Aus dem Centrum für Muskuloskeletale Chirurgie

der Medizinischen Fakultät Charité – Universitätsmedizin Berlin

DISSERTATION

"Evolution of the Tibial Slope until Skeletal Maturity and its Relationship to the Femoral as well as Tibial Offset"

„Entwicklung des Tibialen Slopes bis zur Skelettreife und Seine Beziehung zum Hinteren Femoralen sowie Tibialen Offset"

zur Erlangung des akademischen Grades

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3. List of Abbreviations

PTO: Posterior Tibial Offset

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PFO: Posterior Femoral Offset

ACL: Anterior Cruciate Ligament

PCL: Posterior Cruciate Ligament

MCL: Medial Collateral Ligament

LCL: Lateral Collateral Ligament

PTAA: Proximal Tibial Anatomical Axis

ATT: Anterior Tibial Translation

PTT: Posterior Tibial Translation

MRI: Magnetic Resonance Imaging

CT: Computed Tomography

BMI: Body Mass Index

4. Abstract

Introduction: The posterior tibial slope has gained importance in the field of reconstructive knee surgery over the past few years because of its prognostic influence on the outcome of cruciate ligament surgery. Numerous studies have attempted to define the 'physiological' value of the posterior tibial slope. These studies have been mainly performed in adults and have been principally presented as a range of values using various methods of slope measurement. Information about the posterior tibial slope during the phase of skeletal development is considerably lacking in the current literature. We attempt in our MRI study to measure the slope in the pediatric age group and present the data according to age distribution. Moreover, we also measure two other variables, viz. the posterior femoral offset and the posterior tibial offset and study their relationship to the posterior tibial slope.

Materials and Methods: We included 249 MRI series of knees from the ages of 1 year to 18 years in our study and measured the medial and lateral posterior tibial slope using the proximal tibial anatomical axis. Additionally, we measured the medial and lateral posterior femoral and tibial offset and presented the data as median values in an age-wise distribution. The correlation of the measured posterior tibial slope with the posterior femoral as well as tibial offset was then tested separately for the medial and lateral compartment using the Spearman rank coefficient.

Results: We were able to derive that the posterior tibial slope increases in a linear manner from the age of 1 year (medial PTS 3.36°+/-2°; lateral PTS 1°+/-2.5°) to the age of 10 years (medial PTS 7.5°+/-2.5°; lateral PTS 7.5°+/-2.8°) and then achieves a plateau up to the age of 18 years.

Its correlation with the posterior femoral and tibial offset in the pediatric age group was found to be variable.

Conclusion: Our findings display that the posterior tibial slope, both on the medial and lateral side is a function of the age of the child. As the child begins to bear increasingly more weight along with advancing age, the slope begins to increase, conforming to Wolff's law. This increase in the slope seems to plateau out at the age of 8-12 years, after which the slope remains more or less constant into adulthood.

The posterior tibial slope and the posterior tibial offset correlate with each other, leading to a posterior 'tilt' of the proximal tibia. The medial posterior tibial slope also correlates strongly with the medial posterior femoral offset, conforming to the existent knowledge that the medial femoral condyle mainly rotates over the congruent medial tibial plateau with only minimal translation.

Abstrakt:

Einleitung: Der tibiale Slope hat in den letzten Jahren im Bereich der rekonstruktiven Kniechirurgie deutlich an Bedeutung gewonnen, da er einen erheblichen prognostischen Einfluss auf das Ergebnis der Kreuzbandchirurgie hat. In zahlreichen Studien wurde versucht, den "physiologischen" Wert des tibialen Slopes zu definieren. Diese Studien wurden hauptsächlich an Erwachsenen durchgeführt und unter Verwendung verschiedener Methoden zur Messung des Slopes dargestellt. Informationen über den Slope während der Entwicklungsphase des Skeletts fehlen weitgehend in der aktuellen Literatur. In unserer MRT-Studie versuchen wir, den Slope in kindlichen Knien zu messen und die Daten entsprechend der Altersverteilung darzustellen. Darüber hinaus messen wir auch zwei andere Variablen, nämlich den posterioren femoralen Offset und den posterioren tibialen Offset, und untersuchen deren Beziehung zum tibialen Slope.

Methodik: Wir nahmen 249 MRT-Serien von Knien im Alter von 1 Jahr bis 18 Jahren in unsere Studie auf und maßen den medialen und lateralen Slope anhand der proximalen tibialen anatomischen Achse. Zusätzlich haben wir das mediale und laterale posteriore femorale und tibiale Offset gemessen und die Daten als Medianwerte in einer altersabhängigen Verteilung dargestellt. Die Korrelation des gemessenen Slopes mit dem posterioren femoralen und tibialen Offset wurde dann separat für das mediale und laterale Kompartiment mit Hilfe des Spearman Koeffizienten getestet.

Ergebnisse: Wir konnten feststellen, dass der tibiale Slope vom Alter von 1 Jahr (medialer PTS 3,36°+/-2°; lateraler PTS 1°+/-2,5°) bis zum Alter von 10 Jahren (medialer PTS 7,5°+/-2,5°; lateraler PTS 7,5°+/-2,8°) linear ansteigt und dann ein Plateau bis zum Alter von 18 Jahren erreicht.

Die Korrelation mit dem posterioren femoralen und tibialen Offset in der pädiatrischen Altersgruppe wurde als variabel eingestuft.

Schlussfolgerung: Unsere Ergebnisse zeigen, dass der tibiale Slope sowohl auf der medialen als auch auf der lateralen Seite eine Funktion des Alters des Kindes ist. Wenn das Kind mit zunehmendem Alter immer mehr Gewicht trägt, nimmt der Slope in Übereinstimmung mit dem Wolffschen Gesetz zu. Diese Zunahme des Slopes scheint im Alter von 8-12 Jahren ein Plateau zu erreichen, wonach der Slope bis ins Erwachsenenalter mehr oder weniger konstant bleibt.

Der tibiale Slope und das tibiale Offset korrelieren miteinander, was zu einer posterioren "Kippung" der proximalen Tibia führt. Der mediale tibiale Slope korreliert auch stark mit dem medialen posterioren femoralen Offset, was mit dem bestehenden Wissen übereinstimmt, dass der mediale Femurkondylus hauptsächlich über das kongruente mediale Tibiaplateau mit nur minimaler Translation rotiert.

5. Introduction

5.1 Development of the Human Knee Joint

From an evolutionary standpoint, the human knee seems to have achieved its present anatomy after undergoing far less development and differentiation as compared to other organs, e.g., the hand or the brain.

Later quadruped species like reptiles, amphibians and mammals evolved to exhibit an articulation between a bicondylar femur and a corresponding tibia plateau, which is carefully choreographed by the interplay of muscles and cruciate and collateral ligaments, leading to the ultimate evolution of the knee as a complex rotational hinge joint(Dye, 2003). This constitution persisted and is displayed by primates as well, including humans. Humans, as a logical step to their evolution to erect bipeds are the only species which can extend the knee fully and load the knee mainly in this position(Takroni et al., 2016).

Embryologically, the bicondylar structure of the knee, as well as the collateral ligaments are first visible at an age of 7 weeks. At 8 weeks, the posterior cruciate ligament develops, with the ACL and menisci developing at 10 weeks. The patellar facets start developing at 15 weeks.

5.2 Functional Anatomy of the Knee Joint

At birth, the proximal articular surface of the tibia (tibial plateau) comprises of the cartilaginous lateral and medial articular surface. These are separated by a non-articular, cartilage-free zone called the intercondylar eminence, bordered by two tubercula, the medial and lateral intercondylar tubercles. The two cruciate ligaments attach on the anterior and posterior aspect of the intercondylar eminence. The Extensor mechanism attaches itself on the superior most portion of the tibial crest- the tibial tuberosity. The tibial tuberosity is typically situated about 2.5cm inferior to the joint surface (Figure 1).

The articulating contact area of the medial tibial plateau is 36-64% larger than that of the lateral tibial plateau (Ihn et al., 1993; Kettelkamp & Jacobs, 1972). The concavity of the medial tibial plateau reaches an average maximum depth of 2.7 ± 0.76 mm in females and 3.1 ± 0.99 mm in males(Hashemi et al., 2008). Although the literature often refers to a convex shape of the lateral plateau in contrast to the medial one, it is more reasonable to assume a variable surface ranging around a relatively flat surface. Similarly, one can observe a varus inclination in the coronal plane, this being 2.5 ± 1.9° in females and 3.5 ± 1.9° in males(Hashemi et al., 2008).

5.3 Biomechanics of the Knee Joint

It is now long known that the tibiofemoral knee is not merely a simple hinge joint, which flexes over a single transverse axis. It is a complex synovial joint, the motion of which consists of at least three components:

1. Flexion and extension around a transverse axis
2. Rotation around a (medial) vertical axis
3. Gliding motion in the sagittal plane

The interplay of these components results in a seamless range of 'flexion' of the knee joint from 0° to about 150°. Additionally, the femur articulates with the patella at the femoropatellar joint, which also has an effect on the tibiofemoral articulation.

Multiple interdependent determining factors are required to act in perfect symphony to maintain efficient motion and loadbearing biomechanics on the knee, especially its stability.

5.3.1 Bony Factors

5.3.1.1 Articular Anatomy

The bony tibiofemoral articulation comprises the tibial plateau, consisting of the medial and lateral tibial articular surfaces and the medial and lateral femoral condyles. The medial tibial articular surface is bigger and more oblong in the anteroposterior direction than the lateral tibial articular surface. It is trough shaped to act as a congruent counterpart to the spherical medial femoral condyle and limit its anteroposterior translation. The lateral tibial articular surface is rather flat or sometimes even dome shaped to allow the free and controlled anteroposterior translation of the comparatively cylindrical lateral femoral condyle as a component of the rotation of the distal femur around a medial vertical axis. This anatomy aids in the medial 'pivot mechanism' during flexion.

Johal et al impressively demonstrated this phenomenon in a study using 'interventional MRI', which simulated the weight bearing range of knee motion. They observed a posterior translation of 22mm laterally and a negligible posterior translation medially from 0°-120°. Beyond a range of 120° into squatting, both femoral condyles translated posteriorly by around 9-10mm(Johal et al., 2005).

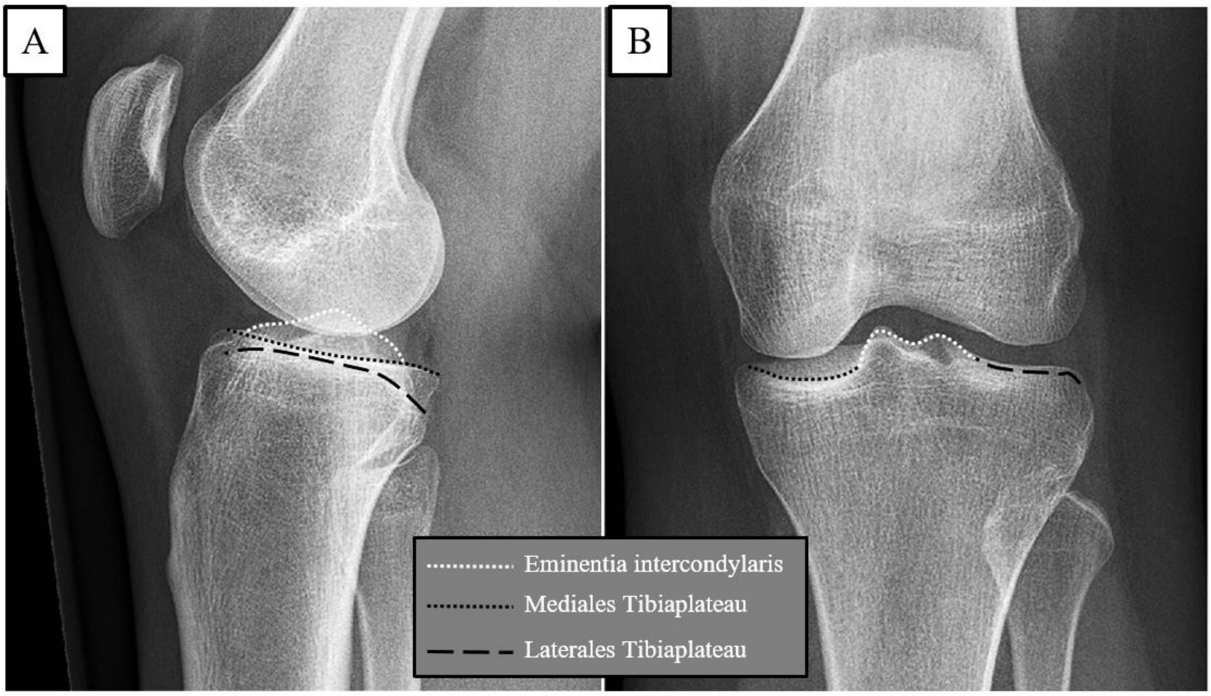

Figure 1- Outline of the Tibia Plateau on the lateral and anteroposterior radiograph of the knee

5.3.1.2 Coronal lower limb axis

The coronal lower limb axis, which is physiologically in 0°-5° of valgus, is of paramount importance in maintaining the complex knee biomechanics, especially near extension. As the vertical axis of femoral rotation is medial to the knee, an inherent or acquired varus lower limb axis leads not only to increased compressive load, but also to increased rotational stresses in the medial compartment and shear stresses in the lateral compartment. This sets in motion a pathomechanical vicious cycle, which ultimately leads to degeneration and failure in varus. A valgus axis on the other hand leads theoretically to an increase in the extent of anteroposterior translation of the medial femoral condyle over the medial tibial articular surface and comparatively less translation laterally. This may be due to a lateralised vertical rotational axis which in turn induces a lateral condylar hypoplasia and a spherical lateral femoral condyle. The medial collateral ligament is subjected to tremendous distraction stresses and ultimately fails, leading to a valgus lurch.

The anterior surface of the distal femur comprises the trochlear groove, formed by the protuberant lateral facet and the flatter medial facet. The patella glides in this groove to articulate with the trochlea.

5.3.1.3 Sagittal Anatomical Features

The sagittal anatomical features like the femoral and tibial bowing are important determinants of knee load bearing biomechanics. The degree of hyperextension or extension deficit in the knee are determined through multiple interacting factors including the bony anatomy.

Anteriorly, a well-developed trochlea is the prerequisite for a well-aligned patella.

The intra-articular posterior sagittal anatomical features are the posterior tibial slope and the posterior tibial and femoral offsets. These are the subject of our study. Their importance will be discussed in the next section.

5.3.1.4 Lower limb rotational alignment

The femoral anteversion is an important determinant of patellofemoral stability. An increased femoral anteversion not only forms an important aspect of hip dysplasia, but also has a consequent effect on the trochlear development and patellofemoral stability. It is frequently related to a valgus leg axis and may present with patellofemoral instability as the primary symptom.

5.3.2 Ligamentous Factors

5.3.2.1 Coronal Plane Stabilizers- Collateral Ligaments

The medial and lateral collateral ligaments stabilize the knee medially and laterally throughout the range of motion, preventing the excessive opening out of the knee in the coronal plane.

Laterally, in addition to the lateral collateral ligament, the iliotibial band and the popliteus tendon play a significant role in stability. Medially, it is influenced mainly by the continuity of the superficial and deep layers of the medial collateral ligament, with a minor role played by the Pes anserinus tendons.

The tension in each of the collateral ligaments is heavily dependent on the coronal plane leg axis. It is usually seen, that in valgus knees due to the constant medial vector of the compression forces during weight bearing, the lateral collateral structures are unusually tight, while the medial collateral ligament is more loose.

In varus knees, the lateral structures, because they consist not only of the lateral collateral ligament, but also other musculotendinous structures, stretch out at a much later stage.

5.3.2.2. Sagittal Plane Stabilizers- Cruciate ligaments

The anterior and posterior cruciate ligaments form the mainstay of the stabilizing elements in the sagittal plane. The anterior cruciate ligament originates from the lateral wall of the femoral intercondylar notch and inserts on the anterior intercondylar ridge on the tibial plateau. The posterior cruciate ligament has a broad, fan-shaped origin on the medial wall of the femoral intercondylar notch and inserts posteriorly on the tibial plateau up to about 15 cm under the tibial plateau surface

The ACL is the main anterior sagittal stabilizer of the knee near extension. As the knee flexes to about 90°, the MCL also plays a major role in the anterior tibial stabilization. The posterior cruciate ligament on the other hand, exerts its posterior stabilizing effect primarily near 90° of knee flexion.

Just like the coronal plane axis plays a major part in the determination of collateral ligament tension, the sagittal plane 'axis', mainly represented by the posterior tibial slope and the posterior femoral offset also plays a significant role in the tension of the cruciate ligaments. This has become increasingly apparent in cruciate reconstruction failures in patients with an abnormal posterior tibial slope.

5.3.2.3. Rotational Stability: Cruciate and Peripheral Ligaments

Owing to the terminal internal rotation of the distal femur over the tibial plateau necessary to achieve full extension, the rotatory stabilizers play a crucial role in the biomechanics of the knee. The anterior cruciate ligament acts as a major rotatory stabilizer to the knee, as it runs in an oblique direction from posterolateral to anterior. Nevertheless, because the ACL is intra-articular, it needs support from the peripheral knee ligaments to control the rotation of the knee. This can be explained using the example of a steering wheel. To effectively control its rotation, the hand needs to be at the circumference, rather than at the center. This peripheral support is provided by the MCL, posterolateral corner, iliotibial band and the configuration of the menisci. We strongly believe that the posterior tibial slope plays a decisive role in this rotation to facilitate the sagittal translation of the lateral femoral condyle, while at the same time limiting the sagittal translation of the medial femoral condyle.

5.3.2.4 Menisci

The menisci are fibrocartilaginous structures, which play an important function, not only as shock absorbers in the prevention of osteoarthritis, but also in the maintenance of knee joint stability. The medial meniscus is C- shaped and attached all along the periphery to the joint capsule. It is considerably larger than the lateral meniscus and more oblong in the anteroposterior direction and acts as a gasket seal for the rotational motion of the medial femoral condyle. The semimembranosus muscle, which has an accessory insertion on the posterior horn of the medial meniscus, pulls the medial meniscus posteriorly during flexion to further provide a congruent surface to the posterior medial condyle beyond 120° of flexion. The lateral meniscus is three-fourths of a circle and is more freely mobile than the medial meniscus. Its attachment to the joint capsule is deficient around the popliteal hiatus. It also has additional attachments from the posterior horn to the femoral attachment of the PCL. These are named the ligaments of Humphry and Wrisberg.

5.3.3 Muscular Factors

5.3.3.1 The extensor apparatus

The extensor apparatus, comprising of the Quadriceps muscle group consisting of the Rectus femoris, Vastus lateralis, medialis and intermedius, the Quadriceps tendon, the Patella, the Ligamentum patellae and the tibial tuberosity is arguably the most important dynamic stabilizer of the knee. It is the only extensor of the knee, acting through the patellar 'pulley' and exerting an immense forward pull on the proximal tibia. A well-developed Quadriceps muscle group can compensate for multiple knee instability disorders and even osteoarthritis.

5.3.3.2 Knee Flexors

The hamstrings are the main flexors of the knee. These are the Semitendinosus, Semimembranosus, Biceps femoris and the hamstring part of the Adductor magnus. They originate from the ischial tuberosity and are inserted around the posterior aspect of the knee. The Semitendinosus, although it inserts anteromedially in the Pes anserinus, has pulleys or vinculae posteriorly, which aid in flexing the knee. The Biceps femoris inserts on the fibular head and aids in the function of the LCL.

The gastrocnemius muscle is an important secondary flexor of the knee joint.

5.3.3.3 Knee Rotator

The Popliteus muscle is a special muscle, which originates from the posterior tibial head and inserts in the lateral epicondyle of the femur. The popliteus tendon runs an intra-articular course and acts as a lateral collateral stabilizer in flexion. The main function of the muscle is to externally rotate the distal femur during initial flexion to 'unlock' the knee joint.

5.3.3.4 Peripheral stabilizers

This group consists of muscles such as the Gracilis and the Sartorius, which are inserted into the Pes anserinus and stabilize the knee from the medial side, as well as the Tensor fasciae latae, which acts indirectly through the iliotibial band to stabilize the knee on the lateral side.

5.4 Kinematics of the Knee Joint

The knee has six degrees of freedom. The translational degrees of freedom of coronal translation and the compression distraction movement are severely restricted by the collateral ligaments and the fibrous capsule along with the bony anatomy respectively, as described above. The rotational degree of freedom around the sagittal axis- the abduction and adduction of the tibia is also restricted by the collateral ligaments. The most relevant degree of freedom is the rotation around the coronal axis, i.e., the flexion and extension of the knee. The second most important degree of freedom is the rotation around the vertical axis- internal and external rotation. Since the cruciate ligaments are situated in the center of the knee and are the main restrictors of the translational degree of freedom in the sagittal plane, they allow for a more relaxed differential translational degree of freedom in the sagittal plane- i.e., greater anteroposterior translation of the lateral femoral condyle as compared to the medial condyle.

Because the absolute surface area of the tibial plateau is much smaller than of the femoral condyles, it is this combination of movements that allows for a flexion up to 150°. If the femoral condyles were only to roll on the tibial plateau during flexion, they would dislocate posteriorly over the short tibial plateau. If they were only to translate anteroposteriorly, they would impinge on the posterior tibial plateau, leading to a severely restricted range of motion. The synchronized effect of all the aforementioned movements, named the 'femoral rollback', principally of the lateral femoral condyle allows for an increased, but at the same time stable range of movement. Pure rolling movement is observed only from 0° to 10-15° of flexion, after which the lateral condyle starts to glide first and the medial condyle rotates, (Traina et al., 2013). This persists up to 120° flexion, after which both condyles translate posterior by about 10mm(Johal et al., 2005).

During terminal extension, the distal femur rotates internally over the tibial plateau in a movement described as the 'screw-home' phenomenon(Hallén & Lindahl, 1966). The cruciate ligaments are the main factors controlling this synergy of the main degrees of freedom resulting in a seamless flow of motion.

5.5. The Posterior Tibial Slope

The physiological tibial plateau is inclined posteriorly in the sagittal plane. The angle between this inclination and a line perpendicular to the tibial anatomical axis is referred to as the posterior tibial slope (Dejour & Bonnin, 1994). This is variable in humans and is reported to range from -7.7° to 18.7° on the medial side in adults with a mean value at approximately 7° to 8° (de Boer et al., 2009; Weinberg et al., 2017). Post-mortem measurements on 1090 full-length tibiae revealed a steeper medial (female: 7.5 ± 3.8°; male: 6.8 ± 3.7°) and lateral (female: 5.2 ± 3.5°; male: 4.6 ± 3.5°) PTS in females than in males. Dark-skinned individuals had equally steeper values compared with light-skinned individuals. No variations in the PTS as a function of age were observed in body donors aged 25 to 55 years used for this purpose(Weinberg et al., 2017). Data on the PTS also vary depending on the measurement method used.

5.5.1 Role of the Posterior Tibial Slope in Biomechanics of the Knee

The hypothesis that a steep posterior tibial slope leads to an increase in the antero-posterior vector component in the axial compressive force exerted by the femur on the tibia has been verified repeatedly (Dejour & Bonnin, 1994; Giffin et al., 2004; Schatka et al., 2018; Wang et al., 2019). In this regard, Dejour and Bonnin are considered pioneers, who observed a 6mm increase in the anterior tibial translation for every 10° of increase in the posterior tibial slope in ACL-deficient patients(Dejour & Bonnin, 1994).

The prognostic importance of the posterior tibial slope in ligament reconstructions of the knee was recognized in the early 2000s, when the initial cruciate reconstructions started presenting for revisions(Agneskirchner et al., 2004).

The effect of the slope on sagittal stability and the cruciate ligaments can be explained by imagining a truck carrying a load held on to the flatbed carrier with two restraint ropes, one at the front and one at the back. In this example, the load is the femur, the flatbed is the tibia, and the front and back ropes are the anterior and posterior cruciate ligaments respectively (Figure 2).

As the truck travels on a flat road, the strain on both ropes is equal and minimum effort is required by both loads to hold the load in place. As the truck travels uphill (increased posterior tibial slope), the load (femur) tends to lean posteriorly (anterior drawer with respect to the tibia), exerting a strain on the front restraint rope (ACL). The back restraint rope (PCL) at the same time, is under reduced tension and thus at a decreased risk of breakage. Thus, in the case of an increased posterior tibial slope, the knee can be considered in a constant state of anterior drawer and the ACL is constantly at risk of injury. At the same time, this situation is protective for the PCL.

Conversely, when the truck travels downhill (decreased posterior slope), the load (femur) tends to slide towards the front (posterior drawer with respect to the tibia), exerting tension on the back restraint rope (PCL) and rendering the front restraint rope (ACL) lax and thus protected from breakage. Hence with a decreased posterior tibial slope, the PCL is in danger of injury and the ACL is protected.

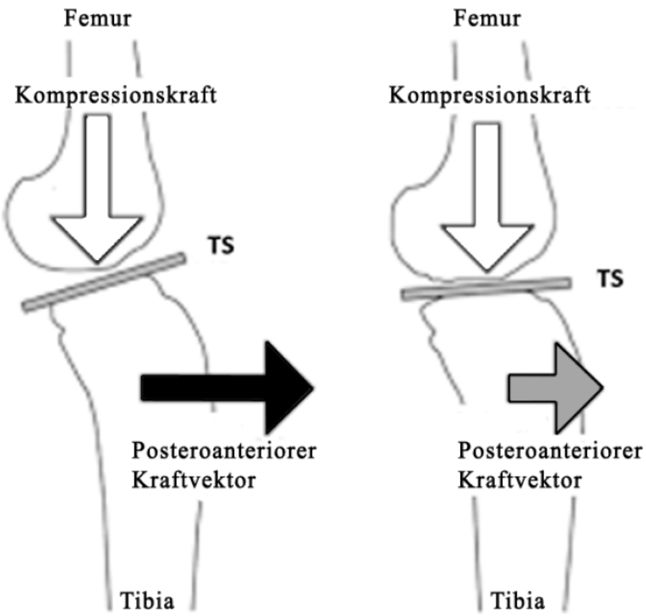

Figure 2- Biomechanical Effect of the Posterior Tibial Slope (Yamaguchi et al., 2018)

5.5.2 The Development of the Posterior Tibial Slope

Wolff's law states that bone in a healthy animal will adapt to the loads under which it is placed. It thus can be extrapolated from this fact, that the posterior tibial slope, along with the knee in general develops gradually as a function of the weight borne by the knee during bipedal stance. Studies measuring the posterior tibial slope in healthy pediatric population are extremely rare due to obvious fact that radiological studies relevant to the measurement of the slope are rarely performed in healthy children.

At the same time, studies have been published confirming a positive correlation between an increased posterior tibial slope and the risk of ACL rupture or graft failure. Dare et al published in a matched case control study in 2015 that an increased lateral PTS is a significant risk factor for an ACL rupture. The incidence of ACL injury was observed to be equal between the sexes(Dare et al., 2015). After the initiation of our study, Anchustegui et al published a cadaveric study about the measurement of the posterior tibial slope in the skeletally immature population. The authors analyzed computed tomography scans of 39 cadaveric pediatric knees between the ages of 2 years and 12 years(Anchustegui et al., 2022). They calculated the mean medial and lateral tibial slope to be 5.53° and 5.95° respectively, without showing any age trends. The age wise sample size in their study ranged from 1 knee to 10 knees.

5.5.3 The Importance of Slope Correction in Cruciate Surgery

According to biomechanical research (Agneskirchner et al., 2004; Giffin et al., 2004; Yamaguchi et al., 2018), a technically challenging tibial anterior closing-wedge osteotomy is a potential surgical treatment of an excessively steep PTS.

Strict caution is advised during establishment of the surgical indication in such cases. After a failed ACL reconstruction and a PTS of less than 12°, a slope correcting osteotomy is propagated by a few authors(Andrew S. Bernhardson et al., 2019; Hees & Petersen, 2018; Jo et al., 2018; Queiros et al., 2019). Patients with minor concomitant varus and complaints of instability after an ACL reconstruction may also be considered for a slope correcting osteotomy. Hees and Petersen even advise considering an osteotomy after a primary ACL rupture if the PTS is 15 degrees or higher(Hees & Petersen, 2018). For our practice, this indication currently appears to be excessively drastic.

The surgical technique involves removing an anteriorly based bone wedge, either supra- or infra- tubercular and closing this space to achieve an extension of the tibial shaft. A postoperative PTS of 6 to 8° is desired; overcorrection to below 5° should be avoided to reduce the risk of tibial plateau damage(A. S. Bernhardson, Z. S. Aman, et al., 2019). The PTS is reduced by 1° with a resection of roughly 1.67 mm, as assessed at the anterior cortex on a lateral radiograph. Therefore, a 10 mm resection would result in a 6° decrease in the PTS(A. S. Bernhardson, N. N. DePhillipo, et al., 2019).

