid consultant), Corin (shareholder; paid consultant; royalties), Knee360 (unpaid consultant; shareholder), and Stryker (consultant). Jeremy Latham works for Zimmer (paid speaker) and Lima LTO (royalties). Jonathan V. Baré works for Corin (shareholder;

Table 2: Summary of ratings for presence of anterior femoral neck osteophyte, by assessor. Analysis was repeated with Rater #2 excluded due to divergence from the others.

Assessor	Absent [n, % of cases]	Minor [n, % of cases]	Extensive [n, % of cases]	Any osteophyte (minor + extensive) [n, % of cases]
#1	56 (14%)	230 (56%)	127 (31%)	357 (86%)
#2	**128 (31%)**	**224 (54%)**	**61 (15%)**	**285 (69%)**
#3	75 (18%)	243 (59%)	95 (23%)	338 (82%)
#4	89 (22%)	210 (51%)	113 (27%)	323 (78%)

royalties; consultant; paid presentations; institutional support), Knee360 (shareholder; consultant), and Matortho (institutional support).

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Clinical Study

Clinical and Radiological Outcomes of Corrective Surgery on Adult Spinal Deformity Patients: Comparison of Short and Long Fusion

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Despite the accumulated knowledge of spinal alignment and clinical outcomes the full corrective surgery cannot be applied to all the deformity patients as it requires considerable surgical burden to the patients. The aim of this study was to investigate the clinical and radiological outcomes of the patients who have received short and long fusion for ASD. A total of 21 patients who received surgical reconstructive spinal fusion procedures and were followed up for at least one year were retrospectively reviewed. Sixteen cases have received spinal corrective surgery that upper instrumented vertebrate (UIV) was thoracic level (group T), or 5 cases were with UIV in lumbar level (group L). Group L had shorter operation time, smaller intraoperative estimated blood loss, and shorter postoperative hospitalization days. Group T tends to improve more in the magnitude of VAS of lumbar pain compared to group L. Improvement of spinal alignment revealed the advantage of long fusion compared to short fusion, in Cobb angle, sagittal vertical axis (SVA), lumbar lordosis (LL), PI-LL C7 plum line (C7PL), and center sacral vertebral line (CSVL). Pelvic tilt (PT) did not differ between the groups. Disc lordosis was the most acquired in XLIF compared to TLIF and PLF and maintained one year. There were 9 adverse events, 3 cases of pulmonary embolism (PE), one case of delirium, and 6 cases of proximal junctional kyphosis. Current study elucidated that long fusion, UIV, is thoracic and can achieve better spinal alignment compared to short fusion, UIV, in lumbar. XLIF demonstrated strong ability to reconstruct the deformity on intervertebral space that is better to apply as much intervertebral space as possible. For the ASD patients with complications, short fusion can be one of the options.

1. Introduction

In world's fastest aging society, one of the issues for quality of daily livings (QOL) of aging population in Japan is adult spinal deformity (ASD). ASD are associated with broad range of clinical and radiological findings such as progressive spinal deformity, chronic back pain, and neurological symptoms. Pathology of ASD includes primary degenerative scoliosis ("de novo" form), progressive idiopathic scoliosis in adult life, and scoliosis secondary to vertebral fracture and/or asymmetric arthritic disease [1]. Among these, the number of degenerative and secondary scolioses is increasing in Japanese aging society. Advanced ASD presents loss of function, refractory to nonoperative treatment, and therefore requires the surgical intervention.

Surgical intervention for ASD with posterior-only procedure consists of pedicle screws, osteotomies, and transforaminal interbody fusion [2]. For advanced ASD, posterior-only procedure usually requires high volume osteotomies that carry increased technical demands, longer operation time, and greater blood loss and associated morbidity. Anterior procedure predominantly utilized the disc space to reconstruct spinal alignment that also have large surgical burden as posterior osteotomies [3].

In recent years, minimally invasive surgery (MIS) for spinal fusion has become increasingly popular. The extreme lateral interbody fusion (XLIF) [4] uses the dedicated retractor installed from lateral, abdominal, retroperitoneal, transpsoas approach to lateral portion of the intervertebral disc. XLIF demonstrates strong ability to reconstruct the deformity on intervertebral space [5].

In addition to XLIF, the sacral alar iliac (SAI) screw extends from the second sacral segment to the anterior inferior iliac spine and enabled powerful compression and distraction maneuvers against greater sciatic notch [6].

Lastly, rod rotation [7] and cantilever bending technique [8] enabled correction of scoliosis and enhanced lumbar lordosis.

This recent advance in techniques, instruments, and retractors provides the means to achieve a radiographic correction for ASD to improve clinical outcomes [9]. Despite the accumulated knowledge of spinal alignment and clinical outcomes [9, 10] the full corrective surgery cannot be applied to all the deformity patients as they require considerable surgical burden to the patients. The aim of this study was to investigate the clinical and radiological outcomes of the patients who have received short and long fusion for ASD with a minimum of one year of follow-up.

2. Material and Methods

2.1. Study Design and Patient Population. A total of 21 patients who received surgical reconstructive spinal fusion procedures for their adult spinal deformity at Nippon Koukan Hospital and were followed up for at least one year, from 2014 to 2017, were retrospectively reviewed. Inclusion criteria were symptomatic degenerative adult scoliosis that has failed conservative treatment of patients with Cobb angle of at least 10°, whereas Parkinson disease and deformity due to the vertebral fracture were excluded. The follow-up period was minimum 14.3 months to maximum 57.4 months and average follow-up was 38 months. The mean age was 75.1 years old (65-88 years old), 4 males and 17 females. Of the 21 patients, 16 cases have received spinal corrective surgery that upper instrumented vertebrate (UIV) [10] was thoracic level (group T), or 5 cases were with UIV in lumbar level (group L) (Table 1). Four cases in group T underwent the same day procedure, whereas 12 cases received staged combined anterior and posterior procedures (Table 1). Staged procedures were performed on 7- to 9-day interval; XLIF was performed for the first stage and posterior surgery for the second stage. Clinical and radiographical outcomes were compared between the groups. Also, disc lordosis (Figure 1(b)) was compared among XLIF, transforaminal lumbar interbody fusion (TLIF), or posterior lumbar fusion (PLF). Lastly, introduction of Bendini (Nuvasive, San Diego, CA, USA) was discussed.

2.2. Surgical Procedure. In all of staged procedures (12 cases), in the initial surgery, multilevel (2 to 4) XLIF was performed [4]. During XLIF, the retractor attached with the light source was docked on the lateral aspect of intervertebral disc *via* retroperitoneal, transpsoas approach. After the discectomy and trial placement, a lordotic interbody cage (Nuvasive, San Diego, CA, USA) was filled with ReFit (HOYA Technosurgical Corporation, Tokyo, Japan) and autologous bone was harvested from ilium.

For posterior surgery, patients were positioned to prone on the frame and their spine was approached in a standard open fashion. Transforaminal lumbar interbody fusion (TLIF) was performed on intervertebral disc, L1/2 to L5/S1 level, where XLIFs were not performed. After the complete exposure of posterior elements, pedicle screws were placed into all targeted segments. Interspinous ligament resection and facet osteotomies or Ponte osteotomy was performed from L1/2 to L5/S1 among instrumented levels as necessary. Rod rotation [7] and cantilever bending technique [8] were performed to correct scoliosis and enhance lumbar lordosis whenever possible. A curved temporary rod was applied to the convex side of the deformity from T12 to L5 and rod rotation maneuver was performed. A final rod was designed by Bendini spinal rod bending system (Nuvasive, after Mar. 2017) and applied to the concave side with sequential compression and rotation and cantilever technique [8]. Finally, the temporary rod was change to the final rod.

2.3. Clinical Assessment. Clinical outcomes were assessed preoperatively and one year and final follow-up using the Japanese Orthopedic Association (JOA) score and the Oswestry Disability Index (ODI). The visual analog scale (VAS) was used for back and leg pain. The medical record was searched for operative data and complications.

2.4. Radiological Evaluation. Standing neural anterior-posterior and lateral thoracolumbar films were obtained before surgery, one month and a year after the surgery for assessment. Coronal alignment parameters included Cobb angle and coronal imbalance by plum line deviation (Figure 1(a)). Cobb angle was determined from degree of most superior and most inferior vertebral body (VB) of the scoliotic curve. Coronal imbalance was measured as the distance between a C7 plumb line to the center sacral vertebral line (C7PL-CSVL). Sagittal alignment parameters included lumbar lordosis (LL) from L1 to S1, pelvic incidence (PI), sagittal vertical axis (SVA), and pelvic tilt (PT) (Figure 1(b)). SVA was measured by the horizontal offset from the center of C7 to posterosuperior corner of S1 (Figure 1(b)). Disc lordosis (DL) was determined from degree of inferior line of superior VB and superior line of inferior VB (Figure 1(b)). In addition to comparison study of groups T and L, DL change was compared among XLIF, TLIF, or PLF.

Proximal junctional kyphosis (PJK) was defined as proximal junctional angle and caudal endplate to UIV to the cephalad endplate of 2 proximal vertebrae increases more than 10 degrees. [11].

2.5. Data Analysis. For numerical variables, means and standard deviations were calculated, and comparisons were made using a 2-tailed Student's t-test. Categorical variables were compared using χ^2 test.

(a) (b)

Figure 1: (a) Measurements of sagittal spinal alignment. C7PL-CSVL, C7 plum line to center sacral vertebral line; Cobb angle; SVA, sagittal vertical axis; PT, pelvic tilt; PI, pelvic incidence; LL, lumbar lordosis. (b) DL, disc lordosis.

3. Results

3.1. Clinical and Operative Data. Sixteen patients in group T had a mean age of 76 years (67-88), while 5 cases in group L had 72.2 years (65-77) with no significance (Table 2). Body Mass Index (BMI) (group T versus L = 22.3 versus 23, p = 0.74) and sex (male/female = 2/14 versus 2/3, 0.17) were also similar between groups (Table 2). The mean operation time was significantly shorter in group L (404 versus 285 min., p < 0.01); as a consequence an intraoperative estimated blood loss was smaller in group L (870 versus 137 ml, p < 0.01), and postoperative hospitalization days were shorter in group L (43.9 versus 26.8 days, p = 0.03) (Table 2). There were 9 adverse events recorded. There were three cases of pulmonary embolism (PE) in group T (cases 10, 11, and 14; Table 1). Three cases were all staged cases. One case had episode of delirium in group T (case 17). PJK were developed in four cases of group T (cases 6, 7, 13, and 17; Table 1) and one case of group L (case 2). PJK developed 277.6 days (14-532), on average, after the surgery. PJK occurred 2 weeks after the surgery in the delirium case (case 17). Four of five PJK cases required the additional surgery to extend their instrumentation superiorly. Comparison of improvement ratio in clinical outcomes revealed no significant differences between groups T and L, at one year after the surgery, in JOA score, VAS of leg pain, and ODI (p = 0.49, p = 0.69, and p = 0.7, respectively). However, group T tends to improve more in the magnitude of VAS of lumbar pain compared to group L (p = 0.067). JOA score improved from 16.9 points and 15.8 points (groups T and L), preoperatively on average to 25.3 and 25.2 at 1 year follow-up (p = 0.96) and 25.1 and 25.2 at final (p = 0.96) (Figure 2(a)). VAS of lumbar pain decreased from 64.8 mm and 43 mm preoperatively on average to 13.4 and 13.3 at 1 year follow-up (p = 0.99) and 16 and 4.8 at final (p = 0.13) (Figure 2(b)). VAS of leg pain improved from 44.3 and 44.3 preoperatively on average to 37.5 and 13.3 at 1 year follow-up (p = 0.23) and 8 and 12.3 at final (p = 0.77) (Figure 2(c)). ODI improved from 41.8 and 32 preoperatively on average to 22.8 and 16.8 at 1 year follow-up (p = 0.7) and 25.1 and 25.2 at final (p = 0.41) (Figure 2(d)).

3.2. Radiological Data. Improvement of spinal alignment revealed the advantage of long fusion compared to short fusion (Figure 3). On average, Cobb angle improved from 26.3° and 24.2° (group T and L) to 8.2° and 14° at one month after the surgery and 8.1 and 17.4 at one year (Figure 3(a)) (p < 0.01 and p< 0.01, respectively). C7PL-CSVL did not differ between the groups during the course (Figure 3(b)). Global sagittal balance investigated by the SVA changed from 92.6 mm and 93.2 mm to 40.9 mm and 94.4 mm at one month and 55.6 mm and 107 mm at one year (Figure 3(c)) (p < 0.01 and p< 0.01, respectively). SVA improved more in group T, Δ-53.5 mm, compared to group L, and Δ1.2 mm, at one month (p < 0.01). LL changed from 9.9° and 16.2° to 33.3°

Table 1: Case summaries.

Group	Case No.	age	sex	stage	XLIF levels	UIS	instrumented levels	PJK
Group L	1	77	F	1	0	L	L2-SAI	
	2	65	M	1	0	L	L2-SAI	+
	3	67	M	1	2	L	L2-5	
	4	77	F	1	3	L	L2-5	
	5	75	F	1	2	L	L3-5	
Group T	6	78	M	1	0	T	T8-SAI	+
	7	72	F	1	0	T	T10-SAI	+
	8	81	M	1	0	T	T10-SAI	
	9	76	F	1	0	T	T10-SAI	
	10	76	F	2	2	T	T7-SAI	
	11	74	F	2	2	T	T8-SAI	
	12	73	F	2	3	T	T9-SAI	
	13	75	F	2	3	T	T10-SAI	+
	14	67	F	2	2	T	T9-SAI	
	15	74	F	2	3	T	T10-SAI	
	16	72	F	2	4	T	T9-SAI	
	17	69	F	2	2	T	T10-SAI	+
	18	79	F	2	3	T	T10-SAI	
	19	88	F	2	3	T	T10-SAI	
	20	76	F	2	3	T	T10-SAI	
	21	86	F	2	3	T	T10-SAI	

Table 2: Clinical and operative variables. BMI = Body Mass Index.

