**Pathologic Achilles Insertion Angle (PAIA): A Novel Radiographic Angular Measurement to Guide the Evaluation and Treatment of Insertional Achilles Tendinopathy**

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**Abstract**

**Background:** Enlargement of the calcaneal tuberosity at the Achilles insertion is a typical feature of Insertional Achilles tendinopathy (IAT). Surgically, it has been traditionally treated with debridement and repair or reconstruction of the Achilles insertion with a long postoperative recovery time. The Zadek osteotomy, a dorsal-based closing wedge osteotomy on the calcaneal tuberosity of the calcaneus, has been proven to be an effective and minimally invasive procedure for IAT. However, there was no study in the literature demonstrating how to determine the size and apex of the osteotomy in general, not to even mention correlating it to the exact enlargement of the tuberosity. This study considered the morphology of the calcaneus and developed a radiographic angular metric, **Pathologic Achilles Insertion Angle (PAIA),** to guide the evaluation of IAT and the design of the Zadek osteotomy.

**Methods:** Lateral weightbearing radiographic images of 40 control feet were used to develop a mathematical algorithm based on a Standard Circle (SC) for predicting the contour of the calcaneal tuberosity in each control foot. The center and radius of the SC were statistically fitted and scaled in relation to the dimensions of the calcaneus. The enlarged calcaneal tuberosities of 40 feet with IAT were plotted and compared to their respective SCs to calculate an algorithm of the angle by which the enlarged tuberosity curve could be rotated around the weightbearing point to fit the SC of each foot. This angular measurement was named PAIA. It was meant to reflect the size of the calcaneal tuberosity enlargement and the size of the Zadek osteotomy with the apex of the osteotomy being at the weightbearing point of the calcaneus.

**Results:** The equation of the Standard Curve was with the offsets of the center (a, b) and the radius (R) of SC being scaled in relation to the dimensions of the calcaneus. From realigning the 40 enlarged tuberosities in the IAT group to their respective SCs, another algorithm was created to automate the calculation of PAIA.

**Conclusion:** PAIA is a novel angle developed with the functions of quantitatively evaluating the enlarged calcaneal tuberosity in IAT and individualizing the design of the Zadek osteotomy. It is the first to take the morphology and biomechanics of the calcaneus into consideration.

**Clinical relevance level: II**

**Key words: Insertional Achilles tendinopathy, IAT, Pathologic Achilles Insertion Angle, PAIA, Zadek Osteotomy, Calcaneal tuberosity, Morphology, Biomechanics**

**Introduction**

Insertional Achilles tendinopathy (IAT) is a common cause of posterior heel pain seen in a variety of foot types [1, 3, 16]. Astrom et al. reported that 20% of 163 patients with chronic heel pain had IAT [8]. According to the literature, about 6% of the general population experience Achilles tendon pain. Of these patients, approximately one-third have IAT [3-7]. Similarly, Paavola et al. reported that 24.7% of patients with chronic ailment of the Achilles had insertional Achilles pathology, with 20% of these patients having pure IAT [9, 10]. The pathology of IAT includes calcification and degenerative changes of the Achilles insertion on the calcaneus [2,11]. IAT is more commonly seen in older athletes and in less athletic, overweight individuals [10, 12, 13] as a result of overuse, mechanical overloading, and improper form when training [10], and possibly stress shielding [14, 15].

If three to six months of continuous conservative treatment fails, surgical management can be considered. [3] Surgical interventions include open or minimally invasive tendon debridement, resection of bone spur/calcification at the Achilles insertion, and reattachment of the Achilles tendon with or without Achilles tendon reconstruction, as well as flexor hallucis longus transfer [17, 18].However, wound healing problems and a long-term rehabilitation course are the most commonly concerns for these open procedures, with deep vein thrombosis, infection, and scar hypersensitivity, etc. have also been described [18].

An alternative to the surgical techniques is the percutaneous Zadek osteotomy. The Zadek osteotomy is a dorsal closing wedge osteotomy of the calcaneus. It was first introduced in 1939 for the treatment of Achillobursitis and has been popularized during the past two decades in the treatment of both IAT and Haglund deformity. It has the advantages of minimal invasive surgery, including reduced post-operative pain, swelling, scarring, and recovery time, as well as improved functional scores [22]. To date, a few studies [19-21] investigated possible mechanisms of the Zadek osteotomy in the treatment of Haglund deformity a bony prominence of the dorsal lateral aspect of the calcaneal tuberosity, which can cause local inflammation, mimicking the symptoms of but different from IAT pathologically [11]. Those studies demonstrated that the Zadek osteotomy can reduce the length of the calcaneus and sometimes elevates the point of insertion of the Achilles tendon depending on where to place the apex of the osteotomy, thereby changing the biomechanical loading at the tendon insertion [19-21].