Contraindications include recurvatum of more than 10°, a varus axis of more than 5°, or 4th degree osteoarthritis. A BMI of greater than 30 kg/m2 and cigarette smoking 20 or more times each day are considered relative contraindications(A. S. Bernhardson, N. N. DePhillipo, et al., 2019; Hees & Petersen, 2018). An extended period (8 weeks) of post-operative partial weight bearing is usually advised(A. S. Bernhardson, N. N. DePhillipo, et al., 2019).

Dejour et al. were able to report complication-free and satisfactory results of the extending closing wedge osteotomy with simultaneous ACL revision in 9 patients with a follow-up period of 2 years(Dejour et al., 2015; Dejour & Bonnin, 1994). Comparable results were also reported by Sonnery-Cottet et al. in 5 patients(Sonnery-Cottet et al., 2011). Currently, only these two studies have been published with a small number of cases regarding long-term outcome. A total of 7 papers involving 77 patients were identified in a systematic review by Gupta et al. These studies include varus-related realignment osteotomies in addition to the two mentioned above, and the common finding in all of them is that there was not a single further ACL revision after the osteotomy(Gupta et al., 2019). Despite initial satisfactory results, the risks of this procedure should not go unmentioned. These include possible damage to neurovascular structures, prolonged duration of surgery and rehabilitation, and possible postoperative complications such as non-union.

5.5.4 Applying Slope Correction in Children

Applying the principles of directed growth is a unique way to change the alignment of the knee joint in skeletally immature patients with pathological genu varum or valgum. This enables the gradual correction of abnormalities by unilaterally limiting the growth of a physeal plate (epiphysiodesis), resulting in angular correction using a low-risk, minimally invasive treatment. The principles of directed growth may be worth further study in situations of repeated ACL injuries in skeletally immature patients with a noticeably steep tibial slope. Hosseinzadeh and Kiapour have recently investigated the anatomical characteristics of the pediatric/adolescent knee(Hosseinzadeh & Kiapour, 2020). In comparison to age-matched male patients, they showed that early and late teenage female patients had smaller femoral notches, steeper lateral tibial slopes, flatter medial tibial plateaus, and shorter tibial spines. They proposed that these anatomical variations might give rise to new methods of treatment in pediatric ages like activity change or other strategies that reduce the incidence of ACL injury. In situations where the anatomy of the tibia is suitable to support tethering devices on the anterior region of the epiphyseal, physeal, and metaphyseal regions which lead to a change in alignment, guided growth or epiphysiodesis to adjust the tibial slope may be technically feasible with currently available implants.

5.6. Objectives of the study and Framing the Research Question

As explained above, there is a dearth of data regarding the normal values of the posterior tibial slope in the pediatric population. Steps taken in this direction may not only provide valuable information as 'baseline data' but may also prove to be a key modality in the ever-growing field of prevention of cruciate ligament injury.

There is also a shortcoming in the age-wise data about the tibial slope, which would also add to our understanding of the development of the slope.

To aid in the establishment of this data bank, we framed the objectives of our study as follows:

5.6.1 Primary Objective

To measure document the medial and lateral posterior tibial slope in the MRT series of children from the age of 0-18 years and to study its trend according to age and consequently, weight bearing

5.6.2 Secondary Objectives

To study the correlation between the medial and lateral posterior tibial slope, posterior femoral offset, and posterior tibial offset in the MRT series of children from the age of 0-18 years and to study its trend according to age and consequently, weight bearing

5.7 Study Hypothesis

The study hypothesis was framed as follows:

Null Hypothesis- The median posterior tibial slope in children does not increase as the child begins to adopt bipedal ambulation

Alternative Hypothesis- The median posterior tibial slope in children increases as the child begins to adopt bipedal ambulation

6. Materials and Methods

6.1 Inclusion and Exclusion Criteria

6.1.1 Inclusion criteria

All magnetic resonance imaging series of the normal knee from the age of 0 to eighteen years depicting the knee with at least 10 cm of the distal femur and at least 7 cm of the proximal tibia performed at our center (Charite Universitätsmedizin, Berlin) from 2010 to 2020.

6.1.2 Exclusion Criteria

1. All MRI series not meeting the above dimensional inclusion criteria
2. MRI series from the age of 0-5 years which did not portray at least the proximal two-thirds of the leg and thus did not take into account the physiological procurvatum often seen in infants and toddlers.
3. MRI series of knees with chronic cruciate ligament insufficiency or those conducted longer than one year after a ligament reconstruction.
4. MRI series of knees with aplasia

266 series were available for the study.

Seventeen series did not meet our inclusion criteria and hence were excluded. 249 MRI series were included in the study.

Ethical Committee Clearance: The study falls under the purview of the Votum of the ethical committee of the Charité no. EA 2/016/21

6.2 Measurements

These MRI series were analyzed in our house PACS (MERLIN Diagnostic Workcenter, Phönix-PACS GmbH, Freiburg) by a single observer. A total of six variables were measured:

1. Medial tibial slope
2. Lateral tibial slope
3. Medial tibial posterior offset
4. Lateral tibial posterior offset

5. Medial femoral posterior condylar offset
6. Lateral femoral posterior condylar offset

Before the respective measurements were performed, the axes of the images were preconfigured with respect to the tibia and the femur, to neutralize the effect of the lower limb axis and rotation on the measurements (Figure 3, 4).

The tibial measurements were performed initially. The axis was adjusted such that the transverse section passed through whole of the tibia plateau. The coronal section was adjusted, so that it exactly bisected both the medal and lateral tibial plateau compartments.

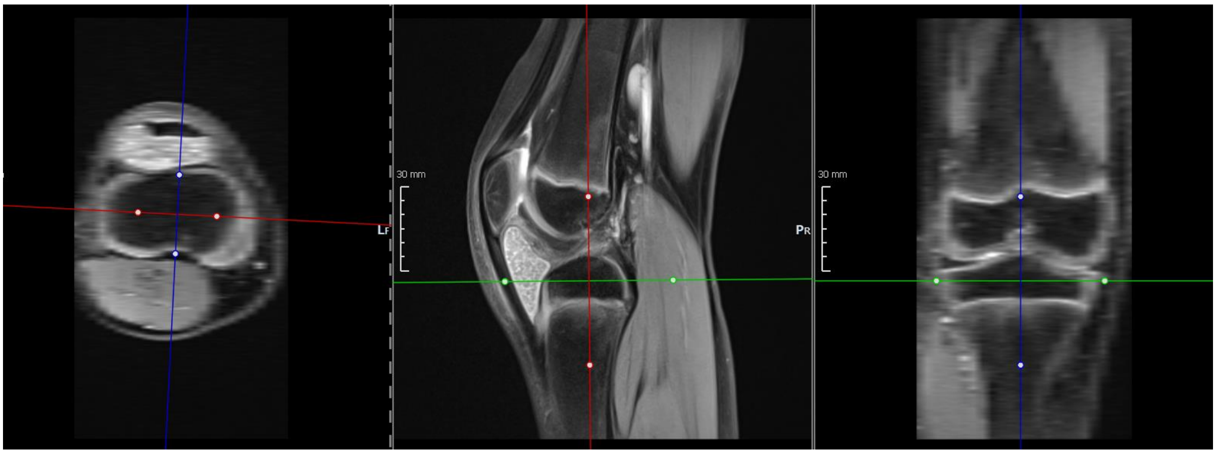

Figure 3- Preconfiguration of the axis on MRI Series for tibial measurements

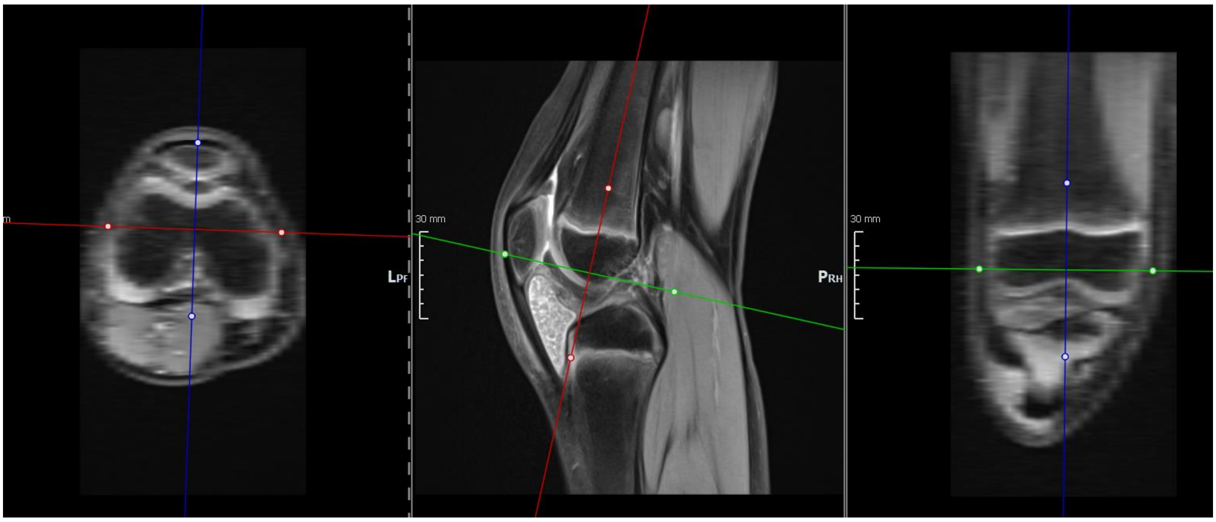

Figure 4- Preconfiguration of the axis on MRI Series for femoral measurements

6.2.1 Measurement of the Posterior Tibial Slope

The reference axis used with this method was the proximal tibial anatomical axis (PTAA), which is the bisector of the angle between the anterior tibial cortex and the posterior tibial cortex. This was measured in the T1 weighted sagittal sections of the MRI sections after axis setting using a layer-spanning angle measurement tool.

The anterior tibial line is a tangential line extending downwards from about 1-2 cm below the tibial tuberosity. The ‘mound’ of the tibial tuberosity is excluded from this measurement, as it does not represent the true anterior cortex.

The posterior tibial line is measured using the inner table of the outer cortex of the posterior tibia (Figure 5).

Not infrequently, a prominent Soleus Line, a transverse ridge situated in the upper third of the posterior tibia, on which the M. soleus originates can obfuscate the accurate determination of the posterior cortical line in the sagittal section. The inner cortical table line of the posterior cortex is undisturbed by the soleus line and thus helpful in determination of the posterior cortical line(Levine et al., 1976).

A four- point angle was plotted between the above-mentioned lines, scrolling through layers of the MRI study to identify the anterior-most and posterior-most extensions of the tibial diaphysis. The bisector of the angle subtended by these two lines is the PTAA. The anterior cortical line was now angulated to represent the PTAA, which was now fixed on the image throughout all layers (Figure 6).

Figure 5- Plotting of the anterior and posterior cortical lines

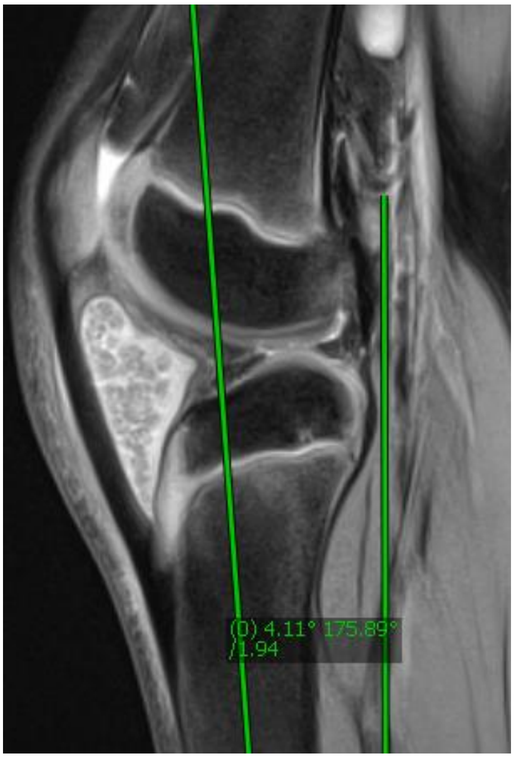

Figure 6- Bisector of the angle between the two lines represents the proximal tibial anatomical axis

The tangent to the medial tibial plateau, it being trough shaped, is relatively convenient to measure using the line joining the anterior and posterior edges of the medial tibial plateau, which usually corresponds to the anterior and posterior horns of the medial meniscus. This measurement is carried out on the layer passing through the center of the medial tibial compartment (50% of the distance between the medial extent of the medial tibial eminence and the medial border of the tibial plateau), which articulates with the center of the medial femoral condyle. The angle between this line and the PTAA is designated as the medial tibial slope (Figure 7).

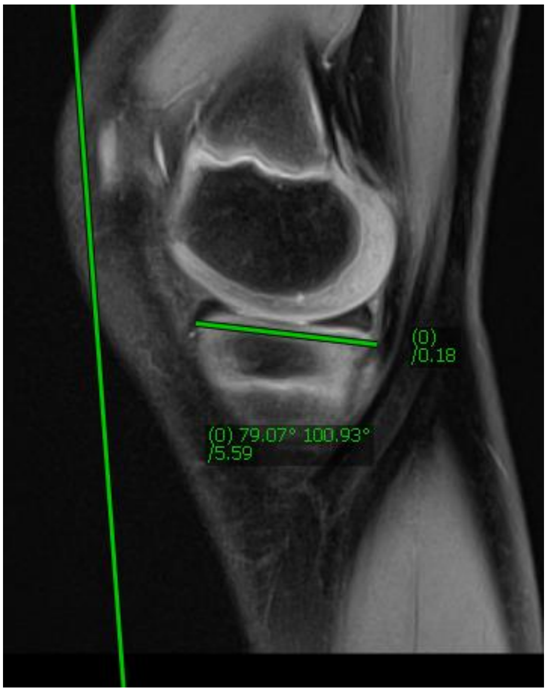

Figure 7- Measurement of the medial posterior tibial slope

The plotting of the tangent to the lateral tibial plateau, on the other hand, is far more complex. This is due to the fact that the lateral tibial plateau is variable in shape, ranging from flat to dome shaped and the lateral meniscus is far more mobile than the medial meniscus. A purely bony measurement of the lateral tibial plateau was performed using the line extending between the most anterior point and most posterior points of the curvature of the dome. This line was found to be tangent to the dome at its most cranial point.

This measurement was likewise carried out on the layer passing through the center of the lateral femoral condyle, which corresponded in most cases with about 60% of the distance between the lateral extent of the lateral tibial eminence and the lateral border of the tibial plateau, i.e., somewhat lateral to the center of the lateral tibial plateau. The angle between this line and the PTAA is designated as the lateral tibial slope (Figure 8).

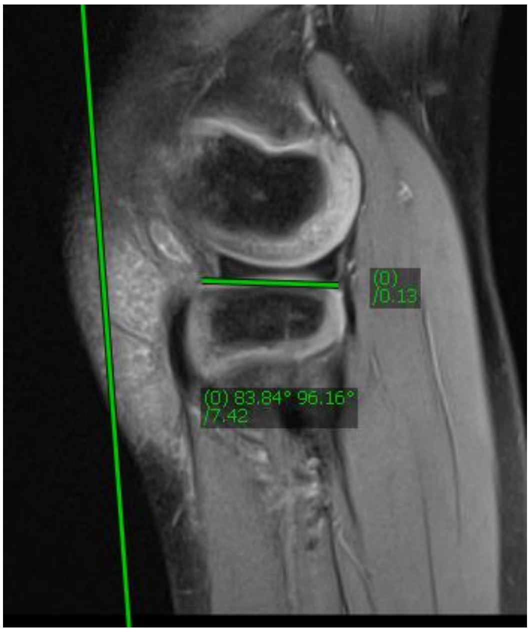

Figure 8- Measurement of the lateral posterior tibial slope

6.2.2 Measurement of the Posterior Tibial Offset

We defined the posterior extension of the tibial head beyond the posterior cortical line as the ‘posterior tibial offset’ to assess if this entity had any relation to the posterior tibial slope as well as the posterior femoral offset. A line parallel to the inner posterior cortical line at the level of the outer posterior cortex was fixed through all the layers(Figure 9) and a plumb line to this line was plotted measuring the medial(Figure 10) and lateral(Figure 11) extent of the ‘champagne glass drop-off’ ledge of the posterior tibial head. These measurements were documented.

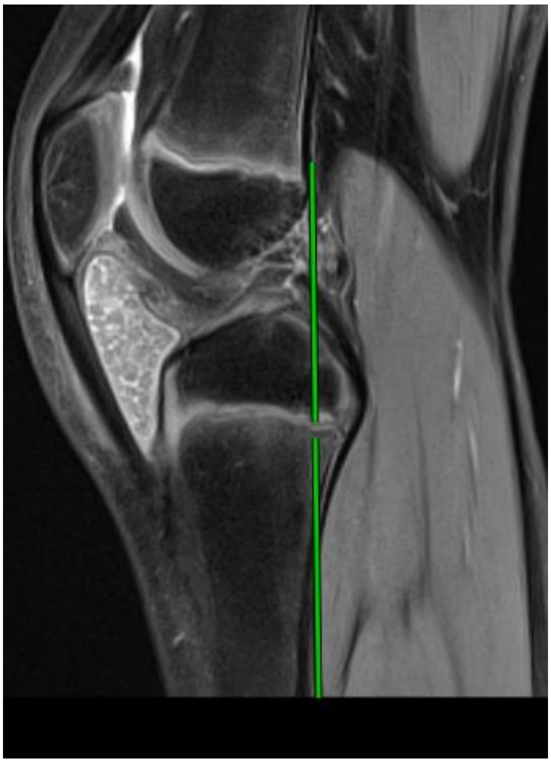

Figure 9- Plotting of the posterior tibial cortical line

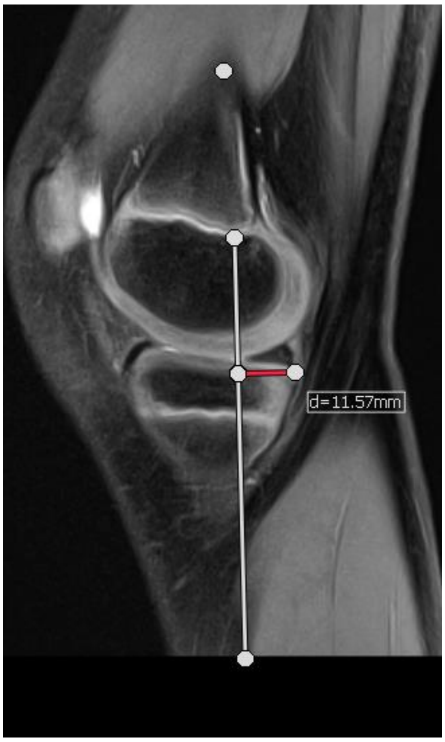

Figure 10- Measurement of the medial posterior tibial offset

Figure 11- Measurement of the lateral posterior tibial offset

6.2.3 Measurement of the Posterior Femoral Condylar Offset

The posterior tibial condylar offset is the maximum posterior extension of both the femoral condyles from the caudal extension of the posterior femoral cortical line. To measure this entity accurately with regards to the bony femur alone, the axis of the sections was now reconfigured with respect to the femur(Figure 4). A transverse axis parallel to the femoral joint line was chosen. In the transverse plane, the anteroposterior axis was set to a line passing through the deepest point of the trochlea and the highest point of the femoral intercondylar notch. This corresponded to the popular Whiteside line prevalent in the field of arthroplasty.

The mediolateral axis after this configuration was observed to pass through the medial and lateral epicondyles, thus supporting the validity of the Whiteside line.

A line extending caudally from the posterior femoral cortex was fixed through the layers (Figure 12) and plumb lines were projected in the posterior direction in the center of the layers passing through the medial(Figure 13) and lateral(Figure14) femoral condyles. The maximum bony extension of the condyles was thus recorded.

Figure 12- Plotting of the posterior femoral cortical line

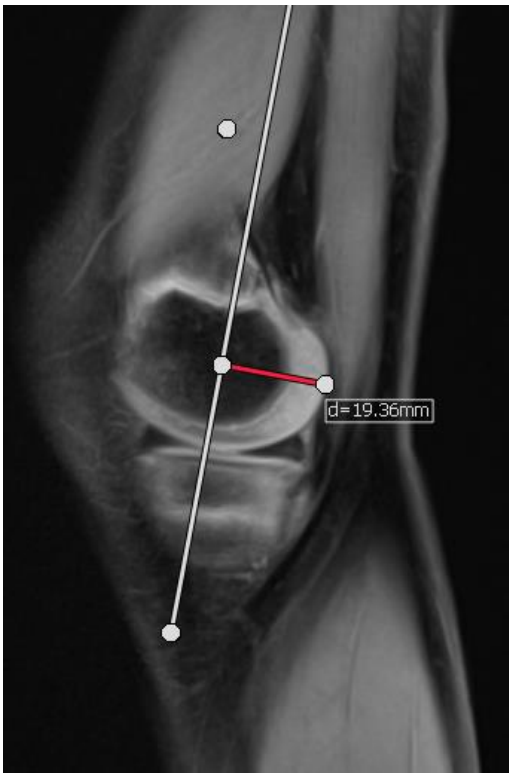

Figure 13- Measurement of the medial posterior femoral offset

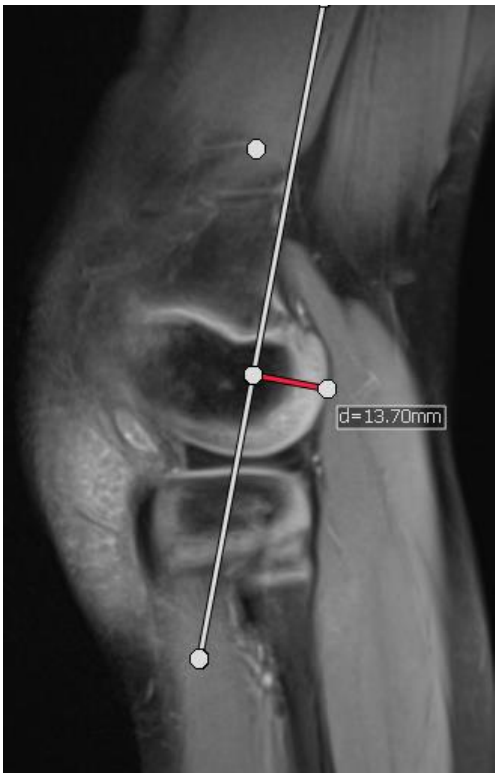

Figure 14- Measurement of the lateral posterior femoral offset

6.2.4 Data Analysis

The obtained data were analyzed in Microsoft Excel (Microsoft Corporation, Seattle, WA). The mean, median and standard deviation were calculated for each group. These were arranged according to every year of age and graphs were plotted to observe the distribution of values.

The data which were organized according to age group were then fed into the data analysis software SPSS (IBM inc.). As the distribution of the variables was not observed to be normal and the number of variables in each group was frequently less than 30, we decided to group the results according to the milestones of gross motor development. These were classified into 5 age groups:

1. 0-2 years
2. 3-4 years
3. 5-7 years
4. 8-12 years
5. 13-18 years

Moreover, the Spearman rank correlation was employed to deduce the correlation between the variable sets. The correlation and the 2- tailed level of significance was then documented according to the age groups. Correlation was tested between the following variables:

1. Medial posterior tibial slope and medial posterior tibial offset
2. Medial posterior tibial offset and medial posterior femoral offset
3. Medial posterior tibial slope and medial posterior femoral offset
4. Lateral posterior tibial slope and lateral posterior tibial offset
5. Lateral posterior tibial offset and lateral posterior femoral offset
6. Lateral posterior tibial slope and lateral posterior femoral offset

7. Results

The images were analysed according to their age distribution. The results classified according to age are presented below and in Table 1:

7.1. Quantitative Data:

Age 1 year

11 knees under 2 year of age, which were included in the study displayed a median medial tibial slope measuring 3.36° with a standard deviation of 1.99°. It was seen to range between -0.9° and 5.12°. The median lateral tibial slope in this age group was observed to be 1.06°, with an SD (Standard Deviation) of 2.52°, ranging from -6.93° to 2.45°. The median medial posterior tibial offset was 6.38 mm, with a standard deviation of 1.73mm and a range from 4.6mm to 10.83mm. The median lateral posterior tibial offset was found to measure 6.95mm and the standard deviation was 1.45mm, with a range from 4.95 to 10.72mm. The median medial posterior femoral offset was observed to be 13.06mm with an SD of 2.22mm and a range between 10.67mm and 16.99mm, while the median lateral posterior femoral offset was observed to be 12.96 mm with an SD of 1.52 and a range between 10.5mm and 14.91mm.

Age 2 years

7 knees between 2 and 3 years of age, which satisfied the inclusion criteria for the study showed a median medial tibial slope measuring 4.56° and a standard deviation measuring 1.89°. The range was observed to lie between 0.07° and 5.88°. The median lateral tibial slope in this age group was seen to be 1.85°, with an SD of 1.84°with a range from -6.78° to 3.42°. The median medial posterior tibial offset was observed to be 8.34mm with an SD of 1.84mm.

Its range was observed to lie between 4.82mm and 10.15mm. The median lateral posterior tibial offset was 8.35mm with an SD measuring 1.34mm and a range from 5.96mm to 9.4mm. The median medial posterior femoral offset was 16.64mm, displaying a standard deviation of 1.3mm and a range from 14.36mm to 17.71mm and the median lateral posterior femoral offset was observed to be 15.64mm with an SD of 3.8mm, displaying a range between 8.58mm and 18.75mm.

Age 3 years

The age group between 3 and 4 years contained 5 knee MRI series, which satisfied the inclusion criteria for the study. The median medial tibial slope was observed to lie at 3.07° with a standard deviation measuring 2.6°. The range was observed to lie between 0.82° and 7.09°. The median lateral tibial slope in this age group was observed to be 2.04°, with an SD of 1.83° and a range from -1.57° to 2.74°. The median medial posterior tibial offset was observed to be 7.74 mm with an SD of 2.3 mm. Its range was observed to lie between 5.04 mm and 11.39 mm. The median lateral posterior tibial offset was observed to be 8.3 mm with an SD measuring 1.96 mm and ranging from 6.03 mm to 11.27 mm. The medial posterior femoral offset displayed a median value of 15.1 mm, and a standard deviation of 3.4 mm. It ranged from 11.97 mm to 21.38 mm, while the median lateral posterior femoral offset was observed to be 15.59 mm. It had a standard deviation of 3.4 mm, displaying a range between 9.7 mm and 17.12 mm.

Age 4 years

In the age group from 4 to 5 years were 6 knee MRI series included. The medial tibial slope showed a median value of 4.9° and a standard deviation measuring 2.1°. The range was observed to lie between 2.12° and 7.7°. The median lateral tibial slope in this age group was observed to lie at 4.6°, displaying a standard deviation of 3.1° and a range between -1.56° and 6.4°. The median value of the medial posterior tibial offset was observed to be 7.96 mm with an SD of 1.7 mm. Its range was observed to be from 6.51 mm to 11.06 mm. The median lateral posterior tibial offset was seen to measure 7.4 mm with an SD measuring 2.3 mm and ranging from 5.28 mm to 12.18 mm. The medial posterior femoral offset displayed a median value of 14.57 mm, and a standard deviation of 3 mm. It ranged from 12.5 mm to 20.57 mm, while the lateral posterior femoral offset showed a median value of 14.71 mm. It had a standard deviation of 1.49 mm. The range lied between 13.76 mm and 15.09 mm.

Age 5 years

The age group between 5 and 6 years contained 9 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 6.23° with a standard deviation measuring 3.34°. The range was observed to lie between 0.62° and 9.66°. The median lateral tibial slope in this age group was observed to be 3.65°, with an SD of 2.75° and a range from 0.92° to 10.36°. The median medial posterior tibial offset was observed to be 9.48 mm with an SD of 1.87 mm. Its range was observed to lie between 6.89 mm and 12.09 mm. The median lateral posterior tibial offset was observed to be 8.4 mm with an SD measuring 2.20 mm and ranging from 5 mm to 11.76 mm. The medial posterior femoral offset displayed a median value of 19.33 mm, and a standard deviation of 2.88 mm. It ranged from 15.4 mm to 23.49 mm, while the median lateral posterior femoral offset was observed to be 18.5 mm. It had a standard deviation of 3.59 mm, displaying a range between 12.02 mm and 23.31 mm.

