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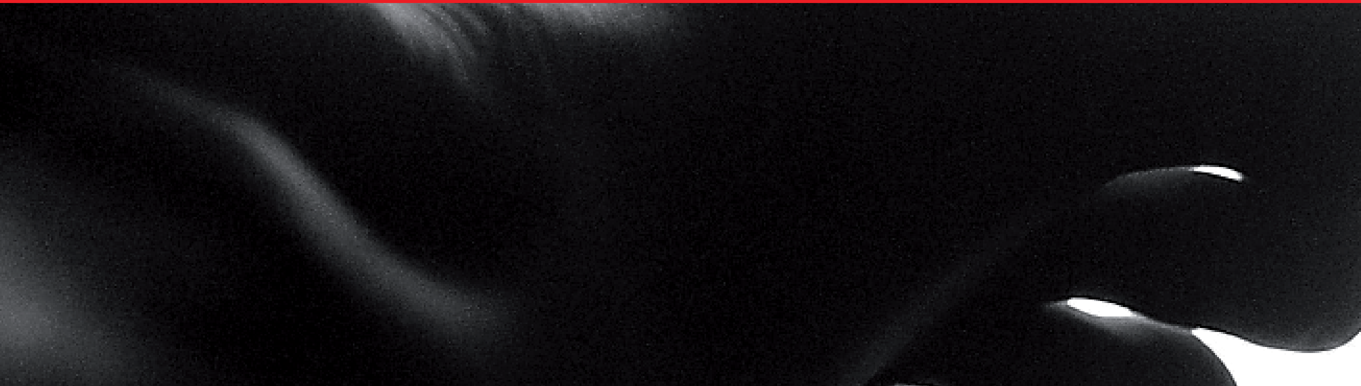
# Update in Management of Foot and Ankle Disorders

*Edited by Thanos Badekas*



# UPDATE IN MANAGEMENT OF FOOT AND ANKLE DISORDERS

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**Update in Management of Foot and Ankle Disorders**
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# Meet the editor

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He is a council member of EFAS (European Foot & Ankle Society) and also served as chairman of the Scientific Committee of EFAS. Dr. Badekas was the director of the Foot and Ankle and Lower Extremities Department in the Polyclinic during the Olympics and Paralympic Games in Athens in 2004. He is currently an editorial member of the Diabetic Foot and Ankle Surgery, reviewer of the Journal Foot and Ankle Surgery, editor in chief of the International Journal of Foot and Ankle, editor in Advance Research on Foot & Ankle Journal, member of the editorial board of the Journal Clinics in Podiatric Medicine and Surgery, member of the editorial board of the Journal of Foot Medicine and Surgery.

# Contents

# Preface

This book, *Update in Management of Foot and Ankle Disorders,* brings together leading practitioners in the field of foot and ankle surgery and pathology.

Recent advances in this field are thoroughly analyzed in four different sections in this book. In foot and ankle surgery in the last fifteen years, major advances have been made and the knowledge in this specific field has advanced dramatically. In this book, you can read about recent advances not only in surgery but also in pathology and patient management.

The first section in this book is the sport injuries section dedicated to Achilles tendon injuries in athletes and to ankle injuries in basketball players. The following aspects are discussed: how these injuries are approached in the athletic population, the diagnosis and treatment modalities, and what we can expect after proper treatment and how and when they return to play. Furthermore, interesting statistics, especially for basketball players, are provided. The next section is about the management of pediatric and adult flatfoot deformity and the recent advances in this field. This is a very interesting topic discussing the concept of hyperpronation, minimally invasive techniques, and the differences in management of rigid and flexible flatfoot deformity in young and adult patients. This section also includes posterior tibial tendon dysfunction: the classification and the treatment.

The third section is unique and includes everything about quality control in patients with foot and ankle injuries. I believe this section will be very helpful to foot and ankle practitioners to better assess the functionality and quality of life in their patients. This section includes the different tools and how you implement these in your daily practice.

The last section is about the third generation of percutaneous forefoot surgery, which is a very hot subject. This section describes the different stages of the MIS in the forefoot. With the third-generation advances, this surgery can be more effective with fewer complications. In this section, you can learn the recent advances and surgical techniques. In addition, you can explore a novel system of Diabetes Ground Control. Foot and ankle pathology with peripheral neuropathy, ulceration, Charcot neuroarthropathy, etc. needs better monitoring, and in this chapter, you can find useful tools to do this.

I hope you will enjoy reading the book and refer to it several times. I think it will be a useful tool in your daily practice armamentarium.

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Section 1

# Foot and Ankle Sport Injuries

Chapter 1

# Achilles Tendon and Athletes

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Additional information is available at the end of the chapter

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**Abstract**

Achilles tendon (AT) is the strongest human tendon. AT disorders are common among athletes. AT pathologies vary from tendinopathy to frank rupture. Diagnosis is made clinically. Imaging modalities are used adjunctively. Management of AT rupture in athletes is challenging to surgeons due to worldwide growing popularity of sports and potential social and financial impact of AT injury to an athlete. Hence, new surgical techniques aim at attaining quick recovery with good outcome, finding similar results with both open and percutaneous techniques when accompanying these with functional rehabilitation protocols. Non-operative strategies include shoe wear modification, physiotherapy and extracorporeal shock wave therapy. Surgical interventions vary based on the AT pathology nature and extent. Direct repair can work for small-sized defects. V-Y gastrocnemius advancement could approximate the tendon edges for repair within 2–8 cm original gap. Gastrocnemius turndown can bridge tendon loss > 8 cm. Autogenous, allogeneous or synthetic tendon grafts were used for AT reconstruction purposes. In AT tendinopathies with no tendon tissue loss, surgical procedures revolve around induction of tissue repair through lesion incision or debridement to full detachment followed by reattachment. Extra-precautions are exercised for prevention of AT disorders especially among susceptible athletes participating in sports involving excessive AT strain.

**Keywords:** Achilles tendon, tendinopathy, AT, Achilles rupture, Achilles tendinosis, Haglund's exostosis, athletic injury, sports injury, percutaneous repair

## 1. Introduction

Injuries to the Achilles tendon (AT) are usually related to sports, especially those that involve jumping, running and sudden accelerations, such as soccer, tennis or basketball [1]. A fraction

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of patients with AT injuries tend not to present for medical care as they feel better following the event. On the other hand, healthcare workers fail to identify a quarter of AT injuries on initial presentation [2–6]. Yet, the precise pathogenesis of AT rupture remains unclear in a great deal of cases, partly because many of those patients never had prodromal symptoms [1, 7].

A patient with AT sport-related injury could present with a clinical picture ranging from mild inflammation to permanent injury [8]. These overuse injuries are increasingly reported; this is attributed not only to the rising number of individuals who participate in recreational sporting activities, but also to the greater intensity and duration of training in professional athletes.

In the following sections, reviews on common AT injuries among athletes are addressed namely: acute tears, chronic tears and different types of tendinopathies.

### 1.1. Epidemiology

AT injuries represent up to 50% of all injuries related to sports [1]. AT injury represents 20% of all tendon pathology in the lower limb [9]. It is interesting that AT is the most frequently injured tendon despite the fact of being the strongest and the thickest among human tendons [8, 10]. Sports-related AT conditions are commonly encountered. Runners are often affected with AT tendinopathy. AT overuse is believed to result in insertional tendinopathy [11, 12]. According to Cassel et al. report, 1.8% of adolescent athletes had AT tendinopathy [13]. Incidence of AT injuries is estimated between 10 and 20 per 100,000 population [14, 15]. Raikin et al. studied a group of patients with AT injuries stating that around a quarter of them were chronic cases [6]. Complete spontaneous AT ruptures have a strong association with sports activities [1]. It has been found that 60–75% of all AT ruptures are related to sports [16–18].

In the last decades, it has observed an increase of AT ruptures in the Western countries [1, 7, 19]. Although the epidemiology varies in the athletic population comparing to those who do not practice sports to a competitive level (the risk of sports act) [6]. About 8–20% of all AT ruptures in the general population are diagnosed in competitive athletes and 75% in recreational athletes [7]. Such injuries are common in individuals who are involved in athletic activities which implicate maximal exertion or explosive acceleration [1, 20, 21]. The incidence in each sport is shown differently depending on the country. For instance, basketball is the predominant sport in AT ruptures in the USA and football in Germany; badminton accounts for most in Denmark and Sweden and skiing is found more in Austrian and Swiss reports [7].

Different reports claim predominance AT ruptures in male population, with confusing data being published about this matter. It has been said there is a male predominance in AT ruptures with ratio men to women varying from 3 to 1 and 17 to 1 [7, 22]. However, some reports deny such a relation referring to AT ruptures in professional athletes [23, 24]. This is consistent with the dramatic increase of sports injury in females observed in the last decades, probably due the greater involvement of women in sports [25].

Additionally, it has been said that AT ruptures follow a bimodal distribution referring to age. Different studies describe different age range for the peak incidence, all coincide with the idea that AT ruptures are much more frequent in the aging athlete [1, 7, 21, 26]. Nevertheless, recent studies found no greater risk of developing tendinopathy or rupture in older athletes and aging has an uncertain meaning on tendon health [23, 24, 27].

There is a minor predominance in AT ruptures on the left limb and this could be explained by means of Hooker's hypothesis which states that the left limb is predominant in pushing off, with knee in extension that explaining the higher prevalence in this side among right-handed people [17, 28, 29].

It is been stated that runners show an incidence of AT tendinopathy between 6.5 and 18% representing the most common injury among them [30]. This is not only for the active young athletes, as former elite male runners have shown 52% risk of presenting AT tendinopathy during their entire life [31].

### 1.2. Biomechanics

Biomechanics related to injury of AT is a challenging subject. AT is a part of a complex myotendinous unit working across three joints, when it contracts; it flexes the knee, plantarflexes the ankle and supinates the subtalar joint. The subtalar joint becomes pronated during ambulation and hence forcing internal rotation to the tibia. This happens along with external tibial rotation imparted from an extended knee; AT is then submitted to this two contradictory forces together, causing a powerful stress [32].

AT functions as the major contributor to the plantarflexion of the foot during the gait cycle, contributing up to 93% to this movement [33]. It is subject to repetitive tensile stress and great loads in athletes. It has been estimated that when walking, AT tendon goes under a tension of 250% of the body weight, while the running load applies from 6 to 8 times the body weight, close to the maximum load tolerable by the tendon [26].

AT tendons have visco-elastic properties that allow the tendon itself to absorb energy during the stance phase of gait and to later release it when recoiling, contributing to an elastic movement. This simulates a spring function, especially important when running, as the time of ground contact decreases. The latter makes an important contribution of the tendon to the limb activity and helps to save muscular energy [34].

Tendons that stretch and recoil repeatedly, might ultimately suffer some variations. Due to its intrinsic properties and special material qualities, the AT becomes stiffer when put through rapid, forceful loads [35]. Different researches have investigated about this matter, stating that when applying a load to the entire lower limb modifies its stiffness trying to maintain the homeostasis in the athlete system [27, 36, 37]. Not only repetitive, long-term loading can cause a change in the tendon stiffness, but also single bouts of force applied to the AT tendon would be responsible for such adaptive changes [37]. These adjustments were thought to be reflected by means of increasing the cross-sectional area of the tendon [38, 39]. However, some researchers believe that in response to resistance training, the tendon cross-sectional area is not affected. They recognize the importance of changes in the material composition of the tendon, which augments collagen synthesis and consequently, modifies the tendon properties and increases Young's modulus and stiffness [37, 40, 41]. This is an adaption to repetitive forces which ultimately transforms the tissue composition and biomechanical behavior [37].

### 1.3. Risk factors and patho-etiology

Etiology of AT tendinopathy/rupture is a controversial dispute. Various hypotheses have been postulated in this context such as inflammatory, degenerative, infectious, drug-induced and neurological theories. Risk factors of AT tendinopathy/ruptures are summarized in **Table 1** [8, 42].

Certain drugs like fluoroquinolones and corticosteroids have been associated with higher potential of adverse effects on AT integrity [43]. Animal models have shown variable AT reactions in response to local steroid injections around the tendon compared to intra-substance infiltration [44, 45]. AT weakness with paratendinous injection was often reversible within 2 weeks during which strenuous activities should be avoided [46]. Clinically, AT ruptures have been reported with orally administered steroids [47, 48].

Excessive tendon hyperthermia, particularly during exercise, might lead to AT degenerative process resulting in tendinopathy or delayed disruption [42, 49].

| |
|---|
| *Intrinsic factors:* |
| Aging (not fully proven) |
| Male gender (not fully proven) |
| High body mass index (BMI) |
| Tendon temperature |
| Systemic diseases |
| Muscle physiological and anatomical properties |
| Genetic predisposition |
| Blood supply |
| Malalignment: hindfoot hyperpronation, hindfoot varus |
| Leg length discrepancy |
| Stiff subtalar joint |
| Hindfoot hypermobility |
| Gastrocnemius-Soleus contracture |
| *Extrinsic factors:* |
| Use of drugs: for example, fluoroquinolones, steroids |
| Overuse: frequent micro-injury |
| Sport training errors |
| Sports shoes with AT impingement |

**Table 1.** Risk factors for AT tendinopathy/ruptures (Reprinted from: Alrashidi et al. Achilles tendon in sport. Sports Orthop Traumatol (2015) 31:282-292, Copyright (2018), with permission from Elsevier).

Traditionally, middle age group male subjects with irregular sports involvement were considered candidates for AT disorders [50, 51]. Neither age nor gender has been proven as a risk factor for AT pathologies [42, 52].

It has been observed that incidence of AT injuries increases dramatically with sport seasons and around 76% of AT injuries studied by Scott et al. were sport-related [52]. Hindfoot hypermobility as well as gastroc-soleus incompetence could be a factor in formation of AT tendinopathy among runners based on a biomechanical research study [53]. Malalignment of the hindfoot, particularly hyperpronation, is another identified contributing factor for AT tendinopathy [8].

Tendinopathy might be an element of what was described as "Haglund's syndrome". Repetitive contact between adjacent tissues at the AT/calcaneal attachment area could result in an abnormal mass formation "pump bump" and retrocalcaneal bursitis [54].

Histopathological studies demonstrated multiple forms of degeneration at the affected tendinous regions mainly hypoxic, mucoid, lipomatosis and calcification with predominance of hypoxic degenerative findings [55]. The classical ischemic degenerative hypothesis concerning pathogenesis of AT tendinopathy is not supported by robust scientific basis [56].

Individuals with metabolic conditions like diabetes, hypercholesterolemia, hyperuricemia and alkaptonuria could be more predisposed to have AT tendinopathy/rupture [57, 58].

It is advisable to exercise extra precautions for prevention of AT tendinopathy especially among susceptible athletes involved in AT-unfriendly sports such as running and soccer at the beach on the sand [8].

AT ruptures' etiology is multifactorial, with participation of intrinsic and extrinsic factors, very important when referring to athletes [19, 59]. In sports, training errors may explain some of the injuries in the AT: too rapid increases or alterations in training routines neglecting recovery times, as well as soft training surfaces as track or sand or treadmill running, and unsuitable footwear can contribute to injuries in athletes [18, 26, 27, 33, 60, 61].

Other biomechanical alterations have been examined: forefoot varus seems to have a detrimental effect and hindfoot malalignment is believed to imply a rotational force into the tendon fibers [16, 53]. Many authors consider foot overpronation is related AT injuries although a recent review denies such an important effect [1, 9, 27, 62]. This is reinforced by biomechanical concepts in which, foot overpronation is accompanied by tibial internal rotation, a well know protective factor to AT injuries [27, 63]. Thus, foot pronation seems to display a moderate effect, and the correction should be taken cautiously given the contradictory result [27, 53]. Reduced stiffness during running has been related to AT injuries [37]. Low arch index is coupled with reduced stiffness in the lower limb, predisposing the athlete to suffer from them, while higher arches have a clear large beneficial effect [64, 65].

There are some theories which could explain the tendon degeneration prior to the rupture. Overuse tendon injuries have been described as those in which the tendon has been strained repeatedly, thereby generating cumulative microtrauma, until the tendon's reparative ability is compromised, leading to injury [55]. Histopathologic studies on ruptured AT showed that a high percentage (from 74% up to 97%) had clear definitory degenerative changes [66, 67]. This theory is also reinforced by different studies that support a poor blood supply due to the repetitive injuring mechanism might damage the tendon in the less vascularized areas—2–6 cm above the calcaneal insertion, precisely where the mid-portion AT ruptures most frequently occur [7, 66, 67].

There is also a mechanical theory in which, the dysfunction of the musculotendinous unit is claimed to be the main cause of rupture, causing an dis-coordinated or excess of muscle contraction that leads to rupture [7]. Three main types of indirect trauma have been described to cause an AT rupture: (i) pushing off while extending the knee, this occurs at the beginning of a sprint, running and jumping (53%); (ii) violent dorsiflexion of the ankle joint in a plantarflexed foot, as occurs when jumping or falling from a height and landing with the foot plantarflexed(10%) and (iii) sudden unexpected dorsiflexion of the ankle, when slipping on a ladder or stepping into a hole or in an unexpected fall (17%) [26, 68].

## 2. Acute Achilles rupture

### 2.1. Presentation

Patients with acute AT tear commonly present with sharp acute-onset pain at the posterior heel associated with forceful ankle push-off or sudden ankle dorsiflexion. An abnormal pop might be felt by the patient. Immediate swelling and walking inability are usually accompanying complaints [69, 70].

Two descriptions related to mechanism of acute AT rupture were reported. AT is subjected to extra rotational forces beyond its strength as the foot is forced into extreme pronation. The second explanation is the occurrence of an abrupt interruption of triceps surae eccentric contraction during support phase [71].

### 2.2. Diagnosis

Diagnosis of AT ruptures is quite straightforward if an appropriate patient history assessment and clinical examination are carried out [67]. However, up to 25% of acute AT ruptures are missed by practitioners [7].

Patients often describe an abrupt 'pop' in the AT area associated with the feeling of being 'kicked by someone. They usually report pain that diminishes sometime after the injury and they remain unable to bear weight or to perform heel rises with the damaged limb [72]. Nevertheless, some of the patients use the extrinsic foot flexors showing remnant function of the ankle.

Regarding clinical examination, edema and bruising are found in most of the patients. A palpable gap may be present—usually 2–6 cm proximal to the insertion of the tendon (**Figure 1**). The diagnosis should be completed with other confirmatory tests, such as:

- The popular Simmond's and Thompson's tests: squeezing the calf to check failure of plantar flexion in AT ruptures [69, 73]. Nevertheless, partial AT ruptures can be missed with this maneuver. A cadaveric study showed that loss of more than 25% of AT tendon substance is required to be detected on Thompson's test [74].
- Matles test: shows a discrepancy of passive plantarflexion between healthy and affected limb [75].
- O'Brien test: an invasive test that uses a needle going all the way through the skin, to the substance of the proximal tip of the tendon. Plantarflexion of the foot will not produce any movement in the needle, diagnosing the rupture [76].
- Copeland test, measuring the elevation of pressure with a sphygmomanometer. The increase of pressure will be close to none in ruptured AT tendons when plantarflexion is forced [77].