Variable	Group T	Group L	p Value
No. of cases	16	5	
age	76 (67-88)	72.2 (65-77)	0.24
BMI	22.3	23	0.74
Sex (M/F)	2/14	2/3	0.17
Operation time	404∗∗	285	<0.01∗
Intra-operative estimated blood loss	870	137	<0.01∗
Post-operative hospitalization days	43.9	26.8	0.03∗

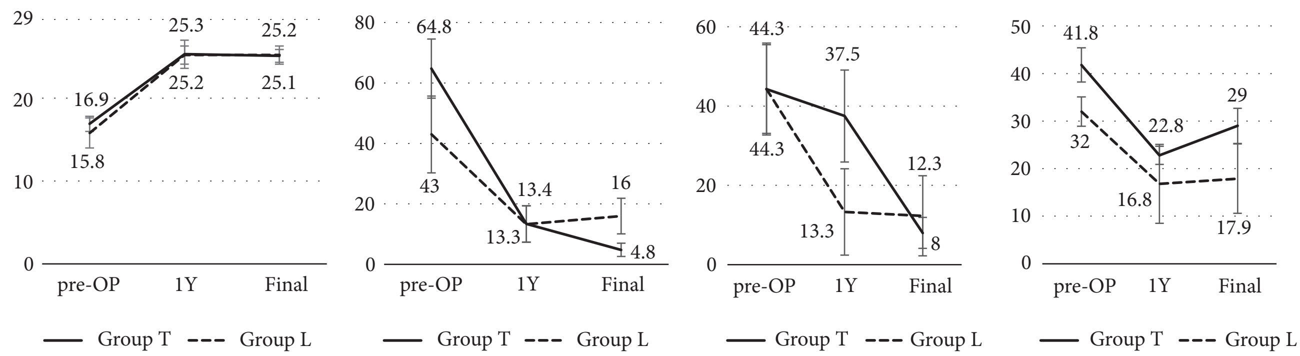
∗ Statistically significant.
∗∗ In staged cases, time of second surgery was adopted.

and 19.4° at one month and 19.5° and 14.2° at one year. LL improved more in group T, Δ23.3°, compared to group L, and Δ3.2°, at one month (Figure 3(d)) ($p < 0.01$). Similarly, PI-LL changed from 42.6 and 33.2 to 20.7 and 30 at one month, 22 and 35.2 at one year, improved more in group T, Δ-23.5, compared to group L, Δ-3.2°, at one month (Figure 3(e)) ($p < 0.01$). PT did not differ between the groups during the course (Figure 3(f)). Disc lordosis was the most acquired in XLIF compared to TLIF and PLF ($p < 0.01$) and maintained till one year (Figure 4) ($p < 0.01$).

Four cases in group T and one case in group L developed PJK after the surgery. In group T, patients were divided into PJK and non-PJK group and were compared. Four cases of PJK had larger SVA (82.5 versus 50.2 mm, $p = 0.11$), whereas other parameters did not reach significance. One case in group L had the largest SVA.

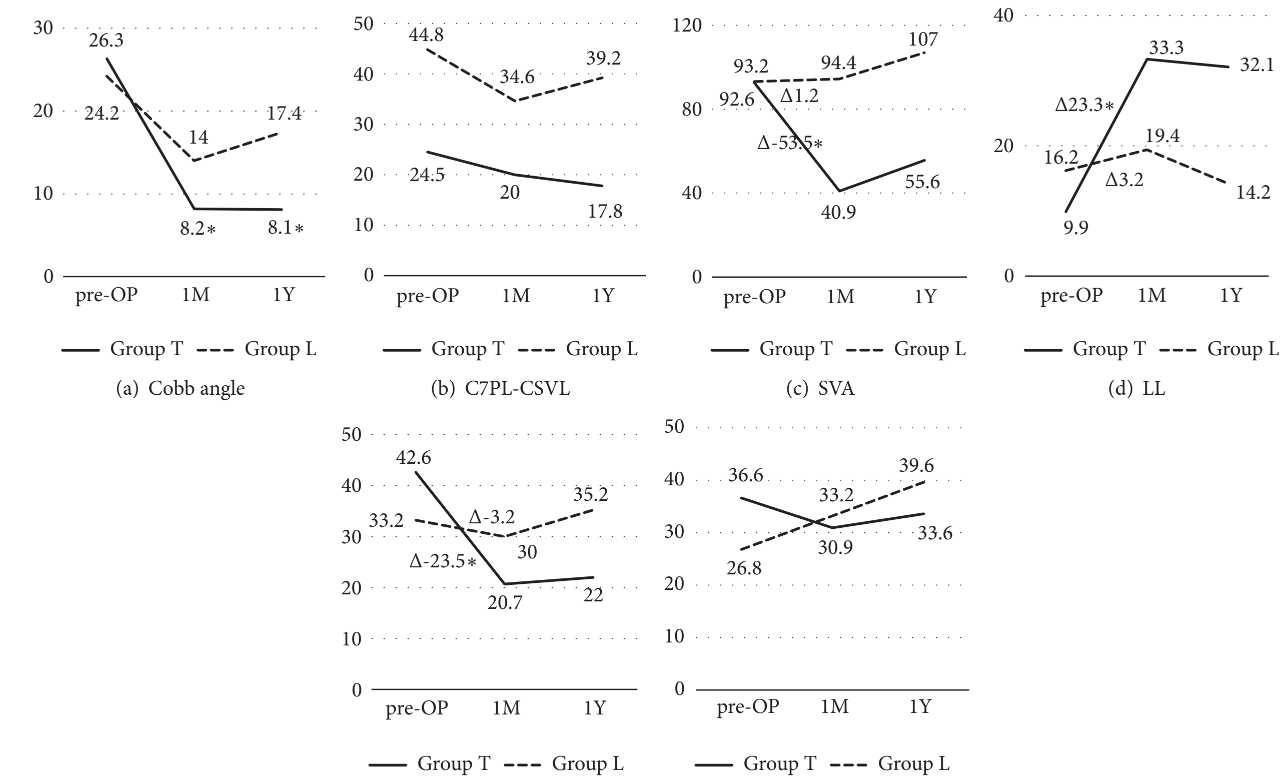
4. Case

Eighty-six-year-old female (case no. 21) received staged spinal corrective surgery on her ASD (Figures 5(a) and 5(b)). XLIF was performed on L2/3,3/4,4/5 with 2 hours 29 min., estimated bleeding of 30 ml. Eight days later, open posterior surgery was conducted from T10 to S2 level with 7 hours and 27 min., estimated bleeding of 1100ml. Postoperative hospitalization days were 64 days. Clinical outcomes improved in



(a) JOA score (b) VAS of lumbar pain (c) VAS of limb pain (d) ODI

Figure 2: Mean values of clinical outcomes at preoperative, 1 year after the surgery and final follow-up of (a) JOA score, (b) VAS of lumbar pain, (c) VAS of limb pain, and (d) ODI. JOA, Japanese Orthopedic Association; VAS, Visual Analog Scale; ODI, Oswestry Disability Index.



(a) Cobb angle (b) C7PL-CSVL (c) SVA (d) LL (e) PI (f) PT

Figure 3: Mean values of radiological measurements at preoperative, 1 month after the surgery and 1 year of (a) Cobb angle, (b) C7PL-CSVL= C7 plum line, central sacral vertical line, (c) SVA = Sagittal vertical axis, (d) LL = lumbar lordosis, and (e) PI = Pelvic incidence. (f) PT = pelvic tilt. ∗ Difference is significant compared to group L.

magnitude of JOA score, VAS of lumbar pain and leg pain, ODI from 23, 64.8, 44.3, and 41.8, preoperatively to 23, 46, and 37, and no data at one month after the surgery, 25, 12, 20, and 17.8 at one year, respectively (Table 3(a)). C7PL-CSVL improved from 62 mm to 3 mm at one month after the surgery and 2 mm at one year. SVA decreased from 119 mm to 12 mm at one month after the surgery and 11 mm at one year (Table 3(b)). Cobb angle improved from 29° to 4° at one month after the surgery and 8° at one year. LL increased from 4° to 42° at one month and 45° at one year. In consequence, PI-LL improved from 50 to 12 at one month and 9 at one year. PT did not change during the course, from 24° to 21° at one month after the surgery and 27° at one year (Table 3(b)).

5. Discussion

ASD are associated with broad range of clinical and radiological findings such as progressive spinal deformity, chronic

Table 3: Clinical scores and alignment parameters of case no. 21.

(a)

Clinical scores	pre-OP	1 M	1 Y
JOA score	19	23	25
VAS of lumbar pain	69	46	12
VAS of leg pain	51	37	20
ODI	33.3	-	17.8

(b)

Alignment parameters	pre-OP	1 M	1 Y
C7PL-CSVL	62	3	2
SVA	119	12	11
Cobb angle	29	4	8
LL	4	42	45
PT	24	21	27
PI-LL	50	12	9

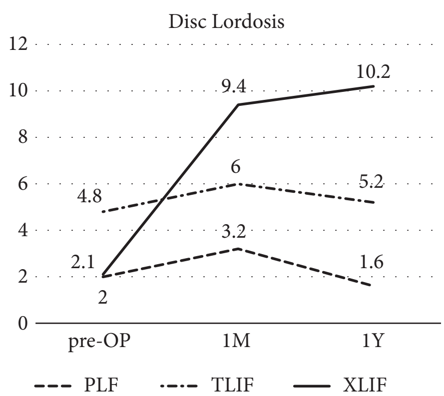
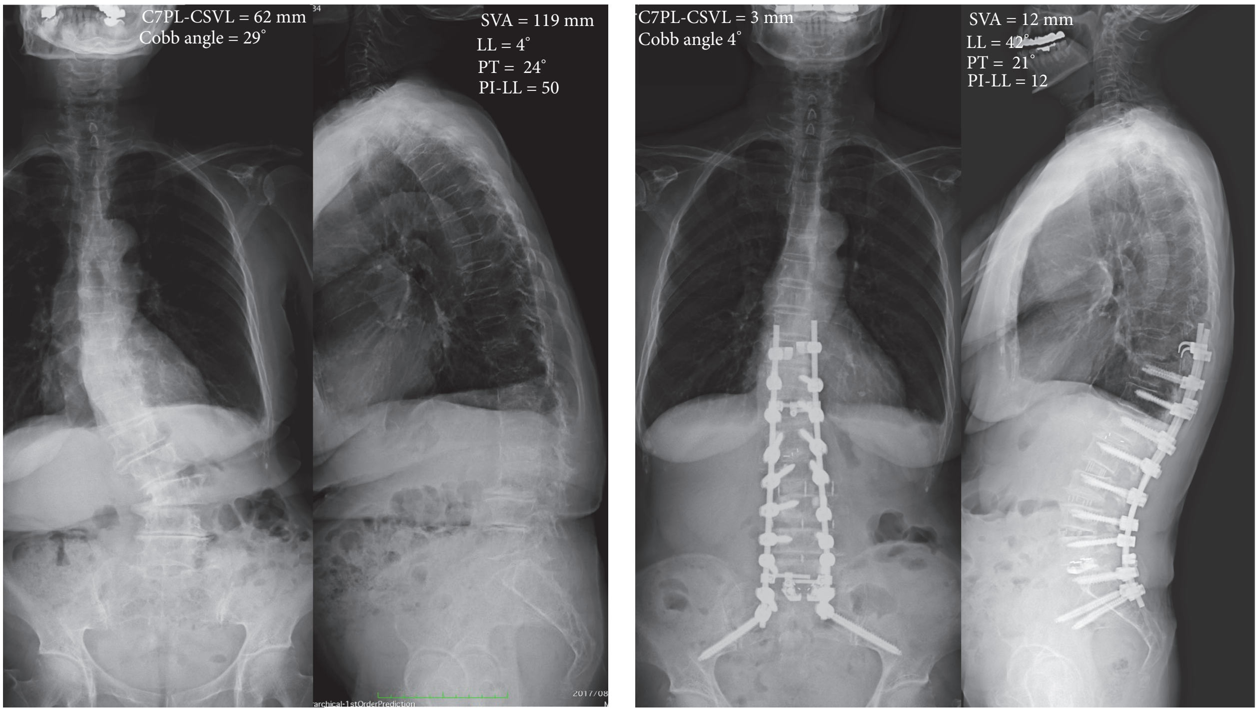


Figure 4: Disc lordosis before operation, 1 month after the surgery, and 1 year.

back pain, and neurological symptoms. Previous studies have shown the spinal sagittal alignment and global balance is essential for patients QOL [9, 10, 12, 13]. To achieve proper spinopelvic alignment in the ASD patients, some of operative interventions require more surgical burden for the patient and more technical and physical demand on the spine surgeons. For advanced ASD, posterior-only procedure usually requires high volume osteotomies. Instead of osteotomies, anterior procedure predominantly utilized the disc space to reconstruct spinal alignment that also has large surgical burden [3]. Recently introduced XLIF [4] can be alternative to the anterior procedure. Combined with XLIF and posterior correction and instrumentation, favorable clinical outcomes have been reported [12, 14, 15]. XLIF use the dedicated retractor which requires smaller incision than open anterior procedure and approach from lateral, abdominal, retroperitoneal, transpsoas approach to lateral portion of the intervertebral disc. Surgical field is bright with light source so that retroperitoneal organs and psoas are visible and surgeon can carefully approach the lateral aspect of the disc without bleeding or damaging vital organs. In this manner, XLIF extremely reduced surgical burden compared to the conventional anterior procedure. In addition to reduction of surgical burden, XLIF demonstrates strong ability to reconstruct the deformity on intervertebral space [5]. It restores disc height and indirectly decompression spinal canal. Previous studies have reported XLIF is effective for coronal correction and only mild effect on improvement of sagittal alignment [16, 17]. Therefore, we perform conventional open surgery for posterior procedure to acquire adequate sagittal alignment. Sagittal correction is enhanced using facet osteotomies, rod rotation [7], and cantilever bending technique [8]. Open conventional procedure requires a decent amount of surgical burden that the long fusion needs to consider for their application on the ASD patients with complications. According to our comparison study, group T had longer operation time, intraoperative estimated blood loss, and longer postoperative hospital stay (Table 2). As expected, this result indicated that surgical burden was higher in group T.