Age 6 years

The age group between 6 and 7 years contained 11 knee MRI series, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 6.44° with a standard deviation measuring 1.95°. The range was observed to lie between 3.31° and 9.45°. The median lateral tibial slope in this age group was observed to be 3.72°, with an SD of 3.27° and a range from 0.39° to 10.32°. The median medial posterior tibial offset was observed to be 11.35 mm with an SD of 1.34 mm. Its range was observed to lie between 9.6 mm and 13.72 mm. The median lateral posterior tibial offset was observed to be 8.66 mm with an SD measuring 1.96 mm and ranging from 6.34 mm to 11.68 mm. The medial posterior femoral offset displayed a median value of 20.22 mm, and a standard deviation of 4.5 mm. It ranged from 9,5 mm to 26.61 mm, while the median lateral posterior femoral offset was observed to be 18.12 mm. It had a standard deviation of 4.8 mm, displaying a range between 8.45 mm and 26.3 mm.

Age 7 years

11 MRI studies in the age group from 7 to 8 years fulfilled the inclusion criteria. These showed the following findings: the medial tibial slope showed a median value of 6.3° and a standard deviation measuring 2.1°. The range of the medial slope was observed to lie between 3.6° and 10°. The median lateral tibial slope in this age group was observed to lie at 4.6°, displaying a standard deviation of 3.2° and a range between -0.8° and 11.61°. The median value of the medial posterior tibial offset was observed to be 10.04 mm with an SD

of 1.76 mm. Its range was observed to be from 7.20 mm to 12.97 mm. The median lateral posterior tibial offset was seen to measure 10.46 mm with an SD measuring 1.88 mm and ranging from 6.3 mm to 10.98 mm. The medial posterior femoral offset displayed a median value of 21.2 mm, and a standard deviation of 2.87 mm. It ranged from 18.66 mm to 29.60 mm, while the lateral posterior femoral offset showed a median value of 20.64 mm. It had a standard deviation of 2.76 mm. The range lied between 17.77 mm and 26.28 mm.

Age 8 years

The age group between 8 and 9 years contained 11 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 6.71° with a standard deviation measuring 2.64°. The range was observed to lie between 3.23° and 9.84°. The median lateral tibial slope in this age group was observed to be 5.19°, with an SD of 2.48° and a range from 1.35° to 9.37°. The median medial posterior tibial offset was observed to be 10.47 mm with an SD of 1.87 mm. Its range was observed to lie between 8.43 mm and 13.43 mm. The median lateral posterior tibial offset was observed to be 11.21 mm with an SD measuring 1.86 mm and ranging from 7.59 mm to 14.72 mm. The medial posterior femoral offset displayed a median value of 21.08 mm, and a standard deviation of 1.96 mm. It ranged from 18.21 mm to 23.92 mm, while the median lateral posterior femoral offset was observed to be 20.4 mm. It had a standard deviation of 2.25 mm, displaying a range between 15.01 mm and 22.79 mm.

Age 9 years

16 MRI studies in the age group from 9 to 10 years fulfilled the inclusion criteria. These showed the following findings: the medial tibial slope showed a median value of 6.95° and a standard deviation measuring 2.47°. The range of the medial slope was observed to lie between 2.17° and 11.16°. The median lateral tibial slope in this age group was observed to lie at 4.65°, displaying a standard deviation of 4.07° and a range between 0.57° and 13.5°. The median value of the medial posterior tibial offset was observed to be 11.33 mm with an SD of 1.94 mm. Its range was observed to be from 6.92 mm to 15.22 mm. The median lateral posterior tibial offset was seen to measure 11.75 mm with an SD measuring 1.61 mm and ranging from 8.32 mm to 14.6 mm. The medial posterior femoral offset displayed a median value of 23.53 mm, and a standard deviation of 4.02 mm. It ranged from 8.95 mm to 25.52 mm, while the lateral posterior femoral offset showed a median value of 21.18 mm. It had a standard deviation of 3.28 mm. The range lied between 9.6 mm and 23.84 mm.

Age 10 years

The age group between 10 and 11 years contained 20 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 7.57° with a standard deviation measuring 2.66°. The range was observed to lie between 3.86° and 14.48°. The median lateral tibial slope in this age group was observed to be 7.57°, with an SD of 2.80° and a range from -0.43° to 10.50°. The median medial posterior tibial offset was observed to be 11.44 mm with an SD of 1.78 mm. Its range was observed to lie between 8.57 mm and 14.72 mm. The median lateral posterior tibial offset was observed to be 12.41 mm with an SD measuring 1.62 mm and ranging from 8.49 mm to 15.67 mm. The medial posterior femoral offset displayed a median value of 23.26 mm, and a standard deviation of 3.09 mm. It ranged from 15.68 mm to 29 mm, while the median lateral posterior femoral offset was observed to be 22.36 mm. It had a standard deviation of 2.79 mm, displaying a range between 15.35 mm and 27 mm.

Age 11 years

15 MRI studies in the age group from 11 to 12 years fulfilled the inclusion criteria. These showed the following findings: the medial tibial slope showed a median value of 8.18° and a standard deviation measuring 2.61°. The range of the medial slope was observed to lie between 3.12° and 13.3°. The median lateral tibial slope in this age group was observed to lie at 7.31°, displaying a standard deviation of 2.80° and a range between 2.19° and 11.24°. The median value of the medial posterior tibial offset was observed to be 11.68 mm with an SD of 2.14 mm. Its range was observed to be from 8.79 mm to 17.23 mm. The median lateral posterior tibial offset was seen to measure 12.49 mm with an SD measuring 2.85 mm and ranging from 7.02 mm to 17.76 mm. The medial posterior femoral offset displayed a median value of 21.99 mm, and a standard deviation of 2.99 mm. It ranged from 16.46 mm to 27.60 mm, while the lateral posterior femoral offset showed a median value of 22.52 mm. It had a standard deviation of 2.33 mm. The range lied between 17.9 mm and 26.37 mm.

Age 12 years

The age group between 12 and 13 years contained 14 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 7.90° with a standard deviation measuring 2.54°. The range was observed to lie between 2.52° and 12.95°. The median lateral tibial slope in this age group was observed to be 7.32°, with an SD of 3.23° and a range from 1.97° to 12.66°. The median medial posterior tibial offset was observed to be 10.78 mm with an SD of 3.33 mm. Its range was observed to lie between 8.57 mm and 14.72 mm. The median lateral posterior tibial offset was observed to be 11.32 mm with an SD measuring 2.03 mm and ranging from 5.61 mm to 13.95 mm. The medial posterior femoral offset displayed a median value of 22.36 mm, and a standard deviation of 2.81 mm. It ranged from 19.27 mm to 28.6 mm, while the median lateral posterior femoral offset was observed to be 21.97 mm. It had a standard deviation of 2.10 mm, displaying a range between 18 mm and 26.4 mm.

Age 13 years

16 MRI studies in the age group from 13 to 14 years fulfilled the inclusion criteria. These showed the following findings: the medial tibial slope showed a median value of 9.71° and a standard deviation measuring 3.04°. The range of the medial slope was observed to lie between 4.36° and 14.4°. The median lateral tibial slope in this age group was observed to lie at 7.42°, displaying a standard deviation of 3.72° and a range between 3° and 14.44°. The median value of the medial posterior tibial offset was observed to be 12.47 mm with an SD of 2.83 mm. Its range was observed to be from 5.56 mm to 15.12 mm. The median lateral posterior tibial offset was seen to measure 12.47 mm with an SD measuring 2.54 mm and ranging from 6.56 mm to 15.5 mm. The medial posterior femoral offset displayed a median value of 23.36 mm, and a standard deviation of 3.11 mm. It ranged from 20.34 mm to 31.85 mm, while the lateral posterior femoral offset showed a median value of 22.71 mm. It had a standard deviation of 3.24 mm. The range lied between 16.86 mm and 28.41 mm.

Age 14 years

The age group between 14 and 15 years contained 18 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 8.61° with a standard deviation measuring 2.07°. The range was observed to lie between 4.07° and 10.92°. The median lateral tibial slope in this age group was observed to be 7.30°, with an SD of 2.58° and a range from 1.35° to 11.91°. The median medial posterior tibial offset was observed to be 12.5 mm with an SD of 2.65 mm. Its range was observed to lie between 9.52 mm and 20.61 mm. The median lateral posterior tibial offset was observed to be 11.87 mm with an SD measuring 1.95 mm and ranging from 8.4 mm to 14.72 mm. The medial posterior femoral offset displayed a median value of 24.05 mm, and a standard deviation of 3.42 mm. It ranged from 16.97 mm to 29.81 mm, while the median lateral posterior femoral offset was observed to be 22.44 mm. It had a standard deviation of 2.85 mm, displaying a range between 17.74 mm and 29.55 mm.

Age 15 years

The age group between 15 and 16 years contained 30 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 8.62° with a standard deviation measuring 2.34°. The range was observed to lie between 2.76° and 14.17°. The median lateral tibial slope in this age group was observed to be 7.26°, with an SD of 3.41° and a range from 1.2° to 13.18°. The median medial posterior tibial offset was observed to be 12.90 mm with an SD of 2.12 mm. Its range was observed to lie between 8.04 mm and 16.08 mm. The median lateral posterior tibial offset was observed to be 10.6 mm with an SD measuring 2.25 mm and ranging from 6.3 mm to 17.27 mm. The medial posterior femoral offset displayed a median value of 26.52 mm, and a standard deviation of 3.11 mm. It ranged from 20.55 mm to 33.98 mm, while the median lateral posterior femoral offset was observed to be 25.24 mm. It had a standard deviation of 2.68 mm, displaying a range between 19.85 mm and 31.25 mm.

Age 16 years

20 knees between 16 and 17 years of age, which satisfied the inclusion criteria for the study showed a median medial tibial slope measuring 8.48° and a standard deviation measuring 2.06°. The range was observed to lie between -1.69° and 13.88°. The median lateral tibial slope in this age group was seen to be 8.86°, with an SD of 3.36°with a range from 2.26° to 14.39°. The median medial posterior tibial offset was observed to be 15.09 mm with an SD of 3.11 mm. Its range was observed to lie between 11.35 mm and 15.25 mm. The median lateral posterior tibial offset was 12.03 mm with an SD measuring 2.38 mm and a range from 7.81 mm to 19.24 mm. The median medial posterior femoral offset was 25.43 mm, displaying a standard deviation of 2.99 mm and a range from 21.47 mm to 32 mm and the median lateral posterior femoral offset was observed to be 25.76 mm with an SD of 2.66 mm, displaying a range between 21.47 mm and 31.31 mm.

Age 17 years

The age group between 17 and 18 years contained 17 knee MRI studies, which satisfied the inclusion criteria for the study. The medial tibial slope was observed to lie at a median value of 8.51° with a standard deviation measuring 3.22°. The range was observed to lie between 2.31° and 15.73°. The median lateral tibial slope in this age group was observed to be 8.45°, with an SD of 2.61° and a range from 3.41° to 14.6°. The median medial posterior tibial offset was observed to be 14.3 mm with an SD of 2.30 mm. Its range was observed to lie between 9.48 mm and 18.26 mm. The median lateral posterior tibial offset was observed to be 12.17 mm with an SD measuring 2.36 mm and ranging from 8.64 mm to 16.58 mm. The medial posterior femoral offset displayed a median value of 25.71 mm, and a standard deviation of 3.55 mm. It ranged from 19.32 mm to 31.73 mm, while the median lateral posterior femoral offset was observed to be 24.63 mm. It had a standard deviation of 3.77 mm, displaying a range between 18.94 mm and 31.79 mm.

Age 18 years

12 knees 18 years of age, which satisfied the inclusion criteria for the study showed a median medial tibial slope measuring 9.08° and a standard deviation measuring 3.23°. The range was observed to lie between 4.77° and 15.7°. The median lateral tibial slope in this age group was seen to be 7.81°, with an SD of 2.93°with a range from 2.92° to 11.51°. The median medial posterior tibial offset was observed to be 12.85 mm with an SD of 1.15 mm. Its range was observed to lie between 10.49 mm and 14.43 mm. The median lateral posterior tibial offset was 12.6 mm with an SD measuring 1.77 mm and a range from 9.5 mm to 15.31 mm. The median medial posterior femoral offset was 23.57 mm, displaying a standard deviation of 2.03 mm and a range from 20.67 mm to 28.22 mm and the median lateral posterior femoral offset was observed to be 24.09 mm with an SD of 1.69 mm, displaying a range between 22.39 mm and 28.3 mm.

Table 1: Age-wise distribution of the median medial and lateral posterior tibial slope with standard deviation

Age (yrs)	N	Median medial PTS (°)	SD (°)	Median lateral PTS (°)	SD (°)
1	11	3.36	1.993092	1.06	2.522749
2	7	4.56	1.891108	1.85	4.316126
3	5	3.07	2.557665	2.04	1.832913
4	6	4.855	2.178008	4.6	3.118991
5	9	6.23	3.341759	3.65	2.754692
6	11	6.44	1.953041	3.72	3.271291
7	11	6.33	2.112254	4.64	3.249336
8	11	6.71	2.643609	5.19	2.484019
9	16	6.95	2.478699	4.645	4.071675
10	20	7.565	2.657892	7.565	2.801296
11	15	8.18	2.613854	7.31	2.809926
12	14	7.905	2.542759	7.325	3.229996
13	16	9.715	3.046635	7.42	3.717099
14	18	8.615	2.078171	7.305	2.588811
15	30	8.62	2.338655	7.265	3.416335
16	20	8.22	3.054457	8.86	3.364374
17	17	8.51	3.221222	8.45	2.61623
18	12	9.085	3.230696	7.815	2.936313

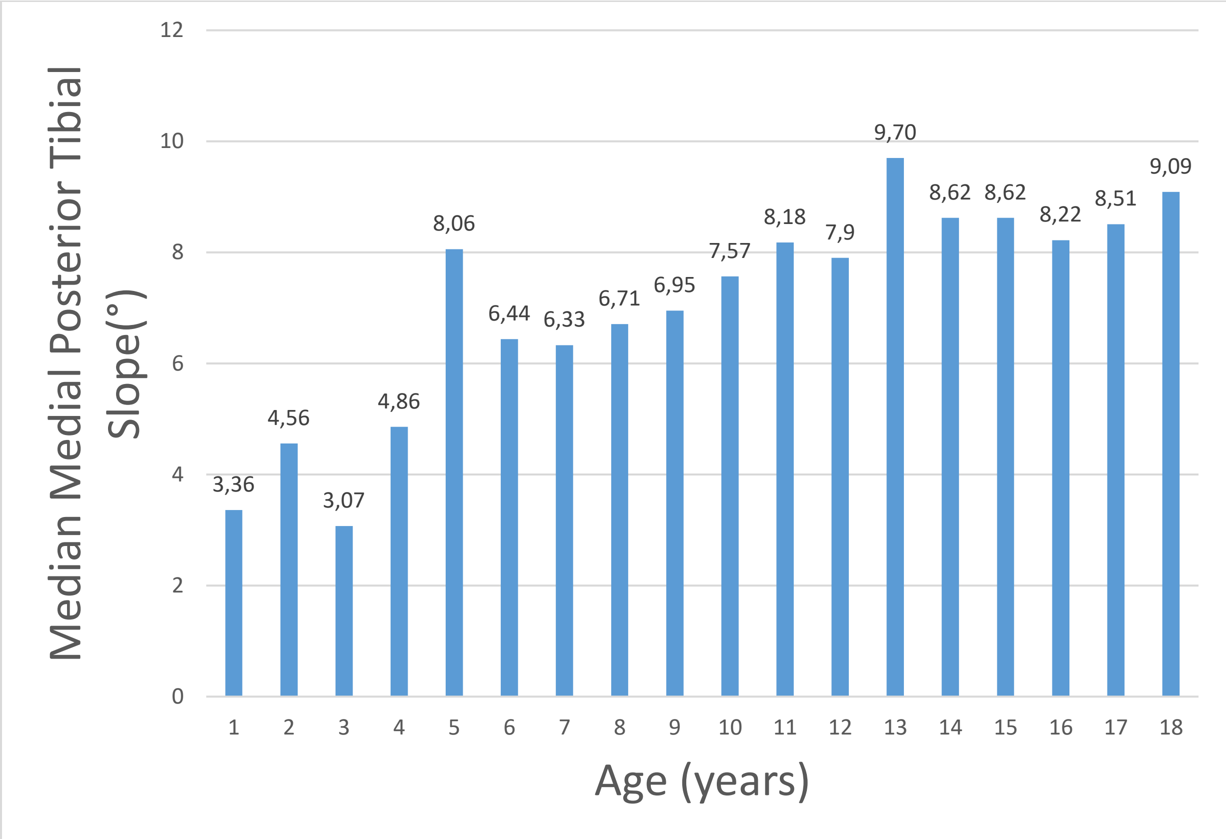

Figure 15- Age-wise distribution of the median medial posterior tibial slope

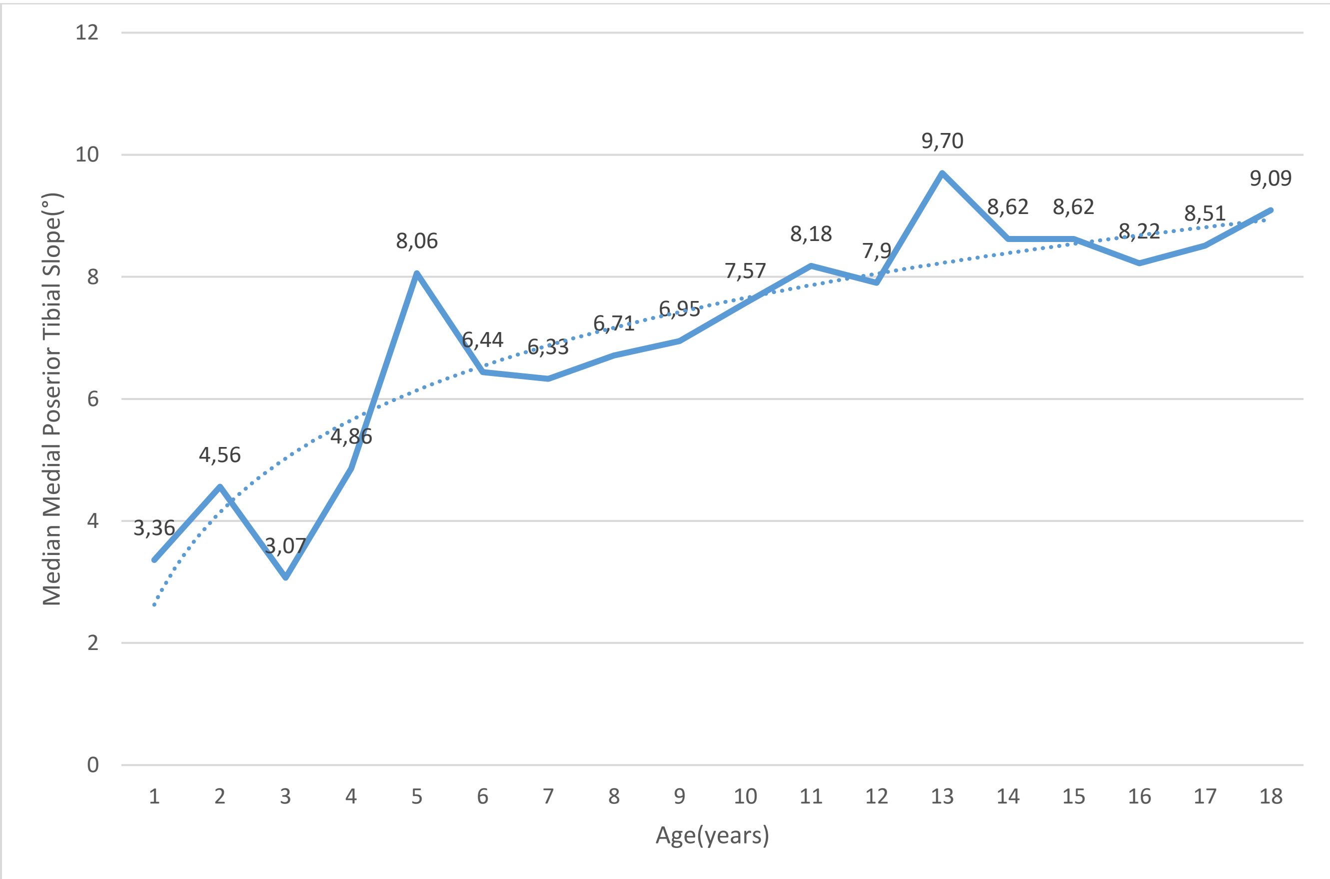

Figure 16- Trend of the median medial posterior tibial slope

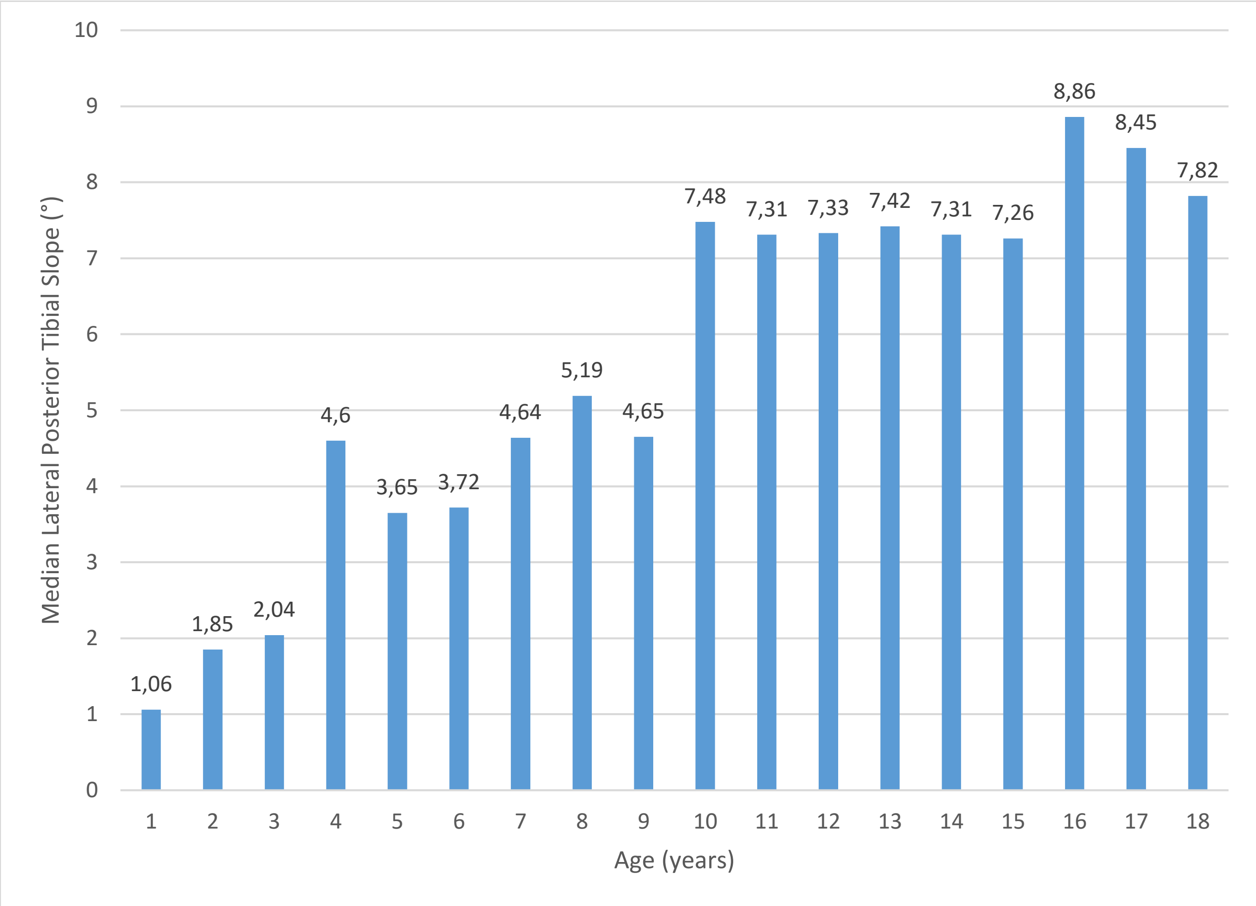

Figure 17- Age-wise distribution of the median lateral posterior tibial slope

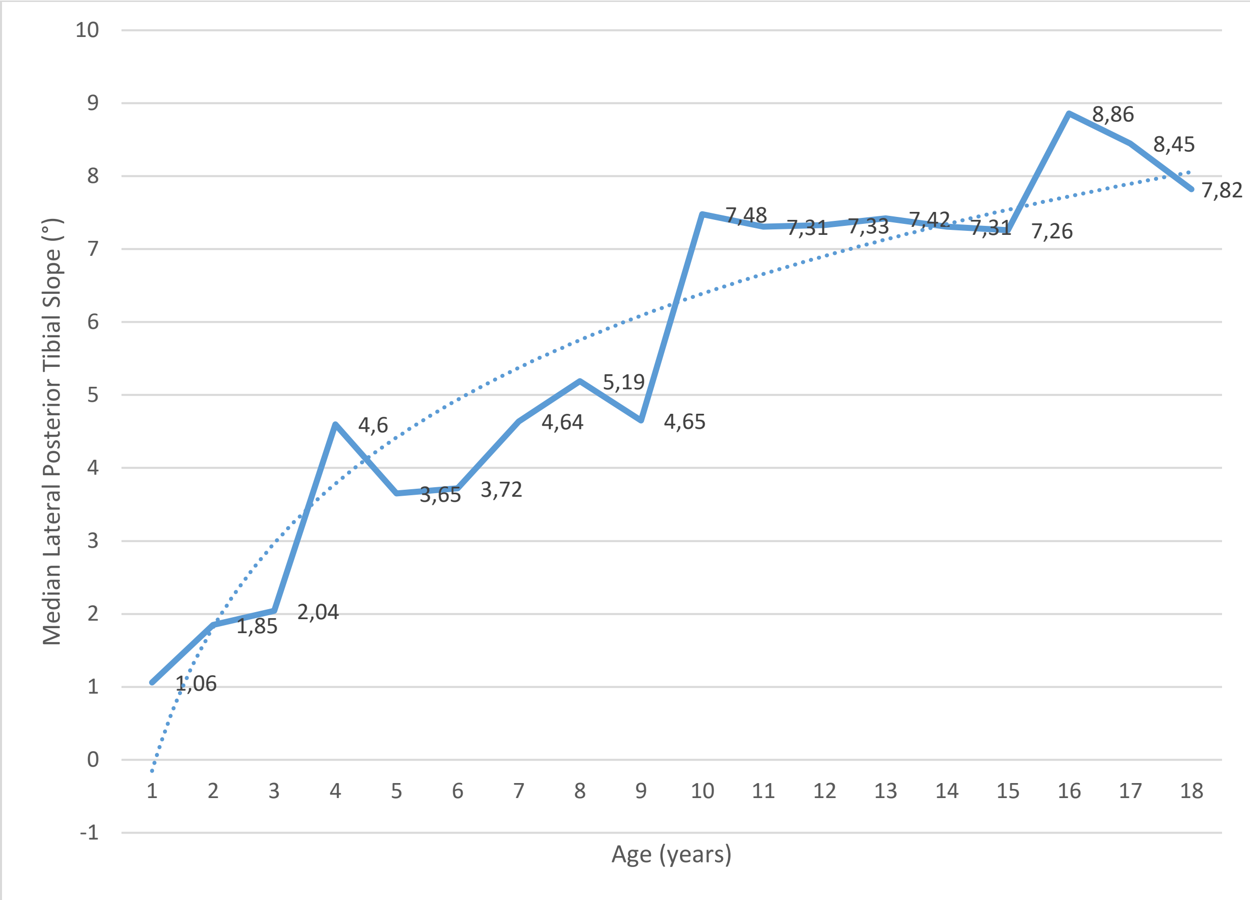

Figure 18- Trend of the median lateral posterior tibial slope

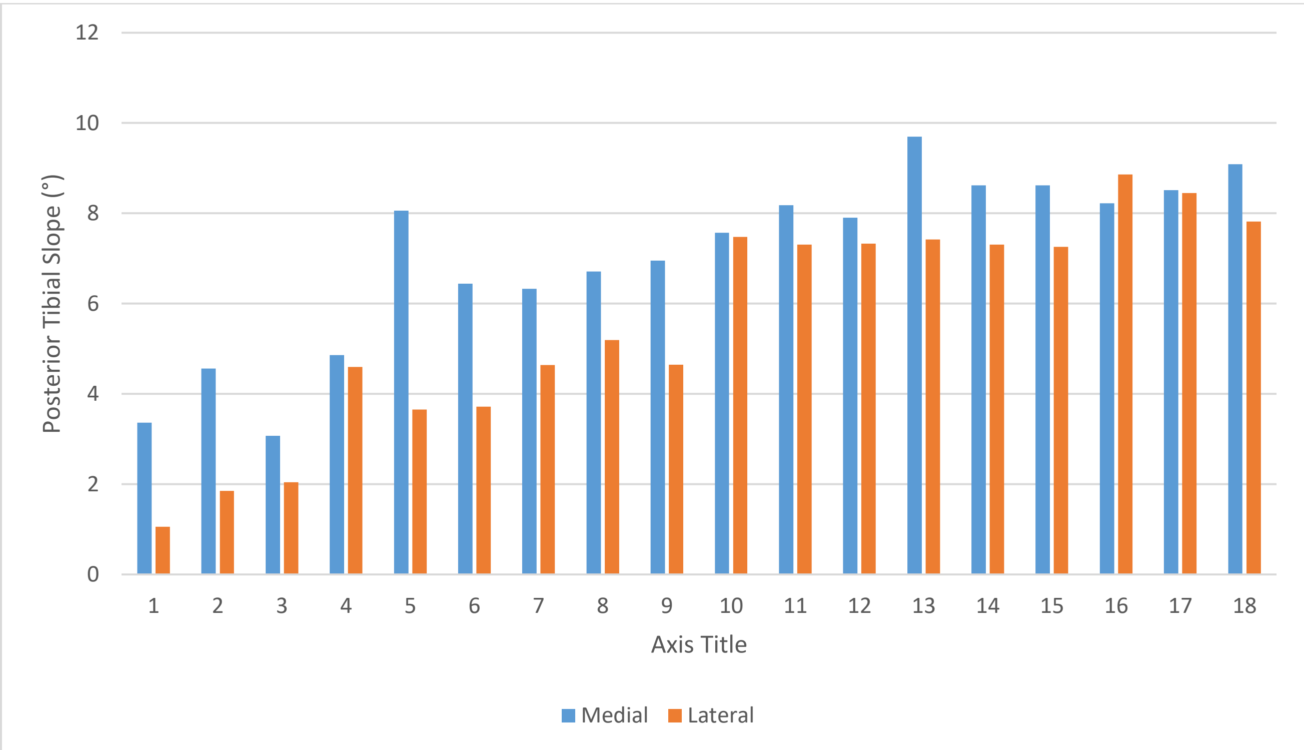

Figure 19- Age-wise distribution of the median medial and lateral posterior tibial slope