Because diagnosis of AT ruptures is mainly clinical, imaging studies have little role in this aspect and should be reserved for uncertain diagnosis or differentiating between partial and complete tears [40, 78]. Diagnosis of acute AT rupture should be made on clinical basis. Relying on imaging diagnostics is questionable [79]. Plain radiography could visualize the soft tissue defect and associated avulsion fractures, if present [26]. Disruption of Kager triangle or presence of Toygar sign is suggestive of AT rupture [24, 80].

Ultrasonography (US) is noninvasive, rapid, repeatable and it allows practitioners to perform a dynamic study [40]. It is also used as part of the treatment follow-up and to measure the gap in between the tendon ends; and may give information about the risk of re-rupture preoperatively. Tendon defects appear as hypoechoic areas on ultrasound images [81, 82].

**Figure 1.** A clinical photo of an acute AT rupture. There is an obvious discontinuity of the tendon (this photo is courtesy of Fernández Torres, MD).

Magnetic resonance imaging (MRI) is a much more expensive technique and it does not allow a dynamic examination. However, it is much more reliable than US to diagnose any AT pathology—including partial ruptures, a very common injury in athletes, with higher sensitivity and specificity than US [7, 83]. Thus, it has been recommended to use MRI for the definitive diagnosis, especially when a partial rupture is suspected. However, it is been demonstrated that not only is MRI expensive, but also it is time consuming, with a mean of 5 days to obtain the images that could mean a delay on the treatment, a crucial factor in recovery for athletes [84]. Moreover, acute AT tears can be demonstrated as focal or linear defects particularly on MRI T2 weighted studies. Bony edema and the retrocalcaneal bursa effusion are characteristic for insertional AT ruptures which can be identified on MRI images [85].

Based on American Academy of Orthopedic Surgeons (AAOS) recommendations, at least two of the following clinical findings are required along with full medical history to establish a diagnosis of acute AT rupture: palpable gap, increased ankle dorsiflexion with gentle passive motion, weakness of ankle planter flexion and positive Thompson's (Simmonds's) test [79].

### 2.3. Treatment strategy

Non-operative treatment involving weeks of limb immobilization using a plaster or brace is known to have high re-rupture rate, which may lead to loss of considerable time off-athletic activity, which is probably not acceptable to athletic people [86]. Prolonged immobilization has been found to cause atrophy of calf muscles and relatively weak healing of tendon [87, 88]. Adding to the previous factors and high expectations of such patients, there has been a tendency to achieve optimal outcomes and lessening the risk of re-rupture through surgical repair [29, 87, 89]. However, certain conditions may make surgical options unfavorable such as diabetes mellitus, neuropathy, immunodeficiency, elder people (age above 65), smoking, sedentary lifestyle, high body mass index, peripheral vascular disorders or regional/systemic dermatologic diseases [79].

Acute AT ruptures with small defects within one-centimeter length usually heal adequately with immobilization in plantarflexion (**Figure 2**) [90, 91]. Conservative treatment course usually lasts for 8–10 weeks. The amount of plantarflexion is decreased gradually in a stabilizing boot to neutral position. A suggested program includes physiotherapy and serial adjustments from plantarflexion of 30° for 2 weeks adjusted to 15° for additional 2 weeks reaching plantigrade foot by the 5th week. Conservative method has increased risk of AT re-rupture and atrophy of calf muscles [22, 92–95]. Non-operative strategy requires rigorous follow-up and skilled orthopedic surgeon [96, 97]. Adjunctive use of platelet-rich plasma (PRP) in acute Achilles rupture is not yet proven [98].

Management of AT rupture in athletes is challenging to the surgeon owing to the high importance of sports worldwide and possible social and financial consequences of an injury to both the player and the team. Thus, new surgical techniques aim at attaining quick recovery with good outcome [86, 89].

Surgical options include open, mini-open and percutaneous techniques [99]. Open repair has shown good outcome postoperatively, but carries high risk of wound complications [24, 86, 95, 100]. Open repair of acute AT rupture is considered the standard surgical intervention.

**Figure 2.** A cast, which is applied in equinus as part of conservative treatment of acute AT rupture (this photo is courtesy of Fernández Torres, MD).

**Figure 3.** An illustration of a patient with acute AT rupture showing hematoma and degeneration of the tendon fibers (this photo is courtesy of Fernández Torres, MD).

Many techniques and modifications have been described in this setting [24, 101–103]. Open method offers full exploration of the injured tissues, adequate debridement, good assessment of tendinous defect and reliable repair strength (**Figure 3**).

Percutaneous techniques have demonstrated an improved outcome since its introduction [104]. Some studies recommend to do percutaneous repair in athletes rather than open [89]. Percutaneous techniques are advantageous in decreasing soft tissue damage, which consequently may improve time to recovery and rehabilitation [24, 89]. Adding to that, some studies demonstrated better outcome of percutaneous repair in acute AT ruptures in terms of less expected infection, adhesions, deep venous thrombosis and have less costs and quicker recovery period [31].Other studies showed no difference regarding results of both techniques [99, 105]. In contrary to open repair, percutaneous repair has a comparable re-rupture rate [95, 99, 106]. On the other hand, sural nerve injury and inability to address the torn soleus component are possible drawbacks of percutaneous methods. Hence, some surgeons do not prefer such a method as it is believed that soleus contributes significantly to the overall AT strength with no less than 40–52% [8, 10, 22, 99].

In professional athletes with acute AT rupture, some surgeons prefer to do mini-open approach to reduce skin complications and allow for faster recovery. Postoperative care program consists of 8–10 weeks of immobilization in an adjustable boot with intermittent physiotherapy. Functional rehabilitation protocols have been established to achieve a fast and successful recovery, showing a reduction of complications associated with cast immobilization without increasing the re-rupture rate. These protocols vary depending on the chosen surgical technique, being the percutaneous surgeries the ones who allow the patient do prompt mobilization and weightbearing [95, 99, 107–109]. Initially, the foot is kept plantarflexed then gradually stretched to neutral position [8].

Time to return to sports ranges from 4 to 6 months based on the sport type. Sanchez et al. claimed that addition of PRP injection along with acute surgical repair can shorten the time to return to sports [110]. However, a randomized controlled trial has shown no significant acceleration in healing of acutely repaired AT [111].

Regardless to treatment approach, resumption of pre-injury normal walking could happen within 12 weeks [112, 113]. Involvement in a functional rehabilitative program remarkably shortens this time to 8 weeks [113, 114]. At least, 4–6 months are required to return to sports. Contact sports need longer periods [8].

Outcomes of treatment of acute AT can be assessed with clinical examination particularly in unilateral cases where the normal side is available for comparison [115]. No significant consistency was appreciated between the clinical scoring systems and biomechanical studies outcomes in treated ruptured AT cases. It seems that trauma to the AT inherently lowers its biomechanical properties to a certain extent. Specific peculiarities were observed during gait analysis in injured AT kinematics. Excessive eversion and diminished peak planter flexion torque (PPFT) at stance phase were noticed in this group of patients [71, 116]. Maximum calf circumference (MCC) correlated well with PPFT and push-off force (POFF) [116]. AT total rupture score (ATRS) is a validated scoring system which provides a reliable instrument to evaluate torn AT post-surgical repair [117, 118].

Heel rise height can be used as an indicator of postoperative functional performance. Heel rise height tends to get less as age increases. Young men scored higher on 12-week-evaluation in terms of functional outcomes. Obese individuals were more symptomatic. Both surgical and non-surgical treatment provided no clue about the final functional outcome. Type of treatment could predict moderately the intensity of subsequent symptoms [119, 120].

## 3. Chronic Achilles rupture

### 3.1. Clinical presentation and diagnosis

Up to authors' knowledge, there is not yet a consensus on the time-limit after which AT injury could be accurately described as chronic. Generally, AT rupture can be labeled as chronic after

4–6 weeks have passed after the injury [2, 6, 8, 85]. Moreover, cases which did not show healing signs or presented after 4 weeks of initial injury is thought to be "chronic" irrespective of rupture etiology [3, 51].

Chronic AT ruptures can present with pain, gait changes, calf muscle wasting and impaired push-up. Adding to that, dramatic effect of physical or athletic activities such as walking, jumping or using of stairs becomes obvious [2]. In some occasions, the rupture defect may be filled with a scar tissue [2, 3, 50]. Such a scar is often not of the same physiological properties (e.g. elasticity and excursion) to substitute a normal AT tissue and subsequently cause a noticeable effect on gait [121].

Chronic AT tears are visualized as low-signaled lesions on MRI images. Furthermore, amount of tissue loss can be measured. Postoperative evaluation of repaired or transferred tissues can be obtained through MRI [85].

### 3.2. Treatment strategy

Non-operative treatment of chronic AT ruptures commonly ends with unsatisfactory outcomes. Consequently, most surgeons prefer surgical treatment approach for cases of chronic AT tears [122]. Chronic AT ruptures with unremitting pain, instability or functional limitations in terms of daily activities or sports performance are considered reasonable indications for surgical reconstruction [121]. Defects of less than 3 cm can be amenable to end-to-end anastomosis. Gastrocnemius-soleus V-Y advancement is useful to manage gap within 2–6 cm in length (**Figure 4**). Gastrocnemius turndown procedure is preferred to address Achilles defects of greater than 6 cm. Plantaris tendon can be employed to augment the repair area [8, 122]. Anterior paratenon harbors the key blood supply to the repair area and should be protected [51].

**Figure 4.** A clinical photo demonstrating V and Y technique for treatment of chronic AT rupture (this photo is courtesy of Fernández Torres, MD).

Chronic AT ruptures are categorized into 3 types according to Myerson: type I includes defects under 2 cm; type II which has a defect ranging from 2 to 5 cm; and type III defect which exceeds 5 cm in size [85].

Tendons of adjacent muscles can be incorporated within AT reconstruction avoiding free graft complications. Sadek et al. reported good satisfaction among 18 patients with Myerson type III AT defects following local reconstruction with triple loop of plantaris tendon along with turndown flap [85]. Instead of removing scar tissue filling the tendon defect, Khaimi et al. advocated including tubular scar tissue within AT reconstruction procedure. Khaimi and colleagues performed shortening Z-plasty of the fibrotic tissue across the defect and augmented that with free sural triceps graft [121]. Besse et al. reported satisfactory results in six subjects with long-standing terminal ruptures of AT using bone-tendon autograft obtained from knee extensor mechanism [123].

For the sake of having more reliable repair, Esenyel et al. attempted adding mesh (Hyalonect) to the gastrocnemius turndown flap in 10 patients. Those patients scored significantly higher postoperatively on AOFAS (American Foot and Ankle Society) score [124]. Similarly, Ibrahim et al. reported good outcomes combining surgical repair with a synthetic polyester graft in 14 chronic AT ruptures [3].

Allografts and synthetic grafts could reduce the operative time by eliminating the harvest time. Avoidance of donor site complications is an advantage of using allografts. Moreover, allografts are relatively biologically active. Allograft-related disadvantages include risk of disease transmission and graft-versus-host disease [2]. Nellas et al. indicated reasonable results following AT reconstruction with freeze-dried allogenic AT grafts [51]. AT reconstruction using polypropylene mesh (Marlex) was reported by Choksey et al. in five cases with promising outcome [125].

Idealization of tension across the repair site of AT is of paramount importance. Weak push-off is predicted with very lax repaired AT. Equinus deformity might be due to overtightening of AT repair. Knupp and Hintermann emphasized using the contralateral side as a control to optimize the desired amount of tension [122].

Paavola et al. followed up 432 patients with surgical AT procedures for 1 year looking for complications. There were 46 patients suffered from complications which required re-operation in 11 of them. The main complications identified were superficial infection, transient sural nerve palsy, incomplete re-rupture and thromboembolism [126].

## 4. Achilles tendinopathy

AT tendinosis is a term that includes a series of different degenerative processes without clinical or anatomopathological signs of inflammation [25, 127]. It is been suggested that tendinosis is the ultimate consequence of repetitive stress applied to the tendon, that is unable to create a homeostasis between synthesis and degeneration of the cell matrix [128].

Grossly, AT tendinopathy can be classified as insertional (pain at the insertion of the tendon to the calcaneus) and non-insertional (lesion found in mid-portion of the tendon).

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### 4.1. Presentation

A detailed medical history should be elaborated including data about the timing and nature of injury, any history of infection, use of steroids, sport shoe type of usual use and any previous orthopedic interventions for the same injury [8].

In 1998, Maffulli et al. has described AT tendinopathy as heel pain and swelling associated with decreased performance of the tendon [127]. An exostosis may be felt at the postero-superior aspect of calcaneus which was called "Haglund's deformity". Mechanical irritation from such a prominence may lead to retrocalcaneal bursitis [54]. In 2011, new terms have been proposed by van Dijk et al. for better guidance of diagnosis and treatment of different AT disorders. Such disorders are summarized in **Table 2** along with their anatomical location and clinical manifestations [129].

### 4.2. Diagnosis

Clinical examination should aim at identifying any systemic or local risk factors of AT tendinopathy (**Table 1**) [8]. The site of pain is localized, whether insertional (within 2 cm from insertion) or mid-portion (within 2–7 cm above the insertion) tendinopathy; any palpable gap, swelling, crepitus or nodules [129–131].

Calcifications of AT in addition to bony spur (Haglund's deformity) can be appreciated from plain radiographs. Some radiographic parameters have been suggested to diagnose bony spur such as Fowler's angle [132, 133].

| Disorder | Anatomical location | Manifestations | Clinical signs |
|---|---|---|---|
| Mid-portion tendinopathy | 2–7 cm from AT insertion | Pain, swelling and impaired performance | Diffuse or localized swelling |
| Acute paratendinopathy | Around mid-portion of AT | Edema and hyperemia | Palpable crepitations and swelling |
| Chronic paratendinopathy | Around mid-portion of AT | Exercise-induced pain | Crepitations and swelling less pronounced |
| Insertional tendinopathy | Within 2 cm of insertion onto calcaneus | Pain, stiffness, sometimes a (solid) swelling | Tenderness of AT insertion at mid-portion of posterior aspect of calcaneus. Swelling may be seen and a palpable bony spur may be found |
| Retrocalcaneal bursitis | Retrocalcaneal recess | Painful swelling superior to calcaneus | Painful soft tissue swelling, medial and lateral to AT at level of posterior superior calcaneus |
| Superficial calcaneal bursitis | Bursa between calcaneal prominence or AT and skin | Visible, painful, solid swelling postero-lateral calcaneus (often associated with shoes with rigid posterior portion) | Visible, painful, solid swelling and discoloration of skin. Most often located at postero-lateral calcaneus; sometimes posterior or posteromedial |

**Table 2.** Achilles tendon disorders and their anatomical location, symptoms and signs (adapted from van Dijk et al. [129]).

| AT disorder | Plain radiography | US | MRI |
|---|---|---|---|
| Mid-portion tendinopathy | Deviation of soft tissue contour is usually present.<br>In rare cases calcifications can be found | Tendon larger than normal in both cross-sectional area and antero-posterior diameter.<br>Hypoechoic areas within the tendon, disruption of fibrillar pattern, increase in tendon vascularity (Echo-Doppler) mainly in ventral peritendinous area | Fat-saturated T1 or T2 images: fusiform expansion, central enhancement consistent with intra-tendinous neovascularization |
| Acute paratendinopathy | — | A normal Achilles tendon with circumferential hypoechogenic halo | Peripheral enhancement on fat-saturated T1 or on T2 images |
| Chronic paratendinopathy | — | A thickened hypoechoic paratenon with poorly<br>defined borders may show as a sign of peritendinous adhesions; increase in tendon vascularity (Echo-Doppler) mainly in ventral peritendinous area | |
| Insertional tendinopathy | May show ossification or a bone spur at the tendon's insertion; possibly deviation of soft tissue contours | Calcaneal bony abnormalities | Bone formation and/or on STIR (short tau inversion recovery) hyperintense signal at tendon insertion |
| Retrocalcaneal bursitis | A postero-superior calcaneal prominence can be identified; radio-opacity of the retrocalcaneal recess; possibly deviation of soft tissue contours | Fluid in the retrocalcaneal area/bursa (hyperechoic) | Hyperintense signal in retrocalcaneal recess on T2 weighed images |
| Superficial calcaneal bursitis | Possibly deviation of soft tissue contours | Fluid between skin and Achilles tendon | Hyperintense signal between Achilles tendon and subcutaneous tissue on T2 weighed images |

**Table 3.** Radiologic signs of AT disorders (adapted from van Dijk et al. [129]).

MRI and US can help in diagnosis of different AT disorders. The radiographic signs of AT disorders are summarized in **Table 3** [129, 134]. In case of suspected underlying metabolic disease, laboratory studies should be considered to predict any healing problems associated with those diseases and further treatment, if indicated [58].

### 4.3. Treatment strategy

Initial treatment regimen of AT tendinopathies includes a course of AT eccentric exercises and/or extracorporeal shockwave therapy (ESWT). Surgery is considered if no significant response to non-operative treatment [135–137].

Rompe et al., in RCT, found a comparable outcome of AT eccentric exercises and low shock-wave therapy at 4th month of outpatient visit [135]. Another high-level study did not show any superiority of heavy slow resistance exercises or eccentric exercises over another in cases of mid-portion tendinopathy, but slow resistance exercises showed a higher patients' satisfaction after 12th week of outpatient follow-up [138].

A recent systematic review has suggested that low-energy ESWT is successful in reducing manifestations of both insertional and mid-portion AT tendinopathies if used over a period minimum of 3 months. Better results are expected if AT eccentric exercises are performed during ESWT treatment period [139]. Another study, an RCT, suggested that physiotherapy and the use of custom made insoles for period of 4 weeks showed a significant alleviation of pain among athletes who were diagnosed as chronic AT tendinopathy, without modification of their athletic activity during treatment period [140]. Modification of shoe wear (e.g. Rocker shoe) and using shock-absorbing insoles may help in prevention of AT tendinopathy [141, 142].

In RCT, by de Vos and colleagues, PRP injection as an additional modality to exercises did not show any significant effect on subjects suffering from mid-portion AT tendinopathy in contrast to patients managed by exercises and placebo [143]. It is claimed that concentrates of platelets were found to have in vivo potential to enhance creating the granulation tissue and helping in repair of AT tendon defects. The latter process was not shown to be applicable in AT tendinopathy [144]. Another double blinded study by de Vos et al. involved 54 patients with chronic AT mid-portion tendinopathy and followed for 24 weeks. They found no significant difference between the PRP group (PRP injection and eccentric exercises) and the placebo group (placebo injection and eccentric exercises) in terms of alteration in tendon ultrasonic picture or vascularity [145].

Operative treatment is indicated in patients who are not responsive to conservative protocols (3–6 months). Generally, surgical option is selected according to the clinical and radiological signs of individual cases. Insertional AT tendinopathy can be treated by open or endoscopic techniques which may include removal of retrocalcaneal bursa, tendon debridement, detachment and reattachment of tendon, intra-tendinous bone excision and/or removal of postero-superior calcaneal prominence [8]. Radiological finding of postero-superior calcaneal prominence (Haglund's exostosis) is not an indication per se for operative treatment and may not explain the reason behind patient's manifestations [54].