It is known that sagittal balance is the most important and reliable radiographic predictor for clinical outcomes [13]. Schwab established the threshold value for the proper spinopelvic alignment in ASD patients, SVA less than 5 cm, PT less than 25°, and PI-LL under 10 [13]. In the current study, improvement of spinal alignments was better in group T compared to group L (Table 3). In group L, the SVA has not changed between before and after; rather it worsened little whereas LL increased after surgery. This might be because the thoracic kyphosis exceeded improved LL. These results indicate that the long fusion is required to achieve adequate sagittal alignment. However, most of the spinal parameters in group T did not satisfy the threshold value of sagittal balance. Correction of coronal deformity is also important in ASD patients. Cobb angle improved in both groups, where group T achieved better correction at one month and one year follow-up. Current study showed correction of Cobb angle was identical to previous report [18]. C7PL-CSVL, however, did not improve to targeted threshold [19]. These insufficient corrections may be because the age of patient of this study was high and bone quality could not tolerate the correction. The other factor for the substandard of the threshold can be the technical issues. For the earlier patients, the rod rotation [7] and cantilever bending technique [8] were not applied, where correction may be inadequate. After these techniques are introduced in combination with Ponte osteotomy and XLIF, postoperative spinal alignment improved compared to previous cases (Figure 5). In addition, disc lordosis was most acquired in the XLIF than TLIF or PLF that XLIFs are performed on many disc spaces as possible (Figure 4). In three cases in group T, Bendini spinal rod bending system was applied for rod bending. This system will save surgeon from the stress of rod bending. Time for rod bending, alignment assessment, and complication such as rod failure needs to be investigated in future.

JOA and some of patients-based outcomes are not significantly different as the spinal parameters. In this study, JOA score is collected by the operators that may cause the bias. Importantly, VAS of lumbar pain improved better in group T compared to group L at the final follow-up, which was parallel to improvement of spinal alignment (Figure 2(b)).



(a) (b)

Figure 5: Before and after images of total spine of the case. The after images were 1 month after the surgery.

The complication rate was 38%, and there were no mortalities related to the procedure. Seven out of 16 cases developed complications in group T and 1 case out of 5 in group L. Although it was not significantly high, group T seems to have more complications compared to group L. Three cases developed PE in our series (14.3%). The ratio was higher than previous report [18, 20]. After compression stockings and intermittent pneumatic compression device were adopted for precaution during the surgery, no symptomatic PE case was observed. The ratio of PJK was lower in current series (28.3%) [11, 21, 22]. It is known that LL change more than 30° is the risk for PJK [22]. Therefore, lower PJK ratio can be our moderate correction of LL. However, large SVA was found as a risk factor for PJK. These results indicated optimal spinal alignment is required for favorable postoperative clinical outcomes. Further clinical study is required to understand optimal spinal alignment. Additionally, wearing hard corset for more than a year after the surgery might help to avoid PJK.

5.1. Study Limitation. This was the retrospective study and the limitation in this study is selection bias and incomplete data. And the number of cases was small to describe conclusion. In future, prospective study with large number of the patients will provide sufficient data to assess defined study.

5.2. Conclusion. Current study elucidated that to acquire harmonious spinal alignment and favorable clinical outcomes, long fusion is better than short fusion. XLIF demonstrated strong ability to reconstruct the deformity on intervertebral space that is better to apply as much as possible. For the ASD patients with complications, short fusion can be one of the options [10].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Review Article

Compensatory Function of the Subtalar Joint for Lower Extremity Malalignment

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It is important to evaluate the subtalar joint and hip-knee-ankle alignment to understand lower extremity alignment. In this review, we focused on the compensatory changes in the subtalar joint alignment for the deformity of the knee and ankle joint, reviewing previous research. The subtalar joint alignment was compensatory valgus in patients with varus knee and ankle deformity, whereas it was uncertain whether the subtalar joint alignment was compensatory varus in patients with valgus knee and ankle deformity. The subtalar joint valgus alignment improved after total knee arthroplasty or high tibial osteotomy for varus knee deformity, even if the deformity was severe. In contrast, whether the subtalar joint alignment changed after the surgery for ankle or valgus knee deformity has not been considered. Further research on the compensatory function of the subtalar joint is needed.

1. Introduction

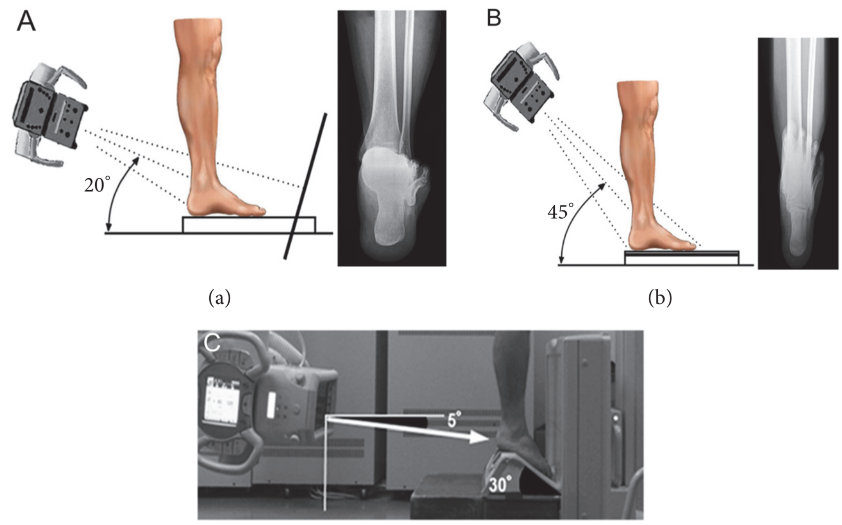
When treatment for lower extremity malalignment is needed, it is important to evaluate the lower extremity alignment correctly. Many studies assessed only the hip-knee-ankle alignment, such as the femorotibial alignment or the mechanical axis running from the center of the femoral head to that of the ankle [1–3]. However, weight-bearing on the lower extremity runs from the hip to the knee, ankle, and foot, and then to the ground. As calcaneus is in contact with the ground, it is necessary to evaluate the alignment of the subtalar joint in addition to the hip-knee-ankle alignment to correctly measure the lower extremity alignment [4].

Each joint of the lower extremity compensates the malalignment caused by deformities of the other joints [10, 11, 20]. In particular, recent studies have discussed the compensatory function of the subtalar joint [7, 13, 19]: several reports show that the subtalar joint compensates for the deformities of the knee and ankle joints [10, 12, 17, 18, 20], and the subtalar joint alignment which was 2°-6° valgus in healthy legs [21, 22] changed after surgery to correct these deformities [7, 14, 16]. When surgery for knee or ankle deformity is needed, it is helpful for surgical planning to understand the mechanism of subtalar joint compensation and how the subtalar joint alignment changes after surgery.

In this literature review, we discuss the compensatory function of the subtalar joint in patients with deformities of the lower extremity, reviewing previous research.

2. Radiographic Assessment of the Hindfoot Alignment

Several methods can be used for the radiographic imaging of the coronal plane alignment of the subtalar joint or hindfoot. Cobey [23] and Saltzman et al. [24] reported the hindfoot alignment view: subjects stood on a floor, and an X-ray beam with an inclination angle of 20° to the floor was directed from the posterior to the anterior side. A modified method was also reported, with a film cassette lying on the floor and the X-ray beam directed at it with an inclination angle of 45° [5, 25] (Figure 1(b)). In these methods, the hindfoot alignment was usually evaluated using the heel alignment distance (HD) as the distance between the contact point of the heel and the intersection of the extended tibial axis and the distal part of the calcaneus [7, 19, 24], and the heel alignment



(a) (b)

(c)

Figure 1: (a) The inclination angle of the beam is 20° to the floor. The film cassette is perpendicular to the central beam of the radiation source. (b) The film cassette is lying on the floor and the subject is standing on the film cassette. The inclination angle of the beam is 45° to the floor. (a) and (b) are reproduced from Reilingh et al. 2010 [5] [under the Creative Commons Attribution License/public domain]. (c) Participants stood on a radiolucent platform with equal weight on both feet. This platform was flat in the rear part and inclined by 30° in the front part, so that the midfoot and forefoot of participants were planter-flexed. The X-ray beam was oriented down 5° from the horizontal position. (c) is reproduced from Ikoma et al. 2013 [6] [under the Creative Commons Attribution License/public domain].

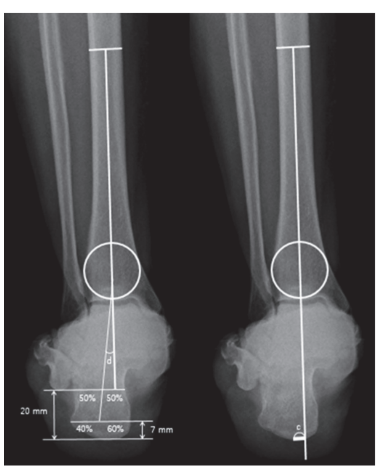
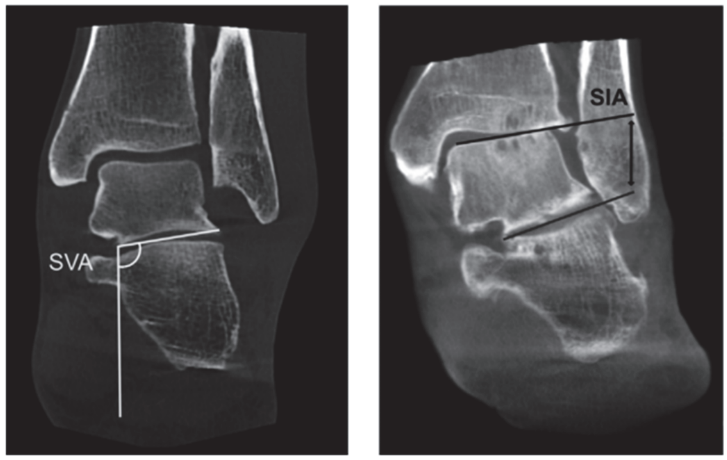


Figure 2: Heel alignment angle (HA) was defined as the angle (d) between the tibial axis and the calcaneal axis. Heel alignment distance (HD) was defined as the distance (c) between the contact point of the heel and the intersection of the extended tibial axis and the distal part of the calcaneus. Figure 2 is reproduced from Jeong et al. 2018 [7].

Figure 3: The measurement of the V-V angle. Line a indicates the long axis of the tibia. Point b indicates the lateral extremity of the calcaneus at the posterior surface of the talocalcaneal joint. Point c indicates the superior margin of the sustentaculum tali. Angle d is the V-V angle. Figure 3 is reproduced from Takenaka et al. 2015 [8] [under the Creative Commons Attribution License/public domain].

angle (HA) measured as the angle between the axis of the distal tibia and the axis of the calcaneus [11, 12, 15, 26, 27] (Figure 2). HA is also referred to as hindfoot alignment angle or tibiocalcaneal angle. On the other hand, Ikoma et al. [6] reported a different method, whereby subjects stood on a radiolucent platform, which was flat in the rear part and inclined by 30° in the front part. The X-ray beam was oriented down 5° from the horizontal position (Figure 1(c)).

This method assessed the hindfoot alignment using the V-V angle, measured as the angle between the axis of the line from the top of the sustentaculum tali to the lateral-inferior end of the posterior facet of the calcaneus and tibial axis (Figure 3). Moreover, the utility of weight-bearing computed tomography (CT) scans has also been recently suggested [28, 29]. In CT scans, the subtalar vertical angle (SVA) and



(a) (b)

Figure 4: (a) Corresponding weight-bearing computed tomography (CT) scan. The orientation of the subtalar joint to the ground was assessed using the subtalar vertical angle (SVA). (b) Corresponding weight-bearing CT scan. The subtalar inclination angle (SIA) was used to assess the inclination of the subtalar joint. Figure 4 is reproduced from Krahenbuhl et al. 2017 [9].

subtalar inclination angle (SIA) were measured for evaluating the subtalar joint alignment (Figure 4).

3. Compensatory Function of the Subtalar Joint for Deformity of the Knee

Norton et al. [12] showed that there was a significant correlation between knee and hindfoot alignment, and a moderately strong correlation in patients with knee deformity, and this correlation was remarkable with larger knee deformity (≥ 10°). The correlation coefficient between hindfoot angle and mechanical axis angle was -0.413 and was -0.536 for those with larger knee deformity. These results indicate that the hindfoot alignment was compensatory valgus in patients with varus knee osteoarthritis (OA) and was varus in patients with valgus knee OA. Several reports supported this hindfoot compensatory function in patients with varus knee OA [11, 14]. However, hindfoot compensation for valgus knee OA could not be found in the report by Mullaji et al. [11].

Nakada et al. [15] demonstrated the subtalar joint compensation for the deformity of knee joints with rheumatoid arthritis (RA). The positive correlation between the femorotibial angle (FTA) and the HA only existed in knees with a Larsen grade≥ 4 ($r = 0.544$), but not in knees with a Larsen grade≤ 3 ($r = 0.180$). In measurement of the FTA, a lesser value is considered as valgus knee and bigger as varus. In measurement of the HA, a lesser value is considered as varus hindfoot and bigger as valgus. This correlation was stronger in patients with less damaged subtalar joints (Larsen grade≤ 3) ($r = 0.705$).