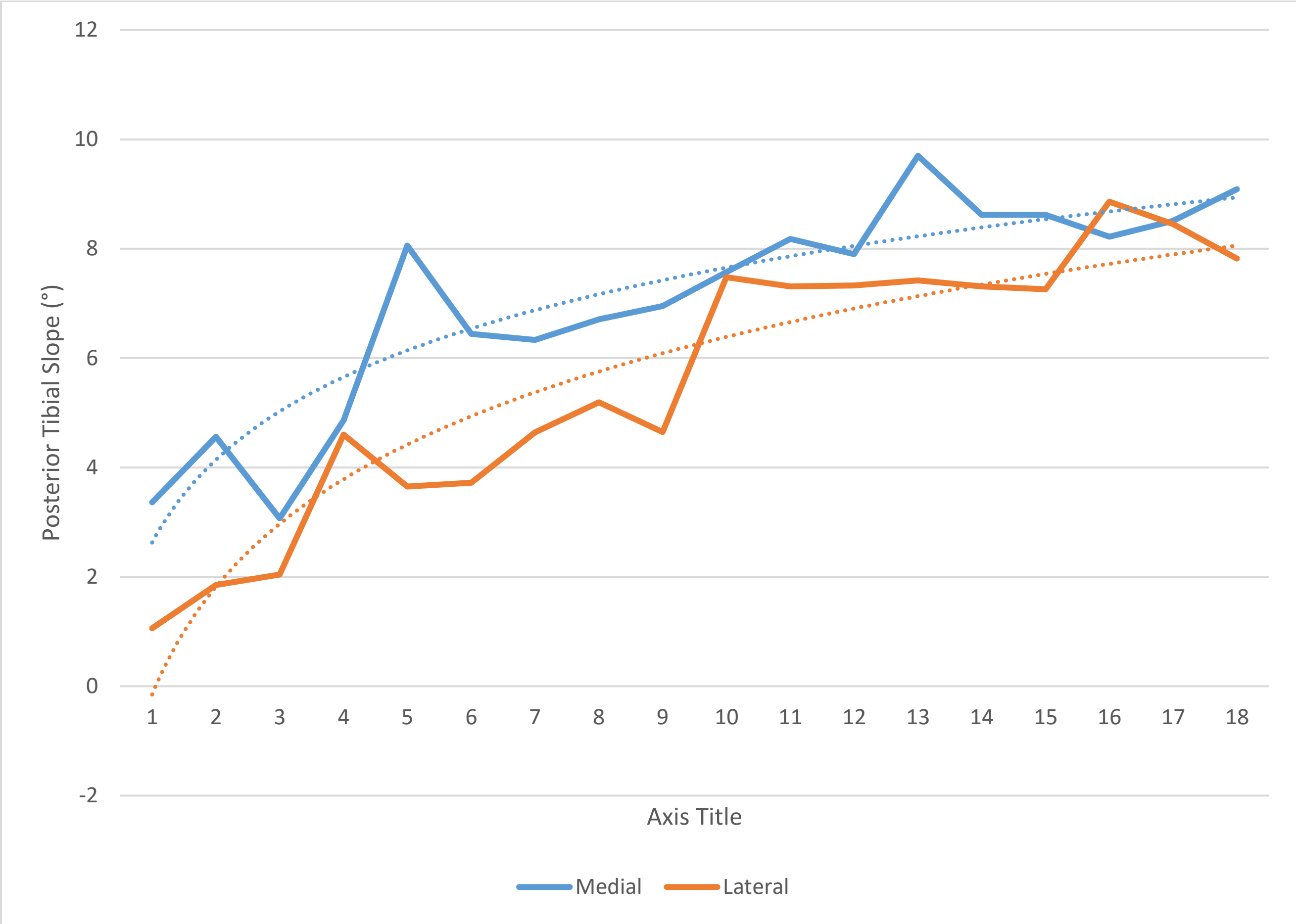

Figure 20- Trend of the median medial and lateral posterior tibial slope

7.2 Testing of Correlation

7.2.1 Age Group 0-2 years

The sample size in this age group was 18

1. **Medial posterior tibial slope and medial posterior tibial offset**

The medial posterior tibial slope in the age group of 0 to 2 years displayed a significant positive correlation with the medial posterior tibial offset with a Spearman rank coefficient of 0.491 and a p-value of 0.038.

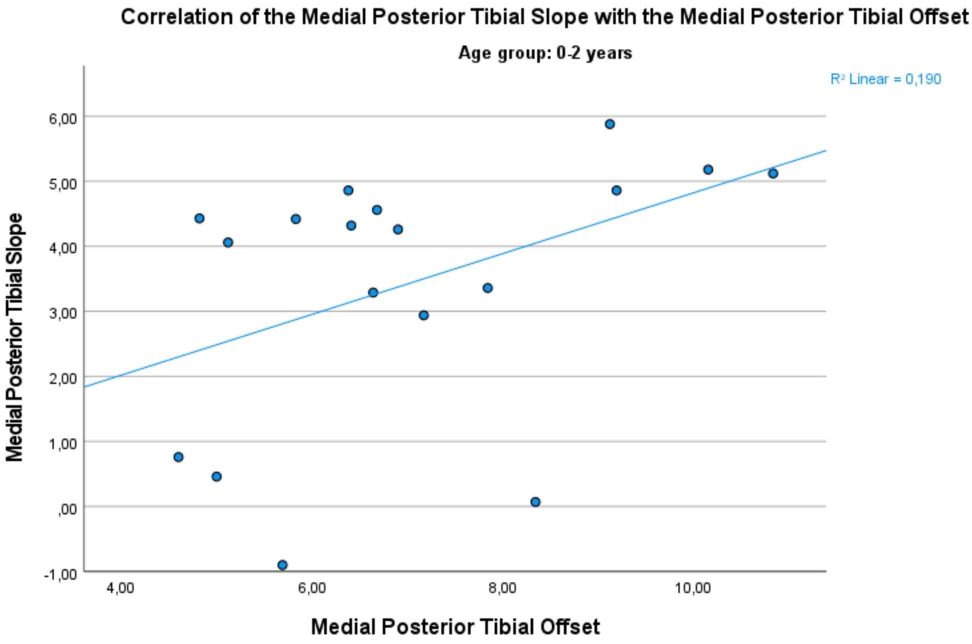

Figure 21- Correlation of the medial posterior tibial slope with the medial posterior tibial offset (age group 0-2 yrs)

2. Medial posterior tibial slope and medial posterior femoral offset

The medial posterior tibial slope displayed a positive correlation with the medial posterior femoral offset, with a Spearman coefficient of 0.194 and a p-value of 0.440. The findings were not significant.

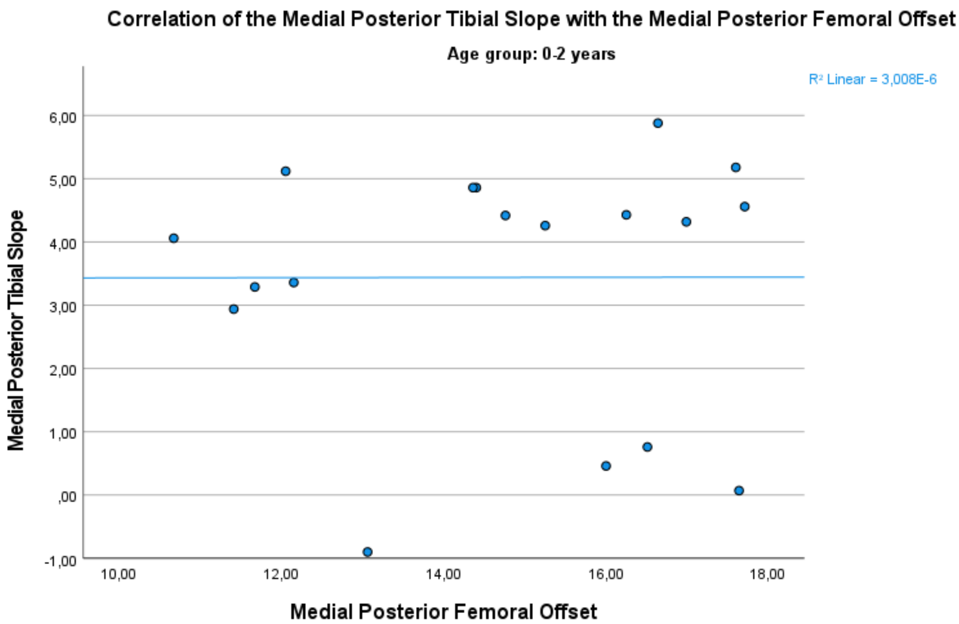

Figure 22- Correlation of the medial posterior tibial slope with the medial posterior femoral offset (age group 0-2 yrs)

3. Medial posterior tibial offset and medial posterior femoral offset

The medial posterior tibial offset in this age group displayed a positive correlation with the medial posterior femoral offset, showing a Spearman coefficient of 0.040 and a p-value of 0.874. The correlation was not found to be significant.

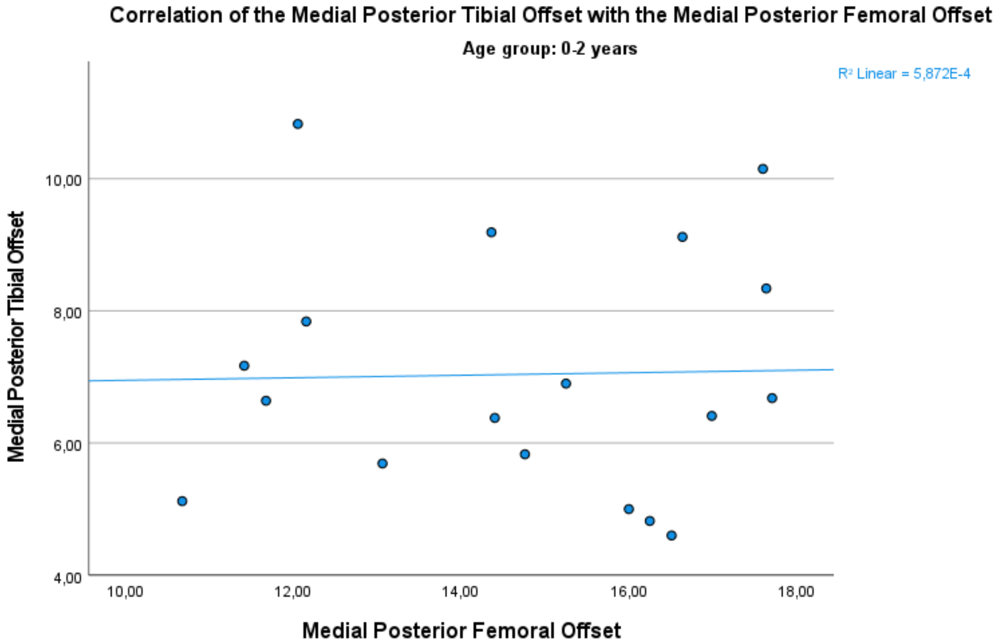

Figure 23- Correlation of the medial posterior tibial offset with the medial posterior femoral offset (age group 0-2 yrs)

4. Lateral posterior tibial slope and lateral posterior tibial offset

The lateral posterior tibial slope and the lateral posterior tibial offset correlated negatively with each other and showed a Spearman coefficient of -0.220 and a p-value of 0.381

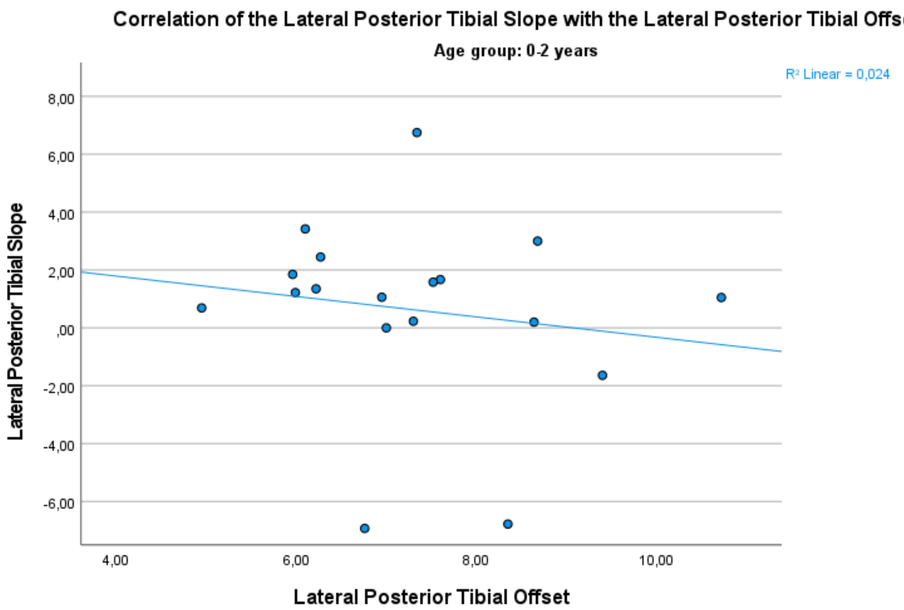

Figure 24- Correlation of the lateral posterior tibial slope with the lateral posterior tibial offset (age group 0-2 yrs)

5. Lateral posterior tibial slope and lateral posterior femoral offset

The lateral posterior tibial slope in this age group correlated negatively with the lateral posterior femoral offset with a Spearman rank coefficient amounting to -0.294 and a p-value of 0.236

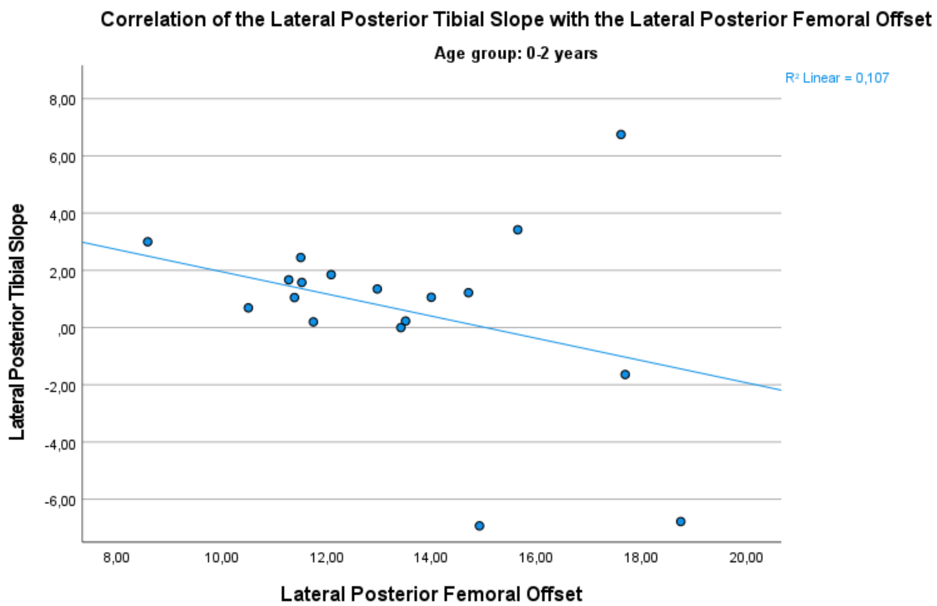

Figure 25- Correlation of the lateral posterior tibial slope with the lateral posterior femoral offset (age group 0-2 yrs)

6. Lateral posterior tibial offset and lateral posterior femoral offset

The lateral posterior slope displayed an insignificant negative correlation with the lateral posterior femoral offset with a Spearman coefficient of -0.036 and a p-value of 0.887

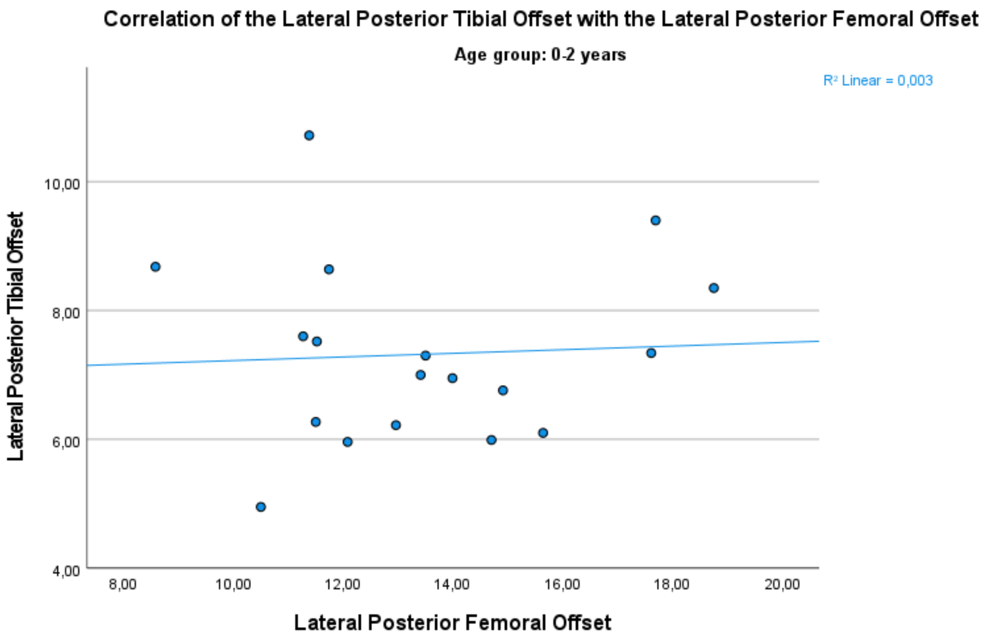

Figure 26- Correlation of the lateral posterior tibial offset with the lateral posterior femoral offset (age group 0-2 yrs)

7.2.2 Age group 3 to 4 years

The sample size in this group was 11

1. **Medial posterior tibial slope and medial posterior tibial offset**

The medial posterior tibial slope at the age group of 3-4 years displayed an insignificant correlation with the medial posterior tibial offset with a Spearman rank coefficient of -0.023 and a p-value of 0.947.

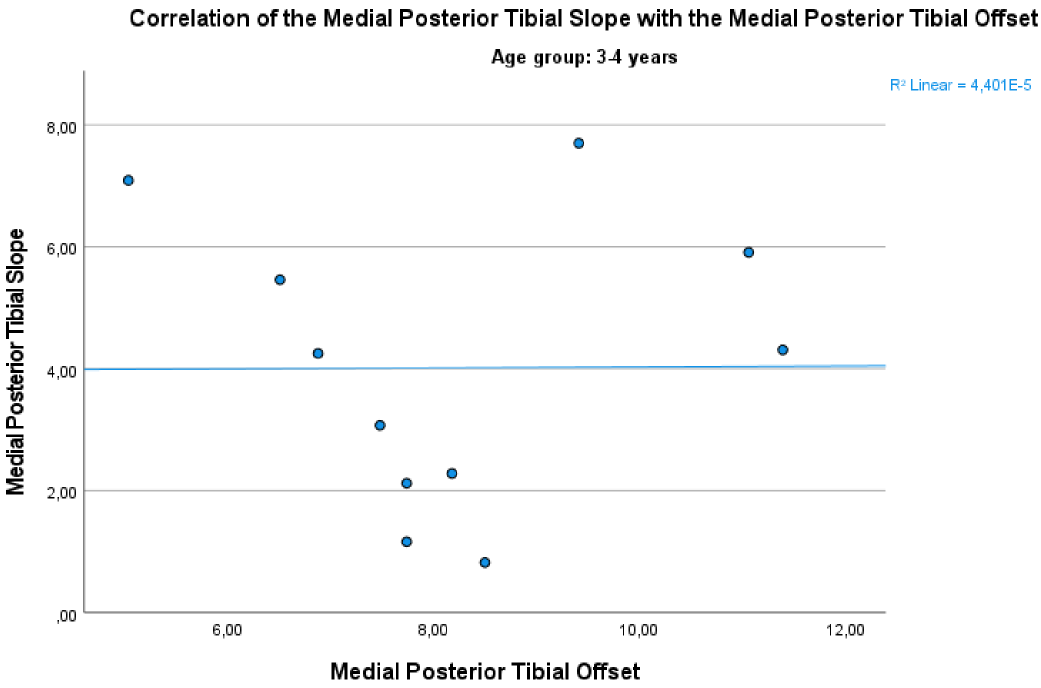

Figure 27- Correlation of the medial posterior tibial slope with the medial posterior tibial offset (age group 3-4 yrs)

2. Medial posterior tibial slope and medial posterior femoral offset

The medial posterior tibial slope displayed an insignificant correlation with the medial posterior femoral offset, with a Spearman rank coefficient of 0.082 and a p-value of 0.811.

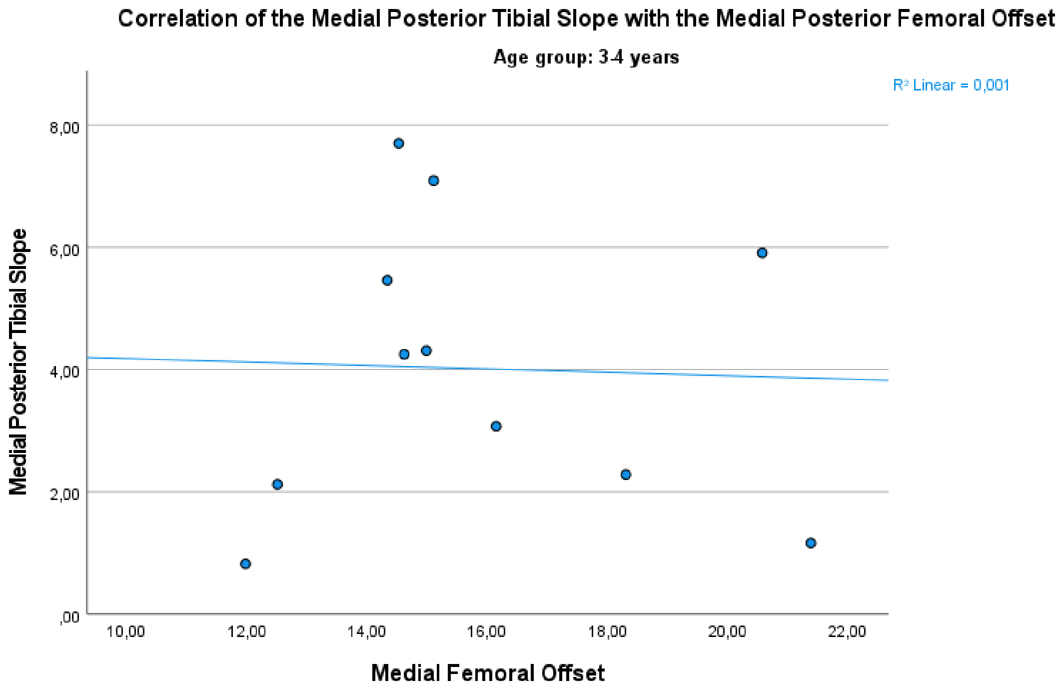

Figure 28- Correlation of the medial posterior tibial slope with the medial posterior femoral offset (age group 3-4 yrs)

3. Medial posterior tibial offset and medial posterior femoral offset

The medial posterior tibial offset in this age group correlated positively with the medial posterior femoral offset, showing a Spearman coefficient of 0.077 and a p- value of 0.821. The correlation was not found to be significant.

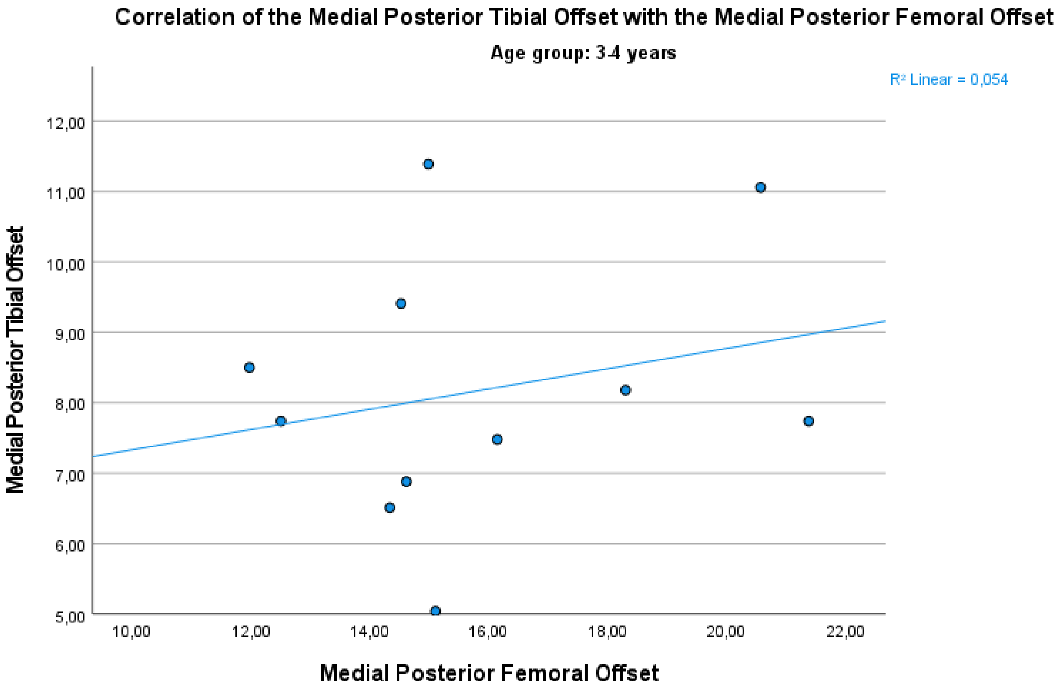

Figure 29- Correlation of the medial posterior tibial offset with the medial posterior femoral offset (age group 3-4 yrs)

4. Lateral posterior tibial slope and lateral posterior tibial offset

The lateral posterior tibial slope and the lateral posterior tibial offset did not correlate significantly with each other and showed a Spearman coefficient of -0.220 and a p-value of 0.381

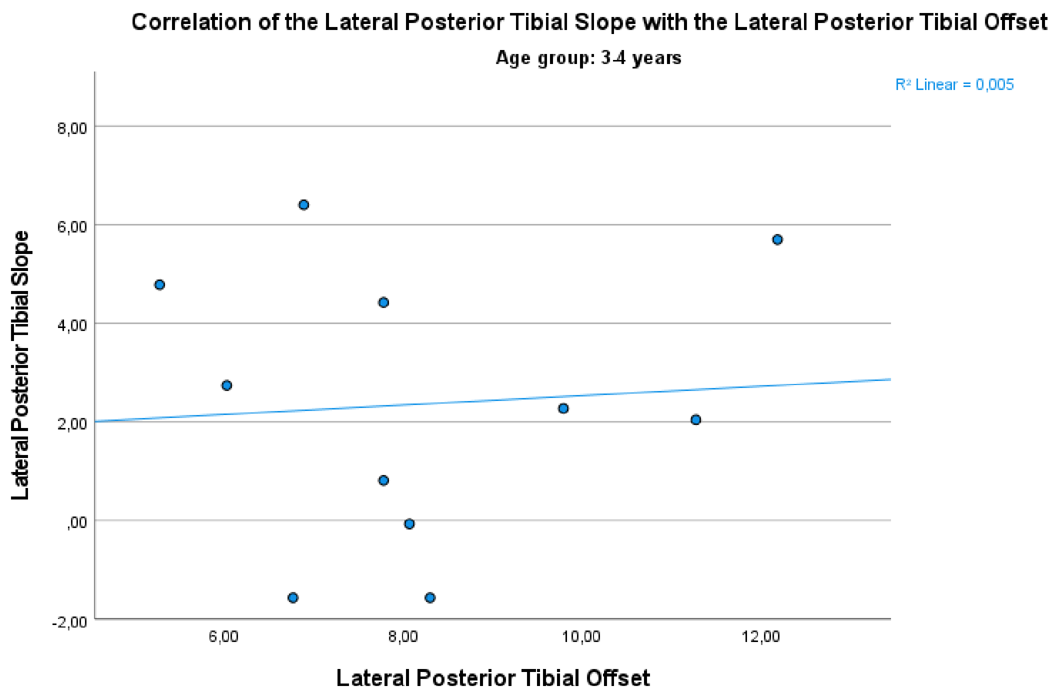

Figure 30- Correlation of the lateral posterior tibial slope with the lateral posterior tibial offset (age group 3-4 yrs)

5. Lateral posterior tibial slope and lateral posterior femoral offset

The lateral posterior tibial slope in this age group correlated negatively with the lateral posterior femoral offset with a Spearman rank coefficient amounting to -0.294 and a p-value of 0.236.