Non-insertional AT tendinosis can be addressed via different surgical options. All of them try to remove the abnormal tissue on the tendon itself and the paratenon and promote the healing process through origination of new viable tissue and vascularization [146]. These options include percutaneous tenotomy, tendon stripping through MIS and endoscopic and open tendon debridement with or without augmentation techniques [147–150].

## Conflict of interest

All authors declare that there is no conflict of interest related to this manuscript.

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Chapter 2

# Ankle Injuries Associated with Basketball Practice: Current Situation and Literature Review

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Additional information is available at the end of the chapter

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**Abstract**

**Introduction**: Basketball is one of the most practiced sports in the world. Traditionally, it has been considered that it is a sport of low physical contact, and that sports injuries occur less frequently than in other sports such as football or rugby. However, we have seen the appearance of several recent studies that count basketball as one of the sports with higher injury rates, and among them, especially ankle injuries. **Material and methods**: In our study, we performed a literature review on ankle injuries associated with basketball practice. We selected the relevant articles of Pubmed using the keywords "basketball", "ankle" (ankle) and "injury", published between 2006 and 2015. We limited the selection to those studies that dealt with injuries associated with basketball, whether descriptive or analytical, without taking into account the populations that the authors studied or whether in addition to basketball, other sports were included. The exclusion criteria were as follows: experimental studies, case reports and then whose text is impossible to obtain. **Results and discussion**: Initially 114 studies were obtained, of which 13 were selected applying the previously mentioned criteria. They observed the incidence of ankle injuries during basketball practice in different population groups, different levels of practice (professional and amateur) and during different periods of time. Among professional athletes, we could observe that ankle sprains account for more than 20% of the injuries suffered by athletes that they are accountable for almost 10% of the matches that a professional player loses because of an injury, and that only about half of them take place during a game, which increases the importance of injuries that occur during practice. When it comes to amateur level basketball, we can observe in several studies that, while the male population is more prone to need medical assistance for ankle injuries during the practice of this sport (from 18.3% of injuries associated with basketball, up to 52%, according to the series), the female population has a greater predisposition for knee

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injuries (63% of injuries associated with basketball for only 21% of ankle injuries in some jobs). **Conclusions**: After analysing the recent literature, we could draw among others the following conclusions: basketball is a sport which is closely linked to the appearance of ankle injuries; the most prevalent ankle injury is sprain; the incidence of injuries increases the higher the level of practice, being maximum in professionals; these injuries have an evident impact on the athlete's usual sports and extrasports practice; and gender may have an influence on the joint affected by basketball related injuries. Basketball is a rising sport at the moment, with a great social and economic impact in the world of today. Its practice is becoming more frequent, and with it the incidence of injuries associated with it, especially those occurring in the ankle joint. It is therefore expected that in the coming years, we are likely to observe the appearance of more works in the literature that confirm this fact, as well as advances in the treatment and recovery of the athletes who suffer them.

**Keywords:** basketball, ankle, sprain, injury

## 1. Introduction

Basketball is one of the most popular sports worldwide. [1] In some countries, such as the USA, it occupies the first place in the sport popularity rank, while on many others, if not the first, it holds one of the top positions.

Those who practice basketball tend to start at early ages, and from that moment on, this sport allows many different degrees of dedication, which extend from sporadic practice to professional basketball. As it is obvious, higher levels of competition associate with an increased incidence of injuries. Professional basketball today has become a highly physical, high-contact sport.

Traditionally, basketball was regarded as a safe sport in terms of risk of injury, mainly because it is a non-contact sport. However, it has drawn attention in the scientific literature of injury surveillance during the last years, and now it is considered the most dangerous non-contact sport in terms of injury [1].

Among all the different kinds of injuries that one can suffer during basketball practice, ankle injuries are perhaps the most frequent. Depending on the series, more than 50% of time loss due to an injury in professional basketball players derives directly from ankle injuries. In addition, all through the actual bibliography one can find that ankle injuries are also the most frequent in those who practice it outside the professional sphere. These numbers become more preoccupying when we find that many of these cases those who suffer ankle injuries do not seek professional care [2].

Several risk factors have been associated with the odds of suffering an ankle injury during basketball practice [2], the main listed: first, having suffered a previous ankle injury. Second, not using proper equipment specially referred to footwear. Last, performing an improper stretching and/or warm-up before the game.

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As we can see, ankle injuries may result from many different kinds of basketball practice. The aim of this study is to perform a bibliographic review on the prevalence of ankle injuries that take part during basketball practice.

## 2. Materials and methods

A literature search was conducted using the PubMed database. We used the following keywords: basketball, ankle and injury, in order to obtain as much relevant literature as possible. In order to limit the search to the most recent articles, we limited our search to the last 10 years (2006–2015).

After the search was finished, we ended up with 114 results. All abstracts and titles were analysed in order to identify those articles that had studied the prevalence of ankle injuries during the practice of basketball, in any kind of population or in association with any other sport. Only descriptive or analytical studies were included. Case reports, literature reviews and experimental studies were discarded, where the full text of the article was unobtainable for any reason. All phases of the selection process are detailed in **Figure 1**.

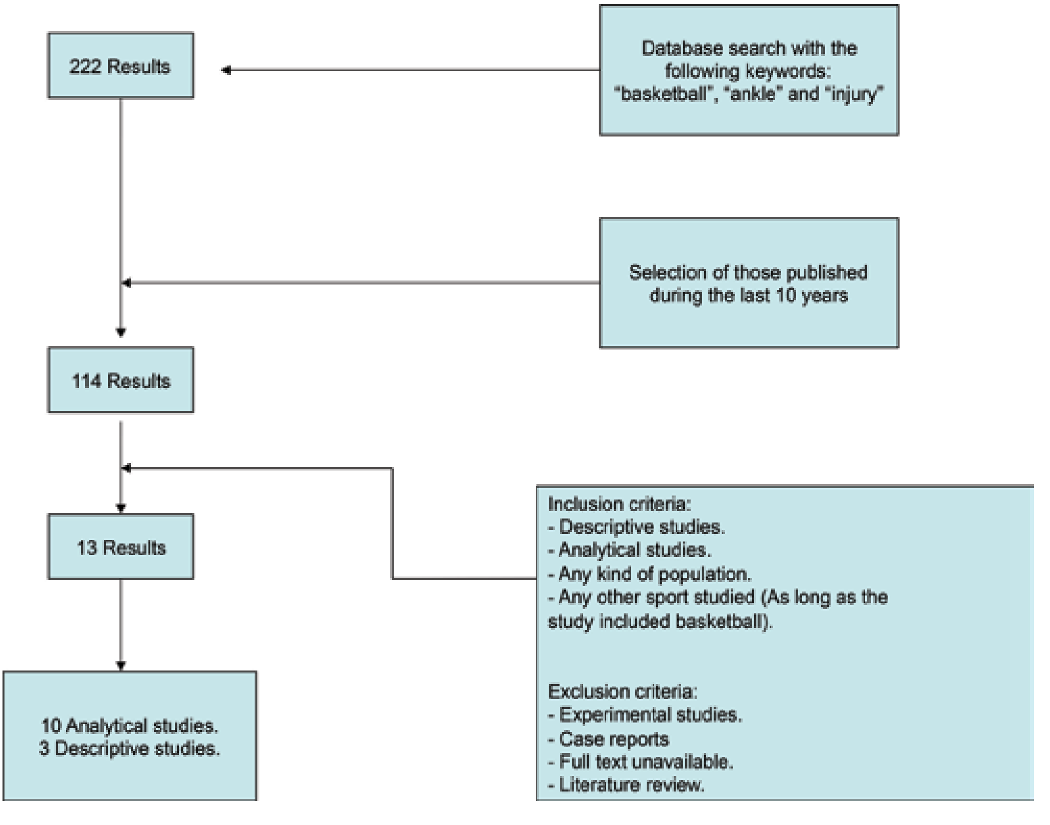


**Figure 1.** Chart which shows the selection process of the papers that were included in our study.

## 3. Results

After applying the inclusion and exclusion criteria, we were left with 13 articles, of which 3 were descriptive studies and 10 were analytical studies. All of them are listed in **Table 1**.

When we analyse the whole set of studies, the first thing that stands out is the fact that the population groups are very different from each other, both regarding their ages and gender, also their occupation and level of play. Moreover, the studies' designs also varied greatly comparing one to the other. As a whole, these studies tend to conclude that ankle sprains are one of the most frequent injuries during any kind of basketball practice, if not the most.

Cumps et al. [1] studied senior players (mean age 23.7 years ±7) of different levels of play during a whole competitive season. During this study, 164 total players were recruited, and the goal was to assess the overall incidence of acute and overuse basketball injuries. After observing prospectively the population, which consisted of 81 male and 83 female players, the researchers concluded that the incidence of ankle sprains as a direct consequence of practicing basketball was 6/1000 play hours, which made them the most frequent acute injury. As a matter of fact, the study also states that the main trigger for an ankle sprain would have been the act of landing on an opponent's foot after a jump, and so, jumping tasks would be the ones which is the reason for higher risks of ankle sprains (52.9% of total) in contrast to such others as cutting (11.8%), running to score (11.8%) or passing and receiving (5.9%).

This last conclusion would match with the one made in Nelson et al. [3] work, which stood that rebounding would be the activity associated with the greatest proportion of ankle injuries, and that among the different positions, basketball centres would be at higher risk. Similar to Fernandez et al. [4] and Borowski et al. [5], Nelson's group gathered a study population consisting in 100 random US high schools. The goal of the three articles was to observe these populations for 1 [3, 4] or 2 school years [5] for sports-related injuries. While in the first case [3], basketball was the top sport in ankle sprains incidence rates, in Fernandez et al. [4] experience, basketball was moved to the third position in that aspect, after football and soccer. In addition, what stands out from these two studies is the difference in injury rates per athlete exposure. Nelson et al. [3] calculated an ankle injury rate of 5.23 per 10,000 athlete exposures, Fernandez et al. [4] observed a 1.31/1000 rate for boys and 1.36/1000 for girls. Both studies would conclude in fact that basketball is one of the top sports accountable for ankle injuries during high school practice.

A similar conclusion and a similar design could be found in Borowski et al. [5] conclusions. This descriptive study also gathered a population of 100 random US high schools, but unlike Nelson et al. [3] and Fernandez et al. [4], they focused only on basketball-related injuries. Their goal was to prove that basketball injury rates differed by gender and type of exposure. After a 2-year-follow-up, their conclusions were that they in fact did. Injury rates per 1000 exposures were far higher during competition (3.27) than during practice (1.40), with a 95% confidence interval, 2.10–2.57. Significant differences were also observed in gender, as girls held a 2.08 injury rate in contrast to the 1.83 that boys did (95% confidence interval, 1.03–1.26). In both groups, the ankle and foot were the most injured parts of the body (39.7%), and sprains the most frequent kind of injury (44.0%). These sex differences

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| Author/year | Participants | Results | Comments |
|---|---|---|---|
| 1. Cumps et al. [1] | 164 senior (23.7 ± 7.0 years) basketball players of all levels of play | Ankle sprains and overuse knee injuries were the most frequent.<br>Ankle sprains were re-injuries in 52.9% of cases. | The mean absence from basketball activity after an acute injury was 2 w 5 d (± 5 w 1 d). |
| 2. Ito et al. [7] | 1219 basketball players (professional and amateur) attending a Sports Medicine Clinic.<br>1991–2011.<br>Mean age was 19.4 years (8–39). | 1414 injuries listed.<br>Foot and ankle: 24.8% male, 23.8% female.<br>Most frequent kind of lesion: sprain. | Knee most frequent (41.7% male, 50.4% female).<br>Most did not seek medical attention. |
| 3. Kim et al. 2014. | 268 female athletes (162 basketball).<br>Public school during 3 sports seasons. | 84 basketball – related injuries.<br>Most common part of the body injured was the knee (67.9%), followed by ankle (21.4%). | 46.4% injuries during competition.<br>53.3% injuries during practice. |
| 4. Pappas et al. [2] | Patients aged 7–17 consulting to ERs for basketball-related injuries Jan 2001 to Dec 2006.<br>(NEISS data). | 9790 annual injuries for an estimated 325,465 US-wide.<br>21% ankle sprains (most common diagnosis). | 7–11 year group accounted for 18.9% of all injuries.<br>12–17 year group accounted for 81.1%.<br>Higher rate of ankle sprains among boys and finger sprains among girls. |
| 5. Waterman et al. [12, 13]. | 100 random hospitals. All ankle sprain injuries presented.<br>(NEISS data). | 82,971 annual ankle sprains.<br>20.3% of total were basketball related.<br>41.1% sustained during sports were basketball related. | Estimated 3,140,132 US-wide ankle sprains.<br>An age of 10 to 19 years old is associated with higher rates of ankle sprain. |
| 6. Deitch et al. [9] | NBA database (702 players) and WNBA database (443 players).<br>6 full seasons. | Ankle sprain accounted for 21% injuries (most frequent injury) during game competition and/or practice. | WNBA players had higher injury rates than NBA players. |
| 7. Drakos et al. [10] | NBA database from season 1988–1989 to 2004–2004.<br>1643 players with 12,594 injuries. | Ankle was first joint in injury frequency (14.7%).<br>Ankle sprains were the most common injury (13.2%) | Ankle sprains were responsible for 8.8% games missed due to injury.<br>49.9% injuries took part during game play. |
| 8. Waterman et al. [12, 13] | USMA cadets from 2005 to 2007. | 614 ankle sprains during 10,511 person-years. | Basketball's incidence rate was 1.67 for men (highest among all sports) and 1.14 for women. |
| 9. Borowski et al. [5] | 100 US high schools during 2005–2006 and 2006–2007 academic years.<br>780,651 AEs. | 1518 basketball related injuries.<br>Injury Rate: 1.94/1000 AEs. (2.08 girls and 1.83 boys). | Girls' rate was significantly higher ($P < 0.01$).<br>Time loss: less than a week: 51.3%. 1 to 3 weeks (30.0%). More than 3 weeks (8.1%) |

| Author/year | Participants | Results | Comments |
|---|---|---|---|
| 10. Fong et al. [6] | 1715 sports related injuries attending an ER department during 2005. | 32.9% derived from basketball (most).<br>81.3% were ligament sprains.<br>Mean age was 24.6 years. | — |
| 11. Hammig et al. [11] | Data from the 1997–2004 National Ambulatory Medical Care Survey.<br>507,000 adults aged 20–59 with basketball related lesions. | Ankles sustained 18.3% injuries.<br>Sprains were the most common injury (31.3%). | 93% ankle sprains received radiological procedures.<br>Females (0.8/1000) had a much lower rate of visits than males (5.7/1000). |
| 12. Fernandez et al. [4] | 100 US high schools in 2005.<br>2289/4350 lesions were low extremity. | Basketball was 3rd in injury rate (1.31 per 1000 athletic exposures). | Estimated 807,222 low extremity lesions per year nationally.<br>Fractures were most common in ankles (41.8%).<br>8% boys and 7% girls needed surgery. |
| 13. Nelson et al. [3] | 100 US schools during the 2005–2006 academic year. | Basketball accounted for 23.8% of all ankle injuries (boys 12.2%, girls 11.6%). | Rebounding was the activity associated with a greatest number of ankle injuries. |

AE: Athlete exposure: 1 athlete participating in 1 basketball competition or practice.

**Table 1.** A summary of the papers that was revised in this study.

are not universal, however. For example in Fong et al. [6] work, which studied 1715 sports injuries attending an emergency department during the year 2005, it is stated that 80.4% of those patients seeking healthcare after a sports-related injury were male. Furthermore, Ito et al. [7] group did not find significant differences in gender upon analysing foot and ankle injuries in male (24.8% of all basketball-related injuries sustained by 1219 players attending one sports medicine clinic between 1991 and 2011) and female population (23.8%).

Another interesting statement held by Ito et al. [7], and confirmed by Kin et al. [8] was that the ankle did not necessarily have to be the most frequently injured body site. Although the studies listed above did sustain that the ankle was the most injured site deriving from basketball practice, both these authors sustained that it was the knee followed by the ankle (in these studies, sprains were still the most frequent injury however). In addition, in Ito et al. (7) conclusions, female athletes were at a higher risk of suffering a knee injury (50.4% of all female injuries) than male athletes (41.7% of all male injuries). This fact is also sustained by Kin et al. [8], who observed 84 basketball-related injuries in 162 female athletes during three sports seasons and found out that 67.9% of the sustained injuries affected the knee.

Evangelos Pappas et al. [2] stated that not only gender, but also age was an independent risk factor for basketball injuries. In their study, Pappas et al. [2] analysed 325,465 annual visits from paediatric patients (aged 7–17) to US emergency departments (ED) from 2000 to 2006. They separated the patients into two groups of age (7–11-year-old and 12–17-year-old). Their results were overwhelming. The 7–11-year-old group accounted for 18.9% of all basketball-related injuries, and the 12–17-year-old group, for 81.1%. The two most frequent diagnoses were ankle sprains and finger sprains. Once again, males held a higher proportion of the ankle sprains, with an incidence rate of 3.4 per 100,000 exposures (3.2 in girls) in the 7–11-year-old group, and an incidence rate of 26.5 per 100,000 exposures (23.2 in girls) in the 12–17-year-old group.

Deich et al. [9] and Drakos et al. [10] observed the incidence of lower extremity lesions in professional basketball (NBA and WNBA). Deich et al. [9] stated that gender-based differences in injury rates have in fact been reported in scholastic and collegiate basketball, and that the purpose of their study is to confirm whether these differences exist in professional basketball. After observing 702 male professional players and 443 female professional players for 6 competitive seasons (gathering a total of 70,420 male exposures and 22,980 female exposures), they concluded that WNBA (female) athletes had a significant higher incidence of lower extremity injuries (14.6 per 1000 exposures) when compared to NBA (male) athletes (11.6 per 1000 exposures, 95% confidence interval, 13.1–16.2). In both leagues, ankle sprain was the most common diagnosis when the injury took part during a game, but the knee was the most overall injured site. Upon reviewing Drakos et al. [10] results, however, we found again that the injured body site was influenced by the gender. In this study, only NBA players were observed, and ankle sprains were the most common injuries both during practice and game play. As we saw before in non-professional athletes, knee injuries increased alongside the number of female athletes in the study group, and male groups tend to suffer more ankle sprains both in professional and amateur basketball [10, 11]. Another conclusion in Drakos et al. [10] work that could be also seen in Kin et al. [8] is that there were no significant differences in overall injury rates when comparing injuries occurring during game play (49.9%) to those occurring out of it (50.1%).

## 4. Discussion

There is solid evidence in the literature to state that basketball is a sport that is strongly linked to ankle injuries, and above all, ankle sprains. The literature has pondered and stated so when observing population groups which differed among themselves in many aspects such as gender, age, occupation, level of play, moment of play (practice vs. competition). All of them have concluded in one way or another that the practice of basketball is a factor that is more closely linked to the risk of developing a sport-related ankle sprain, regardless of the population group they studied. The finding shows that ankle sprains are the most common injury is not surprising in light of the frequency of jumping and landing in a crowd of players.