4. Compensatory Function of the Subtalar Joint for Deformity of the Ankle

Several reports showed that the subtalar joint could compensate the varus ankle OA [9, 17–19]. The subtalar inclination angle (SIA) increased from Takakura Stages 1 to 3a [30] (2.9° ± 7.0° in Stage 1, 8.0° ± 8.6° in Stage 2, and 11.5° ± 5.7° in Stage 3a) compared to the control (1.5° ± 5.9°) and decreased at Stages 3b and 4 (4.0° ± 9.2° in Stage 3b and 3.0° ± 9.8° in Stage 4) [17]. This suggested that the subtalar joint was compensatory valgus in patients with early to intermediate Takakura stage but could not compensate in patients with the end stage. In contrast, Krahenbuhl et al. [9] found that the subtalar joint compensation for the varus ankle OA was independent of the stage of ankle joint osteoarthritis, extent of the talar tilt in the ankle joint mortise.

In patients with valgus ankle OA, the subtalar joint compensation might be small [9, 19]. Wang et al. [19] showed that only 38.6% of valgus ankles were compensated by subtalar joints (HA < -7.7°), whereas 53% of varus ankles were compensated (HA > -13.1°). Krahenbuhl et al. [9] could not find the subtalar joint compensation in patients with valgus ankle OA. In their study using weight-bearing CT scans, SVA and SIA measurement revealed that the subtalar joint was valgus synchronizing the valgus ankle deformity.

5. The Subtalar Joint Alignment after Surgery for the Knee Malalignment

Chandler et al. [10] first described that the hindfoot varus or valgus angle changed after the correction of knee deformity with total knee arthroplasty (TKA), showing that the hindfoot compensated the knee deformity. However, they did not clearly explain the correlation between them. Thereafter, several reports found that the compensatory subtalar valgus was corrected after TKA in patients with knee OA [7, 8, 11, 13, 14, 31]. Hara et al. [31] and Takenaka et al. [8] evaluated the subtalar joint alignment using the V-V angle, which averaged a normal value of 76.0° [6] and showed significant improvement in the subtalar joint alignment in patients with subtalar valgus (V-V angle ≥ 76.0°) from 80.5° ± 3.1° to 78.6° ± 3.7° three weeks after TKA and further improved to 77.1° ± 2.7° one year after TKA. However, in patients with subtalar varus (V-V angle < 76.0°), the preoperative V-V angle (72.7° ± 2.6°) did not improve three weeks and one year after TKA (72.3° ± 3.3°, and 73.5° ± 3.0°, respectively). In another report from Cho et al. [14], greater improvements of hindfoot valgus were found in patients with a severe varus deformity of the knee joint (varus ≥ 10°). Greater improvement of the mechanical axis angle from 13.9° ± 3.7° varus to 2.6° ± 3.5° varus in these patients might result in a greater improvement of hindfoot valgus from 6.5° ± 3.8° valgus to 2.5° ± 4.1° valgus. Similar results were observed by Jeong et al. [7], who found a correlation between the pre-postoperative variance in the mechanical axis angle and the ground-talar dome angle, HA and HD (r = 0.7, -0.348 and -0.418, respectively). Okamoto et al. [13] focused on the American Orthopaedic Foot and Ankle Society (AOFAS) ankle–hindfoot scale in addition to the hindfoot alignment after TKA. They also evaluated calcaneal pitch and naviculocuboid overlap in plane weight-bearing lateral foot radiograph as the index of hindfoot alignment. They found that calcaneal pitch, naviculocuboid overlap, and AOFAS ankle–hindfoot scale with moderate varus deformity of the knee (≤ 6° varus) improved after TKA, but those with severe varus deformity of the knee (> 6°) did not improve after TKA.

In contrast, only one report assessed the subtalar joint alignment after TKA in patients with valgus knee OA [11]. They showed that the subtalar joint was valgus before TKA and remained valgus after TKA. However, because their study included quite a small number (n= 12) of patients with valgus OA, further studies with larger sample sizes are needed.

The change of the subtalar joint alignment after tibial osteotomy for knee malalignment was also assessed. Choi et al. [16] evaluated the hindfoot alignment after high tibial osteotomy. They found that the preoperative degree of hindfoot valgus deviation (7.8° valgus) decreased progressively 3 months, 6 months, and 12 months after HTO (4.0°, 3.4°, and 2.3° valgus, respectively).

6. The Subtalar Joint Alignment after Surgery for the Ankle Malalignment

There is only one report by Choi et al. [16] which evaluated the hindfoot alignment after surgery for ankle OA. They evaluated the hindfoot alignment after low tibial osteotomy (LTO) [32] for ankle OA. They included patients with severe ankle OA averaged Takakura stage of 3.2 [30], and preoperative mild hindfoot varus deviation (1.0° varus) was seen. After LTO, the hindfoot alignment was changed to valgus deviation without any compensatory mechanism 3 months, 6 months, and 12 months after LTO (4.8°, 4.7°, and 4.8° valgus, respectively).

7. Discussion

The subtalar joint alignment was compensatory valgus for varus knee deformity, but this compensatory function remains controversial in the valgus knee deformity (Table 1) [11, 12, 15]. On the other hand, the subtalar joint could compensate for early stage varus ankle OA, but not for end-stage varus ankle OA and valgus ankle OA [9, 17–19]. If the subtalar joint was destroyed, the subtalar joint compensation for deformity in the knee and ankle joints might not occur [15, 19]. Lee et al. [18] reported that patients with a well-preserved subtalar range of motion may better compensate varus ankle OA. These results may indicate that the destroyed subtalar joint was rigid and did not have enough joint movement to compensate for the deformity of the knee and ankle. Nakada et al. [15] assessed the subtalar compensatory alignment for the knee deformity in patients with RA. They found that the subtalar joint could compensate the knee deformity, and this compensation was stronger in patients with less damaged subtalar joints (Larsen grade≤ 3). The subtalar joint without severe destruction could compensate both the varus and valgus deformity of the knee in patients with RA. However, the destructed subtalar joint could not compensate the knee deformity and became varus or valgus synchronizing to the varus or valgus knee deformity.

Surgical procedures such as TKA or HTO for the varus knee OA could also improve the subtalar compensatory malalignment (Table 1) [7, 8, 11, 13, 14, 16]. In particular, greater improvements of hindfoot valgus occurred in patients with a severe varus deformity of the knee joint [14], and the variation of correction of varus knee alignment was significantly correlated with that of valgus subtalar alignment after TKA [7]. In contrast, Okamoto et al. [13] found that subtalar valgus did not improve in severe knee OA. However, they evaluated the subtalar alignment using calcaneal pitch and naviculocuboid overlap in a plane weight-bearing lateral foot radiograph. It was unclear whether these sagittal alignment parameters directly reflected the coronal subtalar joint varus or valgus alignment. Takenaka et al. [8] found that the subtalar joint alignment did not improve after TKA in the subtalar joint varus group. The preoperative subtalar joint varus could indicate that the subtalar joint lost the ability to compensate and result in rigid varus. Therefore, the subtalar joint remained varus after TKA. Although correction of varus knee OA could improve the subtalar valgus alignment, it was unclear whether correction of valgus knee OA could also influence the subtalar joint alignment. Further study is desirable to pursue these additional research gaps.

The influence of surgery for the ankle deformity to the subtalar joint was only evaluated in one study (Table 1) [16] and was quite unclear. They showed that the hindfoot alignment was varus in patients with advanced ankle OA and changed to valgus after LTO. Because the ability of subtalar joint compensation might be lost in advanced ankle OA [17, 18], hindfoot alignment became valgus after LTO, synchronizing to the correction of ankle alignment. Further assessments for change of the subtalar joint alignment at several stages of ankle OA after LTO, total ankle arthroplasty, and ankle arthrodesis could reveal the compensation mechanism of the subtalar joint.

Table 1: Review of studies which assessed the subtalar joint compensation for the knee or the ankle deformity.

	Total number	Reasons for deformation	Surgical procedure	Evaluation of subtalar alignment	Findings
Chandler et al. [10]	86	Varus and valgus knee OA	TKA	plane radiographs	The subtalar joint compensated the deformity of the knee. There was no correlation between the knee and subtalar joint alignment.
Mullaji et al. [11]	165	Varus and valgus knee OA	TKA	plane radiographs	The hindfoot valgus decreased after TKA. 87% of the subtalar joint continued to have valgus alignment even after TKA.
Norton et al. [12]	401	Varus and valgus knee OA	-	plane radiographs	Most of the compensation to angular deformity at the knee occurred in the subtalar joint. There was a correlation between knee and hindfoot deformities in patients with a larger knee deformity ($\geq 10^{\circ}$).
Takenaka et al. [8]	71	Varus knee OA	TKA	plane radiographs	The subtalar joint alignment improved 3 weeks after TKA in the subtalar joint valgus group, and further improvement was noted 1 year following TKA. The subtalar joint alignment did not improve after TKA in the subtalar joint varus group.
Okamoto et al. [13]	75	Varus knee OA	TKA	plane radiographs	Calcaneal pitch, naviculocuboid overlap and hindfoot pain with moderate varus deformity of knee ($\leq 6^{\circ}$ varus) improved after TKA, but those with severe varus deformity of knee ($> 6^{\circ}$) did not improve after TKA.
Cho et al. [14]	195	Varus knee OA	TKA	plane radiographs	Greater improvements of hindfoot valgus occurred in patients with a severe varus deformity of the knee joint ($\geq 10^{\circ}$) after TKA. There was no further improvement in hindfoot alignment between 6 weeks and 2 years post-operatively.

Table 1: Continued.

	Total number	Reasons for deformation	Surgical procedure	Evaluation of subtalar alignment	Findings
Jeong et al. [7]	375	Varus knee OA	TKA	plane radiographs	The variation of correction of varus knee alignment was significantly correlated with that of the valgus ankle and subtalar alignment after TKA.
Nakada et al. [15]	205	Knee RA with varus and valgus deformity	-	plane radiographs	Correlation exists between the knee and hindfoot alignments only in knees with a Larsen grade ≥ 4. This correlation was stronger in patients with less damaged subtalar joints (Larsen grade ≤ 3).
Choi et al. [16]	38 for HTO 46 for LTO	Varus knee and ankle OA	HTO and LTO	plane radiographs	Hindfoot alignment was valgus in patients with advanced arthritis of the knee, but mild hindfoot varus deviation was seen in patients with advanced arthritis of the ankle. Preoperative hindfoot valgus deviation was decreased after HTO, whereas the hindfoot alignment was changed to valgus deviation synchronizing to the ankle alignment after LTO.
Hayashi et al. [17]	133	Varus ankle OA	-	plane radiographs	The subtalar joint compensates varus deformity of the ankle at the intermediate stage ankle OA, but not at the end stage.
Lee et al. [18]	154	Varus ankle OA	-	plane radiographs	Hindfoot alignment was valgus in many ankles in stage II and IIIA, and the mean value was varus in stage IIIB and IV.
Wang et al. [19]	233	Varus and valgus ankle OA	-	plane radiographs	Compensation of the subtalar joint was identified in 39% of valgus ankle OA and 53% of varus ankle OA. The patients with no or mild degenerative changes of the subtalar joint may compensate the ankle malalignment
Krahenbuhl et al. [9]	88	Varus and valgus ankle OA	-	computed tomography	Compensation of the subtalar joint for the ankle deformity could only be verified for varus ankle osteoarthritis and not for valgus ankle osteoarthritis. Subtalar joint alignment had no influence on the stage of ankle osteoarthritis, extent of the tibiotalar tilt and stage of subtalar joint osteoarthritis.

OA: osteoarthritis, TKA: total knee arthroplasty, HTO: high tibial osteotomy, LTO: low tibial osteotomy

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Review Article

Intra- and Extra-Articular Deformity of Lower Limb: Tibial Condylar Valgus Osteotomy (TCVO) and Distal Tibial Oblique Osteotomy (DTOO) for Reconstruction of Joint Congruency

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Osteotomies are the established surgical procedure for the deformity of the lower limb induced by osteoarthritis (OA) of the knee and ankle. Closed-wedge (CW) and open-wedge (OW) high tibial osteotomy (HTO) are extra-articular surgery, which aim to shift the mechanical axis from medial to slightly lateral and reduce the overload in the medial compartment of the varus deformed knee by extra-articular correction. However, varus deformity of the knee with the teeter effect, which could be accompanied with subluxation and thrust due to the medial-lateral soft tissue imbalance, is not resolved only by the shift of mechanical axis. The depression of the medial tibia plateau, so-called pagoda deformity, is the intra-articular deformity, which could potentially cause the teeter effect and involves intra-articular incongruency. In such case, the osteotomy with novel concept should be developed to overcome the issues, both the imbalance of soft tissue and intra-articular deformity. Tibial condylar valgus osteotomy (TCVO) is an intra-articular osteotomy, which improves the joint congruency of the medial-compartment knee OA with subluxation and/or intra-articular deformity and also provides better joint stability. A similar argument is raised in the treatment of the ankle OA. Low tibial osteotomy (LTO) is an extra-articular surgery to correct malalignment of lower leg. Distal tibial oblique osteotomy (DTOO) is a novel surgery to improve the bony congruency of the ankle OA. In DTOO, the distal tibia is cut obliquely from the proximal medial to the distal lateral in the coronal plane and towards the center of the tibiofibular joint to improve the bony congruency of the ankle joint. Tibial condylar valgus osteotomy (TCVO) and distal tibial oblique osteotomy (DTOO) can correct intra-articular deformity of knee and ankle, respectively. The rationale and indication of TCVO and DTOO for the treatment of the lower limb by reconstructing the joint congruency are discussed.

1. Introduction

Deformity of the lower limb induced by osteoarthritis of the knee or ankle causes the adverse effect on daily living due to gait disturbance, which could cause abnormal posture, as well as local problem such as pain. Various surgical procedures have been performed such as femoral, tibial osteotomies, and hip and knee arthroplasties to overcome these issues. Osteotomies are the established surgical options for the treatment of lower limb.