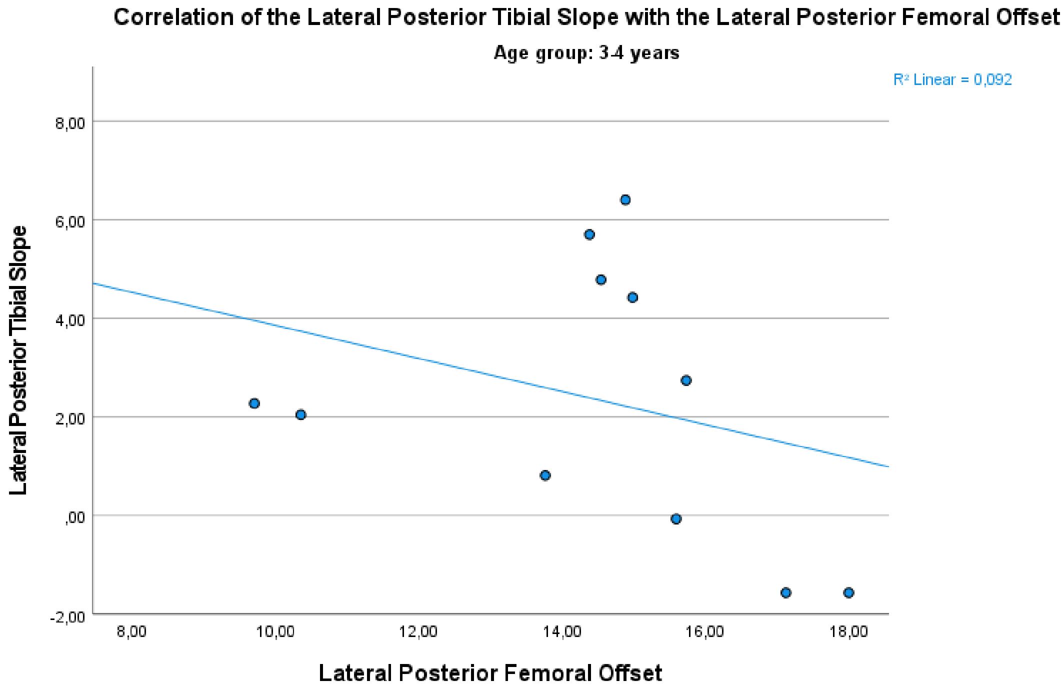

Figure 31- Correlation of the lateral posterior tibial slope with the lateral posterior femoral offset (age group 3-4 yrs)

6. Lateral posterior tibial offset and lateral posterior femoral offset

The lateral posterior slope displayed an insignificant correlation with the lateral posterior femoral offset with a Spearman coefficient of -0.036 and a p-value of 0.887.

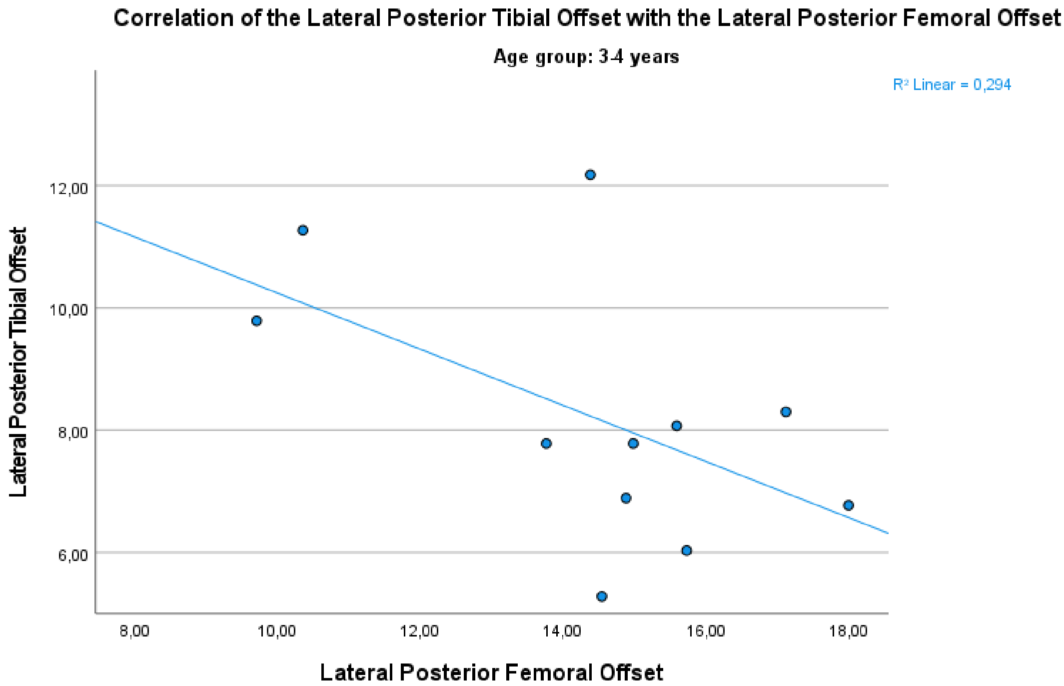

Figure 32- Correlation of the lateral posterior tibial offset with the lateral posterior femoral offset (age group 3-4 yrs)

7.2.3 Age Group 5 to 7 years

The sample size of this group was 31

1. Medial posterior tibial slope and medial posterior tibial offset

The medial posterior tibial slope at the age group of 5-7 years displayed a weak correlation with the medial posterior tibial offset with a Spearman rank coefficient of -0.125 and a p-value 0.503.

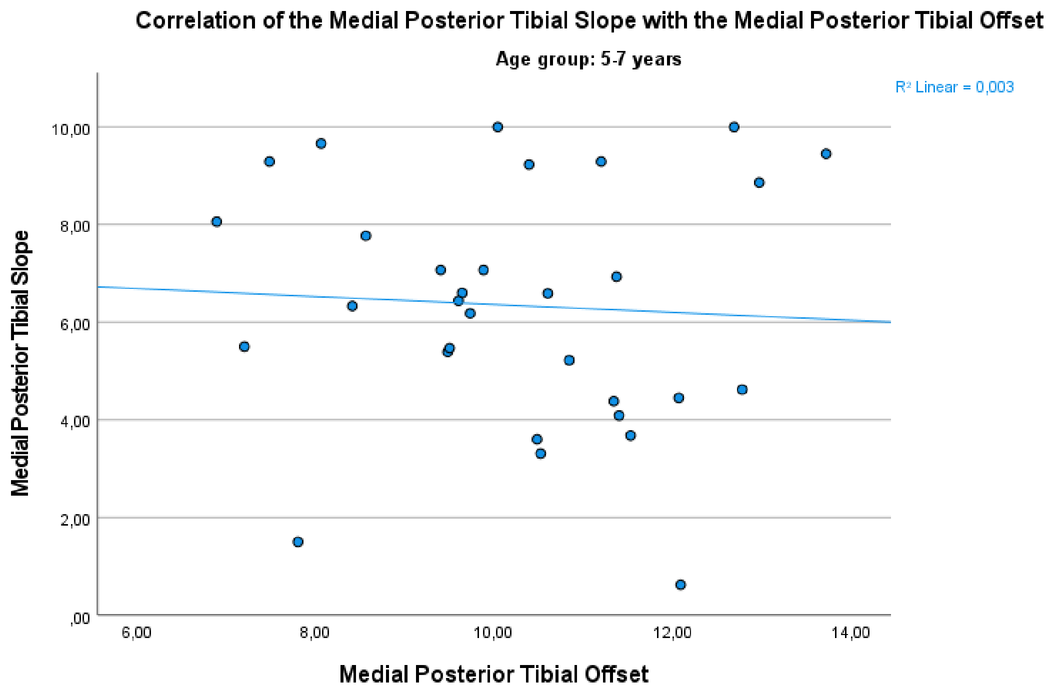

Figure 33- Correlation of the medial posterior tibial slope with the medial posterior tibial offset (age group 5-7 yrs)

2. Medial posterior tibial slope and medial posterior femoral offset

The medial posterior tibial slope displayed no correlation with the medial posterior femoral offset, with a Spearman coefficient of -0.125 and a p-value amounting to 0.503. The findings were not significant.

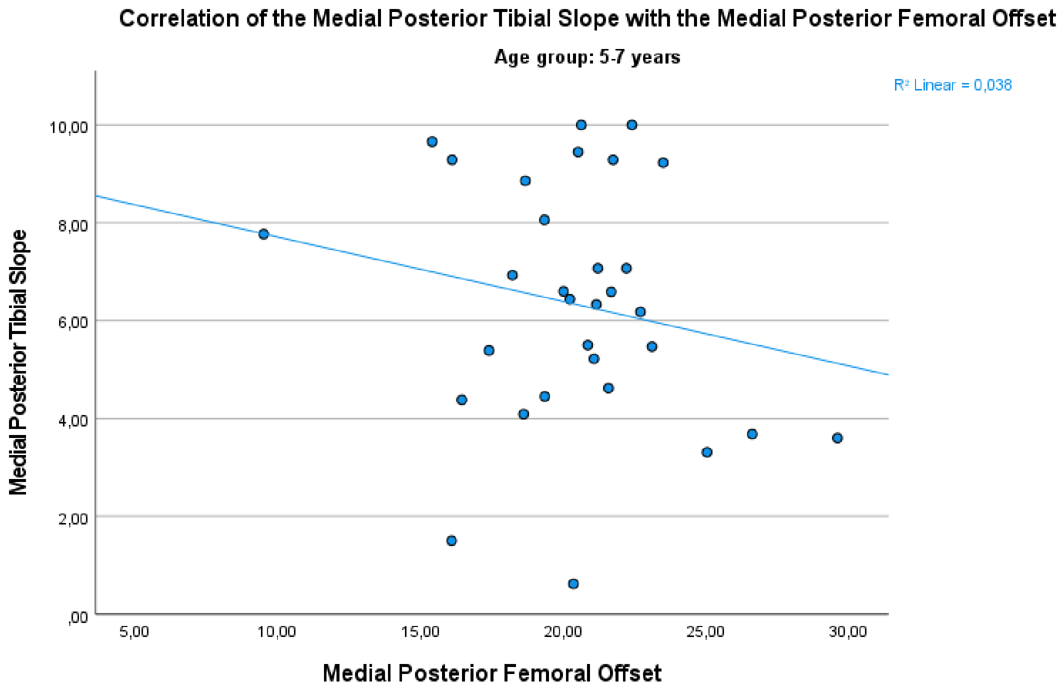

Figure 34- Correlation of the medial posterior tibial slope with the medial posterior femoral offset (age group 5-7 yrs)

3. Medial posterior tibial offset and medial posterior femoral offset

The medial posterior tibial offset in this age group correlated weakly with the medial posterior femoral offset, showing a Spearman coefficient of 0.206 and a p- value of 0.267. The correlation was not found to be significant.

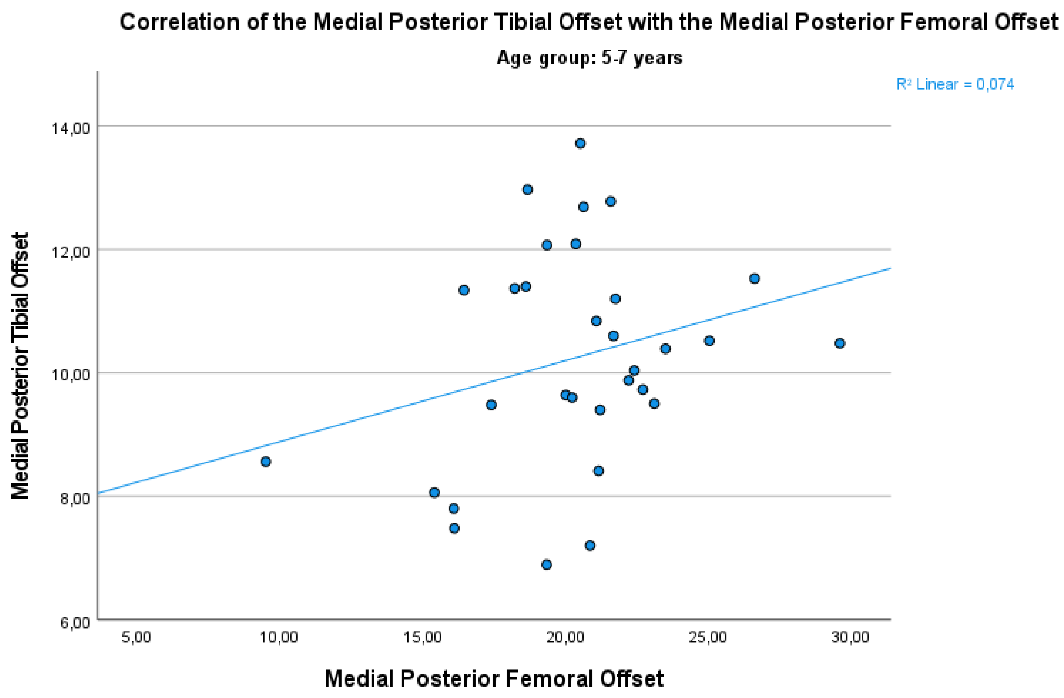

Figure 35- Correlation of the medial posterior tibial offset with the medial posterior femoral offset (age group 5-7 yrs)

4. Lateral posterior tibial slope and lateral posterior tibial offset

The lateral posterior tibial slope and the lateral posterior tibial offset did not correlate significantly with each other and showed a Spearman coefficient of -0.193 and a p-value of 0.299

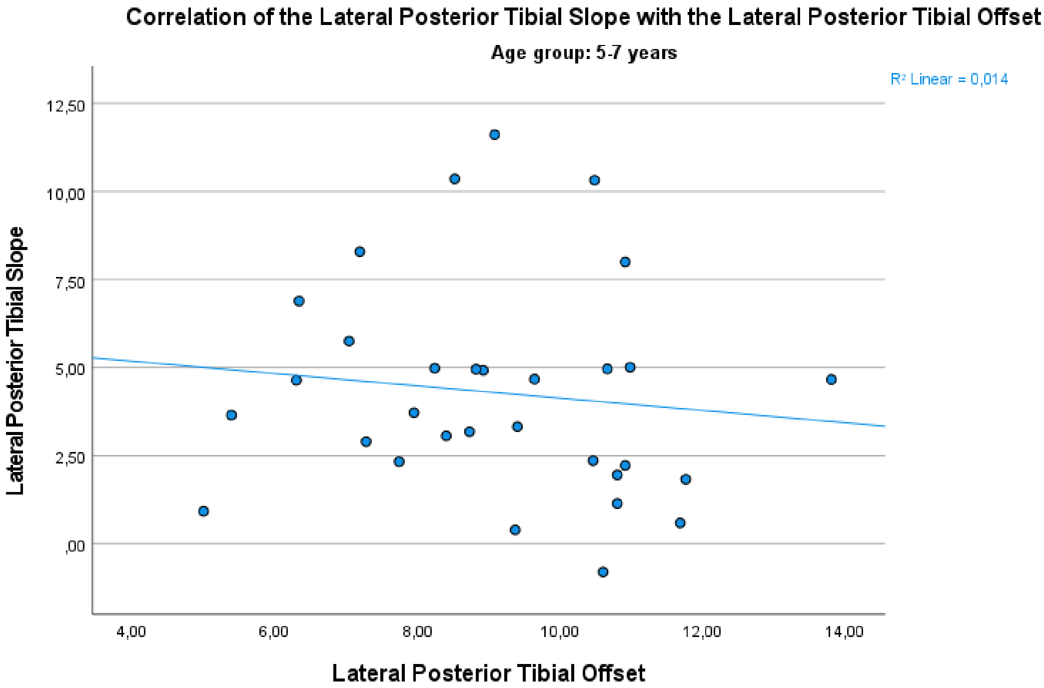

Figure 36- Correlation of the lateral posterior tibial slope with the lateral posterior tibial offset (age group 5-7 yrs)

5. Lateral posterior tibial slope and lateral posterior femoral offset

The lateral posterior tibial slope in this age group correlated weakly with the lateral posterior femoral offset with a Spearman rank coefficient amounting to -0.224 and a p-value of 0.226. The findings were not significant

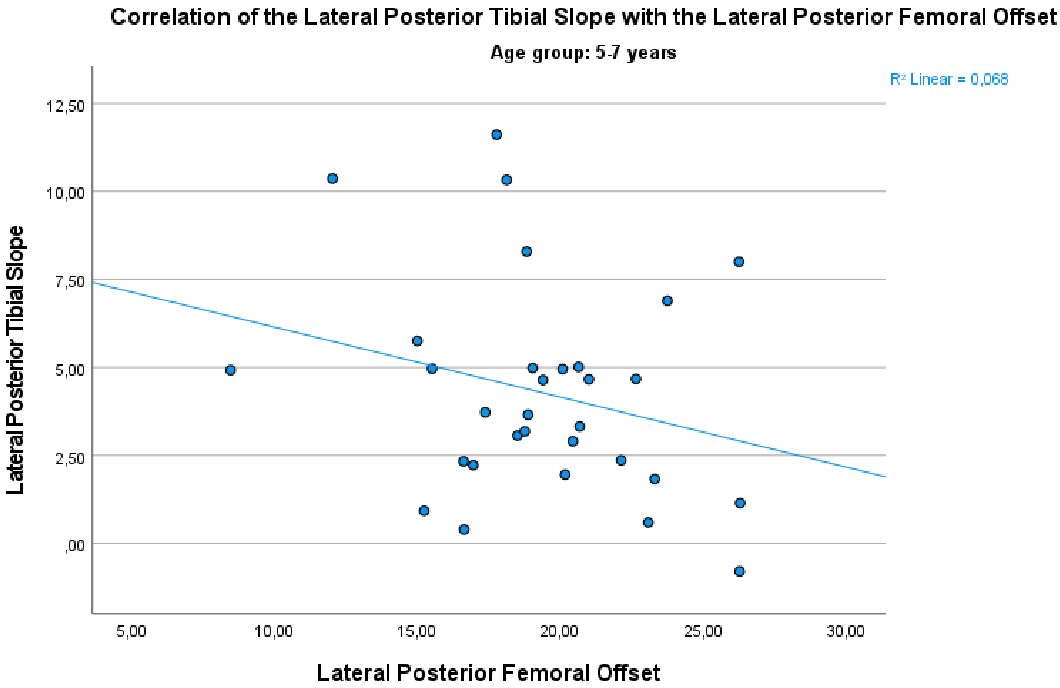

Figure 37- Correlation of the lateral posterior tibial slope with the lateral posterior femoral offset (age group 5-7 yrs)

6. Lateral posterior tibial offset and lateral posterior femoral offset

The lateral posterior slope displayed a significant correlation with the lateral posterior femoral offset with a Spearman coefficient of 0.439 and a p- value of 0.014.

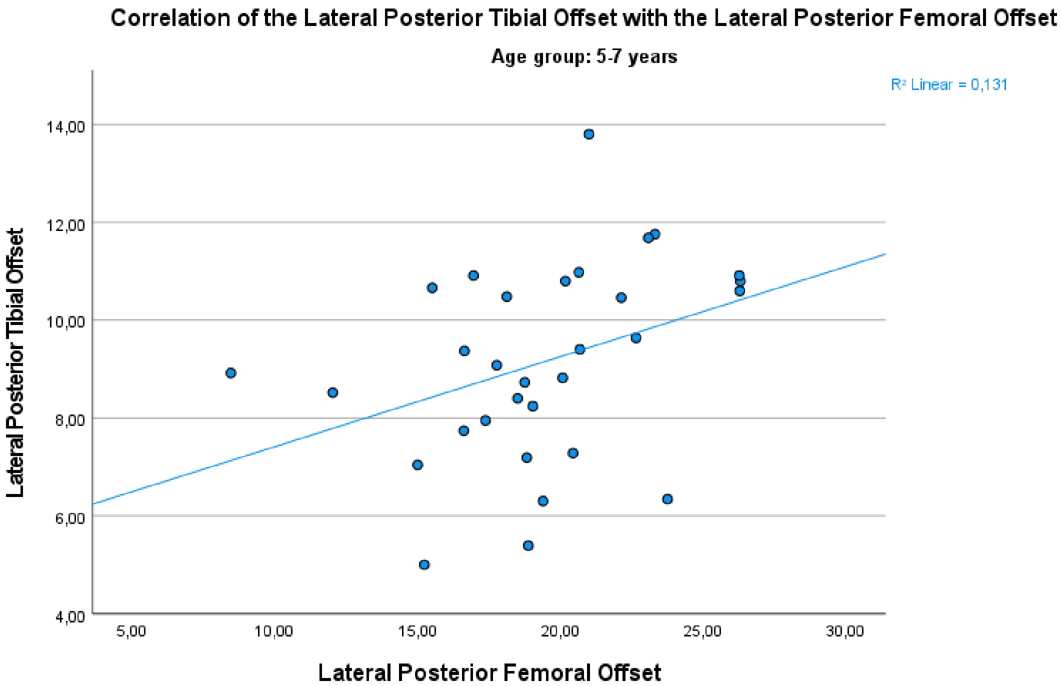

Figure 38- Correlation of the lateral posterior tibial offset with the lateral posterior femoral offset (age group 5-7 yrs)

7.2.4 Age 8 to 12 years

The Sample size in this group was 76

1. **Medial posterior tibial slope and medial posterior tibial offset**

The medial posterior tibial slope in the age group of 8-12 years displayed a significant positive correlation with the medial posterior tibial offset with a Spearman rank coefficient of 0.407 and a p-value of 0.000.

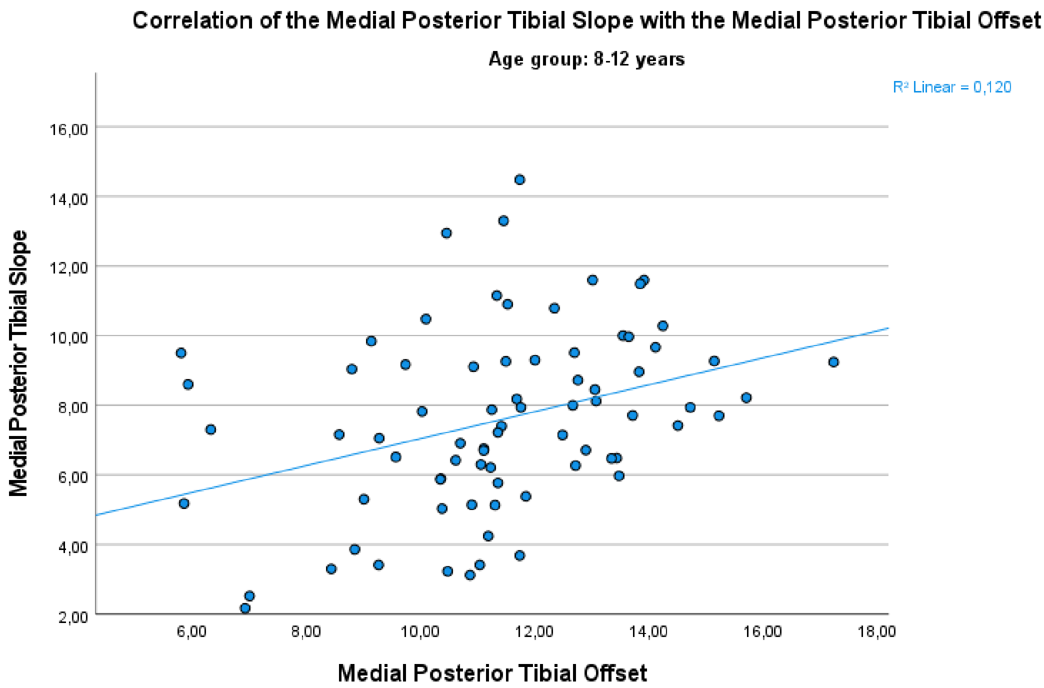

Figure 39- Correlation of the medial posterior tibial slope with the medial posterior tibial offset (age group 8-12 yrs)

2. **Medial posterior tibial slope and medial posterior femoral offset**

The medial posterior tibial slope displayed a weak correlation with the medial posterior femoral offset, with a Spearman coefficient of -0.078 and a p-value of 0.500. The findings were not significant.

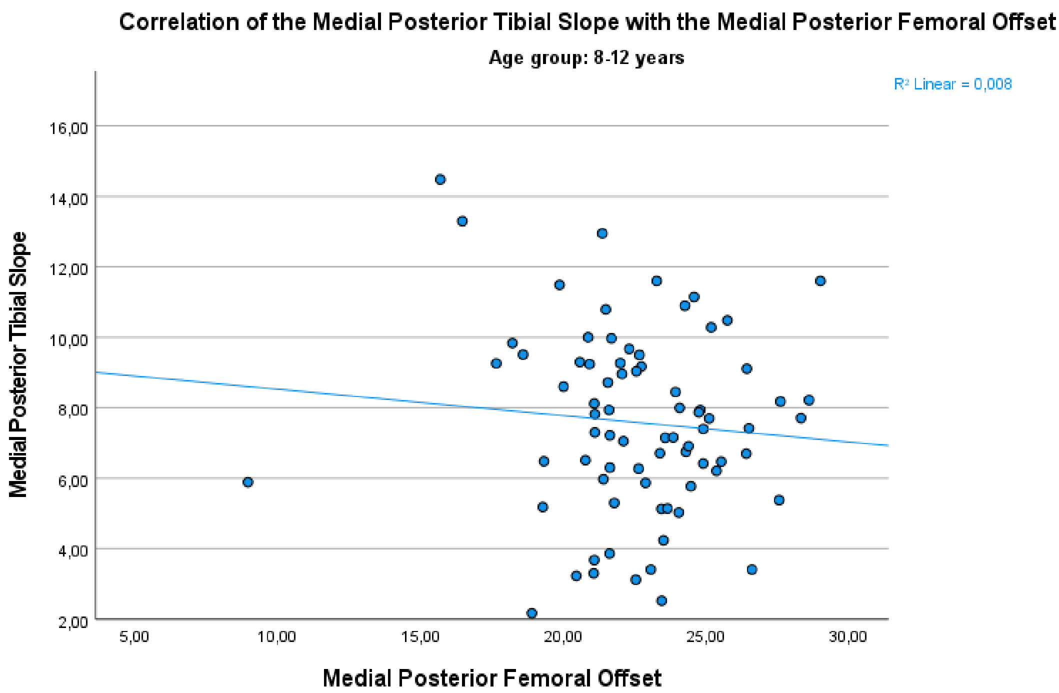

Figure 40- Correlation of the medial posterior tibial slope with the medial posterior femoral offset (age group 8-12 yrs)

3. Medial posterior tibial offset and medial posterior femoral offset

The medial posterior tibial offset in this age group correlated positively with the medial posterior femoral offset, showing a Spearman coefficient of 0.181 and a p- value of 0.118. The correlation was not found to be significant.