Although the use of Zadek osteotomy for IAT is growing in popularity, there is no agreement on the size of the wedge resection and the location or apex of the osteotomy. Moreover, there is no study on the design of the osteotomy according to the severity of the IAT. This study investigated the morphology of the calcaneal tuberosity in normal controls and patients with IAT and introduced a novel angular measurement of the enlarged tuberosity in IAT with the goal to individualize the design of the Zadek osteotomy.

**Material and Methods**

**Selection of study samples**

40 lateral weightbearing X-ray images of feet without IAT nor other Achilles deformities were included as the control group to study the normal morphology of the calcaneal tuberosity of the calcaneus. Another 40 lateral weightbearing X-ray images of feet with IAT were used as the diseased group.

**Delineating Contour of a “Healthy” Calcaneus Tuberosity with the “Rectangle Circumscription & Mapping Method**

The 40 control radiographs were imported into ImageJ {Schneider, 2012 #500}{Schindelin, 2012 #501}. Each calcaneus was circumscribed within a rectangle such that each side of the rectangle corresponded to the anterior, superior, posterior, and inferior border of the calcaneus. Then, 90 points were plotted onto each calcaneus to determine the size of the calcaneus and contour of the calcaneal tuberosity (Figure 1). Among these 90 points, points 1-3 were measurement calibration markers, some of the rest points represented standardized anatomical markers, while the others did not have specific representation but only being evenly distributed between two anatomical markers along the contour of the bone for mapping purposes. (Table 1)

Then the 90 points placed on each of the 40 control feet were collectively mapped to construct a Standard Circle with a fitting algorithm mathematically. Two parameters were used to define the individual Standard Circle for each foot using the above rectangle circumscription and mapping method to include complex dimensional information of the calcaneus: 1) relative position of the circle's center with respect to the rectangle being determined by point 4, 5, 6, and 7, and 2) the radius of the standard circle being determined by the bone markers that represented dimensions of the calcaneus in terms of height, length, pitch angle, etc. These two optimal parameters were established when the least square loss of the Standard Circle, in relation to the control reference data points, was minimized.

The goal of obtaining this individualized Standard Circle was to delineate the contour that best approximates the posterior outline of an “ideally healthy” calcaneus without calcification enlargement/osteophyte and/or bony prominence at the Achilles insertion and the rest part of the tuberosity.

**Defining and fitting the standard Circle Algorithm**

To develop the circle fitting algorithm, the anatomical curvature between the superior aspect of the calcaneal tuberosity and the weightbearing point was determined using weightbearing XR imaging for each of the 40 control feet.

As shown in Figure 2, the center of the standard circle was denoted as , with anatomical markers , , and denoting the relative location of the unit rectangular. The diagonal length of the unit rectangular was denoted as D, while the width and height of the rectangular were denoted as and , respectively.

and can be written in coordinates of A, B, and C as follows:

The curvatures of each control foot were then standardized along the x and y axes respectively and was approximated using the following modified equation of a circle:

(𝑥 − )2 + (𝑦 − )2 = 2

where the position of the center (O) of the Standard Circle is denoted by its offset from the x axis , and its offset from the y axis . The radius of the Standard Circle denoted as .

Average x offset, y offset, and radius of the standard circle were then calculated for all control feet. All anatomical markers and as well as the Standard Circle fitted using the 40 control feet are visualized in Figure 3.

Based on the average circle center location of all healthy subjects, for any given subject, healthy or diseased, the standard circle center coordinates and circle radii can be determined using:

where and are parameters derived from the statistical analysis of the control feet.

**Developing the Pathologic Achilles Insertion Angle (PAIA)**

The enlarged calcaneal tuberosities of the 40 feet with IAT were then outlined using the same rectangle circumscription and mapping method. When outlining the rectangle, the enlargement (osteophyte, calcification) of the calcaneal tuberosity was intentionally not included. For these diseased feet with IAT, only the rectangle and the anatomical markers needed to be plotted with the goal of collecting dimensional information of each individual foot. Then the Standard Circle representing the “ideal healthy” contour of this calcaneus was worked out automatically using the algorithm described above.