Osteoarthritis of the knee is a representative disease, which involves malalignment of the lower limb with the joint degeneration. Arthroplasty of the knee, involving total knee arthroplasty (TKA), unicompartmental knee arthroplasty (UKA), is established as surgical procedures with good clinical results [1–3]. Around knee osteotomies (AKO) have also been performed extensively for the treatment of this disease and have shown the good clinical outcomes by correcting the alignment of lower limb. High tibial osteotomy (HTO) is performed extensively, which aims to correct the varus knee arthrosis. Many studies demonstrated the good results by cutting the proximal tibia as lateral closed-wedge high tibial valgus osteotomy (CWHTO) or dome valgus osteotomy. Medial open-wedge high tibial valgus osteotomy (OWHTO) has also been developed for the correction of the varus deformed knee and extensively spread by the improvement in surgical technique, fixation devices, and patient selection with fewer complications [4–7]. Hybrid closed-wedge osteotomy, combining OWHTO and CWHTO, has currently performed with disadvantages of traditional CWHTO including lateral-offset, loss of the large bone block below the lateral tibial plateau, and discrepancies in the leg length [8]. High tibial valgus osteotomy is an established surgical procedure to correct varus malalignment in patients with medial-compartment OA of the knee; however, the deformity center of the malalignment of lower limb varies in each case. Distal femoral osteotomy (DFO) has also been performed for the patient with osteoarthritis with the deformity in distal femur and increasingly performed alone or combination with HTO with the improvement in such as surgical technique and fixation devices same as development of medial opening wedge HTO.

The concept of traditional HTO has been the extra-articular correction of the alignment, aiming at the reduction of the overload in the medial compartment of the varus deformed knee by shifting the mechanical axis from medial to slightly lateral. On the other hand, deformities of the lower limb are affected by several factors. The bony deformity and soft tissue balance are the different issues relating to the malalignment. Varus deformity in OA of the knee without excessed medial loosening of soft tissue could be corrected by usual HTO, which is the extra-articular correction with transfer of the mechanical axis. However, the varus deformity of the knee with the teeter effect, which is the medial-lateral soft tissue imbalance, is not resolved only by the shift of mechanical axis to lateral. The depression of the medial tibia plateau, so-called pagoda deformity, is the intra-articular deformity, which could cause intra-articular incongruency and the teeter effect. In such case, the osteotomy with novel concept should be developed to overcome the issues, both the imbalance of soft tissue and intra-articular deformity; otherwise the relief of the pain and disability would not be achieved.

For the treatment of osteoarthritis of ankle joint, the same argument exists as the correction of the varus knee. Low tibial osteotomy (LTO) for osteoarthritis of ankle joint has been performed to change the load distribution on the ankle joint by changing the extra-articular alignment [9, 10]. However, if instability of the talotibial joint exists, novel surgical concept should be induced for the treatment of the osteoarthritis of the ankle joint. Distal tibial oblique osteotomy (DTOO) developed is an operation to improve the bony congruency of the ankle joint by the oblique osteotomy from the proximal medial to the distal lateral in the coronal plane and towards the center of the tibiofibular joint to realign the bony congruency of the ankle joint [11–13].

Considering the correction of lower limb alignment, regardless of cause of mal-alignment, such as post-traumatic, degenerative, or congenital, we need to consider two kinds of deformities: extra-articular and intra-articular deformity. Extra-articular deformity can be discussed under static loading condition, and intra-articular deformity should be discussed under dynamic loading condition.

Extra-articular deformity in frontal plane is evaluated by the measurement of the standing long-leg AP view. Theoretically, there are 728 kinds of extra-articular deformity, and these deformities can be accurately corrected by using hexapod system. Evaluation of intra-articular deformity should be evaluated by dynamic motion of the contours of the bone facing in the joint. Tibial condylar valgus osteotomy (TCVO) and distal tibial oblique osteotomy (DTOO) can correct intra-articular deformity of knee and ankle, respectively.

2. Extra-Articular Deformity and Lower Limb Alignment

Traditionally the degree of extra-articular deformity of the frontal plane has been expressed as the degree of deviation from the mechanical axis of the lower extremity [14] (Figure 1). The mechanical axis of the lower extremity is determined by drawing a line from the center of the femoral head to the center of the ankle joint. The distance between the mechanical axis line and the center of the knee in the frontal plane is called as the mechanical axial deviation (MAD) [15, 16] (Figure 2). Normally, the medial MAD is 1 mm to 15 mm.

The frontal plane knee joint orientation line of the distal femur is drawn as a line tangential to the most distal point on the convexity of the two femoral condyles. The frontal plane knee joint line of the proximal tibia is drawn across the subchondral line of the two tibial plateaus. The angle formed between joint orientation lines on opposite sides of the same joint is called the joint line convergence angle (JLCA) [14]. The ankle JLCA is defined as the angle formed between the tibial joint line axis and the talar joint line axis (Figure 3). In the knee and ankle joints, each JLCA is measured as 0°-2° and -1°-1°, respectively.

The deviation from the normal of the lower extremity alignment can be evaluated by the joint orientation angles, such as MPTA, LDFA, LPDA, etc. measured with the full leg standing frontal X-ray image of the lower limb [14] (Figure 1). Malalignment occurs when the center of the joint does not lie close to mechanical axis line. The MAD is described as either medial (varus) or lateral (valgus) MADs (Figure 1).

Angular deformity has four types: varus/valgus deformity at the frontal plane and procurvatum/recurvatum deformity at the sagittal plane. Similarly, there are four kinds of deformities in translation (medial/lateral at the frontal plane, and anterior/posterior at the sagittal plane) and axial (internal/external rotation and shortening/elongation) deformities. Consequently, there are 728 patterns of extra-articular deformities.

The angular deformity correction of lower limb can be achieved using hinges set on center of rotation of angulation (CORA) of the connecting rods by Ilizarov technique [14]. Currently used hexapod external fixator system can correct multi-directional extra-articular deformity accurately within the rage of measurement in units of 1 mm and 1° [17, 18] (Figures 4 and 5).

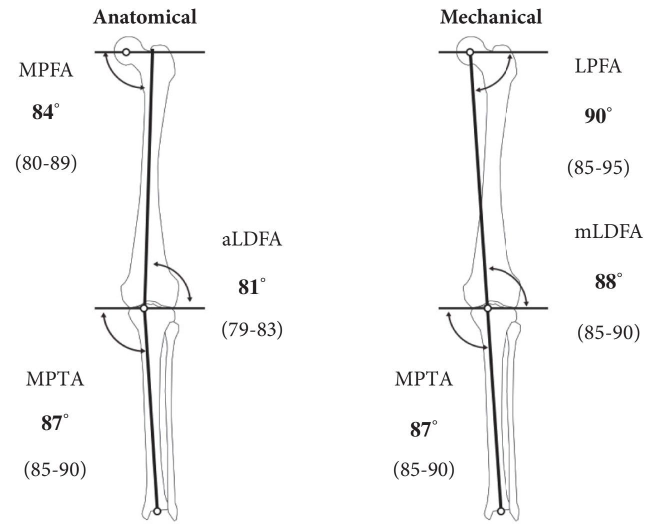


Figure 1: Normal lower limb alignment by Paley D.

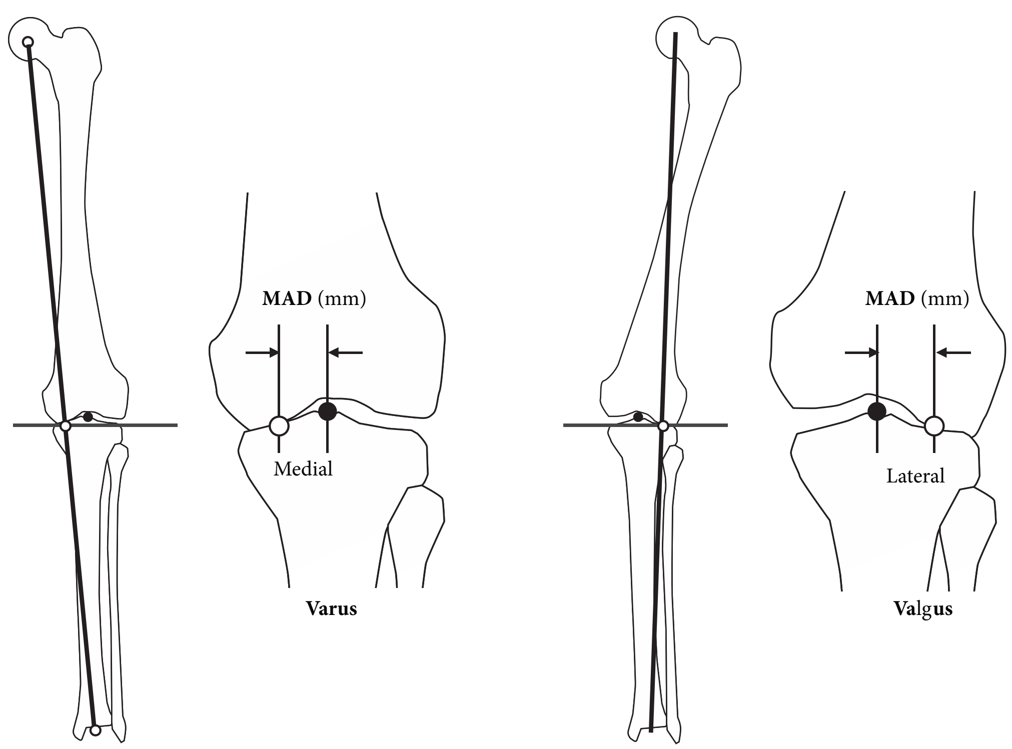


Figure 2: Mechanical axis deviation (MAD) is the perpendicular distance between the mechanical axis of the lower extremity and the center of the knee joint.

3. Intra-Articular Deformity and Joint Congruency

Intra-articular deformity means joint congruency. Joint congruency is defined as the fittings of two opposing joint surfaces as they relate to one another considering the spatial contour of each bone at their interface.

In theory, joint congruency can be mainly explained by three factors: contours of bone, functions of ligament, and integrity of articular cartilage and meniscus. Incongruency of the joint immediately causes joint instability or abnormal joint kinematics resulting in the secondary osteoarthritis in the future. For example, mal-union of tibial plateau fracture and/or knee ligament injury such as anterior cruciate

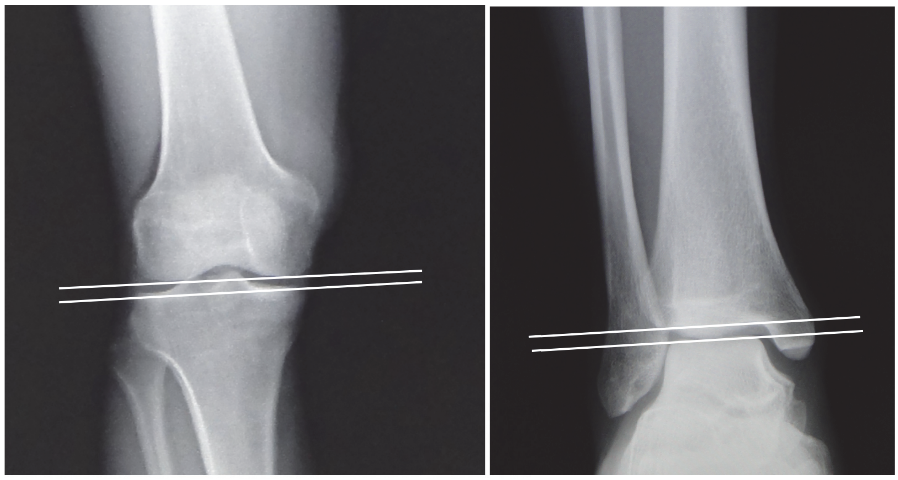
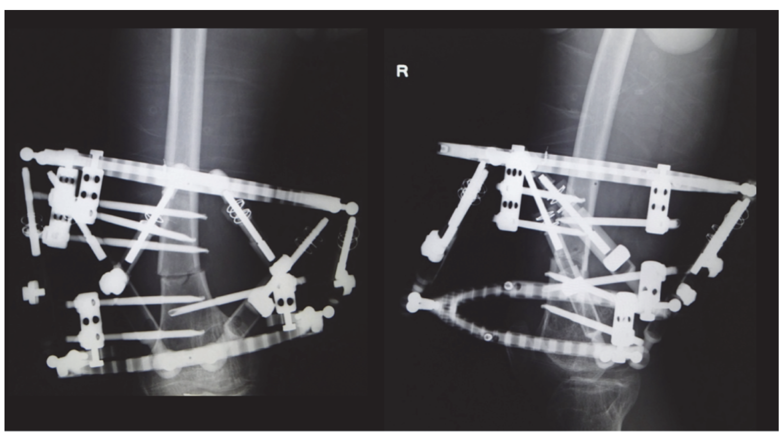
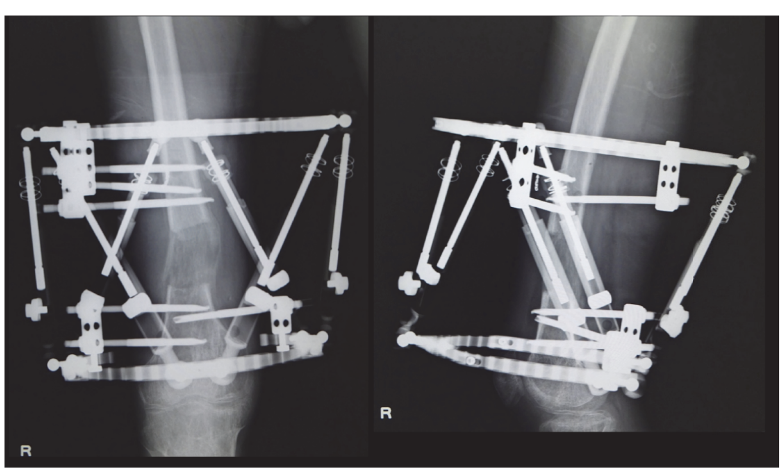


Figure 3: Joint line convergence angle (JLCA) for knee and ankle.