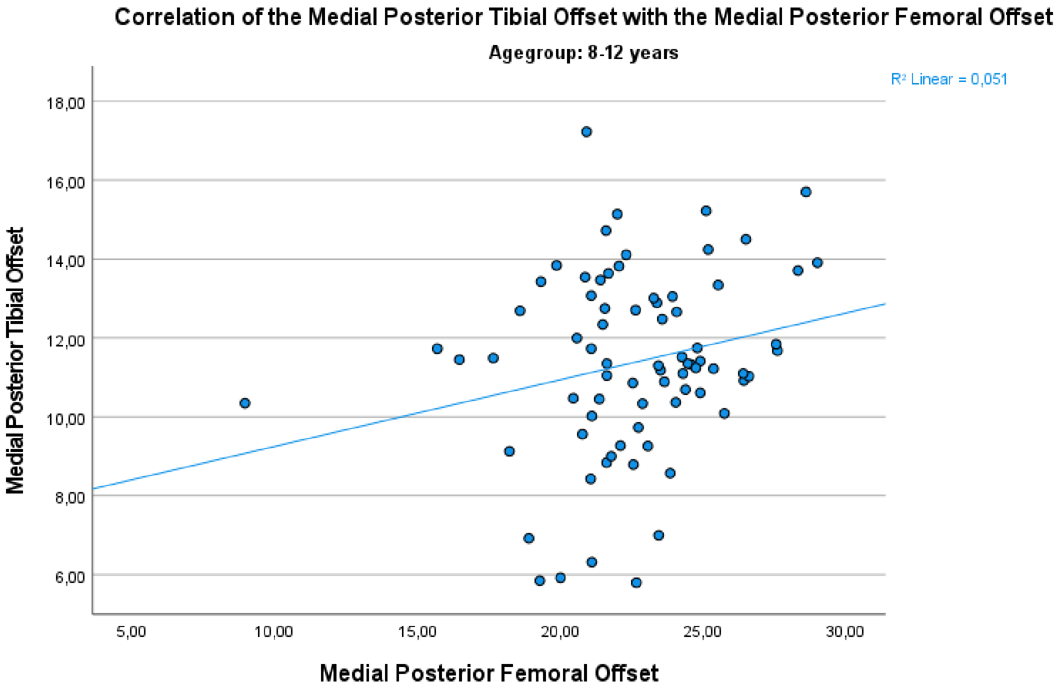

Figure 41- Correlation of the medial posterior tibial offset with the medial posterior femoral offset (age group 8-12 yrs)

4. Lateral posterior tibial slope and lateral posterior tibial offset

The lateral posterior tibial slope and the lateral posterior tibial offset correlated significantly with each other and showed a Spearman coefficient of 0.231 and a p-value of 0.044

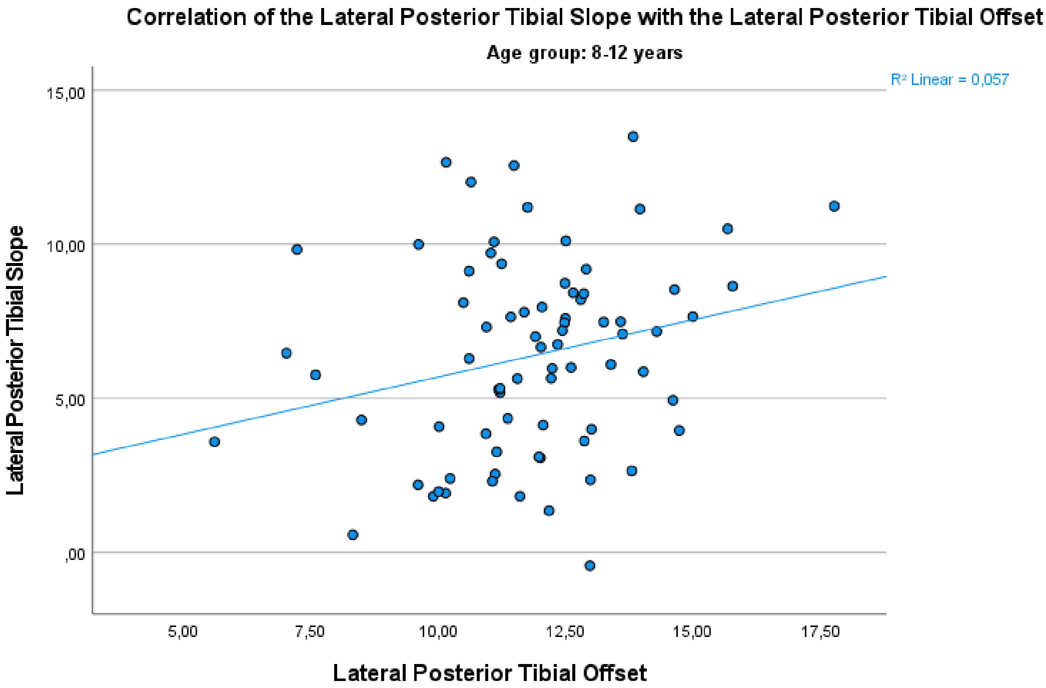

Figure 42- Correlation of the lateral posterior tibial slope with the lateral posterior tibial offset (age group 8-12 yrs)

5. Lateral posterior tibial slope and lateral posterior femoral offset

The lateral posterior tibial slope in this age group correlated weakly with the lateral posterior femoral offset with a Spearman rank coefficient amounting to 0.066 and a p-value of 0.570

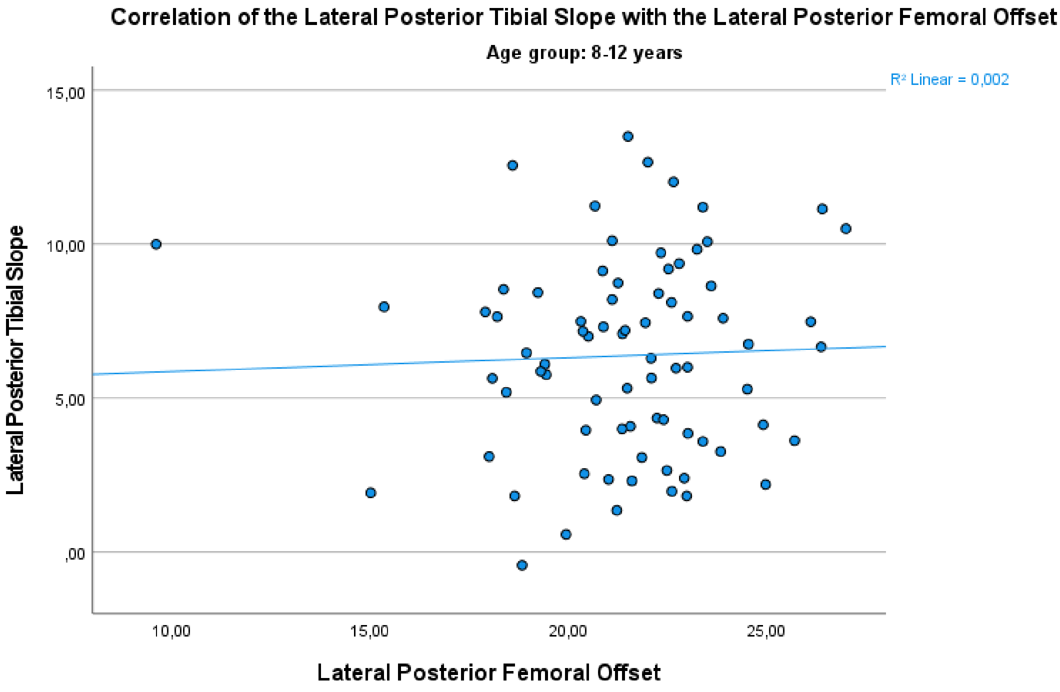

Figure 43- Correlation of the lateral posterior tibial slope with the lateral posterior femoral offset (age group 8-12 yrs)

6. Lateral posterior tibial offset and lateral posterior femoral offset

The lateral posterior slope displayed no correlation with the lateral posterior femoral offset with a Spearman coefficient of 0.027 and a p-value of 0.815.

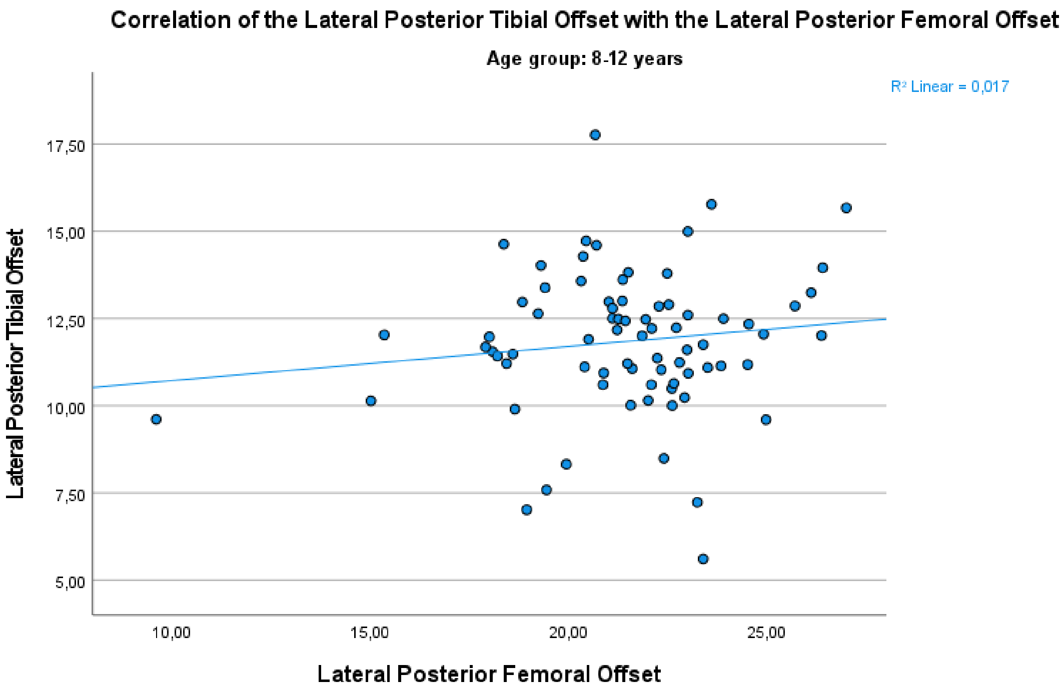

Figure 44- Correlation of the lateral posterior tibial offset with the lateral posterior femoral offset (age group 8-12 yrs)

7.2.5 Age group 13-18 years

The sample size of this group was 113

1. **Medial posterior tibial slope and medial posterior tibial offset**

The medial posterior tibial slope in this age group displayed an insignificant correlation with the medial posterior tibial offset with a Spearman rank coefficient of -0.009 and a p-value of 0.923.

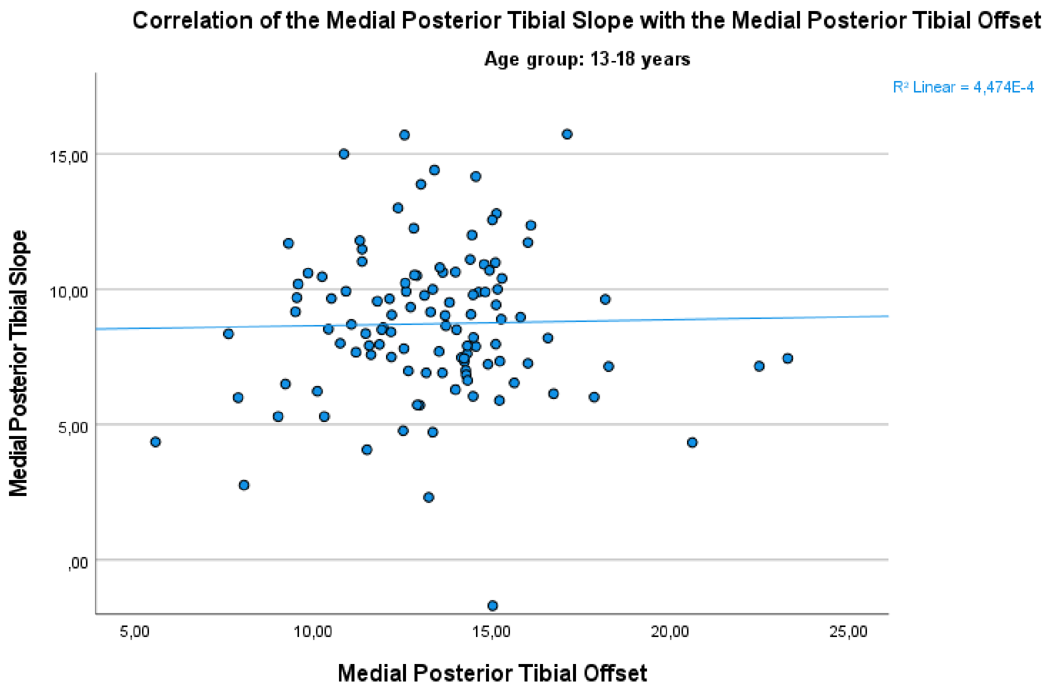

Figure 45- Correlation of the medial posterior tibial slope with the medial posterior tibial offset (age group 13-18 yrs)

2. **Medial posterior tibial slope and medial posterior femoral offset**

The medial posterior tibial slope displayed a weak correlation with the medial posterior femoral offset, with a Spearman coefficient of -0.184 and a p-value of 0.052. The findings were not significant.

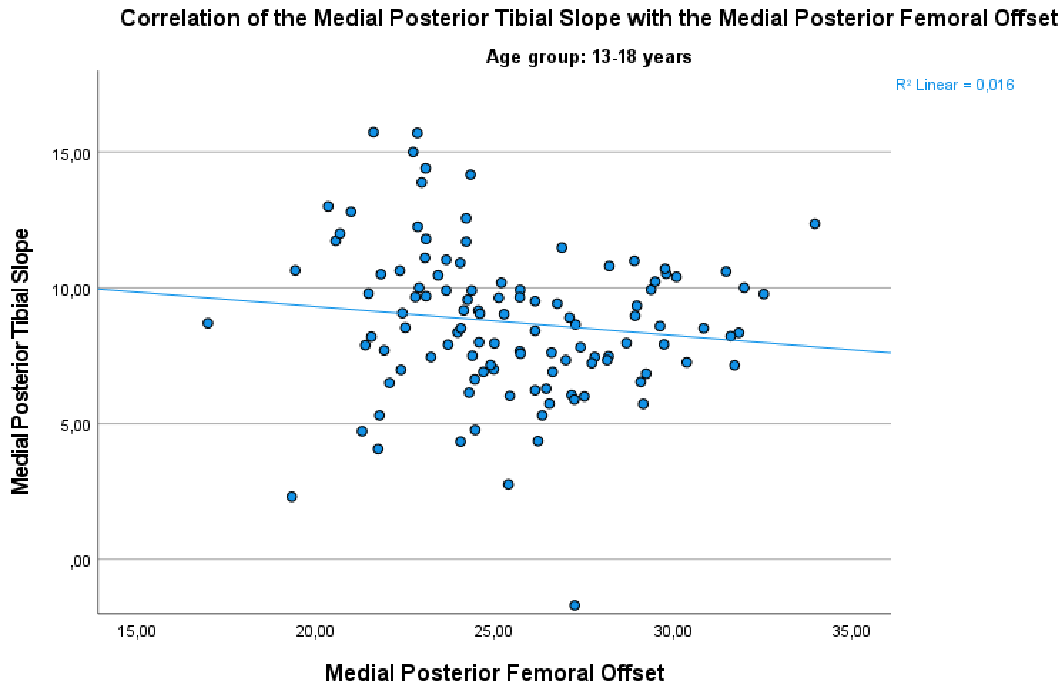

Figure 46- Correlation of the medial posterior tibial slope with the medial posterior femoral offset (age group 13-18 yrs)

3. Medial posterior tibial offset and medial posterior femoral offset

The medial posterior tibial offset in this age group correlated weakly with the medial posterior femoral offset, showing a Spearman coefficient of 0.121 and a p- value of 0.200. The correlation was not found to be significant.

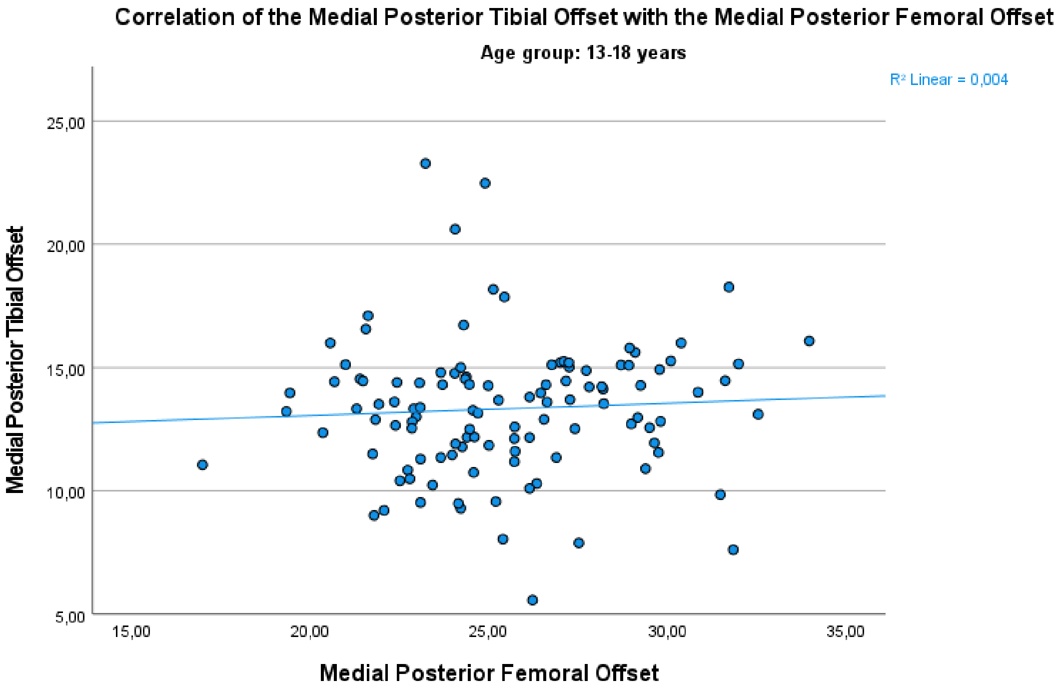

Figure 47- Correlation of the medial posterior tibial offset with the medial posterior femoral offset (age group 13-18 yrs)

4. Lateral posterior tibial slope and lateral posterior tibial offset

The lateral posterior tibial slope and the lateral posterior tibial offset did not correlate significantly with each other and showed a Spearman coefficient of 0.060 and a p-value of 0.526

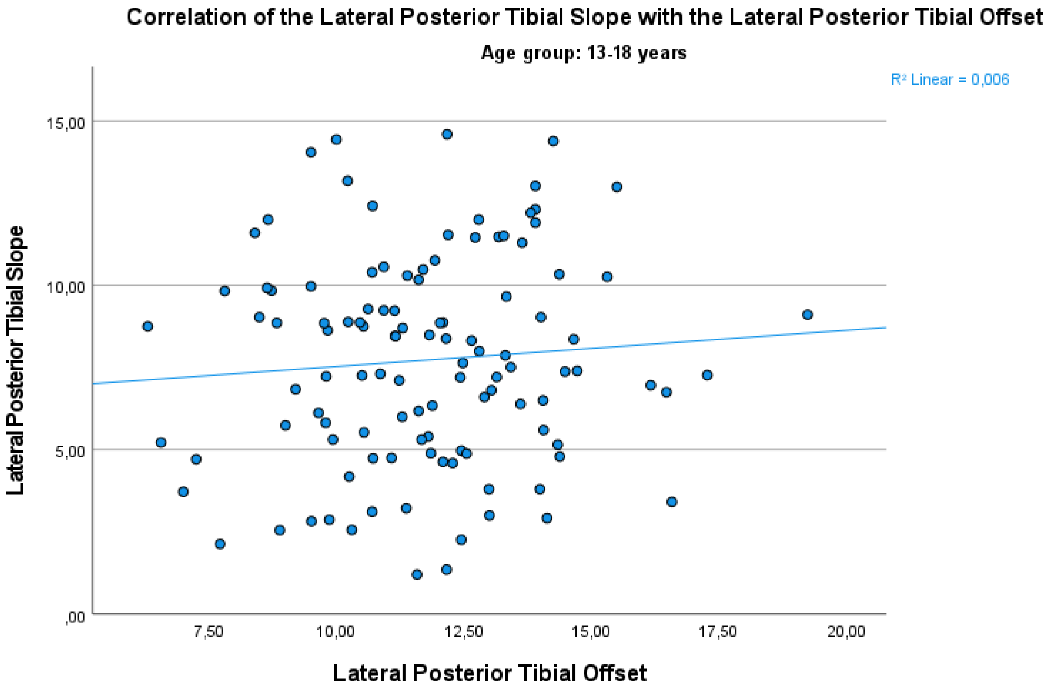

Figure 48- Correlation of the lateral posterior tibial slope with the lateral posterior tibial offset (age group 13-18 yrs)

5. Lateral posterior tibial slope and lateral posterior femoral offset

The lateral posterior tibial slope in this age group correlated negatively with the lateral posterior femoral offset with a Spearman rank coefficient amounting to 0.052 and a p-value of 0.585

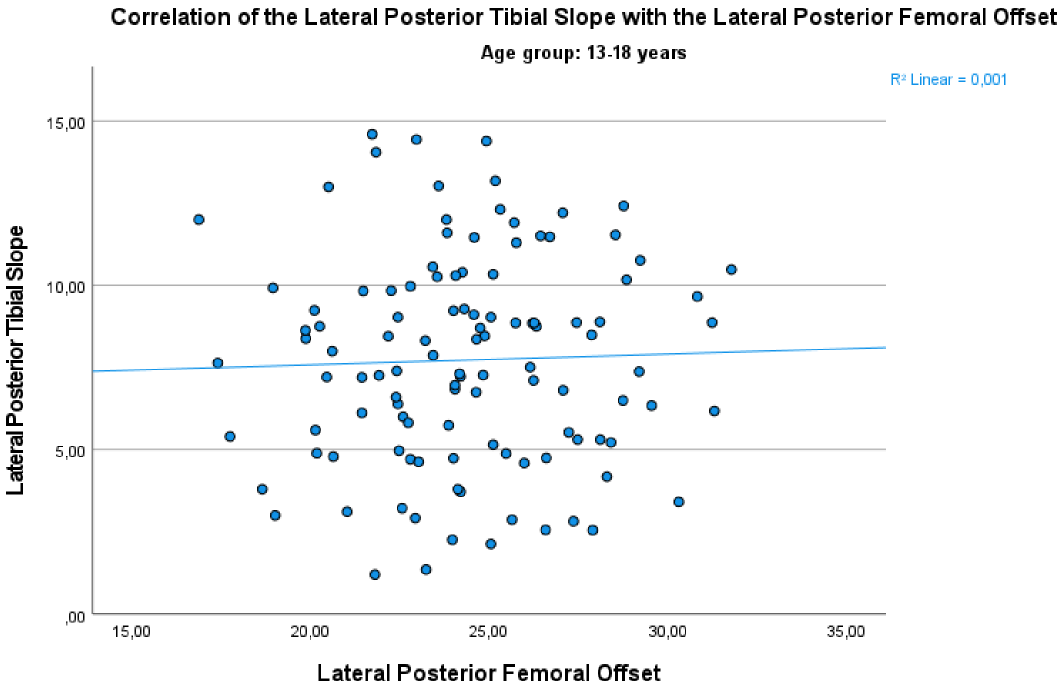

Figure 49- Correlation of the lateral posterior tibial slope with the lateral posterior femoral offset (age group 13-18 yrs)

6. Lateral posterior tibial offset and lateral posterior femoral offset

The lateral posterior slope displayed no correlation with the lateral posterior femoral offset with a Spearman coefficient of 0.039 and a p-value of 0.680.

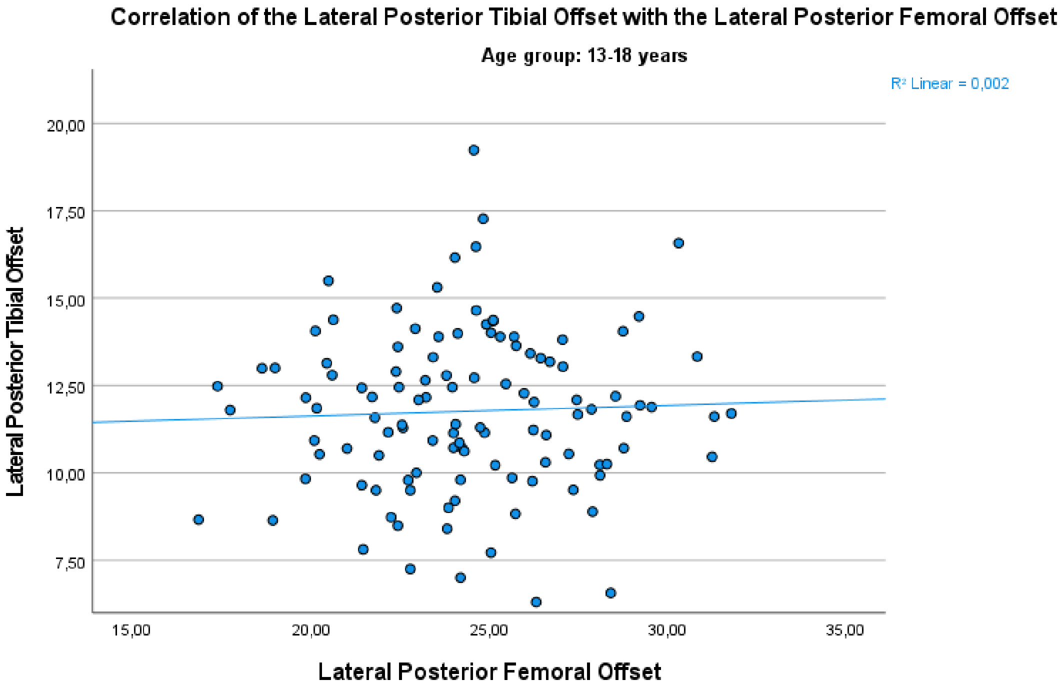

Figure 50- Correlation of the lateral posterior tibial offset with the lateral posterior femoral offset (age group 13-18 yrs)

8. Discussion

6.1 Discussion of the Materials and Methods

8.1.1 Research Question

8.1.1.1 Association of the Slope with Cruciate Ligament Injury

Over the past few years, the slope has shifted into the limelight as an important part of decision-making during revision cruciate ligament reconstruction. A perfectly performed ACL or PCL primary or revision reconstruction, even after addressing all soft tissue components of the instability, may result in graft failure due to the slope as one of the important negative prognostic factors. An increased posterior tibial slope leads to a continuous stretching of the ACL graft, which when combined with the repeated microtrauma with every step ultimately results in permanent elongation or failure of the ACL. Conversely, a decreased posterior tibial slope is a major cause of failure of PCL reconstruction. Conservative management of a chronic PCL insufficiency in a knee with a lateral tibial slope less than 6° has a drastically reduced prognosis(Gwinner et al., 2017).

Theoretically in such cases, a slope correcting osteotomy may be indicated, followed by the cruciate reconstruction. In the clinical setting, performing this two-staged surgical procedure for a primary cruciate insufficiency would increase peri-operative morbidity severely.

In the revision setting, however, the slope plays a significant role and the indication for an osteotomy for slope correction is much stronger, as the cruciate graft has already undergone failure.

In a computer model, Shelburne et al. had postulated increased anterior tibial translation (ATT) and increased stress ratios on the ACL with a concomitant increase in PTS(Shelburne et al., 2011). When simulating walking, standing, and during a knee bend, an almost direct proportionality of the PTS with the ATT was observed for all three movements when tensile forces of the lower extremity muscles were included. Analogous to the results of Dejour and Bonnin (Dejour & Bonnin, 1994), a 5° higher PTS meant a 2 mm increase in ATT. Finally, during walking, this resulted in a 26% increase in tensile stress on the ACL; during standing, these stress relationships were less pronounced. During knee flexion, the tensile stress shifted to the ACL as expected (Shelburne et al., 2011).