Mirroring the method to outline the posterior contour of the control feet, bone markers were plotted along the posterior contour of the enlarged IAT tuberosity (the purple line in Figure 4A, 4C) to collect relative dimensional information of the enlargement in each foot. Then, in each individual foot, the enlarged calcaneal tuberosity curve was rotated to best align with its ideal Standard Circle. Rotational loss, a mean square error measuring the differences between the enlarged calcaneal tuberosities and the Standard Circles of these feet in the IAT group was minimized during the optimization. And the most optimum rotation angle was calculated to reflect the degrees of this rotation angle. (Figure 4B). This newly introduced angle was named Pathologic Achilles Insertion Angle (PAIA) because it represented exactly the enlarged degrees of the calcaneal tuberosity in feet with IAT, as well as the angle by which the enlarged calcaneal tuberosity curve can be rotated around the weightbearing point to best fit the ideal contour predicted by the Standard Circle of the calcaneus. More mathematical details of the calculation of PAIA will be discussed in the section below.

R v4.2.0 was used to conduct the relevant re-alignment calculations and statistical analysis.

**Calculating PAIA from the enlarged posterior contour**

The enlarged posterior tuberosity contour of each foot with IAT was compared to the individualized Standard Circle derived using the methods aforementioned:

Then, each from the enlarged posterior tuberosity contour was projected onto the standard curve:

The counterclockwise rotation of the observed curvature can be written as:

The rotation loss is quantified as a sum of square loss which can be used to determine the similarity between the -rotated curvature and the standard circle. is defined as

And the most optimum rotation angle can be found at the minima of the rotation loss with respect to the rotation angle, or when:

Theoretically, since the ideal normal contour and the enlarged contour of the calcaneal tuberosity share the same center of rotation at the weightbearing point of the calcaneus, the size of the PAIA would be the exact size of the Zadek osteotomy if the apex of the osteotomy is chosen at the weightbearing point of the calcaneus.

To enhance comprehension of how the Zadek osteotomy changes the biomechanics of the calcaneus, as well as how anteriorly translation of the osteotomy apex surpassing the weight-bearing point influences the calcaneal pitch angle, simulated illustration was included in the section of results. Nevertheless, simulation results revealed no statistically significant variation in the insertion angle following this anterior displacement of the apex, suggesting that the insertion angle estimation remains reliable when adhering to the proposed methodology.

**Results**

**Parameters of the Standard Circles for the 40 Control Feet**

The average value and standard error of , , and of the Standard Circles for the 40 control feet were included in Table 2.

**How Could Changing the Apex of the Osteotomy Influence the Biomechanics of the Calcaneus**

The below simulations demonstrated that how the Zadek Osteotomy changed the biomechanics of the calcaneus differently if the apex of the Osteotomy was shifted anteriorly from the weightbearing point (Figure 5).

**Discussion**

This study introduced a novel angle PAIA based on mathematical algorithms to quantitatively describe the enlargement of the calcaneus tuberosity, and to individualize the design of the Zadek osteotomy for treating Insertional Achilles Tendinopathy (IAT).

Introduced in 1939 to address calcaneus bursitis, the Zadek osteotomy was aimed at excising the inflamed bursa and the underlying bony prominence, demonstrating uniformly positive outcomes in that cohort [31, 32]. The procedure gained further traction in 1965 through the work of Keck and Kelly, establishing its effectiveness in managing IAT [33, 34]. A systematic review by Poutoglidou et al. of ten studies encompassing 232 patients revealed significant improvements in functional scores and pain reduction, albeit with minor complications like wound infections and sural nerve paresthesia being the most common [22]. Similarly, Nordio et al. reported a 92% satisfaction rate at a six-month follow-up among 26 patients undergoing the procedure, with only two experiencing complications [35]. Significant enhancements in AOFAS and VISA-A scores were also observed by Georginannos et al. in a study involving 64 athletes, with a return to sports activities between 3 to 7 months [19]. Despite these satisfactory outcomes, the determination of the wedge size and the placement of the apex in Zadek osteotomy has remained a myth and challenge, with no studies in the literature addressing its design particularly based on the enlargement severity of the calcaneal tuberosity in IAT. Traditionally, the osteotomy's dimensions have been roughly determined by the surgeon's intuition and experience. The lack of a standardized approach often leads to confusion among practitioners. The PAIA introduced in this study addresses this issue by normalizing the contour of the enlarged calcaneal tuberosity based on each patient's specific calcaneal dimensions.