As it has been sated, the different studies that we assessed focused on very different population groups each. We found this an advantage, since it allowed us to gain an overall vision of both professional athletes and general population, and so we were able to obtain different and interesting data.

In the majority of the previously listed studies, we could observe that the individuals belonged to similar age groups (school or high schools, professional athletes, USMA cadets, etc.). It is for this that it was difficult to state the role of age in the onset of ankle sprains or any injuries. There are however exceptions. In Pappas et al. [2] results, we could see that in paediatric basketball, there was a direct correlation between age and the risk of suffering an injury such as an ankle sprain. In addition, Brian et al. [12] found also a correlation between age and the incidence of ankle lesions, since in their experience, the risk increased considerably as age did.

Another determining aspect about the demographics of the population was gender. In overall terms, there could seem that there is a higher incidence of all kinds of injuries among the female gender [9, 13]. This fact would be altered whenever the joint in which the injury took place was being considered. Deich et al. [9] stated gender-based differences when they concluded that in professional basketball, the likelihood of suffering from an injury was higher in the female population in comparison with male athletes (14.6 per 1000 exposures vs. 11.6 per 1000 exposures).

Also, as stated earlier, female athletes tended to suffer a greater proportion of knee injuries in comparison with male athletes [11], who more frequently presented with ankle injuries. All in all, when reviewing the recent literature on basketball-related injuries, one can observe that the tendency to report a knee injury grows as the number of female athletes increased in the studied population. In the same manner, the proportion of ankle injuries seems to increase whenever the target population contains more male individuals [3].

The incidence rates of ankle injuries can vary greatly when considering one or other population groups. We observed that the level of play (professional or amateur) had a direct impact, and it could be found as high as 3.2 per 1000 athlete exposures [10] in professional NBA players, while in amateur practice the incidence rates were significantly lower. Moreover, the moment of play in which the injury took part also seemed to be crucial, since ankle sprains would be more likely to take place during a game, but knee injuries would seem more likely to occur during practice in Deitch et al. [9] opinion. This fact was however not common to other authors' experience, which pointed out that ankle sprains would be the prevalent injury, no matter the moment of play [10]. The difference between these two authors' findings could reside that in the group where ankle sprains were always the most common injury only male athletes were being studied, and as we have pointed out before, gender was found to be determining when it came to the body site the injury would affect [11].

Cumps et al. [1] studied senior players of different levels of play during a whole competitive season. One of the aspects he focused on was the moment inside the play in which an injury was most likely to occur. Since perhaps the main trigger for an ankle sprain would have been the act of landing on an opponent's foot after a jump, any tasks which involved jumping would conduct to a higher risk of injury (52.9% of total) in contrast to such others as cutting (11.8%), running to score (11.8%) or passing and receiving (5.9%). For the same reason, rebounding would be the task with a higher risk of landing wrong-footed and thus creating an injury.

Yet another interesting thing was to determine whether the onset of basketball-related injuries of any kind was more prompt to take place during practice or during competition. Even though one could be led to think that the higher intensity of play that athletes experienced during competition would lead to a higher risk of injuries of any kind, we found no solid evidence of this aspect. Even though in Borowski et al. [5] experience injury rates per 1000 exposures were far higher during competition (3.27) than during practice (1.40), it stood up to us that in the majority of the other papers, there was an approximated 50–50% distribution of injuries during these two periods [8–10]. That stood up to us, since one would think that the higher level of intensity during a match would make it easier to suffer an injury. One of the possible explanations for this aspect would be that athletes tend to dedicate more time to practice than to competition.

When it comes to the medical management of basketball-related ankle sprains, the first thing that stood up to us was that not many authors had considered this aspect. For those who had,

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it is frequent to notice that those individuals who suffered from ankle sprains or any other injuries did not seek medical care [7]. In Hammig et al. [11] experience however, the majority of those individuals who did consult to a health centre received X-rays. Regarding the outcome of the athlete after suffering an injury, the vast majority of authors agree that the recovery on long term is complete and the need for surgery was reasonably low [4]. There seems to be a higher variety of opinion concerning the mean absence of play after the injury took part, but the general tendency seems to be less than 3 weeks [3, 5].

We found a great variability concerning the likelihood of suffering from an injury in a single exposure. For example, Nelson et al. [3] stated that the risk of suffering an injury in a single exposure (risk of 5.23 per 10,000 exposures) was remarkably lower than in Fernandez et al. [4] experience (1.31/1000 rate for the male group and 1.36/1000 for the female group), even though both studies focused on similar groups of population.

## 5. Conclusions

To sum up with, many authors have dissected in the last 10 years the subject of ankle injuries onset during basketball practice. From their acknowledgements, one can observe that ankle injuries have a high tendency to take place during the practice of basketball, and sprains are the most common. There is some variability in the way and frequency that these injuries take place depending on the gender, age and level of play, however.

When performing a review of the recent literature, one must be careful at the time to interpret the results and conclusions, as the designs and variables of every study are very different from one another. It is easy to be led to misunderstanding, since every article states its own hypothesis and targets. Our goal as stated before was to review the current literature about the occurrence of ankle sprains during basketball practice, and to analyse the latest additions that have been made to the subject.

## Author details

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Section 2

# Update in Flatfoot Deformity Correction

# Extra-Osseous Talotarsal Joint Stabilization (EOTTS) in the Treatment of Hyperpronation Syndromes

Michael E. Graham

Additional information is available at the end of the chapter

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**Abstract**

The partial dislocation of the talotarsal joint (TTJ) serves as a primary deforming force to many lower extremity pathologies. External measures are limited in their ability to realign and stabilize the TTJ, and osseous reconstruction is associated with many risks, complications, costs, and long-term recovery. EOTTS provides patients an "in-between" solution that can be used with both conservative and other surgical procedures. Hyperpronation syndrome is a generic term used to include many secondary symptoms associated with a prolonged period or an excessive amount of pronation. These include many pathologies within the foot, ankle, knee, hip, and even spine. This chapter discusses the importance of early implementation and importance of EOTTS in the treatment of hyperpronation syndrome.

**Keywords:** partial talotarsal joint dislocation, overpronation, hyperpronation, extra-osseous talotarsal joint stabilization, arthroereisis, flexible flat foot correction

## 1. Introduction

The recurrent partial dislocation of the talus on the calcaneus and navicular is a weightbearing pathologic deformity. EOTTS is a minimally invasive, soft tissue procedure where an orthopedic stent is inserted into the sinus tarsi after the realignment of the talus on calcaneus and navicular. The function of the stent is to maintain the alignment of the TTJ while still allowing a normal range of motion. This procedure is performed in both children and adults as a primary, preferred method of treatment to reduce the strain and realign the osseous structures within the foot and ankle. Many times, EOTTS is combined with other forms of treatment.

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The TTJ is the foundation joint of the body. Misalignment of the TTJ leads to a faulty foot foundation that will lead to misalignment of proximal structures, i.e., the ankle, knee, hip, pelvis, and spine. The tens of millions of steps taken decade after decade lead to abnormal wear and tear upon these joints contributing to the formation of osteoarthritis. EOTTS can therefore have a positive effect to the proximal joint structures.

Historically EOTTS has been a niche procedure. However, due to improved stent designs and the increasing positive results of many scientific studies, this procedure is becoming more mainstream. The inability of conservative measures, such as arch supports and braces, to realign and stabilize the TTJ has been shown. Furthermore, previously recommended surgical procedures, i.e., osteotomy and arthrodesis, are associated with a longer recovery and greater potential risk of complications. Foot surgeons have longed for "in-between" conservative surgical procedures. EOTTS has proven to fulfill that need.

## 2. Biomechanics and stability of the talotarsal joint

The TTJ is one of the most important weightbearing joints of the body. It is responsible for handling oblique forces from the proximal body above and the weightbearing surface below. The talus serves as a "transmission" bone between the proximal limb and the foot. The architecture of the talus allows the forces to interact with the lower limb both posteriorly and anteriorly. The stability and alignment of the TTJ are essential for an efficient lower extremity function (**Figure 1**).

The complex range of motions of the TTJ is a very important consideration. Every joint has a normal, ideal range of motion. The TTJ, which has also been called the acetabulum pedis, exhibits triplane motion collectively called supination and pronation (**Figures 2** and **3**).

Supination occurs as the talus moves laterally, dorsally, and posteriorly on the calcaneus. This supinatory motion serves to strengthen the joints of the foot during weightbearing activities. Pronation has the opposite effect: to weaken the joints of the foot as the talus slightly shifts medially, plantarly, and anteriorly.

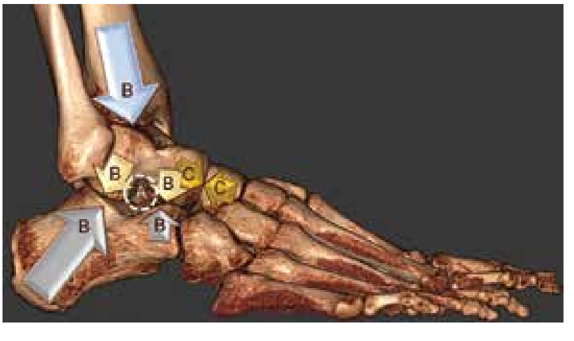


**Figure 1.** This weightbearing three-dimensional CT illustrates the triplane of forces acting on and between the talus. "A" is the sinus tarsi. "B" is the vertical-plantar-oblique forces, and "C" is the proximal-distal forces.

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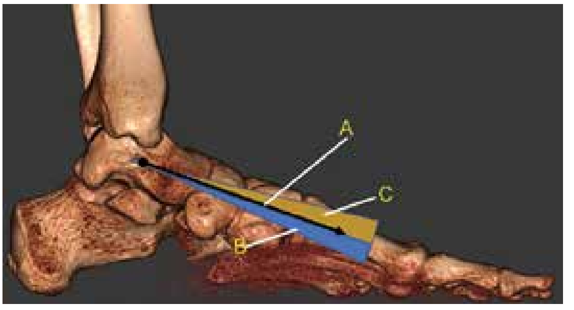


**Figure 2.** Lateral weightbearing three-dimensional CT. TTJ is in neutral position. "A" is the bisection of the talus. "B" indicates TTJ pronation. "C" indicates TTJ supination.

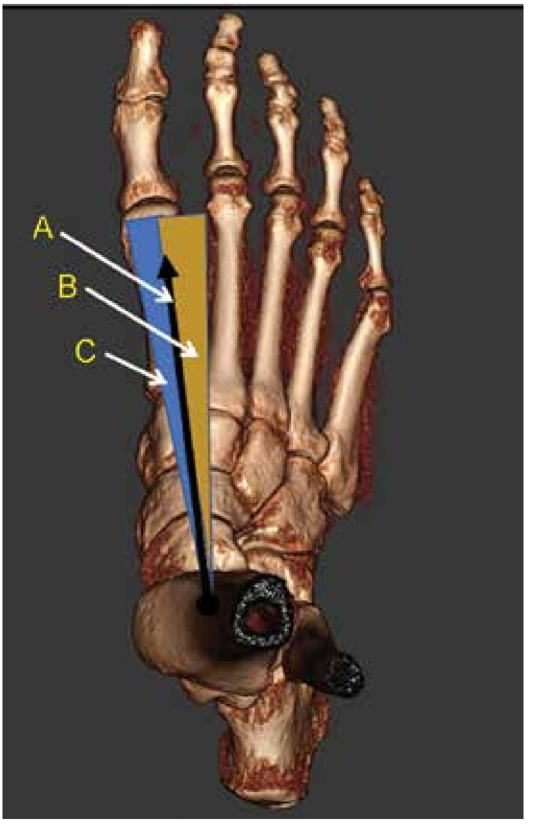


**Figure 3.** Dorsoplantar weightbearing three-dimensional CT. TTJ is in neutral position. "A" is the bisection of the talus. "B" indicates TTJ supination. "C" indicates TTJ pronation.

The normal, ideal ratio of supination to pronation has been determined to be 2/3 supination and only 1/3 pronation [1]. There should be only a slight amount of pronation of the TTJ. This shows that the locking, supination, of the TTJ mechanism is more important than the unlocking, pronation, during weightbearing activities. An excessive pronation motion creates an imbalance of the homeostasis of that joint leading to a prolonged weakness of the foot structure.

An understanding of the stabilizing factors of the TTJ must be understood. The talus is the only foot bone not to have the insertion of a tendon. Therefore, talar stability relies first on the articular surfaces on the calcaneus and then the navicular. There is a vast ligament network that serves to keep talar motion in check. These ligaments are attached anteriorly, medially, posteriorly, laterally, and plantarly in a very strategic pattern to limit excessive talar motion. Furthermore, there are Golgi sensors within the ligament that will signal a neuro-response to trigger muscle activity to also limit excessive talar motion.

## 3. Recurrent talotarsal joint dislocation

The loss of constant congruent articulation within the TTJ serves as a primary pathologic deformity that can lead to many secondary pathologies and hyperpronation syndrome(s). The partial dislocation initially occurs as recurrent deformity, i.e., it occurs again and again or repeatedly. It is possible that due to osseous changes over time or the formation of a coalition, the partial dislocation can become a fixed deformity. Early intervention prior to the formation of a fixed deformity is preferred as it affords more conservative treatment.

The mechanism for the recurrent TTJ dislocation occurs during weightbearing following a period of non-weightbearing. The articular surfaces of talus abnormally displace medially, anteriorly, and plantarly during the early stance phase of the gait cycle. The axis point of the TTJ shifts to an excessive pronatory direction. As the limb/foot becomes non-weightbearing, i.e., during the noncontact, swing phase of the gait cycle, there will be a realignment of the articular surfaces. Immediately following initial heel contact during the weightbearing stance phase, there again will be a loss of alignment and stability of the TTJ.

This orthopedic deformity, recurrent talotarsal joint dislocation (RTTJD), can be observed clinically and documented radiographically by comparing non-weightbearing to weightbearing images. Clinically, the TTJ range of motion can be checked. The preferred method to evaluate TTJ pronation is to grasp the back of the heel with the same hand of the foot being evaluated, i.e., the right hand would cup the right heel. The opposite thumb would be placed under the necks of the fourth and fifth metatarsal, lateral column of foot bones, and maximum pronatory force would be applied (dorsal, lateral, proximal) (**Figure 4**).

There should only exist a few degrees of motion, 3–6. Unfortunately, due to the variation between examiner and examiner, this observation is only a clue to a possible RTTJD deformity. There are no validated tools to adequately and clinically measure this amount of TTJ pronation.

The patient is then told to stand for static, non-weightbearing observation. Common signs of RTTJD include the appearance of a "second" medial malleolus. There could be a lowering of the medial arch, but this is dependent on the presence of a navicular drop, a finding that is

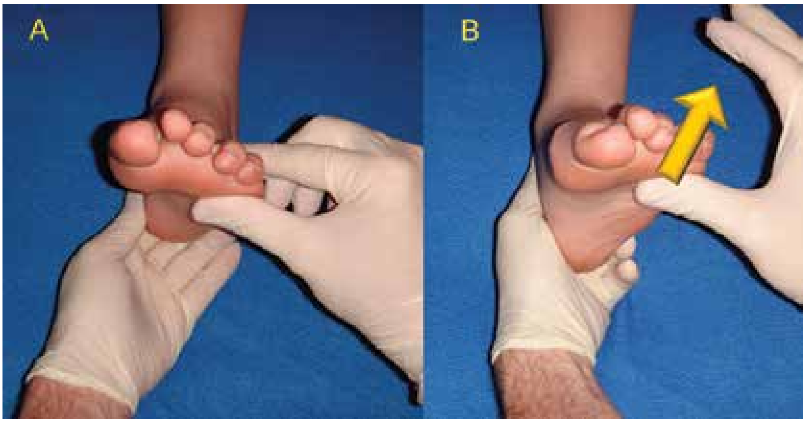


**Figure 4.** (A) The amount of TTJ pronation within a patient's left foot is being examined. (B) The right hand cups the heel, and a pronatory force is exerted to the lateral column of the foot.

not always present. Looking at the back of the heel, the patient may have a calcaneal valgus. However, calcaneal valgus may not always be present. Finally, observation of a forefoot valgus is confirmed with the "too many toes" sign. Normally, only the fifth and a portion of the fourth toe should be observed. If the entire fourth, at minimum, or a portion of the third toe is visually present, then this would indicate a positive "too many toes" sign.

The last portion of the clinical examination is observation of the gait cycle. Many times, RTTJD is suspected during the non-weightbearing portion but is not seen during static weightbearing, only to return during dynamic weightbearing. Common observations are an abductory twist, "too many toes" sign, and a prolonged period of pronation.

Truly, the best confirmation of RTTJD is via weightbearing radiographic imaging. This is the "gold standard" for establishing a diagnosis for osseous pathology. Standardized weightbearing radiographs have the least degree of interobserver error, unlike range of motion testing. They are validated radiographic measurements and observations to establish the diagnosis of RTTJD.

The two most important views are the lateral and dorsoplantar (DP) images. Specific observations on the lateral radiograph include the geometry of the sinus tarsi. Partial to full obliteration of the sinus tarsi is an unnatural finding. The sinus tarsi should remain "open." The abnormal closure of the sinus tarsi is the first indication of RTTJD; however, there are no validated measurements to indicate normalcy. There are several radiographic angles that can be used to determine normal or abnormal talar alignment. The talar declination angle is commonly used to determine sagittal plane alignment of the talus on the lateral radiograph. Historically, the normal accepted value is <21 degrees; however, this has been recently questioned [2] (**Figure 5**).

Other considerations on the lateral radiograph include the anterior deviation of the anterior border of the talus to the anterior border of the calcaneus. There are no validated measurements, but a "significant" anterior deviation of the talus over the calcaneus is considered to

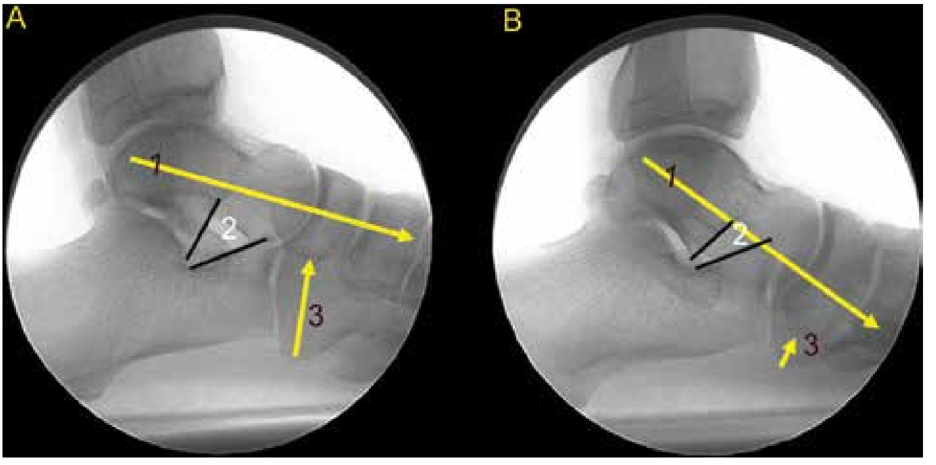


**Figure 5.** Weightbearing lateral radiograph of the same patient's foot. A. Patient's TTJ is in neutral position. (A1) Talar bisection is within normal limits. (A2) The open sinus tarsi space. (A3) Normal navicular height. (B1) Abnormal plantar flexions of the talus. (B2) Abnormal partial obliteration of the sinus tarsi. (B3) Shows a pathologic lowering of the navicular.

be an anteriorly deviated cyma line. The position of the navicular bone to the cuboid also can provide valuable information. Normally, the plantar aspect of the navicular should be located dorsal to the horizontal-vertical bisection of the cuboid.