A recent experimental study by Wang et al. investigated the kinematic tibiofemoral behavior under compression in 13 human post-mortem knee joints, both before and after transection of the ACL(Wang et al., 2019). The special feature of this study was the differentiated consideration of the medial and lateral TS, as well as the expression of concavity in the medial tibial plateau. Measurements of ACL-intact knees demonstrated that for each degree of steeper TS, the increase in ATT was greater by a factor of 1.8 in the lateral compartment than in the medial. This decreased sensitivity to changes in TS can be explained by the concave indentation of the medial tibial plateau, which acts as a protective pit from translational motion. Indeed, a lower volume of the medial concavity was accompanied by an increased ATT of the medial compartment after transection of the ACL. Furthermore, due to ACL deficiency, a bilateral increase in ATT from -1.6 ± 3.1 mm to -0.7 ± 4.8 mm medially and from 3.4 ± 5.3 mm to 6.4 ± 8.9 mm laterally was observed at 15° of flexion, as well as an increase in tibial internal rotation from 3.9 ± 5.4° to 5.4 ± 8.5°(Wang et al., 2019). Despite the small number of knee joints studied and the limited transferability to everyday movements, similar trends can always be seen in the results of biomechanical studies(A. S. Bernhardson, Z. S. Aman, et al., 2019; McLean et al., 2011).

Based on the above theories and the results of biomechanical testing, several studies were carried out to test the association between the posterior tibial slope and the risk of ACL injury. In this regard, a systematic review including all studies performed till June 01, 2018, showed that 11 of 19 studies reported an association between medial posterior tibial slope and ACL injury. Here, the average medial PTS ranged from 3.1° to 12.9°, whereas values ranging from 1.7° to 10.9° were observed in ACL-intact groups. Similarly, 13 studies addressed the lateral PTS, of which 10 confirmed an association with ACL injury. Here, the mean lateral PTS ranged from 1.8° to 11.8° in the studies reporting a significant correlation and from -0.3° to 9.3° in the intact- ACL groups(Bayer et al., 2020). This valuable review article concluded, so did a meta-analysis by Wang et al, that both a steep lateral and medial PTS are associated with increased susceptibility to ACL injury, and this is independent of gender(Wang et al., 2017). This seems to be especially true for the lateral PTS. However, these studies did not take into account the differences in the slope using measurement methodology between various imaging modalities.

At this point, the meta-analysis performed by Wordeman et al. is worth mentioning, which included 14 studies(Wordeman et al., 2012). Five of the six studies that determined medial PTS on lateral radiographs showed a significant difference between the control group and the group with an ACL injury. In MRI based imaging studies, this was true in only one of seven. Lateral PTS could be separately measured only in the MRI studies and was significantly increased in patients with ACL injury in all studies. The mean lateral PTS was 9° ± 4° in the control group and 11.5° ± 3.5° in the ACL-injured patients. Wordeman et al. pointed out the inhomogeneity of the average values of the control groups in the individual studies. For example, the inter-rater difference in the measured values was sometimes greater than the difference between the healthy control group and the ACL-injured group(Wordeman et al., 2012).

Recently published studies continued to confirm the findings of the aforementioned meta-analysis to a certain extend. In a total of 92 knee joints with ACL injury, two independent radiologists with years of experience were able to measure a medial PTS (measured by the method of Dejour and Bonnin(Dejour & Bonnin, 1994) of 7.6° and 8.1°, respectively; the 101 knees in the comparison group had a statistically significantly lower PTS of 6.2° and 6.5°, respectively. No difference between gender was demonstrated(Kızılgöz et al., 2019). Although DePhillipo et al. could not confirm the hypothesis that the PTS differs in ACL-deficient athletes depending on the mechanism of injury (with or without external force), the lateral PTS was steeper than that of the ACL-healthy control group in patients regardless of injury genesis(A. S. Bernhardson, Z. S. Aman, et al., 2019). Giffin et al. equivalently demonstrated increased posterior tibial translation with increased traction forces on the PCL(Giffin et al., 2004). Clinically, Gwinner et al. observed increased postoperative instability years after PCL reconstruction in patients with an excessively flat PTS (Gwinner et al., 2017).

Messner et al published data about the slope in 51 pediatric patients who underwent surgical fixation of bony ACL avulsions and found the slope to be greater than 12°(Messner et al., 2023).

Green et al compared forty knees with Osgood- Schlatter disease with 32 knees in the control group and observed a steeper posterior tibial slope in the Osgood- Schlatter disease group. This interesting observation may explain the etiology of the Osgood- Schlatter disease being caused by excessive strain exerted on the Ligamentum patellae by the extensor apparatus due to the femur starting the extension process from a more posterior position(Green et al., 2020)

8.1.1.2 Association of the Posterior Tibial Slope with the Failed ACL Reconstruction

The increasing prevalence of the wealth of information regarding the slope naturally led to a clinically relevant discussion about its association with ACL graft failure and revision surgery. Although studies here are few and far apart due to low sample sizes, some authors list a PTS of greater than 12 as a relevant negative prognostic factor for long term results of ACL reconstruction (Salmon et al., 2018; Webb et al., 2013).

Webb et al. examined 181 patients in a prospective single-surgeon study with a 15-year follow-up after ACL reconstruction with a semitendinosus/ semitendinosus+ gracilis autograft. The mean PTS of patients who sustained a subsequent rupture of either the ACL graft or an ACL lesion of the contralateral knee (28%; n = 50) was 9.9°. Although the PTS in patients without further ACL injury was, at 8.5° not statistically significantly lower, a striking trend was observed: the incidence of an ACL graft rupture was 59% in patients with a PTS of ≥ 12° (13 of 22 patients). The 4 patients presenting with both ipsilateral ACL graft failure and contralateral ACL rupture had a PTS measuring 12.9°. A slightly negative Pearson's correlation of -0.3 also suggests that a steeper PTS is associated with earlier ACL graft failure. Patients with another ACL lesion were significantly younger at 23 ± 9 years than the ‘successful’ ACL reconstruction group at 27 ± 8 years(Webb et al., 2013).

Salmon et al reevaluated this association five years later in the same population. With a follow-up period of 20 years, they were able to demonstrate the influence of PTS and age at primary ACL reconstruction on the probability of revision. Patients who received the primary ACL reconstruction at an age below 18 years and had a PTS of more than 12° were 11 times more likely to have an ACL re-rupture and 7 times more likely to have a contralateral ACL rupture as compared to patients whose first ACL reconstruction was performed in adulthood and the PTS was less than 12°. Thus, only 22% of these young patients with a PTS greater than 12° had an intact, functioning ACL graft after 20 years, with more than half failing within the first 5 years. In comparison, 86% and 61% of all patients operated on for the first time in adulthood still had an intact ACL graft after 20 years(Salmon et al., 2018). In the same year, Lee et al. published that an average PTS of 13.2° was associated with ACL re-rupture in contrast to an average PTS of 10.9° in patients without a graft failure. The effect of confounding factors such as age, gender, or BMI (Body Mass Index) in the re-rupture group could not be statistically confirmed(Lee et al., 2018). A medial PTS >5.6° or a lateral PTS >3.8° resulted in significantly higher failure after ACL reconstruction, according to Yoon et al in a study of 232 patients followed for at least 10 years. Their method of slope measurement is unclear(Yoon et al., 2020).

Similarly, studies have also emerged confirming a positive correlation between a decreased PTS and the risk of PCL rupture or rerupture. Bernhardson et al. observed in a cadaveric study that a flat PTS increases the strain forces on the PCL under axial loading (A. S. Bernhardson, Z. S. Aman, et al., 2019). They later also concluded in a case control study including 208 matched patients that a decreased PTS increases the risk of PCL injury (A. S. Bernhardson, N. N. DePhillipo, et al., 2019)

Although PCL injuries are uncommon in skeletally immature patients, studying the PTS in adolescents in relation to PCL function may help clinicians more accurately diagnose PCL injuries and deficiencies in young patients.

A negative influence of an increased PTS after an already performed ACL revision has also been reported. Napier et al reported an increased lateral PTS in patients suffering an ACL re-rupture. Due to the methodological use of lateral radiographs here and corresponding questionable differentiation between the two tibial plateaus, the validity of this conclusion must be critically reconsidered(Napier et al., 2019).

All the above-mentioned studies have in common the measurement method on lateral radiographs according to Dejour and Bonnin(Dejour & Bonnin, 1994) or similar and show a clearly conclusive trend. However, studies from primary ACL ruptures have already shown us that MRI results are more inhomogeneous with respect to medial PTS (which is usually measured on lateral radiographs)(Wordeman et al., 2012). Whether this is also true in patients with graft failure after ACL reconstruction has been questioned by several MRI-based papers(Christensen et al., 2015; Cooper et al., 2019; Grassi et al., 2019; Jaecker et al., 2018; Li et al., 2014; Qi et al., 2018; Sauer & Clatworthy, 2018; Zeng et al., 2016).

Both Li et al. and Jaecker et al. reported a significantly steeper PTS in patients with failed ACL reconstruction(Jaecker et al., 2018; Li et al., 2014). In the former study, measured with the method proposed by Hudek et. al (Hudek et al., 2009), the medial TS was significantly elevated at 6.1 ± 2.1° compared to the control group at 3.5 ± 2.5°, as was the lateral PTS at 5.5° ± 3.0° vs. 2.9° ± 2.1°. In the latter study, the measurement method described by Hashemi et al. was employed with equally significantly steeper values in patients with failed ACL reconstruction(Hashemi et al., 2008). The medial PTS here was 6.7° vs. 4.1°, and the lateral PTS was 7.3° vs. 4.6°. The risk of ACL graft failure was observed mainly in patients with a lateral PTS of more than 10°(Jaecker et al., 2018). However, limiting factors in both studies were the small case numbers of 20 and 57 patients, respectively. Grassi et al. were able to include in their study patients who received a primary ACL reconstruction (control group; n = 40), ACL revision reconstruction (n = 25), and patients with failed revision reconstructions (n = 26)(Grassi et al., 2019). Despite the short follow-up period of 24 months without further ACL rupture in the control group, both the medial and lateral PTS differed significantly from each other in all three groups, namely ascending with the number of ACL surgeries.

In contrast to these publications with low case numbers, in addition to the work of Sauer et al, in which no association of lateral PTS with the risk of ACL graft failure was found, a recently published case-control study by Cooper et al. can be considered highly informative with 317 under 21-year-old matched pairs(Cooper et al., 2019; Sauer & Clatworthy, 2018). To exclude possible confounding factors such as age, BMI, gender, ethnicity, femoral fixation method used, or graft origin were included in the pairing between the ACL revision group and a control group without graft failure. Using the Hashemi et al. method of measurement, the median lateral PTS was found to be identical at 6° in both groups, and the medial PTS was similarly not statistically different at 4° vs. 5°. Also, the biomechanically logical concept that a major difference between the lateral and medial PTS may make the ACL more susceptible to re-rupture due to increased rotational forces was not confirmed in this clinical study. The only observation consistent with the other studies was that there were twice as many revision cases associated with a lateral PTS of more than 12° than in the control group. However, this was not statistically significant. Whether the PTS has an impact on the duration to graft failure could not be elicited because of the study design. Similarly, no patients with multiple failed revision reconstructions were included.

An age-wise study of the slope in the pediatric population has only been performed once before and in a relatively small population.

As a secondary objective, we tested the relationship of the posterior tibial slope with other variables in the knee such as the posterior tibial and femoral offsets to test their correlation during the developmental stages.

8.1.2 Sample Size

Measurement of the slope in the pediatric population is an arduous task due to markedly insufficient radiological material available for research. In our center, we collected normal knee MRI series spanning 10 years between the ages of 0 to 18 years. These amounted to 249 MRI series.

Although we were able to harvest a respectable number of pediatric MRI series, the number of MRI series in the toddler age group is nevertheless limited.

Further studies are definitely required in this age group to better define the biomechanical development of the knee.

8.1.3 Methods of Slope Measurement

Several methods have been proposed for the accurate, convenient, and reproducible measurement of the posterior tibial slope on lateral radiographs and MRI images of the knee. We used the method first described by Brazier et al(Brazier et al., 1996), which consists of measuring the angle between the tangent to the tibial plateau and the tibial proximal anatomical axis. In addition, we concluded through a separate validation study on true lateral radiographs of the lower leg that this method is accurate, reliable, easy to use and reproducible. For the purpose of thesis, a single observer study was performed. This can naturally present a limitation

8.1.3.1 Preconfiguration of the Tibial Axis

It is imperative to set the axis in all three planes to exclude any errors due to the tibial sections being oblique. The common source of error, where the tibia is internally rotated with respect to the femur when the axis is set to the femur is thus avoided.

8.1.3.2 Measurement of the Tibial Slope

Owing to the complex three-dimensional anatomy of the tibial plateau, the exact determination of the PTS, especially differentiated into medial and lateral is complicated. Methods using computed tomography (CT), magnetic resonance imaging (MRI) or lateral radiographs of the knee joint are described in the literature. This is further confounded by the absence of the distal section of the tibia on usual imaging methods (Faschingbauer et al., 2014). The axis of the tibia is defined in the sagittal plane as the junction of the center of the tibiotalar joint with the center of the tibial plateau (Han et al., 2008). Since imaging extending to the upper ankle joint is rarely available in clinical practice, several ways have been explored in the respective imaging modalities to estimate the true mechanical tibial axis. In a recent study, these methods were compared. Measurements were taken by two investigators on 20 patients undergoing ACL revision reconstruction. Imaging material of imperfect and inhomogeneous quality was deliberately used to simulate reproducibility in everyday clinical practice.

The differences in the mean value between the methods of up to 5° are clearly recognizable. Therefore, when including the PTS in clinical decisions and discussions, the measurement method used should always be mentioned, since the average values of the individual methods vary, and transferability is limited. Of further interest is the comparability of measurements between several investigators. Naendrup et al observed that all methods have relatively good reliability(Naendrup et al., 2020).

8.1.3.2.1 Measurement of the Slope on Lateral Radiographs

A frequently used and reproducible method of measuring the PTS was described by Dejour and Bonnin in 1994. To measure the PTS on lateral radiographs of the knee joint which exclude the ankle joint, two straight lines were first drawn from the anterior to the posterior cortex, the first just below the tibial tuberosity, the second 10 cm distal to the first one. A line passing through the midpoints of both these lines was considered the proximal tibial axis. Inclination was indicated by another straight line with endpoints at the anterior and posterior edges of the concave medial plateau. The angle subtended by these two lines was defined as the PTS(Dejour & Bonnin, 1994).

Utzschneider et al defined an anterior and posterior tibial axis by marking points for these two straight lines at distances of 5 cm and 15 cm distal to the tibial plateau in the course of the cortex. Their subsequent diaphyseal axis was the bisector of the angle subtended by the two cortical straight lines. Using this method, they arrived at values of 9.4 ± 2.3° for the medial PTS and 10 ± 2.9° for the lateral PTS in 14 measured tibiae. This method applied to MRI and CT images of the same tibiae was reported to have deviations of only 0.1°(Utzschneider et al., 2011).

Faschingbauer et al. tested the results of measurements obtained using the above diaphyseal axes for their deviation from the true PTS. In 100 strictly lateral tibiae with imaging to the tibiotalar joint, values of 6.9 ± 3.3° were obtained using the mechanical tibial axis. Following the method of Dejour and Bonnin, a diaphyseal axis was created using two straight lines located 6 cm and 10 cm from the tibial plateau. The measured values were 9.8 ± 3.3°. When the diaphyseal axis was determined using straight lines 6 cm and 16 cm from the tibial plateau, the PTS was 8.5 ± 3.2°. Although these measurement results differed from each other, there was always the same tendency to overestimate the "true" PTS by no more than 3°. The longer the proximal tibia was imaged on the lateral radiograph, the smaller the deviation was(Faschingbauer et al., 2014). Nonetheless, highly unreliable differentiation between the medial and lateral tibial plateau and failure to consistently obtain a true lateral radiograph remain relevant limitations to accurate measurement of the slope on plain radiographs(Weinberg et al., 2017). Thus, there was an increasing tendency to employ tomographic images to measure the slope more accurately.

8.1.3.2.2 Measurement of the Slope using Tomography

For the measurement method using tomographic imaging methods, the works of Brazier et al, Hudek et al and Hashemi et al are predominantly cited(Brazier et al., 1996; Hashemi et al., 2010; Hudek et al., 2009).

Brazier et al measured the angle between the tangent to the tibial plateau and the tibial proximal anatomical axis. The reference axis used with this method was the tibial proximal anatomical axis (TPAA), which is the bisector of the angle between the anterior tibial cortex and the posterior tibial cortex(Brazier et al., 1996).

Hudek et al. first selected a central section in the sagittal plane showing the eminentia intercondylaris, the tibial attachment of the BUA, and the anterior and posterior tibial cortices in a concave shape. Two circles have been drawn here. A proximal one tangent to the anterior, posterior as well as cranial cortex (at the eminentia intercondylaris) of the tibia and a distal, smaller circle in the tibial shaft that only touched the anterior and posterior cortex. They referred to the straight line drawn through the centers of these circles as the longitudinal axis; an approximation of the true mechanical axis. In the next step, they searched for the two central sectional views of the medial and lateral tibial plateau in the sagittal plane, where equivalent to the method of Dejour and Bonnin, they each set a tangent line with points of contact at the superior anterior and posterior borders of the tibial plateau. The respective included angle of this tangent with the orthogonal of the longitudinal axis was the medial and lateral PTS. Applied to 100 knee joints, the medial PTS was 4.8°, on average 3.4° shallower than the same measurements performed by the method of Dejour and Bonnin. In addition, they were able to show that the lateral PTS was on average only 0.43 ± 3.7° steeper than the medial PTS, but in 21 of 100 patients the difference between the two plateaus was greater than 5°(Hudek et al., 2009).

Hashemi et al. drew two straight lines from the anterior to the posterior cortex at a distance of 4 to 5 cm from each other as caudally as possible in imaging. The longitudinal axis passed through the midpoints of these straight lines. Their 40 measured tibiae yielded an average medial PTS of 5.9° in females and 3.7° in males. The lateral PTS was also steeper in females at 7.0° compared to males at 5.4°(Hashemi et al., 2010).

The same techniques may also be performed using CT imaging. The unacceptable radiation dose for a routine CT scan, especially in children, is the limiting factor for the use of this modality.

The plotting of the tangent to the lateral tibial plateau is far more complex than the concave medial tibial plateau. This is due to the fact that the lateral tibial plateau is variable in shape, ranging from flat to dome shaped and the lateral meniscus is far more mobile than the medial meniscus. The lateral meniscus in a non-weightbearing image (e.g., an MRI scan) often ‘rides high and posterior’ on the lateral tibial plateau as it serves its function as a ‘gasket’ to the lateral femoral condyle. The line joining the anterior and posterior horns of the lateral meniscus is thus an unreliable tangent to the bony lateral tibial plateau. Some authors describe the slope using the meniscal landmarks(Freitas et al., 2021). We consider this ‘meniscal slope’ as unreliable in the biomechanical point of view as the lateral meniscus is a mobile and compressible structure, which undergoes displacement and deformation on weight bearing and its ‘resting’ position is not biomechanically relevant. Further necessitating an accurate measurement is the fact that the lateral tibial plateau plays a more key role in the biomechanics of the knee than the medial tibial plateau(Feucht et al., 2013; Gwinner et al., 2021; Hashemi et al., 2010; Stijak et al., 2008).

8.1.3.3 The Posterior Tibial Offset

We defined the posterior extension of the tibial head beyond the posterior cortical line as the 'posterior tibial offset.'

We observed in multiple adult and pediatric MRI series, that the length of this posterior tibial 'ledge' is highly variable.

We found no relevant literature pertaining to this feature.

We propose that the posterior tibial offset is relevant in the biomechanics of the knee during deep flexion.

We also plan to further study this feature in the adult population.

8.2 Discussion of the Results

8.2.1 Quantitative Data

Since we were able to obtain an age-wise distribution of the PTS, it seems logical to present these data in the context of the developmental milestones for gross motor skills. We used the works of Dosman et al, who published the milestones of child development based on gathered evidence as a reference to present this data(Dosman et al., 2012) and of Leversen et al., who closely observed the gross motor skills development from the age of 6 years to 18 years(Leversen et al., 2012).

For comparison of the slope values, we have considered the study published by Anchustegui et al in 2022. This study examined 39 cadaveric pediatric CT scans between the ages of 2 to 12 years. It is important to note that the axis used was a line parallel to the posterior diaphysis. There is also no mention of a rotational and axial preconfiguration, which we consider extremely important for the accurate measurement of the slope(Anchustegui et al., 2022).

Age 1 year:

Over the majority of the first year of life, the child rarely exerts axial compressive forces on the knee. It first loses its primitive reflexes and sits up on pulling up at the age of six months(Piper & Darrah, 1994). It then first begins to sit without support at the age of nine months, after which it begins to crawl. At the age of one year, the child begins to pull up to stand and even walk with support(Folio, 1983). At this stage of development, the knee first undergoes axial compression. Therefore, it can be considered as a 'baseline' age for the studies on slope development.

Our observations reveal that the medial PTS at one year lies at a median of 3.36 +/- 1.99°, whereas the lateral PTS showed a median of 1.06° +/- 2.5°. In the 8 male knees, the median medial PTS was observed to be 3.71°+/- 1.72°, while in the 3 female knees it was 3.29+/- 3°. For the lateral side, these values were 1.14+/- 0.6° and 1.06°+/- 5° respectively.

To our knowledge, there is no reported data for the PTS at 1 year of age.

Age 2 years:

At the age of 18 months, the child now gets to standing and walks independently. The gait at this stage is described as a 'narrow-based, heel-toe' gait. The child also begins to walk up- and downstairs with support(Folio, 1983). At the age of 2 years, the child starts running, jumping, and walking up the stairs without support. This is the stage where the knee starts experiencing axial impact forces.

In our study, with a sample size of 7 at this age, the median medial PTS at the age of 2 years was 4.56° +/- 1.9° and the median lateral PTS was observed to be 1.85+/- 4.3°. Anchustegui et al reported in their cadaveric CT study a medial slope of 7.56+/- 6.56° and a lateral slope of 12.15°+/- 2.23° (Anchustegui et al., 2022). Their sample size at 2 years is 3.

The 3 male knees in our study at 2 years showed a median PTS of 4.26° +/- 2.5° and a lateral PTS of 1.85° +/- 5.5°, while the 4 females showed the values of 5°+/- 0.6° and 1.6° +/- 3.6° respectively

Age 3 years:

At the age of 3 years, the child now begins pedaling on a tricycle, walking unsupported downstairs and walking upstairs with alternating feet. At this stage, the Quadriceps and other muscles around the knee joint are stimulated and get developed. The knee continues to be under compressive stresses, with additional low-impact stresses due to pedaling.

The 5 knees in our study population displayed a medial PTS of 3°+/- 2.5° and a lateral PTS of 2° +/- 1.8°. Our whole sample group at 3 years was female.

Age 4 years

At 4 years of age, the child begins to hop, walk downstairs with alternating feet and walks backwards in a line. As the balance of the core improves, the load distribution between both knees also becomes more equal.

Our observations in 6 knees of this age showed a medial PTS of 4.8° +/- 2.1° and a lateral PTS of 4.6° +/- 3.1°. The study by Anchustegui et al observed in 5 knees, a medial PTS of 8.34°+/- 3.13° and a lateral PTS of 4.96°+/-2°.

The only male at this age group in our study showed a medial PTS of 5.91° and a lateral PTS of 5.7°. The 5 female knees showed a medial PTS of 4.25° +/- 2.3° and a lateral PTS of 4.42°+/- 3.25°.

Age 5 years

At the age of 5 years, the child begins balancing on one foot for 10 seconds and starts skipping. This shows a maturation of lateralized musculature to maintain balance. The knee begins maturing in response to the axial and rotatory forces.

The 9 knees in our study at this age showed a medial PTS 6.23° +/- 3.3° and a lateral PTS of 3.65°+/- 2.75°. The 5 knees in the study by Anchustegui et al. displayed a medial PTS of 4°+/- 3° and a lateral PTS of 3.08°+/- 2.1°.

5 male knees in our study group showed a medial PTS of 8° +/- 4.3° and a lateral PTS of 3.06° +/- 1.57° and the 4 female knees showed a medial PTS of 7.31°+/- 4.6° and a lateral PTS of 4.8+/- 3.4°.

Age 6 years

At the age of 6 years, the child starts running smoothly with arms opposing legs and a narrow base of support with feet not too far apart, slalom running around obstacles and hopping on one foot.

11 knees were included in this age group in our study. They showed a medial PTS of 6.44°+/- 1.95° and a lateral PTS of 3.72°+/- 3.27°. The 8 male knees showed a medial PTS of 6.52°+/-

1.92° and a lateral PTS of 4.32°+/- 3.42°, while the 3 female knees showed 4.09+/- 1.98° and 2.9°+/-3.2° respectively.

Age 7 years

At 7 years the child continues its development with respect to muscle development and balance due to sporting activities.

We included 11 knees in this age group, which showed a medial PTS of 6.33°+/-2.11° and a lateral PTS of 4.64°+/- 3.24°. Anchustegui et al showed in the 7 knees included in this age group a medial PTS of 4.80°+/- 5.32° and a lateral PTS of 3.87°+/- 3.15°.

The 7 male knees showed a medial PTS of 6.18°+/-2.52° and a lateral PTS of 4.66°+/-3.86°, while the 4 females showed the values as 6.46°+/-1.14° and 2.84°+/- 1.33° respectively.

Age 8-12 years

The gross motor skills between these ages develop at a rather stable rate, depending on the sporting activities undertaken by the child. At the age of 8 years, the 11 knees included in our study showed a medial PTS of 6.71°+/-2.64° and a lateral PTS of 5.19° +/- 2.5°. The sex distribution of the medial and lateral slope at 8 years was 4.89°+/-2.99° and 5.42 +/- 0.82° and 7.05°+/- 2.54° and 4.08°+/- 3.14° in 4 males and 7 females respectively

At 9 years, our 16 knees showed a medial slope of 6.95°+/- 2.48° and a lateral slope of 4.65+/-4°. The 7 male knees displayed a medial PTS of 6.75°+/-2.06° and a lateral PTS of 4.35°+/- 4.77°, while the 9 females showed the values as 6.81°+/-2.96° and 4.56+/- 3.9° respectively. The 10 knees included in the Anchustegui study at 9 years showed a medial PTS of 6.78°+/- 5.28° and a lateral PTS of 6.73°+/-4.63°

The 20 knees included in our study at 10 years displayed a medial and lateral PTS of 7.56°+/- 2.65° and 7.56°+/- 2.8°. The 9 males showed a medial and lateral slope of 7.71°+/-2.38° and 7.48°+/-2.4° respectively. The 11 female knees displayed 8.36°+/- 2.7° and 7.56°+/- 3.10° respectively.

Anchustegui et al. included 2 knees in this age group, which showed a medial and lateral PTS of 3.85°+/-0.72° and 6.17°+/-1.64°.

At 11 years of age, we included 15 knees which showed a medial and lateral slope of 8.18°+/-2.61° and 7.31°+/-2.80° respectively. In the Anchustegui study, this value was observed to be 4.07°+/-1.99° and 5.10°+/-2.94° respectively in 6 knees.

We observed the following values of the medial and lateral PTS in males and females respectively: 9.24°+/-2.22° and 7.8°+/- 2.37°; 7.255°+/-2.56° and 6.89°+/- 3°.

At 12 years of age, we included 14 knees which showed a medial PTS of 7.90°+/- 2.54° and a lateral PTS of 7.32°+/- 3.22°. Anchustegui et al included only 1 Knee with a medial PTS of 6.36 and a lateral PTS of 11.84°

The 7 male knees showed a medial PTS of 8.96°+/- 1.80° and a lateral PTS of 9.13°+/- 2.7°, while the 7 female knees showed a medial and lateral PTS of 6.04°+/-2.04° and 4.80°+/- 2.14° respectively.

