​

**Pathologic Achilles Insertion Angle: A Novel Radiographic Metric to help Evaluate and Treat 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). Traditional surgical treatments including debridement & repair or reconstruction of the Achilles insertion have a long postoperative recovery time. The Zadek osteotomy, a dorsal closing wedge osteotomy on the calcaneus, has been proven to be an effective minimally invasive procedure for IAT. However, design of the size and apex of the osteotomy has never been described, particularly correlating to severity of the enlargement. This study based on normal morphology of the calcaneus tuberosity developed a radiographic angular metric Pathologic Achilles Insertion Angle (PAIA),to guide evaluation of IAT and design of the Zadek osteotomy.

**Methods:** On lateral weightbearing XRs, calcaneal tuberosities of 40 control feet were plotted and used to develop a mathematical algorithm based Standard Circle to predict the ideal contour of each calcaneal tuberosity, with offsets of the circle center and the radius of the circle being scaled in relation to dimensions of the calcaneus. Then enlarged tuberosities of 40 feet with IAT were plotted and compared to their respective ideal standard circles. An angular measurement algorithm was developed to describe how each enlarged tuberosity could be rotated to fit the ideal standard circle of that specific calcaneus using the weightbearing point as the apex. This angular metric was named PAIA.

Results:

**Conclusion:** PAIA can quantitatively evaluate IAT and individualize the Zadek osteotomy design. It is the first metric taking morphology and biomechanics of the calcaneus into consideration.

**Clinical relevance level: II**

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

**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].

When 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**

Lateral weightbearing X-ray images of 40 feet without IAT, other Achilles insertion deformities, trauma history of the calcaneus or other deformities were included as the control group to study the normal morphology of the calcaneal tuberosity. Lateral weightbearing X-ray images of 40 feet with IAT were used as the diseased group.

**Delineating Contour of Contral Calcaneal Tuberosities**

The 40 control radiographs were imported into ImageJ (REF). 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 positional markers 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 set up as calibration markers for measurement purposes, 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).

**Determining Individualized Standard Circle to Predict the Ideal Calcaneal Tuberosity Contour**

These 90 positional markers were collectively mapped to construct and statistically fit an individualized Standard Circle for every subject. To fit the Standard Circle, the positioning and shape of the standard rectangle was first characterized by points 4, 5, 6, and 7, with point 7 denoted as the origin of the x and y coordinates (i.e., x, y = 0 at point 7). The standard rectangle was then normalized to a unit square to mediate differences in foot sizes between the subjects.

The two essential parameters used to define the individualized Standard Circle for each calcaneal tuberosity were relative x and y coordinates of the circle's center, denoted as , and the radius (R) of the Standard Circle determined by bone markers representing dimensions of the calcaneus in terms of height, length, the Calcaneal Pitch angle, etc. The goal of obtaining this individualized Standard Circle was to delineate the contour that best approximates the posterior outline of an “ideally relatively normal” calcaneal tuberosity using dimensions of the calcaneus.

As shown in Figure 2, the center of the Standard Circle was denoted as Three corners of the rectangle were corresponding to point 7, corresponding to point 6, and corresponding to point 4 in Figure 1. The width, height and diagonal length of the rectangle were denoted as , , and D respectively. D can be expressed in terms of and as:

Each point on the curvature of the control calcaneal tuberosity was standardized along the x and y axes respectively and then approximated using the following equation to determine the Standard Circle:

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

For all the control calcaneal tuberosities, their respective , , and circle radius are calculated and used to construct distributions with averages and standard errors to parameterize the Standard Circle.Average x offset, y offset, and radius of the standard circle were then calculated for all control feet. All plotting points as well as the average Standard Circle fitted using the 40 control feet were visualized in Figure 3.

Based on the average circle parameters established using the control feet, for any future given calcaneus, with or without IAT, the individualized Standard Circle can be determined using the same formula with the statistically fitted parameters , , and .

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

The calcaneal tuberosities of the 40 feet with IAT were then analyzed by circumscribing the same positional bone markers as defined in the control feet, while intentionally excluding the enlargement of the calcaneal tuberosity (See Figure 4A). For these diseased feet with IAT, only the four corners of the rectangle and those anatomical markers were plotted to collect dimensional information of each calcaneus. Then the individualized Standard Circles were created for all individuals with IAT.

Following that, the enlarged posterior contour of the calcaneal tuberosities with IAT were outlined using positional bone markers 37 – 90 (the purple line in Figure 4A, 4B) to collect the x and y coordinate information of each enlarged calcaneal tuberosity. Then, these enlarged calcaneal tuberosity curves were rotated around the weightbearing point (point 90) to best align with their respective “ideal” curvatures predicted by the Standard Circles using mathematical optimization. The optimization is done by projecting the y coordinates of each plotted dot on the enlarged posterior tuberosity onto the Standard Circle of that calcaneus. In this transformation, the Standard Circle (SC), upon projection, can be written as:

where and are respectively the x and y coordinates of all the points on the Standard Circle. The x coordinates of the projected Standard Curve can be expressed as a function of the y coordinates.