The DP radiographic image provides transverse plane data. There are several radiographic angles that can be evaluated; however, the ideal is the talar second metatarsal angle. Many

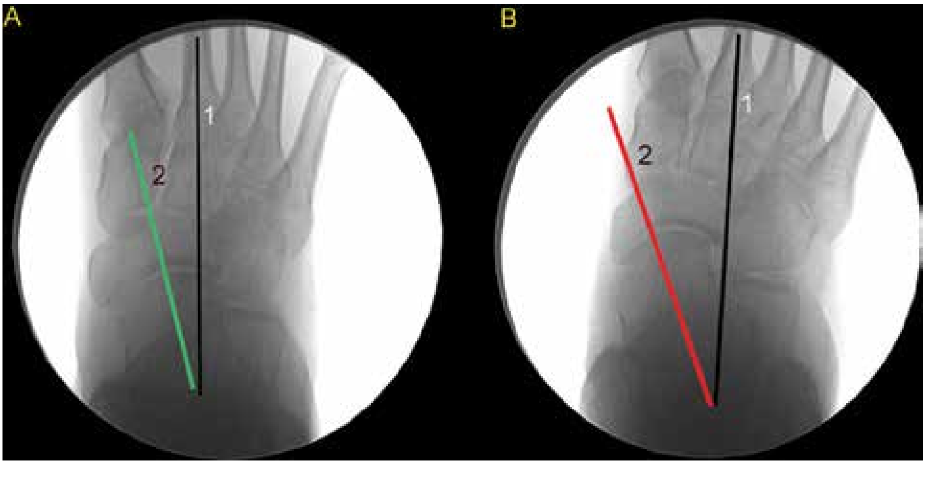


**Figure 6.** This DP weightbearing fluoroscopic image illustrates the talar second metatarsal angle. (A) The patient can realign the TTJ into neutral position. (A1) This is the bisection of the second metatarsal. (A2) This is the bisection of the talus. This angle is within normal limits, greater than 3 and less than 16. (B) The patient now is standing in relaxed stance position. Notice the increased angle between the (1) talar bisection and (2) the second metatarsal. This angle is greater than 16 and is considered abnormal.

authors have historically advocated the talar first metatarsal angle, but many times, patients can have an increased first intermetatarsal angle that compromises a medial transverse plane talar rotation measurement. This would result in a false-negative finding, when in fact the talus was pathologically rotated medially. The ideal talar second metatarsal angle is 3–6 degrees, but up to 16 has been considered within normal [3] (**Figure 6**).

When a patient has abnormal radiographic findings indicating TTJ dislocation, a second set of radiographs should be taken with the TTJ in neutral position. This will help to diagnose a fixed or flexible deformity and assist with ruling out a tarsal coalition. A "reopening" of the sinus tarsi and normalization of other radiographic findings should be visualized in a flexible deformity. Ruling out a flexible versus rigid TTJ dislocation is important when considering treatment options.

## 4. Hyperpronation syndromes

Medial, anterior, and/or plantar misalignment of the TTJ leads to a prolonged period of pronation during the gait cycle. This, in turn, leads to excessive strain to joints and soft tissues within the foot, ankle, knee, hip, pelvis, and spine [4–6]. Eventually, the excessive strain leads to an imbalance of the ability of the cartilage and supporting tissues to handle the pathologic forces. If the critical tissue strain threshold is reached, that tissue will exhibit a symptom.

The negative effect of TTJ hyperpronation will eventually lead to symptoms in one or more parts of the body. Every symptom has an underlying etiologic factor. Rarely does the etiologic factor become symptomatic. Take, for instance, an ingrown toenail. The portion of the offending nail border that is embedded into the tissue does not hurt; rather, it is the reaction of the tissue that causes the pain, swelling, and infection. Hyperpronation syndrome is a collection of symptoms that can present because of the RTTJD deformity during weightbearing.

Every individual will experience a slightly unique set of symptoms due to the complexity of the TTJ misalignment and the form of compensation of the body. Common foot pathologies that name TTJ excessive pronation as a leading etiologic factor include calcaneal apophysitis, plantar fasciitis/fasciosis, posterior tibial tendon dysfunction, plantar neuropathy/tarsal tunnel, hallux valgus, hallux limitus/rigidus, flexor stabilization hammertoes, intermetatarsal neuroma formation, abductory twist, and metatarsalgia. Proximal symptoms can include osteochondral lesions of the talar dome, growing pains, shin splints, patellofemoral pain, ACL strain, knee OA, sciatica, hip OA, functional leg length discrepancy, pelvic tilt, and spine malalignment.

People with hyperpronation syndrome find that it is difficult to perform weightbearing activity and many times simply give up this important form of exercise. As a result, there is a lowering of their metabolism that can lead to weight gain, obesity, hypertension, diabetes, and heart disease. The leading recommendation for patients with the so-called metabolic syndrome is to simply walk to increase their metabolic rate.

## 5. EOTTS device classification and mechanism of action

Once the articular facets of the TTJ are realigned, it will require an internal method to maintain the alignment and stability. There have been many materials to achieve this outcome including the insertion of bone graft, Silastic, or an orthopedic screw into the lateral floor of the sinus portion of the sinus tarsi. The partial insertion of a material into the bone is referred to as intraosseous. The mechanism to maintain TTJ stability is via arthroereisis or joint blocking. This method acts as a doorstop to abruptly block joint motion. Also, intraosseous TTJ stabilization has been studied [7–9]. It is effective in the short term, but the long-term results remain under debate. This is primarily due to the fact that the majority of these devices are removed after 1½–2 years. There is little to no data to support the long-term TTJ alignment following removal of the implant.

Due to the limitation of intraosseous devices, surgeons began using extra-osseous stents. There are two types of EOTTS stents, arthroereisis and non-arthroereisis [10]. The arthroereisis device, “first-generation” EOTTS, acts in a similar method to the intraosseous devices, that is, to block the forward motion of the lateral process of the talus. The stent is “sandwiched” between the anterior end of the lateral process and posterior portion of the calcaneal floor. During TTJ supination, the talus externally rotates increasing the diameter of the sinus tarsi. Then, as the TTJ pronates, the sinus tarsi diameter decreases until the motion is blocked with the EOTTS arthroereisis device.

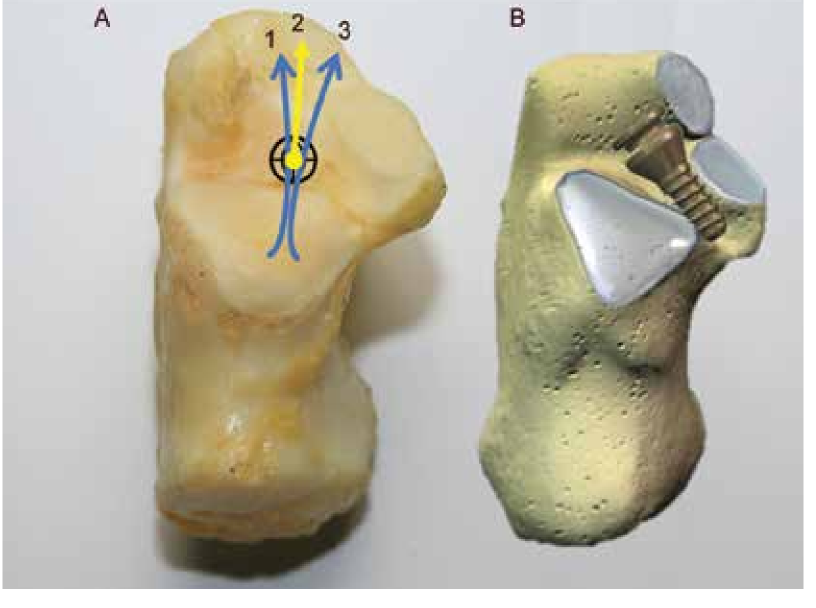


**Figure 7.** This shows the dorsal surface of the calcaneus. (A1) Indicates the amount of normal TTJ pronation. (A2) Indicates TTJ neutral position. (A3) Shows TTJ supination. (B) Shows the dorsal surface of the calcaneus with the HyProCure sinus tarsi stent (GraMedica, Macomb, Michigan).

The non-joint blocking EOTTS, "second-generation," devices function with the normal biomechanics of the TTJ. Rather than abruptly blocking talar motion, the second-generation devices reestablish the ideal axis point of the TTJ. The non-arthroereisis EOTTS stents act like the pin within the hinge of a door. There will be minimal contact on the stent without a forced pressure during pronation. Due to the improved biomechanic function of the non-joint blocking EOTTS stent, its success has been measured at a much greater long-term success rate over the arthroereisis devices [11–13] (**Figure 7**).

## 6. Patient selection for the EOTTS procedure

The need to internally realign and stabilize the TTJ with an EOTTS stent is very important. While RTTJD does not pose an immediate threat to someone's life, it can severely affect the quality of life and overall health, both physical and mental, even worse are the many associated musculoskeletal deformities that have long been associated with RTTJD. Pain should not be a consideration in the recommendation of EOTTS, when indicated. There are many diseases that are "pain-free" but are still treated. The cumulative effect of walking on feet with RTTJD can reach a point where irreversible damage occurs to other parts of the body. Prevention and early treatment of disease are highly recommended over watch and wait.

EOTTS stents have been used in tens of thousands of pediatric and adult patients for many decades. The ossification of the sinus tarsi occurs by 3 years of age. Therefore, the insertion of the sinus tarsi stent could be considered an option at that point. Most foot surgeons would suggest waiting until the child is a few years older than 3, but it is a case by case determination. There is no upper end age restriction. Upon reaching osseous maturity, the primary deciding factor is the reducibility of the RTTJD deformity. The sinus tarsi space must be restored to its "open" position for the stent to be inserted. Ideally, the reducibility of the RTTJD deformity should be confirmed with radiographic imaging.

There are a few factors that should be ruled out or taken into consideration when recommending the EOTTS procedure. The realignment of the talus on the calcaneus to make sure a tarsal coalition is not present is a very important consideration. This could be an issue when performing EOTTS in younger children because the coalition may not occur until years later. A coalition is not a contraindication, if the coalition can be resected. The posterior heel must be checked for a calcaneal varus deformity. Although rare, a varus deformity of the calcaneus could be exacerbated by performing EOTTS.

The stability and alignment of the first metatarsal must be taken into consideration. Hypermobility or a fixed elevatus could compromise the long-term success of the EOTTS procedure. The altered position of the first metatarsal will lead to a forefoot valgus with heel lift during the gait cycle. This will increase the forces acting on the subtalar joint. The use of an insole or first ray stabilization surgery may be required in addition to the EOTTS procedure.

Metatarsus adductus is another possible coexisting pathology. If the patient is osseously immature, still growing, it is possible the EOTTS procedure could theoretically improve a mild metatarsal adductus. However, if a significant metatarsus adductus is present in an osseous mature person, EOTTS could exacerbate the appearance. Therefore, metatarsal corrective surgery would be necessary along with the EOTTS procedure.

The inclination of the calcaneus is yet another factor that should be taken into consideration. The increase in anterior-distal forces acting on the calcaneus could cause an abnormal lowering of the normal calcaneal inclination angle (CIA). It is possible that the insertion of an EOTTS device and normalization of forces will also normalize the CIA. On the other hand, it is possible that the lower than normal CIA becomes a fixed deformity and requires surgical intervention. A lower than normal CIA could compromise the overall effectiveness of the EOTTS procedure. A lower than normal CIA is not considered a contraindication of the EOTTS procedure.

Due to the complexity of the foot mechanism, a variety of treatment options could be required from conservative measures to osseous reconstruction. EOTTS can be performed as a standalone procedure, when indicated and after coexisting deformities are ruled out, identified, and properly addressed.

## 7. Evidence basis for the EOTTS procedure

There have been numerous scientific, peer-reviewed articles and textbook chapters published on EOTTS. The medical necessity for EOTTS is well established. There has been much research published on the importance of a balanced and aligned TTJ and the negative impact RTTJD will have to the lower extremity. Scientific studies have approached the use of sinus tarsi implants from many different points. There have been theoretic, cadaveric, radiographic, gait analysis, outcome-based, prospective, and retrospective studies.

The basic evidence that is required to prove the usefulness of EOTTS is simply that it is as effective as or even more effective than other treatment solutions. Foot specialists regularly recommend shoe inserts/arch supports to realign the TTJ. However, their limitations have been long known. A recent article studied their effectiveness against EOTTS. It was found that arch supports are unable to improve TTJ alignment [14]. There have been several manuscripts published on many different EOTTS stents showing radiographic normalization and stabilization of the TTJ [12, 13, 15–95]. The alternative internal surgical options of osteotomy and arthrodesis have been shown to be too aggressive of a treatment. That is, until the RTTJD has reached end-stage when that is the only remaining option.

The overall "staying power" of EOTTS stents must be taken into consideration. Some foot surgeons advocate the short-term use of the sinus tarsi implant, while others would prefer a more permanent solution. Regardless, the insertion of an internal fixation device is used on a regular basis by foot surgeons. Additionally, the removal of orthopedic screws, pins, and plates occurs on a regular basis. The benefit of the EOTTS solution is that the sinus tarsi stent can be removed, if necessary, with little to no ill-effect to the local anatomy.

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## 8. Conclusion/summary

EOTTS serves as a very important treatment option, when indicated. RTTJD should be addressed and internally corrected, the sooner, the better. It is a time-tested, medical necessity and is backed by extensive evidence. This treatment option has historically been considered a niche procedure. Surgeon advocates have found that EOTTS offers their pediatric and adult patients an internal option that makes sense and is more effective than other forms of "similar" treatment. The far-reaching positive effects of EOTTS will be discovered on the knee, hip, pelvis, and spine. Furthermore, because patients can become more active following the correction of RTTJD, they will increase their metabolic rate. This will have a positive effect to their physical and mental health in general. EOTTS is a cost-effective solution with a shorter return to function over more aggressive surgical procedures. It is for these reasons that the advocacy of EOTTS continues to increase year over year, globally.

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Chapter 4

# Surgical Management of Posterior Tibial Tendon Dysfunction

Kyle E. Wamelink

Additional information is available at the end of the chapter

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**Abstract**

Management of posterior tibial tendon dysfunction can be a controversial topic. Posterior tibial tendon dysfunction is a progressive deformity of the foot and ankle and can be very debilitating if not properly treated. The key to successful outcomes begins with a prompt diagnosis and staging of the deformity. Often the early stages of posterior tibial tendon dysfunction can be conservatively managed and progression can be halted before significant deformity ensues. Those that require surgical intervention can be treated with soft tissue balancing and osseous reconstruction. The focus of this chapter is to review the surgical options available for correction of posterior tibial tendon dysfunction.

**Keywords:** posterior tibial tendon dysfunction, flatfoot, pes valgus deformity, pes planus deformity, arthritis

## 1. Introduction

Pes valgus or flatfoot deformities are defined as a combination of forefoot abduction, rearfoot valgus and loss of the medial longitudinal arch [1]. A patient with a pes valgus deformity who was treated early typically response well to conservative management including orthotics, anti-inflammatory therapy, stretching to relieve equinus, immobilization and physical therapy. In certain patients this regimen can relieve symptoms and slow progression of the deformity.

Correction of valgus deformities is dependent on a number of factors; the most overriding being the severity of the deformity and the flexibility of the rearfoot, midfoot and forefoot. Other principles that guide procedure selection include the patient's activity level, age, pain

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and the etiology of the deformity. The main objective when treating these patients to relieve pain and manage progression of the deformity is by preventing excess pronation.

In adult patients the most common etiology of unilateral acquired adult pes valgus is secondary to insufficiency of the posterior tibial tendon, the most powerful inverter of the foot [1]. In addition, the posterior tibial tendon is an important stabilizer of the midfoot. Treatment of this disorder is dependent upon the stage of posterior tibial tendon dysfunction [2].

Surgical management is typically initiated once the patient has failed multiple conservative efforts. Generally, conservative treatment is unsuccessful in a patient with an unstable foot, rigid deformity or in those who develop arthritic changes secondary to a neglected, long-standing and poorly supported pes valgus foot-type. Dysfunction of the posterior tibial tendon can be divided into three stages [3]. A fourth stage of disease of the posterior tibial tendon was proposed by Kleeman and Myerson [4].

Stage I of posterior tibial tendon dysfunction involves either tenosynovitis or tendonitis with no clinical deformity. The posterior tibial tendon remains intact and functional. Most often non-operative treatments include bracing, orthotics and taping. Stage II PTTD entails advanced disease of the tendon in which the posterior tibial tendon is no longer able to maintain the arch. Typically the foot is flexible in this stage and the valgus deformity can be passively corrected. Conservative measures, including bracing and orthotics, can be effective in treating this phase of the deformity. Surgical management typically involves soft-tissue balancing, a tendon transfer and/or joint-preserving osteotomies. In stage III the deformity becomes more rigid and joint degeneration becomes evident in the subtalar joint and transverse tarsal joints. Joint-preserving osteotomies are ultimately unsuccessful in treating this late stage due to the rigidity of the deformity. A rearfoot arthrodesis is often required to achieve proper alignment and support of the foot. Long standing stage III deformities can lead to subsequent ankle valgus. Ankle valgus can be described as stage IV PTTD and surgical correction needs to address the ankle with a rearfoot procedure in conjunction with soft-tissue reconstruction or, in more advanced cases arthrodesis/arthroplasty of the ankle. In this chapter the role of both soft tissue and osseous correction will be described in correction of posterior tibial tendon dysfunction.