Age 13-18 years

The development of the knee plateaus in this age group. The slope remains relatively unaffected, also during the pubertal growth spurt. We observed the following values of the PTS in our study:

Table 2: Age- and Sex- wise distribution of the posterior tibial slope in the age- group of 13-18 years

	Study Group			Males			Females		
Age (yrs)	N	Medial PTS (°)	Lateral PTS (°)	N	Medial PTS (°)	Lateral PTS (°)	N	Medial PTS (°)	Lateral PTS (°)
13	16	9.71+/-3	7.42+/-3.7	3	12.8+/-1	12+/-2.8	13	8.35+/-2.8	6.84+/-3.7
14	18	8.61+/-2	7.30+/-2.6	8	8.47+/-1.9	6.8+/-2	6	9.2+/-2.5	8.8+/-3.6
15	30	8.62+/-2.3	7.26+/-3.4	10	7.9+/-2	8.87+/-3.1	20	8.9+/-2.5	6.6+/-3.4
16	20	8.22+/-3.05	8.86+/-3.3	8	7.25+/-1.68	10.48+/-4.13	12	8.9+/-3.74	8.8+/-2.82
17	17	8.51+/-3.2	8.45+/-2.6	7	7.45+/-2.4	6.96+/-2.6	10	9.07+/-3.57	8.8+/-2.49
18	12	9.08+/-3.23	7.82+/-2.93	5	8.5+/-3.8	7.3+/-2.6	7	9.6+/-2.9	9.28+/-3.3

Several authors have previously published their data on the PTS in children.

Vyas et al. compared ACL injured teenagers with ACL intact teenagers(Vyas et al., 2011). They reported a median medial PTS of 8.9°+/- 3.8° in their control group with 23 knees. It is important to mention that they measured the slope on the lateral radiograph using the method described by Brandon et al, which is essentially a modification of the method described by DeJour and Bonnin.

Deng et al published a similar study and reported a medial PTS of 8.8°+/- 1.7° and a lateral PTS of 10.9+/- 2.6° in the 36 knees in their control group(Deng et al., 2021). They performed their measurements on plain radiographs using the posterior cortex as the tibial shaft axis.

Dare et al. observed a medial PTS of 5.1° +/-2.3° and a lateral PTS of 3.4° +/- 1.7° in the control group of their study comprised of 76 teenage knees(Dare et al., 2015).

They performed their measurements on MRI images using the method described by Hudek et al.

We observed that the medial tibial slope increases relatively steadily up to the age of 10 years. The findings of our study lead us to conclude that the effective slope is a derivative of the weight bearing behavior in the developmental stages. Wolff's law states that bone in a healthy animal will adapt to the loads under which it is placed. Our findings lead us to believe that this is indeed the case in the development of the posterior tibial slope.

The human child first adopts a bipedal posture around the age of one year. As the child begins becoming steady on its legs, the slope progresses gradually till it stabilizes at around 8-10 years and then plateaus further. This seems to hold true for both the medial as well as the lateral slope.

Since we studied the age wise distribution of the medial and lateral tibial slope, we decided against calculated the average slope for the entire population and present our results in an age-wise manner. It is important to mention that the results were calculated using the method described by Brazier et al.

We observed that the lateral PTS was less than the medial tibial slope, irrespective of age.

8.2.2 Discussion of correlation testing

1. Testing the correlation between the medial posterior tibial slope and the medial posterior tibial offset

We tested to determine if the posterior slope in the medial compartment is a function of the posterior tibial offset, i.e., if the slope is determined by forces due to the posterior translation of the femur on the tibial plateau or the posterior rotation of the proximal tibia.

We found a significant correlation in the age groups of 1-2 years and 8-12 years. At the same time, the other age groups display no correlation between these two variables (Fig. 51)

Based on the theoretical knowledge of the minimal posterior gliding movement of the medial femoral condyle on the tibial plateau and our findings, we concluded that the likelihood of the medial tibial slope developing due to the posterior 'rotation' of the tibia plateau is indeed more than it being due to the posterior shifting of the tibial head on the shaft.

This is also supported by the fact that the average value of the medial tibial slope was consistently observed to be more than that of the lateral posterior tibial slope.

Nagamine et al published similar findings in their retrospective study including 276 patients undergoing total knee arthroplasty. They measured the slope on a plain radiograph and concluded that the posterior tibial slope occurs at the proximal metaphysis of the tibia due to a posterior 'tilt' and not a 'shift'(Nagamine et al., 2020).

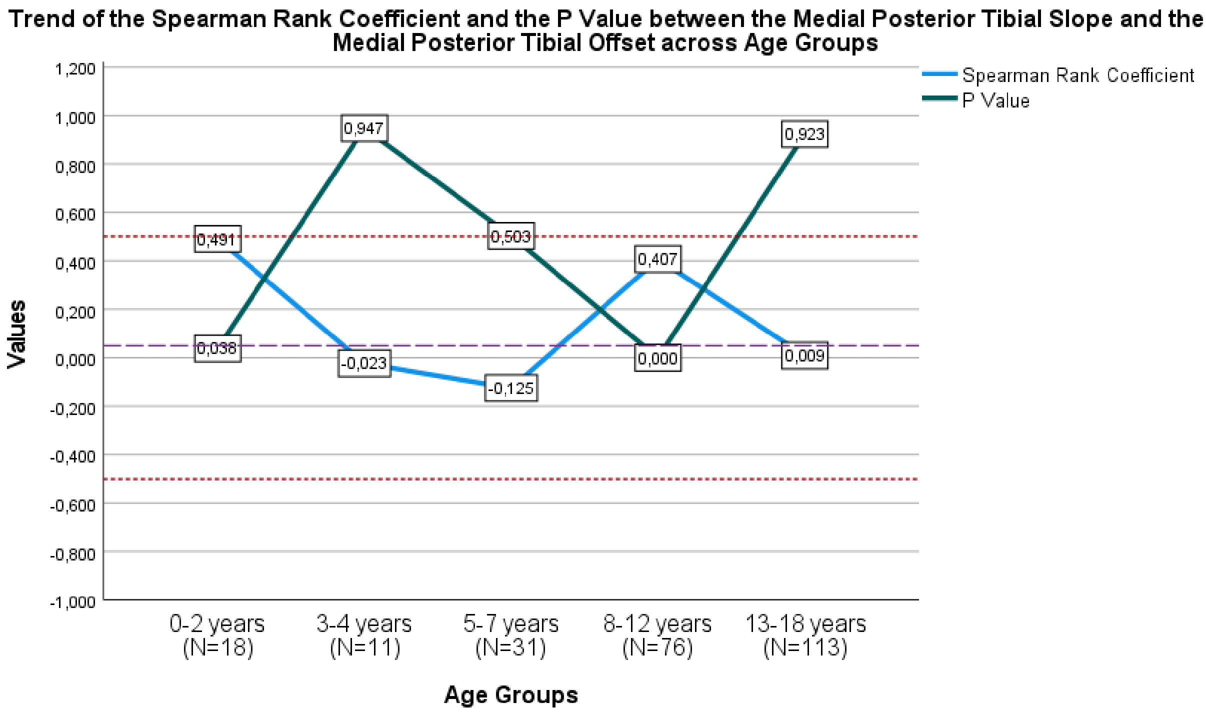

Figure 51- Trend of the Spearman rank coefficient and the p value between the medial posterior tibial slope and the medial posterior tibial offset across age groups

2. Testing the correlation between the medial posterior tibial slope and the medial posterior femoral offset

Our findings only suggest a correlation between the medial posterior tibial slope and the medial posterior femoral offset in the age group of 13 to 18 years, i.e., as the human child enters into adulthood (fig. 52) The posterior femoral offset is a crucial factor in the femoral rollback on the tibial plateau during deep flexion. Its value cannot be stressed enough in the determination of the flexion biomechanics of the knee, especially during weight bearing. That the slope has a major influence on its value and vice versa is thus well imaginable. The rotational motion of the condyle on the medial side is an important determinant of the posterior tibial slope.

Cinotti et al observed in their MRI study of 80 normal adult knees using the Dejour- Bonnin method that the medial compartment indeed displays a good correlation between the PTS and the posterior femoral offset(Cinotti et al., 2012).

Bao et al on the other hand, found an inverse correlation in their eighty normal knees in their study based on 3D CT reconstructions. Further studies are clearly necessary on this subject(Bao et al., 2021).

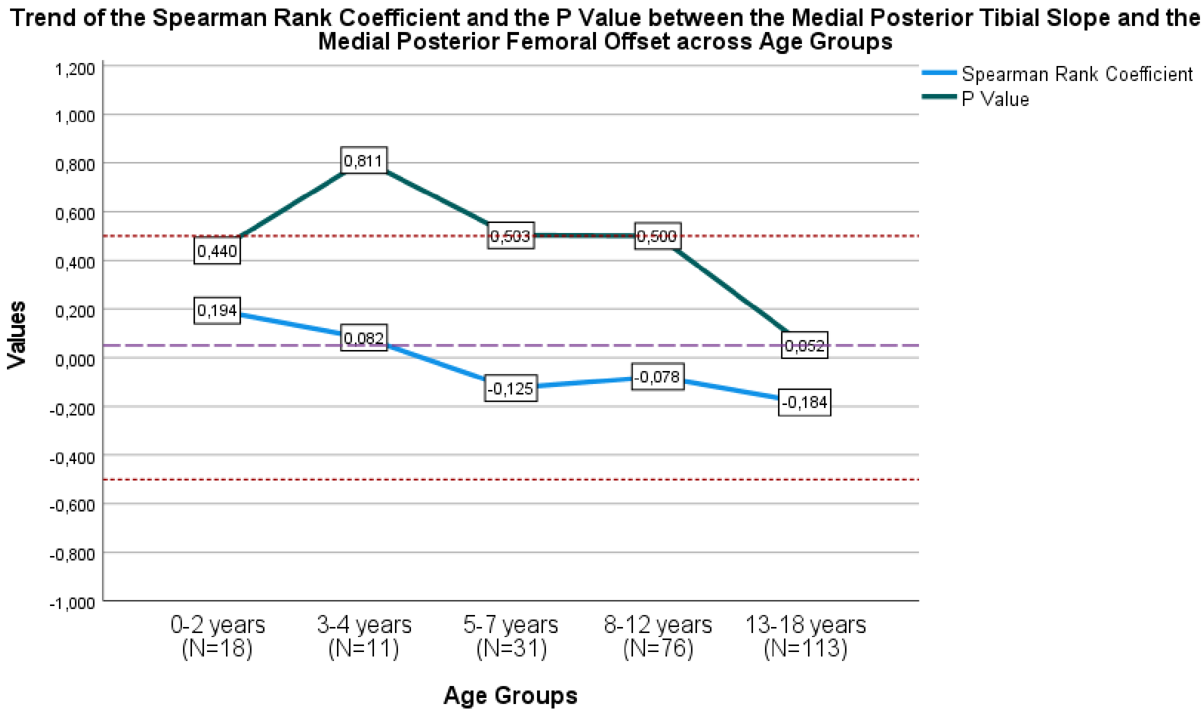

Figure 52- Trend of the Spearman rank coefficient and the p value between the medial posterior tibial slope and the medial posterior femoral offset across age groups

3. Testing the correlation between the medial posterior tibial offset and the medial posterior femoral offset.

Finally, on the medial side, we tested the correlation between our postulated medial posterior tibial offset and the medial posterior femoral offset. These two values displayed no correlation to each other in any of the age groups(fig. 53).

This information is important to deduce that the evolution of the posterior tibial offset cannot conclusively be attributed to the stresses occurring in deep flexion, although it seems theoretically plausible. It can be safely concluded that the compressive forces occurring in or near full extension provide a greater contribution to the development of the posterior tibial offset. Further studies are required in this regard.

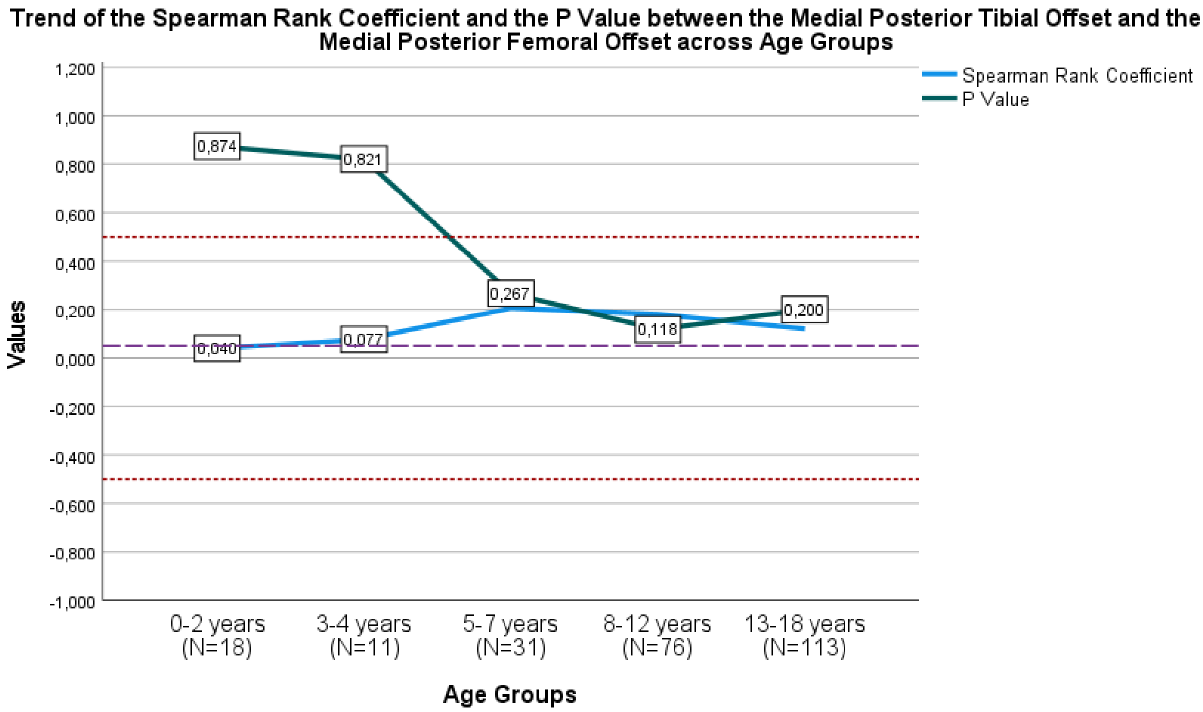

Figure 53- Trend of the Spearman rank coefficient and the p value between the medial posterior tibial offset and the medial posterior femoral offset across age groups

4. Testing the correlation between the lateral posterior tibial slope and the lateral posterior tibial offset

The lateral PTS displayed a correlation with the posterior tibial offset only in the age group of 8-12 years(fig. 54).

The translational movement of the lateral tibial condyle on the lateral tibial plateau suggests that these two variables develop dependant on each other. To our knowledge, there have been no studies till date testing the correlation between these two variables on the lateral side. There seems to be a gap in the existent knowledge here.

The greater difficulty in mearing the PTS on the lateral side and the existence of the proximal tibiofibular joint may obfuscate the true findings.

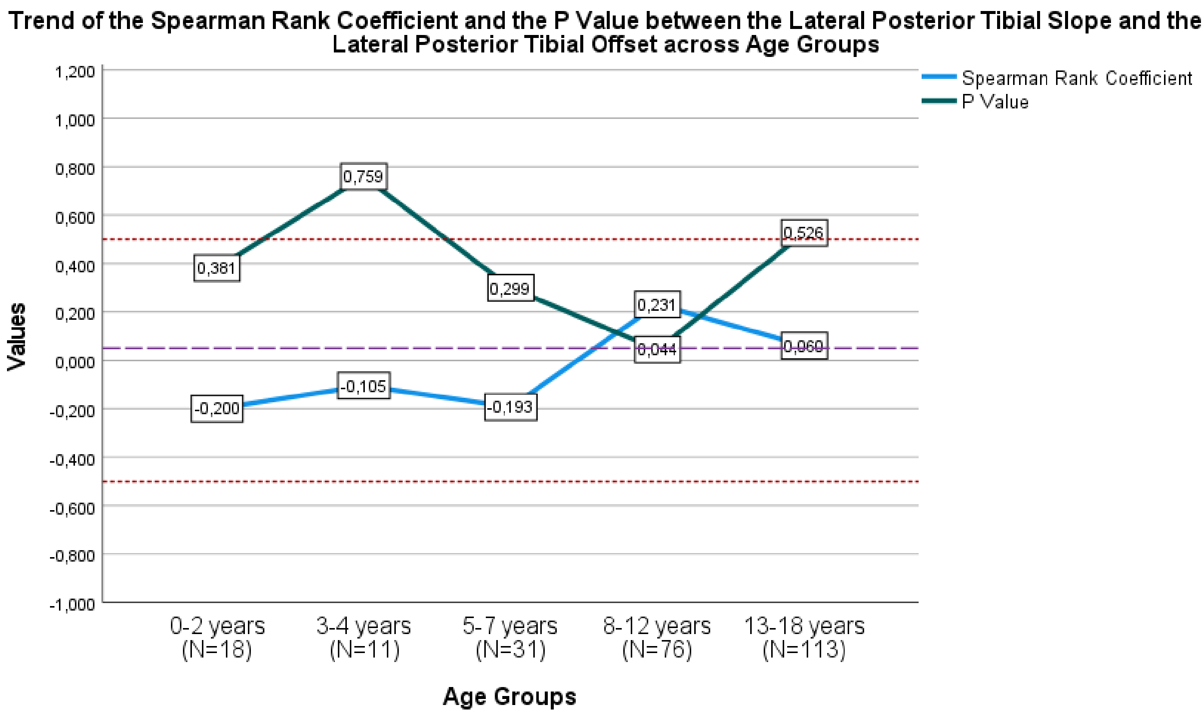

Figure 54- Trend of the Spearman rank coefficient and the p value between the lateral posterior tibial slope and the lateral posterior tibial offset across age groups

5. Testing the correlation between the lateral posterior tibial slope and the lateral posterior femoral offset

We observed that the posterior tibial slope on the lateral side does not correlate with the posterior femoral offset (fig. 55). This is credible, given the fact that the posterior femoral condyle translates further on the lateral side in its interaction with the tibial plateau leading to a contact area along a greater surface and not over a point.

Our findings also echo that of both Cinotti et al and Bao et al, who observed in their respective studies that these two factors do not seem to correlate on the lateral side(Bao et al., 2021; Cinotti et al., 2012).

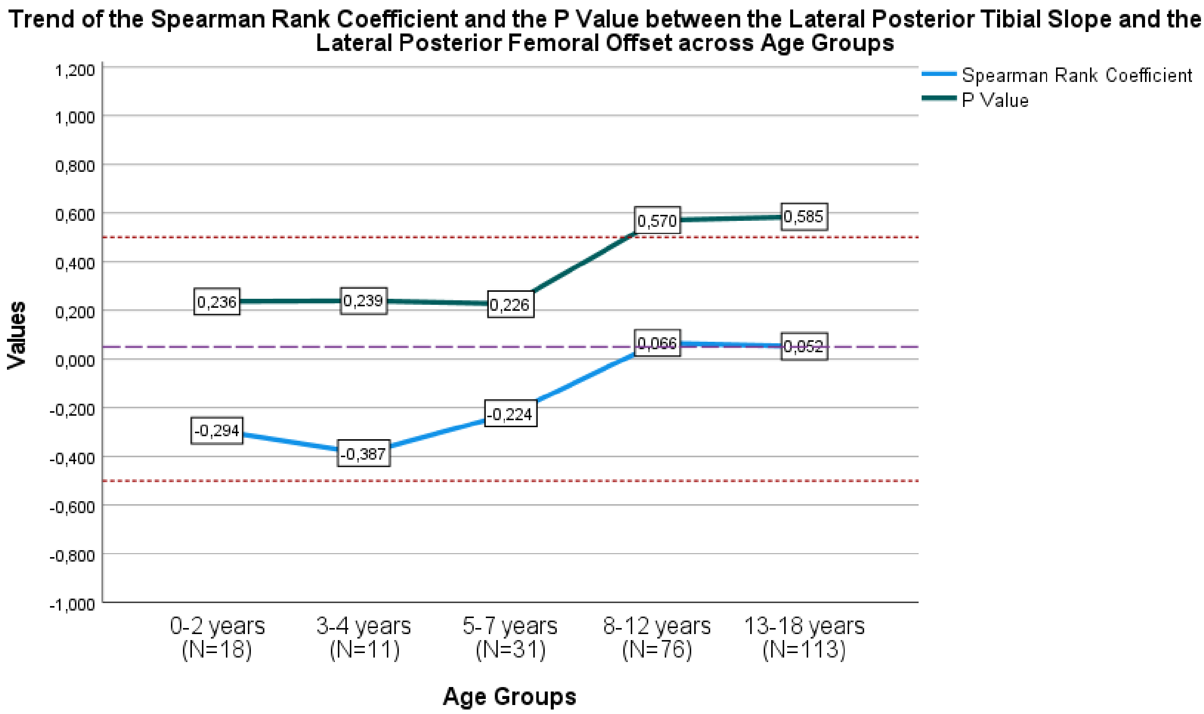

Figure 55- Trend of the Spearman rank coefficient and the p value between the lateral posterior tibial slope and the lateral posterior femoral offset across age groups

6. Testing the correlation between the lateral posterior tibial offset and the lateral posterior femoral offset

The lateral posterior tibial offset correlated with the posterior femoral offset in the age group of 5-7 years, but the other age groups displayed no correlation (fig. 56). This goes to reiterate the observation that the compressive forces in or near extension determine the posterior tibial offset and the flexion forces do not influence it greatly.

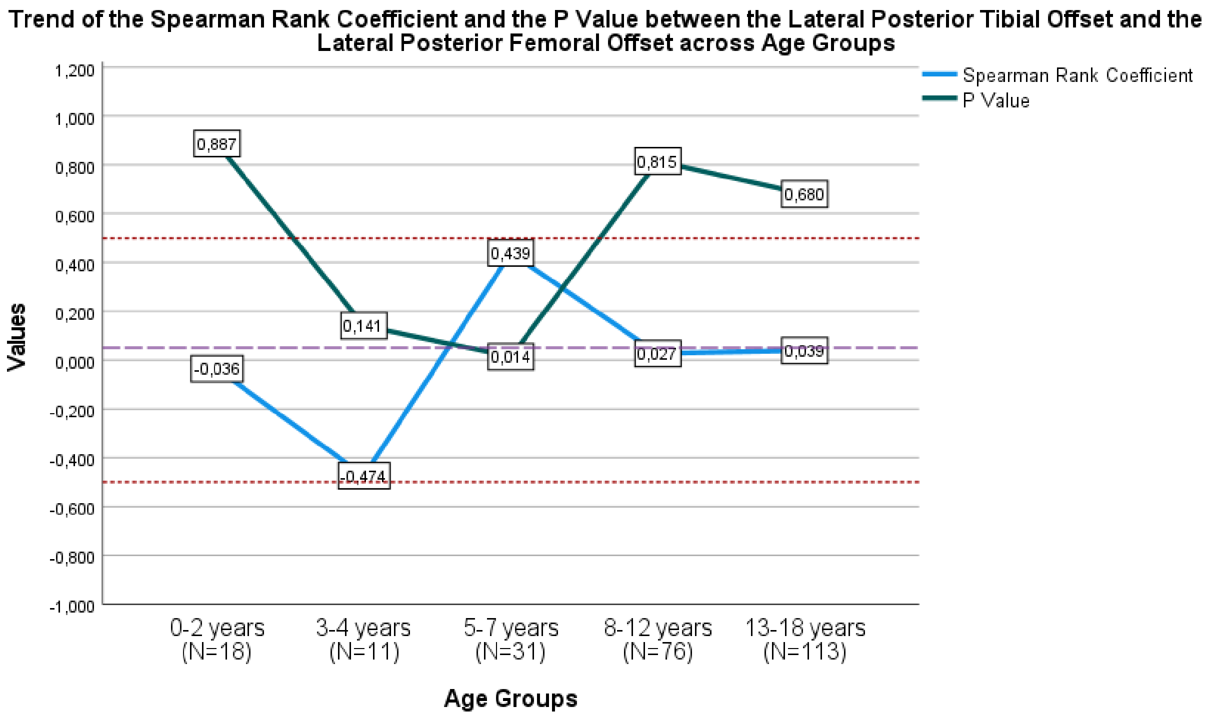

Figure 56- Trend of the Spearman rank coefficient and the p value between the lateral posterior tibial offset and the lateral posterior femoral offset across age groups

8.3 Conclusion and Vision

Our findings display that the posterior tibial slope, both on the medial and lateral side is a function of the age of the child. As the child begins to bear increasingly more weight along with advancing age, the slope begins to increase, conforming to Wolff's law. This increase in the slope seems to plateau out at the age of 8-12 years, after which the slope remains more or less constant into adulthood.

The posterior tibial slope and the posterior tibial offset correlate with each other, leading to a posterior 'tilt' of the proximal tibia. The medial posterior tibial slope also correlates strongly with the medial posterior femoral offset, conforming to the existent knowledge, that the medial femoral condyle mainly rotates over the congruent medial tibial plateau with only minimal translation.

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10. Declaration

EIDESSTATTLICHE VERSICHERUNG & ANTEILSERKLÄRUNG

Eidesstattliche Versicherung

„Ich, Pushkar Parag Bhide, versichere an Eides statt durch meine eigenhändige Unterschrift, dass ich die vorgelegte Dissertation mit dem Thema: "Evolution of the Tibial Slope until Skeletal Maturity and its Relationship to the Femoral as well as Tibial Offset" /

„Entwicklung des Tibialen Slopes bis zur Skelettreife und Seine Beziehung zum Hinteren Femoralen sowie Tibialen Offset"

selbstständig und ohne nicht offengelegte Hilfe Dritter verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel genutzt habe.

Alle Stellen, die wörtlich oder dem Sinne nach auf Publikationen oder Vorträgen anderer Autoren/innen beruhen, sind als solche in korrekter Zitierung kenntlich gemacht. Die Abschnitte zu Methodik (insbesondere praktische Arbeiten, Laborbestimmungen, statistische Aufarbeitung) und Resultaten (insbesondere Abbildungen, Graphiken und Tabellen) werden von mir verantwortet.

Ich versichere ferner, dass ich die in Zusammenarbeit mit anderen Personen generierten Daten, Datenauswertungen und Schlussfolgerungen korrekt gekennzeichnet und meinen eigenen Beitrag sowie die Beiträge anderer Personen korrekt kenntlich gemacht habe (siehe Anteilserklärung). Texte oder Textteile, die gemeinsam mit anderen erstellt oder verwendet wurden, habe ich korrekt kenntlich gemacht.

Meine Anteile an etwaigen Publikationen zu dieser Dissertation entsprechen denen, die in der untenstehenden gemeinsamen Erklärung mit dem Erstbetreuer, angegeben sind. Für sämtliche im Rahmen der Dissertation entstandenen Publikationen wurden die Richtlinien des ICMJE (International Committee of Medical Journal Editors; www.icmje.og) zur Autorenschaft eingehalten. Ich erkläre ferner, dass ich mich zur Einhaltung der Satzung der Charité – Universitätsmedizin Berlin zur Sicherung Guter Wissenschaftlicher Praxis verpflichte.

Weiterhin versichere ich, dass ich diese Dissertation weder in gleicher noch in ähnlicher Form bereits an einer anderen Fakultät eingereicht habe.

Die Bedeutung dieser eidesstattlichen Versicherung und die strafrechtlichen Folgen einer unwahren eidesstattlichen Versicherung (§§156, 161 des Strafgesetzbuches) sind mir bekannt und bewusst.“

Datum Unterschrift

11. Curriculum Vitae

Mein Lebenslauf wird aus datenschutzrechtlichen Gründen in der elektronischen Version meiner Arbeit nicht veröffentlicht

Mein Lebenslauf wird aus datenschutzrechtlichen Gründen in der elektronischen Version meiner Arbeit nicht veröffentlicht

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13. Statistician's Certificate

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Bescheinigung

Hiermit bescheinige ich, dass Herr *Pushkar Parag Bhide* innerhalb der Service Unit Biometrie des Instituts für Biometrie und klinische Epidemiologie (iBikE) bei mir eine statistische Beratung zu einem Promotionsvorhaben wahrgenommen hat. Folgende Beratungstermine wurden wahrgenommen:

- Termin 1: 15.09.2022
- Termin 2: 06.10.2022

Folgende wesentliche Ratschläge hinsichtlich einer sinnvollen Auswertung und Interpretation der Daten wurden während der Beratung erteilt:

- Korrelation und Interpretation
- Box-plot und Scatter-plot

Diese Bescheinigung garantiert nicht die richtige Umsetzung der in der Beratung gemachten Vorschläge, die korrekte Durchführung der empfohlenen statistischen Verfahren und die richtige Darstellung und Interpretation der Ergebnisse. Die Verantwortung hierfür obliegt allein dem Promovierenden. Das Institut für Biometrie und klinische Epidemiologie übernimmt hierfür keine Haftung.

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