(a)



(b)

Figure 4: Reconstruction of multidirectional deformity by using the hexapod external fixator system. (a) Application of a hexapod external fixator; (b) completion of the reconstruction program.

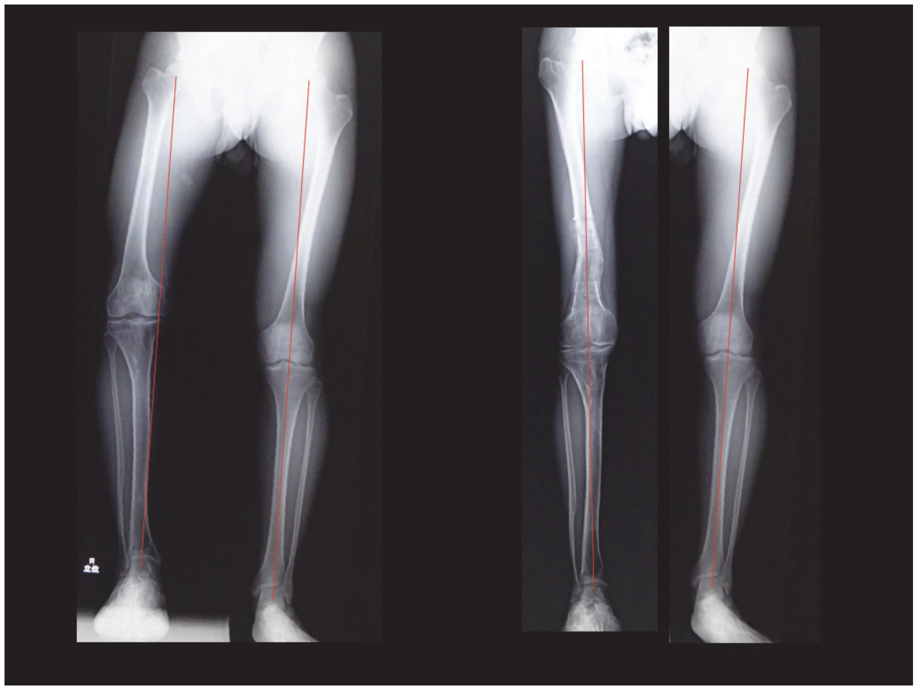


Figure 5: Correction of extra-articular deformity by using hexapod external fixator system. X-ray photos (a) before and (b) after reconstruction.

ligament and/or collateral ligaments causes easily knee instability and secondary osteoarthritis of the involved knee with joint incongruency (Figure 6(a)).

Two primary biomechanical purposes of the articular cartilage are lubrication and shock absorption. The articular cartilage provides a smooth lubricated surface for low friction articulation and acts as a remarkably efficient shock absorber [19, 20].

From the view point of joint congruency, it is considered that the effect of articular cartilage as the shock absorber is not large because the thickness of articular cartilage is thin as 1 – 4 mm. Rather in the cartilaginous element, the menisci may be more important because they have a large effect of filling the gap of the joint [21]. However, cartilage and meniscus do not function enough when the intra-articular bony deformity occurred. Furthermore, ligament function is effective only when the contour of bone is not impaired. Therefore, joint congruency due to the contour of bone plays the most important role.

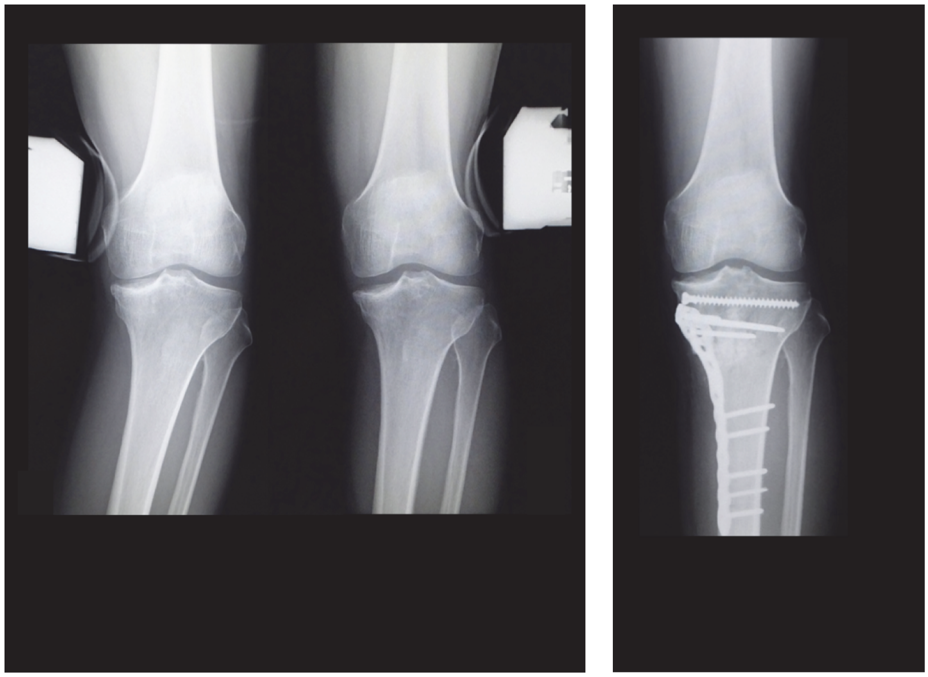
4. TCVO (Tibial Condylar Valgus Osteotomy) and HTO (High Tibial Osteotomy)

High tibial osteotomy (HTO) is intended to transfer the mechanical axis from medial to slightly lateral to the midline of the knee to decrease the load and subsequently delay osteoarthritis (OA) [22–24]. There are discussions about which alignment is best in HTO but we think that it should be discussed first whether accurate lower extremity alignment can be obtained by the procedures reported [25–31]. If we aim to acquire more accurate lower limb alignment, we should use hexapod external fixator which can theoretically correct extra-articular alignment accurately within the range of measurements in units of 1 mm and 1°.

On the other hand, tibial condylar valgus osteotomy (TCVO) developed by Chiba G et al. in 1989 and published in 1994 is an operation that corrects intra-articular deformity [32, 33] (Figures 6(b) and 7). The main strategy of this surgery is to obtain joint stability and congruency, which is totally different from that of HTO to correct malalignment [32, 33] (Figure 8). TCVO is an operation to acquire the bony joint stability between femur and tibia by the “L” shaped osteotomy of medial tibial condyle and spreading it [32, 33] (Figure 7). It is determined how much the medial tibial condyle is spread by judging joint stability under fluoroscopic dynamic stress test including the rotational stability. However, performing TCVO on a common varus knee improves lower limb alignment (Figure 8). The correction of alignment is an accessory benefit, which is subsequently brought by TCVO. It should not be misunderstood that TCVO is one of HTO subtypes and be aware that the main concept of TCVO is to obtain the joint stability and congruency.

5. Distal Tibial Oblique Osteotomy (DTOO) and Low Tibial Osteotomy (LTO)

The same argument holds for distal tibial oblique osteotomy (DTOO) and low tibial osteotomy (LTO) for osteoarthritis of ankle joint. LTO is an operation of an attempt to change the load distribution on the ankle joint by changing the extra-articular alignment. However, if instability of the talo-tibial



(a) (b)

Figure 6: (a) Teeter effect due to intra-articular deformity after medial tibial plateau fracture. (b) After reconstruction by tibial condylar valgus osteotomy (TCVO).

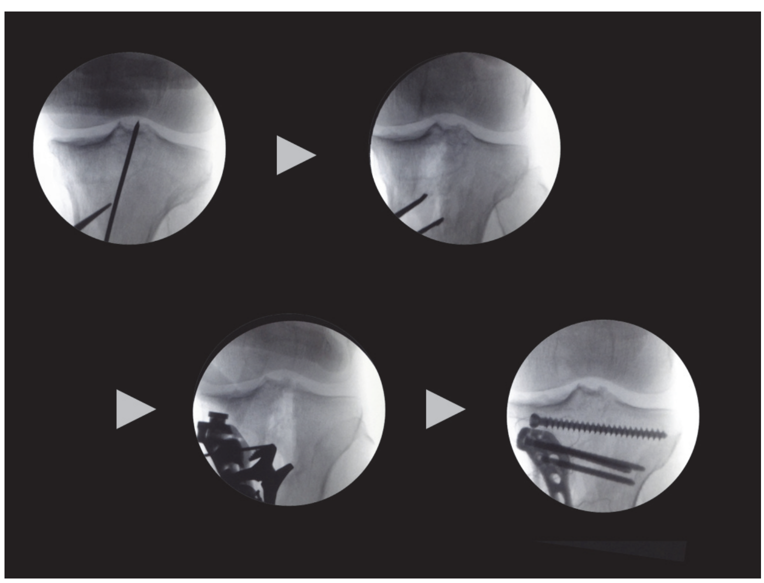


Figure 7: Tibial condylar valgus osteotomy (TCVO).

joint exists (Figure 9), improvement of the joint function by LTO depends on luck by self-centering function of the talus.

On the other hand, DTOO developed by Teramoto in 1994 is an operation to improve the bony congruency of the ankle joint [11]. DTOO consists of oblique osteotomy from the proximal medial to the distal lateral in the coronal plane and towards the center of the tibiofibular joint and then widening of the osteotomy site to realign the bony congruency of the ankle joint (Figure 10). DTOO is a surgical technique to realign the ankle joint surface. The shape of the ankle joint surface is changed by cutting and tilting the tibial plafond without osteotomy of the fibula. The inclination of the distal tibial articular surface with respect to the tibial axis is altered, with associated improvement in ankle stability [11–13]. The oblique osteotomy site is spread until the lateral talar articular surface contact with the lateral fibular malleolus.

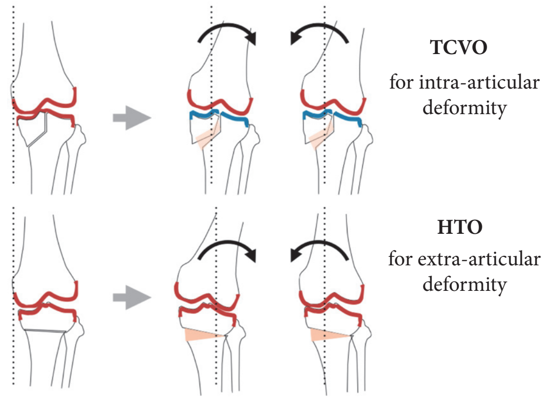


Figure 8: TCVO can reconstruct the joint congruency and alignment, however, HTO change only static lower limb alignment. Teeter effect cannot be improved by HTO.

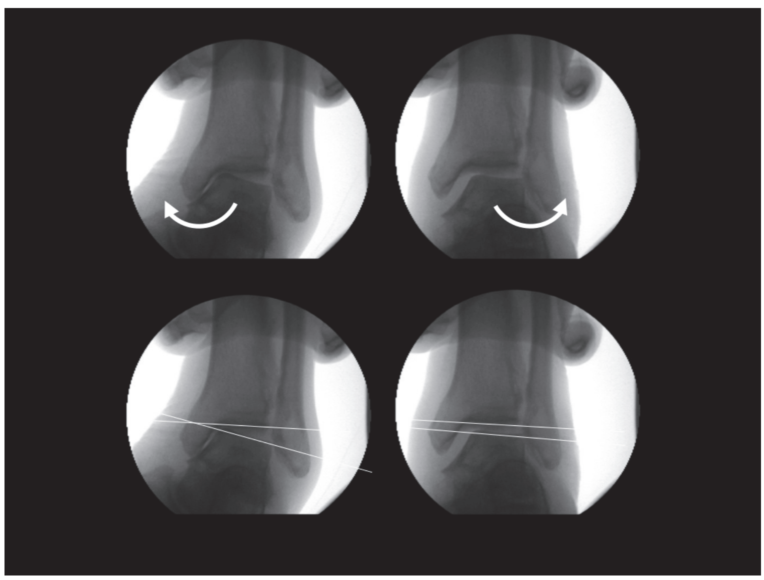


Figure 9: Instability of talotibial joint.

The ankle mortise congruency is restored since medial and lateral articular gutters on either side of the talar body are symmetrical which induces the increase of contact area of the talar articular surface with the tibia and fibula. The increased contact area, dispersed load pressure across the ankle joint, and decrease in the load pressure per unit area applied to the ankle joint would improve congruency between the articular surfaces of the talar dome and distal tibial plafond and the medial and lateral gutters of the ankle mortise would improve ankle stability.

6. Discussion

Although osteotomies are effective in managing malalignment of knee and ankle arthrosis, determination regarding the type of osteotomy should be based on the pathology in each patient. The cause of deformity of the knee varies, which involves intra- and extra-articular or the combination of them. Center of the deformity may also vary. Soft tissue balance should be another critical issue for the selection of optimal osteotomy type. Traditional HTO should be an optimal strategy to overcome the malalignment in OA of the knee; however, the excessed medial-lateral soft tissue imbalance and intra-articular deformity are not solved by this surgical procedure. Tibial condylar valgus osteotomy (TCVO) should be an optimal option to overcome these issues that improves intra-articular deformity followed by acquisition of medial-lateral stability of the knee, not lower limb alignment. Although LTO is the good treatment for the deformity in OA of ankle by the extra-articular correction of alignment, treatment for incongruency and instability for OA in ankle is the remaining issue of this surgical technique. Distal tibial oblique osteotomy improves the bony congruency of the ankle joint by the oblique osteotomy.