## 2. Biomechanics & Pathophysiology

The posterior tibial tendon passes posterior and inferior to the medial malleolus and partially inserts on the plantar aspect of the navicular tuberosity. Distal to its partial insertion on the navicular tuberosity, the main tendon spreads out in an anteriolateral direction, and inserts onto the plantar aspect of the intermediate and lateral cuneiforms the cuboid and the bases of the second, third, fourth and sometimes fifth metatarsal. The function of the foot during ambulation is to act as a shock absorber. The foot functions most efficiently when it is in a tripod formation. The calcaneus is the posterior leg of the tripod while the first and fifth metatarsals are the anterior legs. The functional subtalar joint is composed of the articulation between the posterior calcaneal facet of the talus and the posterior talar facet of the calcaneus and the talocalcaneal portion of the talcalcaneonavicular joint. The posterior tibial tendon passes posterior and medial to the axis of the subtalar joint. The tendon allows equal amounts of inversion and adduction of the foot during supination of the foot [5]. The midtarsal joint is made up of the calcaneocuboid and the talonavicular joint. This joint complex has two separate axes of motion, a longitudinal and oblique axis. The posterior tibial tendon exerts a force around the oblique axis which is primarily a plantarflexion and adduction force. It essentially has no force around the longitudinal midtarsal joint axis. The posterior tibial tendon produces a strong supinatory force at the subtalar joint at heel contact and during the midstance phase of gait. The tendon also decelerates internal rotation of the tibia and subtalar joint during early stance phase. The tendon will accelerate external tibial rotation during midstance and early propulsion [5]. By crossing the transverse tarsal joints, the posterior tibial tendon plays a role in enabling progression of the midtarsal joint from the unlocked to the locked position. Subsequently, the gastrocsoleus complex acts on the calcaneus to supinate the rearfoot additionally, locking the midtarsal joint and allowing for efficient force of transmission for gait [1].

Once the rearfoot is tilted into a pronated position secondary to a diseased posterior tibial tendon, the subtalar joint is unable to maintain a stable configuration of the foot. With the rearfoot in a valgus position the Achilles tendon forces are redirected laterally, creating an eversion force to the rearfoot and adding to the loss of medial arch stability [1]. The Achilles tendon will exert increased stress at the talonavicular joint contributing to increased stress on the talonavicular capsule and spring ligament [1]. The force leads to the loss of the soft tissue restraint of the talonavicular articulation. The talar head will eventually become uncovered and peritalar subluxation will ensue leading to an abducted forefoot and a loss of the medial longitudinal arch. The midtarsal joint will function in an unlocked position and fail to progress to a locked position without adequate posterior tibial tendon function as well.

## 3. Preoperative evaluation

The preoperative evaluation of the patient with PTTD involves both clinical criteria and radiographic evaluation. The clinician must determine if the pes valgus deformity is flexible or rigid. If the valgus deformity of the rearfoot is flexible, the presence of forefoot supinatus should be assessed as well. Forefoot supinatus is seen with ankle equinus and subtalar joint pronation. This forefoot deformity develops as a soft tissue adaptation in which the forefoot is inverted on the rearfoot due to calcaneal eversion. The patient will typically present with pain along the course of the posterior tibial tendon as it passes the medial malleolus toward its medial insertion at the navicular tuberosity. Tendon dysfunction can be evaluated with a heel rise maneuver in which the patient rises onto their forefoot. In a patient with a healthy posterior tibial tendon the heel rise can be completed without pain and inversion of the heel will be observed. Weight bearing radiographs of the ankle should be obtained in addition to radiographs of the foot. Peritalar subluxation can be appreciated on the AP view of the foot due to the dysfunction of the tendon at decelerating internal rotation of the tibia and subtalar joint during the early stance phase of gait. Ankle valgus is observed on the AP and mortise ankle views in late stage posterior tibial tendon dysfunction.

MRI is the study of choice to diagnose posterior tibial tendon tears. An area of hypovascularity along a segment of the tendon also may contribute to degeneration of the tendon. Frey et al. described the areas of vascularity of the posterior tibial tendon at the osseous insertion and the myotendinous junction. A zone of hypovascularity was identified posterior and distal to the medial malleolus. The combination of the avascular portion of the tendon and the chronic mechanical strain may be a predisposing factor to degeneration of the posterior tibial tendon [6].

Posterior tibial tendon injuries are classified into three types [7]. Type I represents incomplete tear with fusiform enlargement, typically a longitudinal split. An inhomogeneous signal intensity pattern can be appreciated with this type most often on T2-weighted images. Type II injuries are seen with an incomplete tear with decreased tendon caliber. A complete rupture of the tendon is classified as a type III injury. MRI can be a useful modality, however it is not a necessary study in later stages of posterior tibial tendon dysfunction which can be identified with plain films and clinical exam.

## 4. Tenosynovectomy

After a patient has failed multiple efforts at conservative care then in some situations a tenosynovectomy is indicated. The purpose of a tenosynovectomy is to eliminate inflammatory tissue that may contribute to further degradation of the tendon or worse rupture of the tendon. A patient requiring a tenosynovectomy is often in the early stages of posterior tibial tendon dysfunction and a deformity has not fully manifested itself. In more long standing cases there may be a valgus position of the rearfoot compared to the contralateral limb with a gastrocnemius or gastrocsoleus equinus deformity. In these scenarios a corrective procedure may be indicated.

The incision is started from below the tip of the medial malleolus and extended to the navicular. Once the tendon sheath is identified it is opened and the inflamed synovial tissue is excised. The posterior tibial tendon is inspected for pathology. It is important to inspect the posterior surface of the tendon. Small tears can be debrided while larger tears must be debrided and repaired. Often significant tendon hypertrophy can be appreciated. A normal posterior tibial tendon is approximately three times the caliber of the flexor digitorum longus tendon. If the tendon is found to be pathologically enlarged then the tendon can be debulked. A 2–0 absorbable or non-absorbable suture can be used to repair the tendon. A running stitch imbricating the tendon followed by a buried knot can be performed. If the tendon deficit is significant following the debridement of diseased tissue then the tendon can be augmented with a bioengineered product. In addition a secondary procedure may be indicated in the case of severe tendon pathology. Depending on the degree of the repair the patient may be placed in a below knee fiber glass cast for 3–4 weeks followed by a transition to an aircast. The patient can then transition to normal supportive shoes.

## 5. Evans calcaneal osteotomy

This procedure was introduced in 1961 by Dillwyn Evans for patients with poliomyelitis and is now routinely used to correct flexible valgus deformities [7]. This procedure primarily corrects in the transverse plane, but the argument has been made that it also works in the sagittal as well as the frontal plane. Typically those patients with a significant uncovering (greater than 50%) talonavicular joint and a flexible deformity. The procedure is typically reserved as first line therapy for pediatric pes planovalgus. One contraindication for an Evans calcaneal osteotomy is in patients with moderate to severe metatarsus adducts as lengthening their lateral column will unmask the patient's forefoot adduction.

An oblique incision is made over the lateral rearfoot from the anterior beak of the calcaneus distally and then extended proximally inferiorly to the inferior surface of the calcaneus. The incision is created 1 cm proximal to the calcaneal-cuboid joint. The extensor digitorum muscle belly is exposed and the peroneal tendons are reflexed inferiorly. A periosteal incision is then made 1 cm proximal and parallel to the calcaneal-cuboid joint. A pearl at this point in the procedure is to leave the periosteum of the calcaneal-cuboid joint intact to avoid disruption of the ligaments surrounding the joint. The osteotomy is made with a sagittal saw 1 cm from the calcaneal-cuboid joint. The osteotomy is started at the lateral wall of the calcaneus parallel to the calcaneal-cuboid joint. The lateral, dorsal and plantar cortices are cut, while leaving the medial cortex intact to create a hinge [7]. A distractor is placed into the osteotomy and the foot is evaluated [8]. Once the proper correction is achieved then structural allograft can be cut to insert into the osteotomy site. Adequate correction can be determined by relocation of the talonavicular joint. Typically a 1 cm allograft can be inserted, however the surgeon may take resorption of the graft into account when fashioning the appropriate size. The graft is carefully tapped into place and typically internal fixation is not required. The post-operative course involves 6 weeks of non-weight bearing in a cast followed by transition to weight bearing in an aircast. Graft incorporation can be variable based on the patient's age.

## 6. Medial displacement calcaneal osteotomy

Alfred Gleich first described calcaneal osteotomies for treatment of pes valgus in 1893. The purpose was to re-establish the calcaneal inclination angle [9]. This was accomplished with a medial closing wedge osteotomy with displacement of the posterior fragment forward, medially and plantarly. Koutsogiannis reintroduced the medial displacement calcaneal osteotomy through the posterior tuberosity in 1971 [10]. In 1996 Myerson proposed the use of the medial displacement osteotomy augmented by an FDL transfer for the treatment of PTTD [11].

The medial displacement calcaneal osteotomy is an effective procedure for correction of multiple types of deformities when rearfoot valgus is present. The intention of this varus producing calcaneal osteotomy is not only to regain normal rearfoot architecture, but also to salvage the utility of the Achilles tendon relative to the axis of the subtalar joint. Medial translation of the calcaneus restores the supinating moment of the Achilles tendon and realigns the axis of the subtalar joint. Regaining the powerful dynamic pull of the Achilles tendon is a significant advantage of this osteotomy.

The medial displacement calcaneal osteotomy is performed under general anesthesia using a thigh tourniquet. A 6 cm oblique incision is made one fingerbreadth posterior to the lateral malleolus. This will allow retraction of the peroneal tendons and sural nerve anterior within the incision. The osteotomy is created using an oscillating saw. The cut is made perpendicular to the lateral border of the calcaneus and is inclined 45° to the plantar surface of the rearfoot.

In order to monitor the cephalic shift during medial translation of the osteotomy a marking pen can be used to draw the line of the osteotomy followed by a second line perpendicular to the anticipated osteotomy creating a cross in the center of the calcaneus. The perpendicular crossed line allows the surgeon to monitor cephalic shift of the posterior fragment during medial translation produced by the surrounding soft tissue structures, especially the Achilles tendon.

The osteotomy is started perpendicular to the lateral aspect of the calcaneus to prevent anterior or posterior translation of the fragment. Care is taken to avoid aggressively punching through the medial cortex with the oscillating saw. An osteotome can be used free the posterior section of the calcaneus upon completion of the cut.

Typically the osteotomy is translated 10–12 mm medially. It can be subjective to discern exactly how far to translate the calcaneal osteotomy to achieve the desired correction. Utilizing the surface anatomy can be particularly useful. Visualization of the knee helps in determining proper alignment [4]. In addition, taking a bisection of the heel plantarly and aligning it with a point on the anterior ankle between the medial and lateral malleoli. This point is generally located approximately 40–50% between the medial and lateral malleolus with 40% being closer to the lateral malleolus. This allows the surgeon to locate the moment arm between the weight bearing axis of the leg and the contact point of the heel in addition to correcting the valgus rearfoot.

Prepping of bilateral limbs may be beneficial if the contralateral limb has been successfully corrected previously. Intraoperatively on the already corrected limb a bisection of the heel is made parallel with a line on the anterior ankle using a marking pen. The surgeon then attempts to obtain a match on the surgical limb using these landmarks. This can be helpful in achieving complementary results between the two feet. Additional care should be taken not to over correct in this situation as the more symptomatic foot is typically treated first.

While translating the osteotomy, it is critical to be cautious of an over aggressive shift, which can lead to depression of the fragment analogous to troughing. Once the calcaneus is shifted, it is provisionally fixated and then permanently fixated with one 6.5 mm cannulated screw. The orientation of the fixation is typically introduced from inferomedial to anterolateral aiming toward the sinus tarsi. Having two points of temporary fixation can help to prevent rotation of the inferior fragment which can lead to a situation analogous to troughing of the calcaneus.

Resection of the overhanging lateral ledge of bone is important to prevent irritation on the surrounding soft tissues and sural nerve. A tamp and mallet can be used to dull the sharp lateral cortical edge. Closure of the deep and superficial fascia requires particular attention due to the medially shifted inferior portion of the heel. Care must be taken to approximate the soft tissues due to the modified position of the heel. A drain is placed before skin closure.

Radiographs are performed at 5 weeks at which time the patient is transitioned into an air-cast. Physical therapy is initiated between 6 and 8 weeks. Normal activities are permitted at 6 months.

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## 7. Flexor digitorum longus tendon transfer

Stage II PTTD can be treated with an anastomosis and transfer of the flexor digitorum longus tendon and combined with one of the above calcaneal osteotomies and additional adjunctive procedures such as medial arch reconstruction.

Dissection is begun similar to a tenosynovectomy. If the tibialis posterior tendon has a mid-substance rupture, this is repaired in an end-to-end fashion or the degenerative tendon is excised and the defect is repaired. The FDL tendon is harvested inferior to the PT tendon between the abductor fascia and medial border of the foot at the level of the medial cuneiform. The FDL tendon is transected under direct vision proximal to the junction of the master knot of Henry. The tendon can then be secured under physiologic tension either with a drill hole in the navicular tuberosity or using a bone anchor or a biointerference screw. The tendon does need to be placed under considerable tension as it will stretch over time, however caution must be made not to over tighten the tendon as it can lead to subluxation of the tendon out of the tarsal tunnel.

The post-operative course is typically based on the adjunctive procedures performed along with the FDL transfer. Early rehabilitation is encouraged with isolated FDL transfers, although rarely is this procedure performed alone.

## 8. The Young's tenosuspension procedure

An alternative tendon transfer that is successful in treating PTTD is termed the Young. The Young's tenosuspension entails rerouting all or one-half of the anterior tibial tendon through a slot fashioned in the navicular. The tendon is not detached from its insertion at the medial-plantar aspect of the medial cuneiform-first metatarsal base. Rather, it is slipped into the navicular key-hole slot by supinating the foot and stretching the tendon plantarly and posteriorly creating a new insertion for the anterior tibial tendon into the dorsam of the navicular. The remainder of the tendon will function like a ligament to support the medial arch [11]. This procedure is typically more appropriate in patients with stage II PTTD when the posterior tibial tendon muscle is still functional and the valgus deformity is still flexible.

The incision is made from the medial malleolus along the medial foot distally toward the first metatarsal cuneiform joint. The incision is carried down through the superficial fascia. The tributaries from the medial marginal vein are ligated and the vein is retracted superiorly. The sheath of the posterior tibial tendon is identified and opened proximally too distally.

The anterior tibialis tendon sheath is then incised from its insertion distally. The tendon is incised in half in a longitudinal fashion. Dissection is then carried beneath the navicular tuberosity to allow for relocation of the anterior tibialis tendon. A drill hole or medium sized trephine is used to create hole in the navicular from a dorsal proximal to plantar distal direction. If a trephine is used the bone plug can be reinserted once the tendon has been translocated through the hole [12]. A saw is then used to make two parallel cuts from the medial aspect of the navicular to the trephine or drill hole. The cuts are angulated from proximal to distal. Translocation of the tendon is accomplished using two pieces of moist umbilical tape around the anterior tibialis tendon for mobilization of the tendon. The foot is held in an adducted and plantarflexed position and the anterior tibialis tendon is manipulated using the umbilical tape into the slot. Care must be taken not to disrupt the integrity of the tendon during insertion of the tendon into the slot on the navicular. With the tendon locked in place, the periosteum is closed, reinforcing the tendon's new insertion into the dorsal navicular [11]. The wound is then closed. A below knee cast is applied for 4–6 weeks.

Adjunctive procedures can be performed including an advancement of the posterior tibial tendon, plication of the spring ligament and a transfer of the flexor digitorum longus tendon. The Young's tenosuspension has proven to be a technically difficult procedure, but lead to positive outcomes when used in conjunction with other soft tissues procedures to stabilize the medial column, particularly in a more flexible deformity.

## 9. Cotton medial cuneiform osteotomy

The cotton osteotomy is a procedure known best for its use in pediatric and adolescent flexible valgus deformities, and it is used for medial column collapse [14]. This procedure is rarely performed as an isolated flatfoot procedure and often is done in conjunction with an Evans calcaneal osteotomy or arthroeresis procedure. Forefoot varus or forefoot supinatus can become accentuated during the correction of a valgus deformity. The Cotton osteotomy corrects this deformity by plantarflexing the medial column, establishing an appropriate forefoot to rearfoot relationship [14].

The procedure is performed with the patient in a supine position. Typically, a gastrocnemius recession or tendo-achilles lengthening along with more proximal osseous or soft tissue procedures are performed first. A linear dorsomedial incision is made over the medial cuneiform. Care is taken to avoid the medial dorsal cutaneous and saphenous nerve. A periosteal incision is made medial to the extensor hallucis longus. The dorsal ligaments and anterior tibial tendon are avoided. The anterior tibial tendon will be medial to the osteotomy. C-arm can be useful to identify the location of the osteotomy. The osteotomy is best performed just proximal to the level of the second metatarsocuneiform joint as the adjacent joint aids in allowing easier mobilization and plantarflexion of the osteotomy. By placing the osteotomy just proximal to the osteotomy it prevents possible interposition of the graft into the second metatarsocuneiform joint. The transverse osteotomy is created using a sagittal saw. The osteotomy is made dorsal to plantar mirroring the first metatarsocuneiform joint. The plantar cortex is preserved. The medial and lateral cortex should be visualized prior to performing the opening the osteotomy to avoid an accidental fracture of the osteotomy site. Once the osteotomy is complete feathering using the sagittal saw may be necessary to allow distraction and opening of the osteotomy without compromising the plantar cortex. A lamina or pin-based distractor can be used to carefully dial the desired amount of first ray plantarflexion. The forefoot to rearfoot relationship can then be assessed prior to inserting the graft. The objective is to achieve equal plantar surface contact with the first and fifth metatarsal heads. The graft is then fashioned appropriately and carefully tamped into place. The graft can be fixated with a k-wire, staple, screw or plate, however fixation is not always necessary. The post-operative course involves 6 weeks of non-weight bearing in a cast followed by transition to weight bearing in an aircast. As with the Evans calcaneal osteotomy graft incorporation can be prolonged in adult patients (12 weeks) compared to pediatric patients (8 weeks) [13].

## 10. Arthroeresis

Subtalar arthroeresis describes a procedure where a spacer is placed into the sinus tarsi, restricting pronation by limiting the contact of the lateral talar process against the calcaneal sinus tarsi floor, therefore maintaining a more neutral talocalcaneal joint [13]. The primary indication for this procedure is a frontal plane deformity; however, a small amount of correction can be achieved in the sagittal and transverse planes. The procedure is contraindicated if the midtarsal joint is unstable [15]. A distinct advantage of the arthroereisis procedure in the pediatric population is that the implant provides structural realignment of the rearfoot complex during skeletal growth, which may become permanent correction as the child reaches and surpasses skeletal maturity [13]. It is important to note that with realignment of the rearfoot utilizing an arthroeresis implant, as with any rearfoot procedure, it may uncover forefoot supinatus or forefoot varus which may need to be addressed as well.

## 11. Arthrodesis

Arthrodesing procedures are also used for treatment of PTTD. These procedures consist of the calcaneocuboid, talonavicular, subtalar and triple arthrodesis. The calcaneocuboid distraction arthrodesis was popular for a while, but is losing favor because of the increased incidence of nonunions and delayed unions and its inability to correct the deformity [15]. These joint destructive procedures are reserved for the rigid valgus foot type in which arthritis has become clinically and radiographically evident. In general, older patients and those who have more severe or rigid deformities secondary to PTTD are candidates for consideration of an arthrodesis. An isolated subtalar joint arthrodesis is not as effective for controlling midtarsal joint motion as other procedure and may not correct deformity in all flexible flatfeet. Yu et al. found that there was good correction of collapsing pes planovalgus deformity with an isolated subtalar joint arthrodesis [16]. The isolated talonavicular arthrodesis is indicated in a flexible flatfoot deformity when degenerative changes are not present in the subtalar joint. The talonavicular arthrodesis can prevent further degenerative changes because it significantly limits motion by 80–90% [15]. O'Malley showed that isolated fusion of the talonavicular joint is capable of correcting rearfoot valgus, forefoot abduction, forefoot supinatus and midfoot collapse [17]. The major complication of a talonavicular joint arthrodesis is a non-union. The triple arthrodesis is the gold standard in long-standing difficult rearfoot deformities, the role of more limited fusion procedures is controversial.