Rotational loss, a mean square error measuring differences between the rotated enlarged calcaneal tuberosities and the Standard Circles of these calcaneal tuberosities in ­­­the IAT group was minimized during the optimization. And the most optimum rotation angle was solved during the optimization (Figure 4C). This rotation angle was named Pathologic Achilles Insertion Angle (PAIA) because it represented exactly the enlarged degrees of the calcaneal tuberosity in a foot 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 that individual calcaneus.

Mathematically, the counterclockwise -angled rotation of the observed curvature can be written as:

where is the rotated enlarged contour of the calcaneal tuberosity with x coordinates , and y coordinates , and and are the coordinates for the original enlarged tuberosities. Then the rotation loss with respect to 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:

where , are the x and y coordinates of the Standard Circle, and , are the x and y coordinates of the rotated enlarged contour. N is typically equal to 54 because from point 37 to point 90, 54 points in total were used to depict the enlarged contour.

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.

**Results**

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

The parameters of the Standard Circle were determined from 40 control feet. The x coordinate of the Standard Circle is 0.53 +/- 0.07, the y coordinate is 0.39 +/- 0.03, and the circle radius is 0.47 +/- 0.06. When combined, given any calcaneus, with or without IAT, upon standardizing its width and height to unit length, the individualized Standard Circle can be written as:

**Comparing Standard Circle Parameters and PAIA between Control and Feet with IAT**

Compared to control feet, feet with IAT manifest significantly lowered center of the individualized Standard Circle (p = 0.021), with the y coordinates at 0.39 +/- 0.03 for the control feet and 0.41 +/- 0.06 for the feet with IAT. In addition, PAIA in feet with IAT averages around 12.6 +/- 5.7 degrees. However, control feet have near-zero predicted PAIA at 0.27 +/- 0.72 degrees. As expected, feet with IAT have much greater PAIA compared to their control counterparts (p < 0.001).

**Predicted alterations of the biomechanics of the calcaneus upon Zadek osteotomy**

Please see Figure 5 for comprehension of how the Zadek osteotomy changes the biomechanics of the calcaneus, as well as how anteriorly translation of the osteotomy apex from the weight-bearing point influences the Calcaneal Pitch angle.

**Discussion**

This study introduced a novel angle, Pathologic Achilles Insertion Angle (PAIA) based on mathematical algorithms to quantitatively describe the enlargement of the calcaneus tuberosity, and to individualize the design of the Zadek osteotomy in evaluating and 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 ones for traditional open Achilles insertion repair & reconstruction procedures [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, how to determine the wedge size and the placement of the apex for the Zadek osteotomy has remained a myth and challenge, with no studies in the literature addressing its design particularly based on the severity of the calcaneal tuberosity enlargement in IAT. Traditionally, the osteotomy's dimensions have been roughly determined by the surgeon's intuition and experience. This type of lacking standardized approach often leads to confusion among practitioners. The new angular metric 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 the 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 as well as 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, a calcaneus with an X/Y ratio of less than 2.5 could be deemed “long” and therefore has the potential of causing impingement and excessive 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, ie, simple removal of the Haglund deformity. [39, 40][{Tourné, 2022 #171}]

Although IAT is a completely different disorder from the Haglund deformity, in our morphology study of the calcaneal tuberosity, several biomechanical features of the calcaneus were directly or indirectly taken into consideration, including height, length, the Calcaneal Pitch angle, severity of the enlargement, possible “ideal” contour prior to developing IAT, lever length of the Achilles, etc. The PAIA concept presents a significant advancement in 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.

Another significant strength of the 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 a few limitations worth noting. Primarily, the algorithm for the individualized Standard Circle was developed using morphological information from 40 control feet, specifically excluding those with Achilles insertion disorders and other significant deformities. Given the exploratory nature of this research, determining an optimal sample size for establishing the Standard Circle parameters for the control group was challenging. Although 40 samples 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 this concern, Figure 3 demonstrates that the calcaneal 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. Secondly, PAIA was developed using only morphological data of the calcanei on lateral radiograph, a limited 2-dimensional single view. While morphological metrics in other planes, and the alignment of the whole foot in addition to the isolated calcaneus bone, like 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 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 minimal invasive procedure, Zadek osteotomy. This was the first to take the morphology and biomechanics of the calcaneus into consideration. Further biomechanical cadaveric and clinical studies are needed to prove the above concept.

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