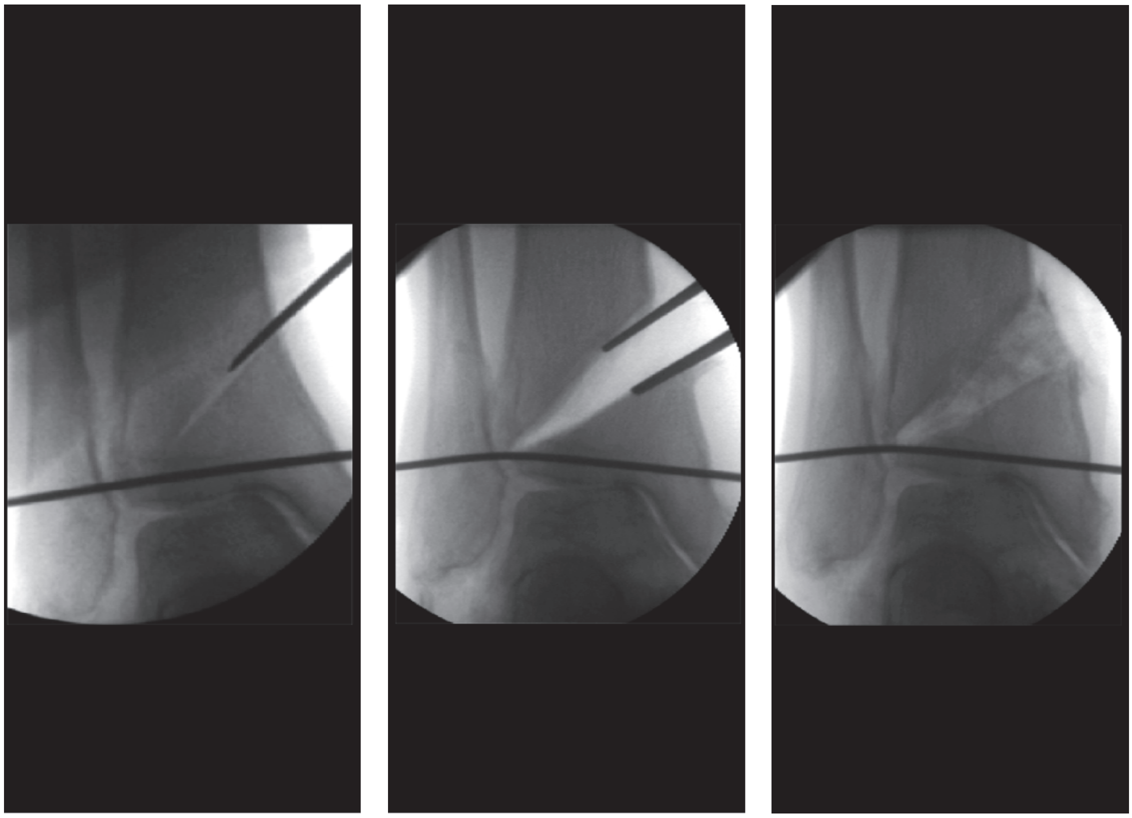


Figure 10: Distal tibial oblique osteotomy (DTOO).

Tibial condylar valgus osteotomy and DTOO that correct intra-articular deformity of knee and ankle are the optimal osteotomies for OA with intra-articular deformity and instability.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Rasterstereographic Analysis of Lateral Shift in Patients with Lumbar Disc Herniation: A Case Control Study

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Objective. Detection of a lateral shift (LS) in patients with diagnosed disc herniation compared to healthy controls. *Summary of Background Data*. A specific lateral shift (LS) pattern is observed in patients with disc herniation and low back pain, as shown in earlier studies. *Methods*. Rasterstereography (RS) was used to investigate the LS. Thirty-nine patients with lumbar disc herniation diagnosed by radiological assessment and low back pain and/or leg pain (mean age 48.2 years, mean BMI 28.5, 28 males and 11 females) and 36 healthy controls (mean age 47.4 years, mean BMI 25.7, 25 males and 11 females) were analysed. LS, pelvic tilt, pelvic inclination, lordotic angle, and trunk torsion were assessed. *Results*. The patient group showed a nonsignificant increase in LS, that is, 5.6 mm compared to the healthy controls with 5.0 mm (p = 0.693). However, significant differences were found between groups regarding pelvic tilt in degrees (patients 5.9°, healthy controls 2.0°; p = 0.016), trunk torsion (patients 7.5°, controls 4.5°; p = 0.017), and lordotic angle (patients 27.5°, healthy controls 32.7°; p = 0.022). The correlation between pain intensity and the FFbH-R amounted 0.804 (p = < 0.01), and that between pain intensity and the pain disability index was 0.785 ($p < 0.01$). *Discussion*. Although some studies have illustrated LS with disc herniation and low back pain, the present findings demonstrate no significant increase in LS in the patient group compared to healthy controls. *Conclusion*. The patients with lumbar disc herniation did not demonstrate an increased LS compared to healthy controls. Other parameters like pelvic tilt and inclination seemed to be more suitable to identify changes in posture measured by RS in patients with low back pain or disc herniation.

1. Introduction

Low back pain is currently a common problem with a considerable medical and therapeutic impact [1]. The lifetime prevalence amounts up to 80% and higher in the general population [2–4]. In approximately 85% of cases, the underlying cause is unknown, while in around 15%, the cause is known, for example, lumbar disc herniation [5]. Lumbar disc herniation has a high prevalence and affects the spine in younger and middle-aged patients [6–9]. For clinical decision making and to initiate a specific and appropriate therapy for the patient group, a systematic investigation of patients with lumbar disc herniation and low back pain is required. One parameter that can be assessed is the lateral shift (LS), which is an important clinical sign. It occurs ipsilaterally or contralaterally, with no relation to the side of pain [10]. There are different definitions available for the LS [11]. A LS is a deviation from the spinal midline. This is shown by the sagittal arrangement of the lumbar spinous processes. They are typically arranged asymmetrically. The upper body is clearly shifted to the side [11]. The LS can be determined with different methods, for example, visual investigation using a plumbline and palpation using the side-glide test sequence [12, 13]. The LS can be determined with an accuracy of 5 mm using the plumbline technique [14]. The prevalence of LS in patients with low back pain has been previously examined [10, 12]. In a collective of patients with an acute episode of low back pain, Gillan showed an abnormality in LS ranging from 5 to 50 mm and called it a "new phenomenon associated with the onset of back pain" [12]. Porter et al. examined 100 patients with back pain and LS; the majority (71 patients) reported pain distribution below the knee [10]. Healthy controls were not evaluated.

One measurement method that illustrates important spine parameters is rasterstereography [15]. RS is a contact-free, noninvasive technique to detect spinal deformities, for instance, scoliosis, on the basis of surface asymmetry. The validity and reliability of this method have been described elsewhere [16–22].

Khallaf examined 16 patients with lumbar disc herniation using rasterstereography [23]. The patients showed a significantly increased lateral pelvic tilt and an increased lordotic angle compared to healthy subjects. However, the lateral shift as an important clinical sign is not evaluated by Khallaf. Therefore, the primary aim of this study was to evaluate LS in patients with diagnosed lumbar disc herniation compared to healthy controls measured by RS. The secondary aim was to assess posture modifications in relation to spine, pelvic, and functional parameters. These parameters should be correlated to each other. According to the main aim of the study, the null hypothesis (H0) is that patients with lumbar disc herniation will have no LS compared to healthy controls. The alternative hypothesis (H1) is that patients with lumbar disc herniation will have a greater LS compared to healthy controls.

2. Methods

2.1. Patients and Recruitment Procedure. All participants were recruited in 2011. The individuals in the patient group were enrolled in a rehabilitation hospital with a special section for chronic spinal diseases at Montanus-Klinik Bad Schwalbach, Germany. The healthy individuals in the control group were recruited from the general population and were examined at a second hospital, that is, University Hospital in Marburg, Germany. Both hospitals used the same measurement system.

2.2. Patient Group. The inclusion criteria for the patient group were underwritten patient information and informed consent, the ability to speak the German language, the ability to stand free without any assistance, the ability to lay flat on their back, evidence of lumbar disc herniation or protrusion detected by magnetic resonance imaging (MRI), and low back pain and/or leg pain; all stadia of pain (acute, subacute, chronic) were included.

The exclusion criteria for the patient group were age younger than 18 years, cancer, previous spinal surgery, relevant bone degeneration, red flags, pension request, relevant tattoos or scars on the surface of the back, and no pain on a numeric rating scale (NRS = 0).

2.3. Control Group. The inclusion criteria for the healthy controls were the ability to speak the German language, no back or leg pain on a numeric rating scale (NRS = 0), the ability to stand free without any assistance, and the ability to lay flat on their back. The exclusion criteria were age younger than 18 years, cancer, previous spine surgery, relevant spinal degeneration, red flags, pension request, relevant tattoos or scars on the back, chronic low back pain, and lumbar low back pain and/or leg pain.

2.4. Ethical Aspects. The study received ethical approval from the independent ethics committee of University Hospital Marburg (reference number Az. 22/11). Information about the procedure and risks were included in the patient information. Participants in the patient and control groups had to provide written informed consent.

2.5. Methods of Measurement

2.5.1. Self-Assessment Questionnaire. All participants had to complete a general self-assessment questionnaire to provide individual data, for example, age, height, weight, comorbidities, pain anamneses, and a pain chart.

2.5.2. Numeric Rating Scale (NRS). The Numeric Rating Scale for Pain (NRS) was used to measure pain intensity. The numeric scale has 11 items with "0" representing no pain and "10" representing the worst pain imaginable [25].

2.5.3. Hannover Functional Ability Questionnaire (FFbH-R). The level of functional ability was measured by the Hannover Functional Ability Questionnaire (FFbH-R). This instrument was developed for patients with musculoskeletal disorders, comprising 12 short self-administered questionnaires on functional capacity in the activities of daily living [26].

2.5.4. Pain Disability Index (PDI). The PDI is a comprehensive self-administered questionnaire for assessing disability associated with pain. The respondents indicate the amount of perceived pain-related disability in seven different areas of daily living on an 11-point Likert scale with one end point of 0 (no disability) and the other end point set at 10 (maximum disability). The areas are home, social activities, recreational, occupational, sexual functioning, self-care, and life support activities. Higher scores indicate greater disability. The PDI has been shown to have a correlation of r = 0.7-0.9 with the Oswestry Disability Questionnaire in patients with low back pain [27].

2.5.5. Mainz Pain Staging System (MPSS). The MPSS is classified in three chronification levels. Four axes were considered: temporal aspects of pain, pain distribution, drug intake, and utilisation of health care. The final score described three chronification levels. On level I, the pain is intermittently, temporary, with changeable intensity, mostly in one

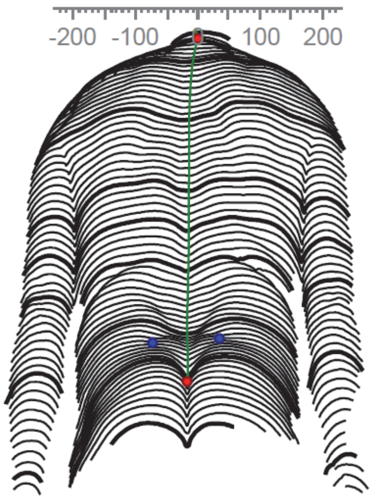

Figure 1: View of the raster lines on a patient's back. Blue dots: left and right lumbar dimples. Lower red dot: dimple mid-point (DM).

localization, adequate drug intake, visiting just one medical specialist, and not more than one stay in a hospital due to pain. Level II is characterized as follows: the pain during a longer time, more than one pain localization, drug abuse, changing medical consultations, and 2-3 clinical stays caused by pain. Continuous pain, pain on a large areal and changing localizations, long-time drug abuse, and more than three alterations of the medical specialist and clinical stays describe level III.

2.5.6. Straight Leg Raise (SLR). The SLR is widely used and is well suited for clinical investigations. The subject lies in a supine position with their head on the ground. The tester lifts the measured leg passively with an extended knee and ankle in the neutral position as high as possible. If the subject indicates pain or the investigator notices resistance, the investigator measures the hip flexion angle at the limit of the SLR using a plurimeter. A positive test result is associated with nerve root compression. The SLR is a reliable tool with a high intraclass reliability of 0.99 [28].

2.5.7. Rasterstereography (RS). RS is a noninvasive technique for analysing back and spinal deformities that uses the triangulation method [29]. Parallel white lines are projected onto the unclothed back of the subject (see Figure 1). This horizontal light raster is detected by a camera system. RS evaluates surface contours formed by the underlying tissue, for example, the spinous process. The system identifies anatomical fixed points with an accuracy of ±0.1 mm standard deviation [30, 31].

The lateral shift is a lateral deviation in the frontal plane. For the calculation the perpendicular from vertebrae prominence was dropped and the difference from this perpendicular to the DM was measured.

For this study, the following parameters were measured according to Degenhardt 2017 [32]:

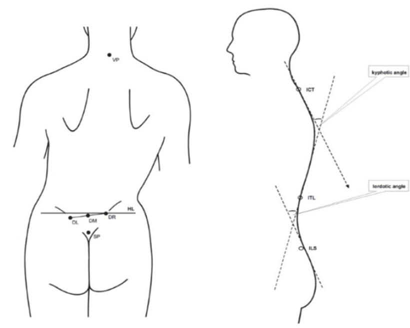

Figure 2: Rasterstereographic parameters: pelvic tilt (left) and lordotic angle (right) adapted by Lippold et al. [24].

(1) Pelvic tilt (PT): Difference in the height of the lumbar dimples is shown in Figure 2 [24]. A positive value indicates a higher right dimple than on the left and a negative value denotes the opposite. This value is quantified in millimetres (mm) and degrees (°).

(2) Pelvic inclination (PI dimples): A positive value indicates the vertical component of the left dimple and the right dimple is adjusted to the top; negative values denote the opposite. This value is provided in degrees.

(3) Pelvic inclination (PI symmetry line): This parameter is a symmetry line of the spinous processes. A positive value indicates an anterior pelvic inclination and a negative value indicates a posterior pelvic inclination. This value is provided in degrees.