The technique for an isolated subtalar joint arthrodesis employs a lateral incision that runs from the tip of the fibula to the calcaneal-cuboid joint. The sural nerve, lateral dorsal cutaneous nerve and the peroneal tendons are protected during dissection. The subtalar joint is accessed with a vertical "L" incision over the extensor digitorum muscle belly. The joint is prepared typically using curettage. Access to the subtalar joint can often be difficult in an isolated procedure. Once the joint is prepared one or two large screws can be introduced from either the inferior lateral heel or from the talar neck across the posterior facet of the subtalar joint.

The talonavicular joint is approached through a longitudinal dorsomedial incision between the posterior tibial tendon and anterior tibialis. The talonavicular capsule is incised and the talonavicular joint is prepared using either curettage resection or saw resection. Exposure can be facilitated with a lamina spreader or a pin-based distractor. After the joint surfaces are prepared the joint is reduced and temporarily fixated. Once proper position is confirmed two large screws are passed from the navicular tuberosity through the talar neck and into the talar body.

A double or triple arthrodesis may be utilized in a stage III deformity or in some early stage IV deformities. The calcaneal-cuboid joint can be fixated with staples, screws or even a plate. Care must be taken not to over shorten the lateral column of the calcaneal-cuboid joint during joint preparation. Those patients with severe radiographic and clinical ankle valgus will often require a pantalar arthrodesis.

## 12. Conclusion

Tibialis posterior tendon dysfunction is a common foot and ankle deformity with various treatment options. Selecting the appropriate procedure and formulating a treatment plan based on the stage of the deformity can be difficult. It is important to understand the available surgical and conservative options for the proper treatment of each individual patient. Due to the progressive nature of this deformity; many patients will eventually end up requiring some form of surgical intervention. The surgeon must use caution when selecting the best procedure for each individual patient to fully address the deformity and prevent the need for future operations.

## Nomenclature

| | |
|---|---|
| PTTD | posterior tibial tendon dysfunction |
| EDB | extensor digitorum brevis |
| FDL | flexor digitorum longus |

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Section 3

# Quality Control in Foot and Ankle Patients

Chapter 5

# Quality of Life and Functionality in Patients with Flatfoot

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Additional information is available at the end of the chapter

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**Abstract**

The objective of the study is to determine the prevalence of a plan, its impact on quality of life, dependence and functional limitation in a random population of 40 years and over. Cross-sectional study in a random population sample in Cambre (A Coruña-Spain) (n = 835) ($\alpha$ = 0.05; precision = ±3.4%). Anthropometric variables are studied, comorbidity (Charlson Score), foot functionality (FFI questionnaire), foot health questionnaire (FHSQ), quality of life (SF-36) and dependence on activities of daily living (Barthel index and Lawton). A logistic and linear multiple regression analysis was performed. The prevalence of flat feet was 26.62%. Patients with flat feet presented higher: age (65.73 ± 11.04 years), comorbidity index (0.92 ± 1.49), BMI (31.45 ± 5.55) and foot size (25, 16 ± 1.66 cm). Having flat feet decreases the quality of life and function of the foot. The association of flat feet with age, Charlson index, and BMI and foot size was found. The SF-36, Barthel and Lawton questionnaires remained unchanged due to the presence of the flat foot, a difference between the FHSQ and FFI that were significantly sensitive.

**Keywords:** flat foot, quality of life, dependence, prevalence, functionality

## 1. Introduction

Flexible flatfoot is a common deformity in adults [1]. It is characterized by medial rotation and plantar flexion of the talus, eversion of the calcaneus, collapsed medial arch, and abduction of the forefoot [2].

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In clinical practice flat foot may be diagnosed through different procedures, such as clinical diagnosis [3], radiological study [4] and footprint analysis [5].

Footprint analysis using a pedograph is a simple, swift, and cost-effective method. The three measurements habitually used in the diagnosis of flat foot using a pedograph are: Clarke's angle [6] the Chippaux-Smirak index [7] and the Staheli index [8].

Studies have found relation between these indices [9, 10] and their validity has been determined using diagnosis carried out with a podoscope on children as a reference group [11].

Prevalence changes with age, the type of population studied and the presence of other pathologies. Some studies show prevalence between 26.5% [12] and 19.0% [13] and other studies on patients with associated comorbidity report a prevalence of 37% [14].

Flat foot has been associated to family history, the use of footwear in infancy, obesity and urban residence [15], and it has also been associated with age [16], gender [17] and foot length [18].

The presence of flat foot has also been associated with the presence of different states of health [19], the presence of pain, and the fatigue in women [12]. Other studies, however, find no relationship of pain or functionality with the changes in the foot [20, 21].

We conducted this study, in order to determine the variables associated with the prevalence of flat foot in a random population sample, and the impact on quality of life, dependence, foot pain, disability and functional limitation, using specific and generic questionnaires.

## 2. Materials and methods

A cross-sectional study was conducted in a random population sample from 2009 to 2012 in Cambre (A Coruña-Spain).

The sample size was taken from people who lived in Cambre and were identified through the National Health System card census. People aged 40 and over were included who signed the informed consent.

The sample size is calculated of the total population of the municipality (n = 23,649) after stratification by age and gender. Finally, a total of 835 people were included in the study. This sample size (n = 835 people; 445 aged 40–64 years old and 390 aged 65 years and older) makes it possible to estimate the parameters of interest with a confidence of 95% ($\alpha = 0.05$) and a precision of ±3.4%). The general characteristics of a different sample from the same population have already been described above [22].

For each person included in the study, the following variables were studied: anthropometric variables (age, gender, body mass index), study of chronic comorbid diseases (comorbidities) using the Charlson comorbidity index [23], quality of life (SF-36 questionnaire) [24], Foot Health Status Questionnaire (FHS) [25], Foot Function Index (FFI) [25] Barthel index [26], Lawton index [27], podiatric examination and type of footwear. The podiatric examination was carried out by an experienced podiatrist.

The Charlson Index contains 19 categories of comorbidity, which are primarily defined using the ICD-9-CM diagnosis codes (a few procedure codes are also employed). Each category has an associated weight, taken from the original Charlson paper [20], which is based on the adjusted risk of one-year mortality. The overall comorbidity score reflects the cumulative increased likelihood of one-year mortality; the higher the score, the more severe the burden of comorbidity.

In order to study quality of life, the SF-36 health questionnaire was used, adapted and validated for Spain by Alonso et al. [21].

The questionnaire sf-36 is formed by 36 questions that evaluate the Physical Function, Physical Role, Corporal Pain, General Health, Vitality, Social Function, Emotional Role and Mental Health. The score scale varies from 0 to 100, with 100 the best state of health.

Foot Health Status Questionnaire (FHSQ) [22] is a health-related quality of life questionnaire and is specific to the foot, is divided into 4 domains that assess pain, functional capacity, footwear and overall health of the foot. The questionnaire does not provide an overall score. The score varies from 0 to 100, 0 is the worst state of health.

The questionnaire Foot function Index (FFI) [22] measures disability and pain in the feet.

The FFI consists of 23 items divided into 3 subscales: pain (9 items), disability (9 items) and functional limitation (5 items). To evaluate each item, it consists of a visual analog scale with values between 0 and 9, where 0 is the minimum score and 9 is the maximum score. To get the result, we must add all the scores made by the person and then divide this result by the maximum value that could reach. This result is then multiplied by 100 and rounded to integers. The final score will be between 0 and 100. Higher scores indicate worsening foot health and quality.

### 2.1. Flat foot diagnostic

The study of the footprint was obtained by a pedograph. Three measurements were used: Clarke's angle, the Chippaux-Smirak index, and the Staheli arch index [6–8].

The specific methods of measurements of these indexes was described previously [25].

For the study of the footwear, the type of footwear most used, the heel (flat, low, medium, high) and the shape (shoe, sporty, boot, clog) or type of closure (moccasin, zipper, buckle, drawstring).

### 2.2. Statistical analysis

A descriptive analysis of the variables collected in the study was carried out. The quantitative variables are expressed as mean ± standard deviation, median and range. The qualitative variables are expressed as frequency (n) and percentage with the estimation of the corresponding 95% confidence interval.

The association between qualitative variables was estimated using the Chi-square test or Fisher's test as appropriate. The assumption of normality was checked by the Kolmogorov-Smirnov test, which determined the use of the Student's T test or the Mann-Whitney test for the comparison of two means.

### 2.3. Ethics

The study complies with the principles laid down in the Declaration of Helsinki. Informed consent was obtained from all the participants in the study. Confidentiality was preserved in accordance with the current Spanish Data Protection Law (15/1999). Patient and ethical review approval was obtained previously (code 2008/264 CEIC Galicia).

## 3. Results

The general characteristics of the sample studied, according to different variables are shown in **Table 1**. The mean age is 61.70 ± 11.60 years, with a prevalence of overweight of 42.2% and a median Charlson comorbidity index from 2.0.

People with flat feet use closed shoes (88.0%), followed by sports (3.8%). The most used heel was the medium heel (2–4 cm) (71.8%). The most used footwear style would be moccasin type (48.1%) followed by cord shoe (44.2%).

This study shows that the prevalence of flatfoot is 26.62% (**Table 2**).

The presence of flatfoot is significantly associated with bivariate analysis with: age, comorbidity, BMI and foot size. Among patients with flat feet, there was a higher mean age (65.73 years vs. 61.03 years), higher comorbidity (2.99 vs. 2.09), higher BMI (31.45 kg/m$^2$ vs. 28.4045 kg/m$^2$) and have a greater average foot size (25.16 cm vs. 24.82 cm). They were not associated in the analysis bivariate with the presence of flat foot or forefoot width, or sex (**Table 3**).

After performing a multivariate logistic regression analysis, we observed that the variables that have an independent effect associated with the presence of flat feet are: BMI (OR = 1.137), age (OR = 1.029), mean foot size OR = 1.287) and comorbidity (OR = 1.217) (**Table 3**). That is, higher values of the different variables previously described increase the greater probability of flat foot.

If we study the area under the curve (AUC) to predict presence of flat feet according to each of the previously described variables, the most likely predictor is BMI (AUC = 0.683) and age (AUC = 0.614) (**Figure 1**).

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| **Variables** | **n** | **Mean ± SD** | **Median** | **Minimum–maximum** |
|---|---|---|---|---|
| *Age* (years) | 835 | 61.70 ± 11.60 | 63 | 42–91 |
| *BMI* (kg/m²) | 835 | 29.18 ± 4.74 | 28.65 | 19.13–64.09 |
| *Charlson comorbidity index* | 786 | 2.31 ± 1.89 | 2 | 0–14 |
| | **n** | **%** | **95% CI** | |
| *Gender* | | | | |
| Male | 369/835 | 44.2% | (40.76;47.62) | |
| Female | 466/835 | 55.8% | (52.38;59.34) | |
| *Age groups* | | | | |
| <65 years | 445/835 | 53.3% | (49.85;56.74) | |
| 65 years and over | 390/835 | 46.7% | (43.26;50.15) | |
| *BMI categories* | | | | |
| Normal weight (18.5 kg/m² ≤ BMI < 25 kg/m²) | 140/832 | 16.8% | (14.17;19.36) | |
| Overweight (25 kg/m² ≤ BMI < 30 kg/m²) | 369/832 | 44.2% | (40.19;47.62) | |
| Obesity (BMI ≥ 30 kg/m²) | 323/832 | 38.7% | (35.32;42.05) | |
| *Smoking habit* | | | | |
| Former smoker | 212/835 | 25.4% | (22.38:28.40) | |
| Yes | 136/835 | 16.3% | (13.72;18.52) | |
| No | 213/835 | 58.3% | (22.49;28.53) | |
| *Charlson comorbidity index* | | | | |
| Diabetes | 100/815 | 12.3% | (9.71;14.24) | |
| COPD | 55/816 | 6.7% | (4.84;9.33) | |
| Peripheral vascular disease | 48/818 | 5.9% | (4.11;7.39) | |
| Peptic ulcer | 46/818 | 5.6% | (3.69;6.85) | |
| Leukemia | 44/812 | 5.4% | (3.69;6.85) | |
| Myocardial infarction | 37/819 | 4.5% | (2.97;5.89) | |
| Liver disease | 26/814 | 3.3% | (1.88;4.35) | |
| Connective tissue disease | 21/818 | 2.6% | (1.39;3.68) | |

| Variables | n | Mean ± SD | Median | Minimum–maximum |
|---|---|---|---|---|
| Cerebrovascular disease | 14/818 | 1.7% | (0.75;2.61) | |
| Moderate to severe chronic kidney disease | 9/815 | 1.1% | (0.32;1.84) | |
| Congestive heart failure | 7/819 | 0.9% | (0.16;1.52) | |
| Dementia | 6/819 | 0.7% | (0.09;1.35) | |
| Metástatic | 1/813 | 0.1% | (<0.01;0.66) | |
| AIDS | 1/814 | 0.1% | (<0.01;0.66) | |
| Peripheral disease | 0/819 | — | — | |
| Hemiplegia | 0/819 | — | — | |

**Table 1.** Distribution of patients according to demographic characteristics and comorbidity.

### 3.1. Quality of LIFE scales taking into account the foot and functionality of the foot

The scores of the different questionnaires used to measure the functionality, quality of life and dependence according to the presence or absence of flat foot in the entire sample studied and stratified by sex is shown in **Table 4**.

This table shows that patients with flat feet have significantly lower scores of the different quality of life domains of the FHSQ than those without flat feet. These values are consistent in both men and women being significantly inferior in the women and being in the men next to be significant.

It is also objected that FFI is greater in patients with flat feet than in patients who do not, and that difference is in the limit of statistical significance. This index reflects that the higher the score the worse functionality.

They are not significantly modified with the flatfoot or the dimensions of the physical and mental summary of the SF-36 questionnaire nor the Barthel index.

Although significant differences have been found between the values of the Lawton scale and whether or not having flat feet, in the bivariate analysis, dependence for instrumental activities (Lawton Scale) is not related to the presence of flat feet but to age and comorbidity (**Table 4**).

After identifying in the univariate analysis that the different FHSQ and FFI scores are modified with the presence of flat feet, the extent to which this effect is maintained after considering other variables such as age, gender and comorbidity is studied. For this, we perform different regression models presented in **Table 5**.

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| Anthropometric variables | n | Mean ± SD | Median | Minimum–maximum |
|---|---|---|---|---|
| Foot size (cm) | 812 | 24.92 ± 1.66 | 24.75 | 20.50–29.80 |
| Forefoot width (cm) | 796 | 9.37 ± 0.62 | 9.40 | 7.55–11 |
| *Left footprint* | **n** | **%** | **95% IC** | |
| Normal left footprint | 413/803 | 51.4% | (47.91;54.95) | |
| Left flat footprint | 174/803 | 21.7% | (18.76;24.59) | |
| Left cavus footprint | 216/803 | 26.9% | (23.77;30.03) | |
| *Right footprint* | | | | |
| Normal right footprint | 385/793 | 48.50% | (45.01;52.09) | |
| Right flat footprint | 184/793 | 23.20% | (20.20;26.20) | |
| Right cavus footprint | 224/793 | 28.20% | (25.05;31.44) | |
| *Flat foot* | 213/800 | 26.62% | (22.49;28.52) | |
| Unilateral | 72/213 | 33.8% | (27.215;40.39) | |
| Bilateral | 141/213 | 66.2% | (59.61;72.78) | |
| *Hallux abductus valgus* | 325/805 | 40.4% | (36.92;43.82) | |
| Unilateral | 38/325 | 11.7% | (8.04;15.34) | |
| Bilateral | 287/325 | 88.3% | (84.66;91.95) | |
| *Hallux rigidus* | 97/801 | 12.11% | (9.79;14.43) | |
| Unilateral | 32/97 | 32.99% | (23.12;42.86) | |
| Bilateral | 65/97 | 67.01% | (57.14;76.88) | |
| *Hallux extensus* | 109/805 | 13.5% | (11.11;15.97) | |
| Unilateral | 13/109 | 11.93% | (5.39;18.47) | |
| Bilateral | 96/109 | 88.07% | (81.53;94.61) | |
| *One or more claw toes left* | | | | |
| Yes | 297/836 | 36.9% | (32.22;38.83) | |
| No | 507/836 | 63.1% | (57.27;64.02) | |
| *One or more claw toes right* | | | | |
| Yes | 290/836 | 36.1% | (31.40;37.97) | |
| No | 513/836 | 61.4% | (58.01;64.72) | |

**Table 2.** Description of the sample according to type of footprint and presence of different foot pathologies.

| | **Flat foot** | | | | |
|---|---|---|---|---|---|
| | **Yes** | **No** | | | |
| | **Mean (SD)*** | **Mean (SD)** | **P** | **Crude OR** | **Adjusted OR** (95% CI)** |
| *Age (years)* | 65.73 (11.04) | 61.03 (11.45) | **<0.001** | 1.037 | **1.029 (1.012–1.046)** |
| *Charlson comorbidity index adjusted for age* | 2.99 (2.11) | 2.09 (1.75) | **<0.001** | 1.275 | |
| *Charlson comorbidity index* | 0.92 (1.49) | 0.50 (0.98) | **<0.001** | 1.335 | **1.217 (1.042–1.421)** |
| *BMI (kg/m²)* | 31.45 (5.55) | 28.40 (4.17) | **<0.001** | 1.147 | **1.137 (1.094–1.181)** |
| *Forefoot width (cm)* | 9.42 (0.64) | 9.41 (2.01) | 0.983 | 1.001 | |
| *Foot size (cm)* | 25.16 (1.66) | 24.82 (1.65) | **0.011** | 1.131 | **1.287 (1.102–1.504)** |
| | **n (%)** | **n (%)** | **p** | | |
| *Age groups* | | | **<0.001** | | |
| 40–64 years | 86/425 (20.22%) | 339/425 (79.8%) | | 1 | |
| ≥65 years | 127/375 (33.9%) | 248/375 (66.1%) | | 2.019 | |
| *BMI categories* | | | **<0.001** | | |
| Normal weight (18.5 kg/m² ≤ BMI < 25 kg/m²) | 23/135 (17%) | 112/135 (83%) | | 1 | |
| Overweight (25 kg/m² ≤ IMC < 30 kg/m²) | 57/351 (16.2%) | 294/351 (83.8%) | 0.832 | 0.944 | |
| Obesity (IMC ≥ 30 kg/m²) | 133/312 (42.6%) | 179/312 (57.4%) | **<0.001** | 3.618 | |
| Gender | | | 0.419 | | |
| Male | 99/353 (28%) | 254/353 (72%) | | 1 | 1 |
| Female | 114/447 (25.5%) | 333/447 (74.5%) | | 0.878 | 1.618 (0.963–2.717) |

*SD: standard deviation.