In the past, multiple imaging modalities were used to investigate a possible correlation between calcaneus morphology and IAT. such as the Folwer-Philip angle [36], Ruch calcaneal pitch angle [28], Chauveaux angle [37], and Heneghan-Pavloc parallel pitch lines [38]. However, these parameters were proven to have poor specificity and reliability and do not incorporate the length of the calcaneus.[39, 40] In light of this, Tourne et al. devised the radiographic X/Y ratio to aid in determining surgical indications for patients with Haglund syndrome including IAT. [39] In that measurement, X represents the calcaneal length and Y represents the greater tuberosity length on lateral weight-bearing radiograph. They found that an X/Y ratio below 2.5 effectively differentiated patients with Haglund syndrome from those without. In other words, any calcaneus with an X/Y ratio of less than 2.5 could be deemed “long” and therefore causing impingement and excess tension at the Achilles insertion [39]. Following that logic, patients with Haglund syndrome and X/Y ratio of less than 2.5 would likely benefit more from a Zadek osteotomy to reduce the length of the calcaneus as opposed to a calcaneoplasty. [39, 40][{Tourné, 2022 #171}]

Although IAT is a completely different disorder from the Haglund deformity, in our morphology study of the calcaneal tuberosity, both the length of the height of the calcaneus were taken into consideration. The PAIA concept presents a significant advancement in both the diagnosis and surgical treatment of IAT by offering a highly individualized methods that adapts the Zadek osteotomy to the unique calcaneal shape of each foot. This customization allows for precise alignment and fit, which could potentially lead to better surgical outcomes while taking several biomechanical features of the calcaneus into consideration: height, length, pitch angle, severity of the enlargement, possible “ideal” contour prior to developing IAT, lever length of the Achilles, etc.

Another significant strength of the Precision Angle Insertion Algorithm (PAIA) lies in its robust mathematical framework. In clinical environments, the morphology of a diseased calcaneal tuberosity exhibits substantial variability across patients. The robustness of PAIA's algorithm to consistently compute the optimal insertion angle is crucial. This consistency facilitates reliable diagnostics of enlargement and provides standardized surgical guidance, particularly in cases involving severe deformity.

This study possesses several limitations worth noting. Primarily, the algorithm for the individualized Standard Circle was developed using morphological metrics from 40 feet, specifically excluding those with inflammatory arthropathy and other significant deformities. Given the exploratory nature of this research, determining an optimal sample size for establishing the Standard Circle parameters for control feet was challenging. Although 40 subjects might seem adequate, this sample size is considered modest if the selected control feet do not accurately reflect the overall population distribution or if outliers exist within the control cohort. Despite these concerns, Figure 3 demonstrates that the calcaneus tuberosities of the control feet are closely clustered, with no distinct subgroups, suggesting that the sample may adequately represent and capture the variation of the calcaneus tuberosities within the control group. However, we cannot discount the possibility that the sample of 40 subjects may not encompass the complete range of variation in the dataset, potentially leading to biased Standard Circle parameters for the control subjects. Moreover, the PAIA was developed using only morphological data of the calcaneus on lateral radiograph, a limited 2-dimensional single view. While morphological metrics in other planes, as well as the alignment of the whole foot in addition to the isolated calcaneus bone, such as hindfoot alignment and arch height, which have been shown in some preliminary studies to have correlation with IAT, might also influence the biomechanics of IAT and the design of the Zadek osteotomy accordingly. However, on the other side, if too many parameters are considered in the design of a metric, it will compromise ease-of-use, increase noise, and reduce precision & specificity. Therefore, the authors of this study think the benefits of PAIA in general overcome the above limitations

**Conclusion:**

PAIA is a novel angle which can be used to both quantitatively evaluate the enlarged calcaneal tuberosity in feet of IAT and individualize the design of the Zadek osteotomy as an optimal minimal invasive surgical treatment. This was the first to take the morphology and biomechanics of the calcaneus into consideration, including height, length, pitch angle of the calcaneus, and severity of the enlargement, etc. Further biomechanical cadaveric and clinical studies are needed to prove the above concept.

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