(4) Lordotic angle (LA): There are two tangents estimated relating to the surface of the back. The angle between surface tangents of ITL (thoracic-lumbar transition) and ILS (lumbar-sacral transition) is shown in Figure 2 [24]. The higher the value is, the greater the degree of lumbar lordosis is. This value is provided in degrees.

(5) Trunk torsion (TT): This value is provided in degrees.

(6) Lateral shift (LS): This describes the difference in the translative shift (lateral shift) from L1 to DM. This value is provided in degrees. See Figure 3.

2.5.8. Measurement Setup. For this study, the Formetric® III 4 D system (Diers International GmbH, Schlangenbad, Germany) was applied for data collection. It can assess individual clinical parameters under static and dynamic conditions.

To avoid potential bias, the positioning of the subject was standardised. The subjects stood barefoot on a wooden platform with slightly extended knees. The upper extremities hung down lateral to the body, and the subject looked forward. One record took 6 seconds. Two pictures were taken per second. The mean of these 12 pictures of every record was used for the analysis.

2.5.9. Statistical Power Analysis and Statistics. The calculation of the power was based on the data of a pilot study. The difference of LS between healthy subjects and patients was 5.3 mm, the standard deviation 7.9 mm. The significance

Table 1: Characteristics of participants.

Parameter	Group	Mean	SD	p
Age (years)	Patient group	48.2	9.4	.721
	Healthy controls	47.4	9.5	
Height (cm)	Patient group	175.1	10.8	.898
	Healthy controls	175.4	10.1	
Weight (kg)	Patient group	87.4	15.0	.014*
	Healthy controls	79.3	12.6	
BMI (kg/m^2)	Patient group	28.5	4.5	.002**
	Healthy controls	25.7	2.9	

Comparison between patient group and healthy controls: mean, standard deviation (SD), and p value were illustrated for age, height, weight, and BMI.
* Significance on the level of $p \leq .05$.
** Significance on the level of $p \leq .01$.

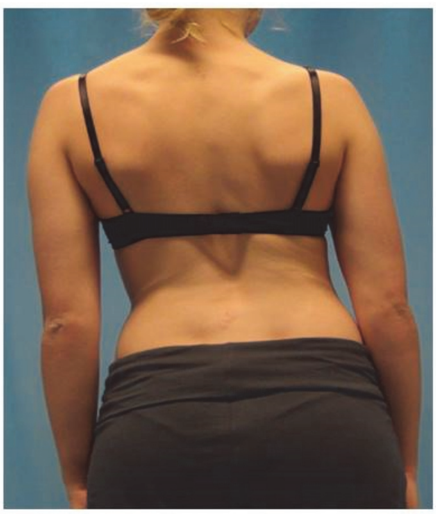

Figure 3: A person with a left LS from the posterior view.

level was 0.05 and power 0.8. The statistical power analysis suggested a minimal number of 35 subjects for each group (the patients and the healthy controls). A dropout rate of 10% for the sample size was estimated; therefore four additional volunteers were enrolled in each group as a safety margin.

Mean, minimum and maximum values, and standard deviations were calculated for all parameters. The Shapiro-Wilk-Test was used to estimate the normal distribution. The independent sample t-test was used to compare the patient and healthy controls. Correlations between the parameters were made using the Pearson correlation coefficient. Differences were accepted as significant when the probability was below 5% ($p < 0.05$). The comparisons of more than one parameter were performed by using one-way ANOVA, with the Bonferroni post hoc test. All statistical analyses were performed with SPSS Version 17 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Characteristics of the Study Participants. In the patient group, 39 patients with a radiologically diagnosed herniated disc were enrolled. Out of the 36 healthy controls, three volunteers had to be excluded: one volunteer reported back pain, and two volunteers had scoliosis. Scoliosis is defined as a deviation of the spine greater than 10° in the coronal plane and an axial rotation [33]. The age range was 25–65 years with a mean age of 48.2 years in the patient group and 47.4 in the control group. 11 women were examined in each group, 28 male patients and 25 healthy men. The characteristics of the participants are shown in Table 1.

3.2. Lateral Shift. The lateral shift had a mean value of 5.6±6.0 mm in the patient group and 5.0±7.6 mm in the healthy controls. This difference was not significant (p = 0.693). The trunk of the participants with diagnosed disc herniation did not deviate laterally more than the healthy controls.

3.3. Lateral Shift in relation to SLR. The participants with a positive SLR demonstrated a slightly increased LS (5.5±5.0°) compared to the participants with negative SLR (5.2±8.1°). However, the difference was not significant (p = 0.829).

3.4. Trunk, Lumbar Spine, and Pelvis. The patients showed an increased pelvic tilt in [°] as well as [mm], a decreased anterior pelvic inclination (dimples [°] as well as symmetry [°]), an increased trunk torsion [°], and a decreased lordotic angle [°] compared to the healthy controls (Table 2).

3.5. Localization of Pain (Pain Chart). In relation to the localization of pain, there was a significant difference in pelvic tilt in degrees (p = 0.036) and pelvic inclination in degrees (p = 0.017). The localization of pain has a considerable influence on pelvic inclination (dimples). If pain is not present, the pelvis showed a more anterior tilt (17.8±6.9°) compared to pain up to the feet (11.4±6.6°) (p = 0.022).

3.6. Correlations between Rasterstereographic Parameters. There was a very high correlation between pelvic tilt [°] and pelvic tilt [mm] of 0.985 ($p \leq 0.001$) and between pelvic inclination (dimples) [°] and pelvic inclination (symmetry) [°] of 0.904 ($p \leq 0.001$). A lower correlation was found between trunk torsion [°] and pelvic tilt [°] of 0.390 ($p \leq 0.001$) and between trunk torsion [°] and pelvic tilt [mm] of 0.382 ($p \leq 0.001$).

Table 2: Parameters of trunk, lumbar spine, and pelvis.

Parameter	Group	Mean	SD	p
PT [°]	Patient group	5.9	9.2	.016∗
	Healthy controls	2.0	2.4	
PT [mm]	Patient group	10.6	19.9	.033∗
	Healthy controls	3.3	3.7	
PI (dimples) [°]	Patient group	12.5	7.5	.002∗∗
	Healthy controls	17.8	6.9	
PI (symmetry) [°]	Patient group	15.0	10.2	.015∗
	Healthy controls	20.4	8.5	
TT [°]	Patient group	7.5	6.2	.017∗
	Healthy controls	4.5	4.1	
LA [°]	Patient group	27.5	9.6	.022∗
	Healthy controls	32.7	9.5	

Comparison between patient group and healthy controls: mean, standard deviation (SD), and p value were illustrated for PT [°], PT [mm], PT (dimples), PI (symmetry) [°], TT [°], and LA [°].
PT = pelvic tilt; PI (dimples) = pelvic inclination (dimples); PI (symmetry) = pelvic inclination in relation to the symmetry line; TT = trunk torsion; LA = lordotic angle T12 – DM
∗ Significance on the level of $p \leq .05$.
∗∗ Significance on the level of $p \leq .01$.

Table 3: Correlations with the FFbH-R.

Parameter	Pearson r	p
BMI	0.310	.007∗∗
MPSS	0.445	.005∗∗
Pain chart	0.643	≤ .001∗∗
NRS	0.804	≤ .001∗∗
Drug intake	0.545	≤ .001∗∗
PDI	0.793	≤ .001∗∗

BMI, MPSS, pain chart, NRS, drug intake, and PDI were correlated with the FFbH-R.
∗ Significance on the level of $p \leq .05$.
∗∗ Significance on the level of $p \leq .01$.

3.7. Correlation to FFbH-R. The correlation between FFbH-R and pain intensity was 0.804 ($p < 0.001$), between FFbH-R and BMI 0.310 ($p = 0.007$), between FFbH-R and MPSS 0.445 ($p = 0.005$), between FFbH-R and drug intake 0.545 ($p < 0.001$), and between FFbH-R and PDI 0.793 ($p < 0.001$). A magnitude of 0.643 ($p < 0.001$) revealed the strength of the relationship between FFbH-R and pain chart. See Table 3.

3.8. Correlation with the PDI. The correlation between the PDI and weight was 0.246 ($p = 0.033$), between PDI and BMI 0.360 ($p = 0.002$), between PDI and MPSS 0.369 ($p = 0.021$), between PDI and pain chart 0.623 ($p \leq 0.001$), between PDI and drug intake 0.379 ($p \leq 0.001$), and between PDI and FFbH-R 0.793 ($p \leq 0.001$). As the pain intensity increased, then the disability in areas of living increased, too. The magnitude was r = 0.785 ($p \leq 0.001$). See Table 4.

4. Discussion

This study demonstrated that there is no significant LS in patients with diagnosed lumbar disc prolapse compared to healthy controls. Harrison et al. indicated a LS of the thoracic cage relative to the fixed pelvis with digitised anterior-posterior radiographs in a group of healthy volunteers [34]. The displacement was measured from T12 to S2 through a vertical line. The mean value in the left was 53.2±8.4 mm and in the right was 52.1±9.0 mm [34]. Although other studies have illustrated a LS with disc herniation and low back pain, this phenomenon could not be validated in this study. However, other studies did not compare their findings with a control group that included healthy individuals.

This is the first study to evaluate the lateral shift using the rasterstereography. The findings in the present study showed a mean LS in healthy controls of 5.0±7.6 mm and 5.6±6.0 mm in the patient group. This difference was not statistically significant ($p = 0.693$). Other studies did not define LS exactly. A threshold with a precise definition for the presence or absence of LS was also missing. However, in a study by Donahue et al., two therapists indicated a LS range of 1-7 mm in 26 out of 49 patients with low back pain [13]. Harrison and colleagues assessed a spinal rehabilitation program and the effect of LS in patients with chronic low back pain [35]. The control group demonstrated an average LS of 7.2±6.2 mm and an average LS of 15.0±5.9 mm in the treatment group. However, both studies

Table 4: Correlations with the PDI.

Parameter	Pearson r	p
Weight	0.246	.033∗
BMI	0.360	.002∗∗
MPSS	0.369	.021∗
Pain chart	0.623	≤ .001∗∗
NRS	0.785	≤ .001∗∗
Drug intake	0.379	≤ .001∗∗
FFbH-R	0.793	≤ .001∗∗

Weight, BMI, MPSS, pain chart, NRS, drug intake, and FFbH-R were correlated with the PDI.
∗ Significance on the level of $p \leq .05$.
∗∗ Significance on the level of $p \leq .01$.

did not compare the results with healthy controls. Donahue et al. reported nonphysiological LS in their patient group [13]. If this phenomenon occurs in healthy subjects, it has not yet been reported. Therefore, in this case-control study, healthy volunteers were included. The LS in the healthy controls was not significant compared to that of the patient group. It is possible that the healthy volunteers had similar disc pathologies as there is a high prevalence of disc pathologies in asymptomatic patients [36, 37] which could explain the lateral shift also in healthy subjects in the current study. However, whether the healthy volunteers were suffering from disc herniation was not systematically investigated by MRI or CT. The healthy controls were only investigated clinically. This should be taken into account in further research.

There are different methods available to measure LS, for example, the plumbline method and the shadow method [13, 14, 38]. The plumbline technique investigated by McLean et al. indicates that it is possible to measure a trunk list within a reliability of 4 mm [14]. In the present study, RS was chosen as the method of measurement for LS. RS is a radiation-free, noninvasive technique that has demonstrated very good inter- and intratester reliability as well [18, 21].

Fritz and Georg analysed LS in patients with acute and chronic pain [39]. The present study included patients with acute or chronic back pain as well as healthy volunteers. The stage of chronification measured by the MPSS has no influence on the posture or the measured parameters.

The patients demonstrated a significant different posture compared to the healthy subjects which was shown also by Khallaf [23]. In both studies the pelvis is increased lateral tilted in patients. The lordotic angle was increased in the patient's group of Khallaf. In contrast to Khallaf, our patients demonstrated a decreased lordotic angle which fits to the decreased anterior inclined pelvis.

In our study, there was a significant difference with respect to the BMI in both groups. Liljenqvist and colleagues reported that the thickness of soft tissue may result in measurement inaccuracies [40]. In contrast, Mohokum et al. did not find any differences in accuracy between subgroups with respect to BMI in a collective of young, healthy volunteers. Therefore, we did not assume any coherence of our results in relation to BMI. The differences in body weight or BMI were not caused by gender effect. 11 women and 28/25 men were examined in both groups. One reason of an increased body weight in patients could be that the patients were not so sporty and agile compared to the healthy subjects due to their pain.

The force of gravity affects bone positions and trunk muscle activities. In the supine or standing position, these parameters are different. In patients with low back pain, the onset of symptoms typically decreases in the supine position and increases in the standing position. Therefore, an RS investigation is more functional than MRI or CT, which is often performed in the horizontal position. Some researchers have investigated LS by radiography [35, 41]. One limitation of the present study is that there was no reference standard used for detecting LS, for instance, radiography.

RS can be applied to monitor postural changes, but caution should be taken when comparing absolute values because RS uses reference contours only. Radiological methods can derive the position of the spinous process directly from the morphology of internal bone structures.

Further research on this topic needs to be done. An investigation should be performed into other spine pathologies to find a specific pattern and to define demarcations between different pathologies.

5. Conclusions

The rasterstereography can identify changes of the posture of the spine in all three dimensions. This is the first study which illustrated the lateral shift using RS. Patients with disc herniation and low back pain show no increase in LS compared to healthy controls. Maybe, a lateral shift is more common in healthy patients as supposed. Alternatively, patients with disc herniation demonstrate other distinctive, significant parameters: an increased pelvic tilt, a decreased anterior pelvic inclination, a lower lordotic angle, and a higher amplitude of trunk torsion. In a further study, patients should be grouped, for example, based on their pathology like radiculopathy and discogenic pain to evaluate differences in posture.

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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