**Adjusted OR: Adjusted Odds Ratio by age of the patient. Charlson's comorbidity score. BMI, foot size and gender.

Statistical significative results are indicated in bold

**Table 3.** Differences between the presence or not of flatfoot and different variables.

After this regression, we objectified how the presence of flat feet continues to modify the score of the different dimensions of the FHSQ after adjusting or taking into account age, gender and comorbidity.

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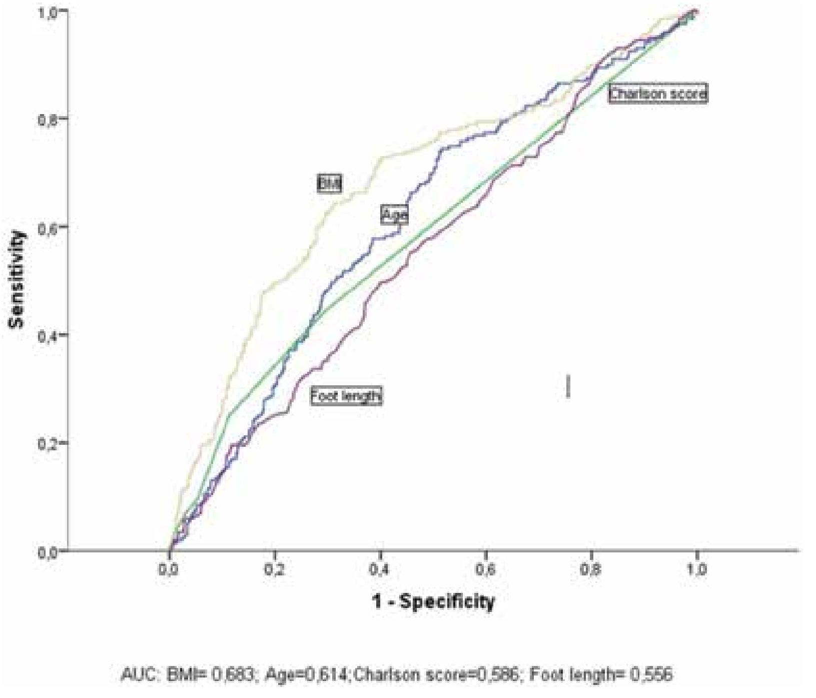


**Figure 1.** Area under the curve (AUC) to predict flatfoot according to different variables.

| | **Total sample (n = 835)** | | | **Female (n = 466)** | | | **Male (n = 369)** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Flat foot** | | | **flat foot** | | | **flat foot** | | |
| | **Yes** | **No** | | **Yes** | **No** | | **Yes** | **No** | |
| | **Mean (SD)** | **Mean (SD)** | ***p*** | **Mean (SD)** | **Mean (SD)** | ***p*** | **Mean (SD)** | **Media (SD)** | ***p*** |
| *SF-36* | | | | | | | | | |
| Physical summary | 53.72 (8.25) | 54.55 (7.78) | 0.189 | 53.06 (9.60) | 55.48 (7.95) | **0.017** | 54.48 (6.29) | 53.34 (7.37) | 0.148 |
| Mental summary | 47.25 (9.55) | 48.53 (8.48) | 0.086 | 48.14 (9.94) | 48.49 (8.98) | 0.744 | 46.22 (9.02) | 48.60 (7.80) | **0.015** |
| **Barthel index** | 97.38 (11.23) | 99.43 (4.03) | 0.052 | 96.80 (12.42) | 99.41 (3.23) | 0.112 | 97.95 (9.97) | 99.46 (4.83) | 0.183 |
| **Lawton index** | 6.14 (1.89) | 6.52 (1.57) | **0.040** | 7.54 (1.51) | 7.87 (0.63) | 0.104 | 4.74 (0.96) | 4.91 (0.42) | 0.188 |
| *Foot Health Status Questionnaire* | | | | | | | | | |
| Foot pain domain | 86.91 (29.63) | 90.52 (17.62) | **0.024** | 82.12 (22.56) | 86.90 (19.97) | **0.047** | 92.47 (10.19) | 95.28 (12.49) | 0.132 |
| Function domain foot | 90.30 (19.64) | 94.36 (14.55) | **0.006** | 86.51 (21.96) | 92.13 (16.81) | **0.014** | 94.71 (15.53) | 97.30 (10.19) | 0.129 |
| Footwear domain | 60.07 (37.38) | 68.44 (35.60) | **0.004** | 53.95 (37.79) | 64.48 (35.77) | **0.008** | 67.26 (35.75) | 73.62 (34.77) | 0.130 |

| | Total sample (n = 835) | | | Female (n = 466) | | | Male (n = 369) | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Flat foot** | | | **flat foot** | | | **flat foot** | | |
| | **Yes** | **No** | | **Yes** | **No** | | **Yes** | **No** | |
| | **Mean (SD)** | **Mean (SD)** | *p* | **Mean (SD)** | **Mean (SD)** | *p* | **Mean (SD)** | **Media (SD)** | *p* |
| General foot health domain | 48.88 (21.66) | 53.67 (20.89) | **0.005** | 44.19 (22.99) | 49.89 (21.02) | **0.021** | 54.34 (18.66) | 58.63 (19.67) | 0.064 |
| Foot function Index | 7.63 (13.93) | 5.22 (11.58) | 0.055 | 9.76 (13.53) | 12.73 (6.86) | 0.082 | 4.91 (14.06) | 2.84 (9.17) | 0.178 |

SD, standard deviation.
Statistical significative results are indicated in bold

**Table 4.** Differences between the presence or not of flatfoot stratified by sex according to the questionnaires studied: SF-36, Barthel and Lawton index, Foot Health status questionnaire and Foot function index.

| **Variables** | **B** | **Standard error** | **Beta** | **t** | **p** |
|---|---|---|---|---|---|
| | *Linear regression model to predict dimension score foot pain FHSQ* | | | | |
| Gender | −9.225 | 3.743 | −0.249 | −7.016 | **<0.001** |
| Age | −0.007 | 0.060 | −0.004 | −2.134 | 0.913 |
| Charlson Score | −1.284 | 0.602 | −0.080 | −2.134 | **0.003** |
| Flat foot | −2.931 | 1.510 | −0.070 | −1.942 | 0.053 |
| | *Linear regression model to predict dimension score function foot FHSQ* | | | | |
| Gender | −5.872 | 1.148 | −0.183 | −5.116 | **<0.001** |
| Age | −0.054 | 0.053 | −0.039 | −1.029 | 0.304 |
| Charlson Score | −1.009 | 0.525 | −0.073 | −1.922 | 0.055 |
| Flat foot | −3.329 | 1.317 | −0.092 | −2.528 | **0.012** |
| | *Linear regression model to predict score footwear dimension FHSQ* | | | | |
| Gender | −10.305 | 2.591 | −0.142 | −3.977 | **<0.001** |
| Age | −0.519 | 0.119 | −0.165 | −4.351 | **<0.001** |
| Charlson Score | 1.286 | 1.185 | 0.041 | 1.086 | 0.278 |
| Flat foot | −6.897 | 2.979 | −0.084 | −2.315 | **0.021** |
| | *Linear regression model to predict overall health score foot dimension FHSQ* | | | | |
| Gender | −9.214 | 1.527 | −0.215 | −6.035 | **<0.001** |
| Age | −0.094 | 0.070 | −0.051 | −1.336 | 0.182 |
| Charlson Score | −1.248 | 0.699 | −0.068 | −1.786 | 0.074 |
| Flat foot | −3.614 | 1.752 | −0.075 | −2.063 | **0.039** |
| | *Linear regression model to predict final score of the Foot Function Index* | | | | |
| Sexo | 4.400 | 1.031 | 0.177 | 4.269 | **<0.001** |
| Edad | 0.056 | 0.049 | 0.051 | 1.155 | 0.249 |
| Charlson Score | 1.242 | 0.489 | 0.112 | 2.540 | **0.011** |
| Pie plano | 1.821 | 1.187 | 0.066 | 1.534 | 0.126 |

Statistical significative results are indicated in bold

**Table 5.** Multiple linear regression to predict the different dimensions of foot health status questionnaire and the FFI adjusting for gender, age, comorbidity and presence of flatfoot.

As for the functionality measured by the FFI we objectify how the presence of flat foot is in turn close to being significant and has a positive regression coefficient which implies that the presence of flat foot increases the FFI score and therefore decreases the functionality.

## 4. Discussion

This study shows that the prevalence of flatfoot was 26.62%. This finding is practically identical to a study carried out in Japan in a sample of 242 women and 98 men, with a prevalence of 26.5%, and as this finding is related to obesity and affection of pain and function [9].

Similar findings are found in other publications regarding the prevalence of flatfoot. In other population studies (Springfield, Massachusetts) the prevalence of flatfoot was 19.0% (20.1% in women and 17.2% in men) [10]. Another study conducted in the Boston area found a prevalence of 20% in women and 17% in men [11]. There are even studies in diabetic population in a sample of 230 patients that even refer to a prevalence of 37% [11].

It is evident that the characteristics and age of the population under study are determinants of this prevalence, so we also found that among Saudi Arabian army recruits in a sample of 2100 recruits aged 18–21 found a prevalence of 5% and factors associated with their presence have been family history, use of shoes in childhood, obesity and urban residence, no differences in functionality or discomfort in the foot [12].

Some studies conducted in India indicate that the use of shoes at earlier ages increases along with obesity and ligament laxity the prevalence of flat feet [26].

Another study carried out in Nigeria in 560 children between 6 and 12 years shows that although in the univariate analysis we found association with the type of footwear and age. However, after considering both, only age remained as a variable associated with the presence of flat foot [13].

The urban residence as a risk factor for the prevalence of flatfoot has also been described in a study carried out in Congo children where it was objected after studying 1851 footprints of 906 girls and 945 children between 3 and 12 years old that the prevalence decreases with the age is higher in urban areas, in the male sex and the use of footwear has little influence on this prevalence [14].

This study shows how BMI, age, comorbidity, and foot size are associated with the prevalence of flatfoot. Some studies describe how podologic pathology increases with age [17] while other studies describe how flatfoot decreases with age, after adjusting for other covariates [18], while others indicate that neither age nor gender nor the BMI, are related to the flat foot [19].

Studies carried out in primary schools identified gender and being overweight as a risk factor for flatfoot [20, 21] while studies with adolescents [22] and preschoolers [23] identified associated flatfoot to an increase in BMI.

Foot length and the presence of flatfoot associated with flatfoot have also been referenced in the literature [24] although there are also authors who say that it is not associated with length [19].

In the adult population this pathology was also found to be associated with race and concomitant pathology of the foot [16, 27–29].

Some studies even describe radiological findings of different morphology in the foot according to different ethnic groups [30].

Others point out how the different morphology radiology (angle of talus with the first metatarsal) is related to the symptomatic presence or not of flat foot [31].

Although obesity has been repeatedly associated with obesity [32]. Not all show this association with it [33].

### 4.1. Related to health

Some articles indicate not only the association of the flat foot with different characteristics such as age, sex, BMI, concomitant pathology, but also as a health modifier [16].

Thus there are studies of 97,279 recruits of the armed forces, who give flat feet to localized pains in the knee [34].

As we have previously pointed out in the article that finds a flat foot prevalence identical to ours, they also objectify how this alteration is also associated with the presence of pain and fatigue in women [9].

Others performed in Australian recruits of area forces show how foot alterations are not related to pain, injury or functionality, although flatfoot is associated with a lower subjective feeling of physical health than those with normal foot [18].

In another study where the adult population (n = 784) was studied in Boston, there was no association between foot alteration, pain and functionality [17].

Other studies find an association between the presence of flat feet and accidents produced in the training of professionals of the armed forces [35]. Although this finding is not consistent in all publications [36].

We also found an association between flat feet with disabilities in workers with spondylarthrosis [37] and fractures of the lower limbs [38].

This study shows that the quality of life and functionality in patients with flatfoot is lower than in those who do not, and that this effect is maintained after adjusting for age, sex and comorbidity using the FHSQ and FFI questionnaires. The use of specific instruments to measure this affectation is important because general health questionnaires such as the SF-36 in this study have shown no differences between those with or without flat feet. Similar results were found by other authors who did not objectify differences between patients with podiatric pathology and did not use SF-36 as a quality of life measurement instrument [39].

The SF-36 is sensitive to changes but is a generic questionnaire. The SF-36 was described as a relevant tool to detect changes in results after Hallux valgus surgery [40].

Other authors have described a progressive reduction of SF-36 components as the severity of Hallux valgus increases [41].

The use of specific questionnaires to study the quality of life and the functionality of the foot is widely documented in the literature [22, 42, 43].

The changes experienced in quality of life by the FHSQ questionnaires and the pathological pathology have also been described in the literature [42, 44, 45].

The validity of the Spanish version of the FHSQ and the FFI has been described in the literature [46, 47].

It is therefore reasonable to have objectified in this study that the use of specific questionnaires on the foot objective significant differences that other more generic questionnaires have not detected.

## 5. Conclusions

Age, Charlson's comorbidity index, BMI and foot size are associated with the presence of flat feet.

The questionnaires SF-36, Barthel and Lawton were not altered with the presence of flat feet, while the questionnaires FHSQ and FFI were sensitive to the presence of flat feet.

## Conflict of interest

The authors declare no conflicts of interest.

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# Quality Initiatives in Foot and Ankle Surgery

Tanja Kostuj

Additional information is available at the end of the chapter

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**Abstract**

Quality initiatives in orthopedics and traumatology are becoming more and more popular worldwide. They can include both mandatory and voluntary methods, such as standardized mandatory surveys, compulsory quality reports, registries, personal certificates, or launching centers of excellence, which means a certification of a whole department. Even in foot and ankle surgery registries, certifications and centers of excellence have been established. This chapter provides an overview of different approaches used to improve quality of care in patients with foot and ankle disorders. We present different methods in use today and discuss their key characteristics.

**Keywords:** quality initiatives, registries, certifications, PROMS

## 1. Introduction

Since the arthroplasty registries were established in the 1970s and 1980s [1, 2], it became apparent that even total ankle replacements would be reported in these registers. Today, registries for total ankle replacement exist in Finland, Germany, New Zealand, Norway, Sweden and the United Kingdom.

Studies comparing registry data on patient outcomes after total joint replacement report significant and clinically relevant differences, especially with regard to revisions and survival curves [3]. This underlines the value of registries in outcome research. In addition, registry data can be useful in postoperative surveillance of medical device implants for establishing regulations.

Stemming from registry data on silicon breast implant problems, and metal related problems in total hip replacements, in 2017, the European Union adopted the medical device regulation (MRD). The MDR will have a great impact on industry and their implants, since manufacturers will not only have to comply with more extensive regulations in order to introduce new

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or modified implants, in addition, it will have to provide clinical data about their existing implants. In this context, implant registries will play an important role; thus, total hip, knee, shoulder and total ankle replacement registries will have to be taken into consideration.

Another initiative aimed at improving quality in foot and ankle surgery is specialist certification. There are different methods of obtaining certification; it can be based on participation in a number of different cadaver courses, or scientific activity, or even verification of having done surgical interventions. In addition to national certification in individual countries, the European Foot and Ankle Society (EFAS) also offers specialist certification as well.

Mandatory public external quality assurance programs—like those in Germany [4] that cover total hip and knee replacement, as well as osteosynthesis in proximal femur fractures—to our knowledge have not yet been established for foot and ankle surgery procedures.

Finally, a third type of initiative in foot and ankle surgery is to establish competence centers/centers of excellence. This would entail certifying an entire department or institution as a means of improving quality in patients care. One such system is based on the ISO 9001 quality standards and focuses on optimizing structural and process quality. Thus, by having a way of checking, recording, and analyzing quality indicators and surrogate parameters, this leads to improved clinical outcomes.

Quality can be defined by surrogate parameters for clinical results such as X-ray parameters, number of revisions, survival rates, as well as by patients' perspective and satisfaction.

Today, the patients' perspective and the use of the so-called patient-related outcome measures (PROMs) play an important role in registries [5] and in centers of competence.

This chapter provides a review of such quality initiatives, presenting characteristics of individual systems. In addition, reasons why individual, national or, regional registries are not interchangeable and why they have to be seen in the context of their national health care systems are discussed.

## 2. Registries

There are many types of medical registries, some that focus on diagnosis, like cancer registries, others like trauma registries containing data on hip dysplasia, or medical treatment registries with data on pharmaceutics or medical devices

Total ankle replacement registries have been established in New Zealand as well as in some European countries (**Table 1**).

All of these registries focus on hard endpoint/outcome measures as a surrogate parameter representing quality of treatment. Those quality indicators are mainly peri- and postoperative complications, reoperations without exchange of components, revisions with exchange of components, complete total joint replacement, as well as implant and patient survival rates. These endpoints are related to indications/diagnoses such as idiopathic osteoarthritis, posttraumatic conditions or inflammatory diseases, or providers/hospitals, or implants [6, 7]. Despite being similar, minimal datasets also exist making it such that results from the different comparable benchmarks

| |
|---|
| Finland |
| France |
| Germany |
| Lithuania |
| Norway |
| Spain |
| Sweden |
| United Kingdom |

**Table 1.** European countries with total ankle replacement registries.

must be entered carefully due to national particularities. Implants are not necessarily the same in different countries; therefore, differences in reporting and structural differences may occur. For example, in Sweden, all total ankle replacements are done in 12 centers [8]; in contrast, in Germany, 1 to more than 100 total ankle replacements are performed in 205 different centers [9]

Foot and ankle surgery registries can be managed by the national foot and ankle societies, like in Sweden or Germany [10, 11], or they can be part of the national joint replacement registries like in Norway [7] or in the United Kingdom [6].

Registries can contain hard endpoints like revisions, survival rates, patient satisfaction, pain relief, and improvement of function by using patient reported outcome measures called PROMs [10, 11].

**Figure 1** gives an example of data on pain and function from the German registry for total ankle replacement showing the American Foot and Ankle Societies' ankle and hindfoot scale (AOFAS-AHS) computed from 144 patients preoperatively, as well as 3–6 months, 1 year and 2 years after total ankle replacement, respectively. **Figure 2** shows data on patient satisfaction, recorded at different follow-up times.

Ideally, not only one surgical procedure, for example, ankle prosthesis implantation but also alternative therapy options are included in a registry. A good example is the Swedish ankle registry that uses PROMs and covers total ankle replacement as well as ankle fusions and supramalleolar osteotomies [10]. Adding to this, Sweden is working on a national foot registry that includes other surgical procedures.

Other examples of foot and ankle registries, besides those focused on total ankle replacements, are hallux valgus and amputation registries in patients with diabetic foot syndrome, or one from Norway that focuses on total replacement of the first metatarsophalangeal joint [7]. These registries are mentioned as examples of other registers, in Europe and worldwide, focused on treatment of foot and ankle disorders.

Studies using registry data linked to data from health insurance companies/systems can be used to analyze and report quality in healthcare [12]. However, this has not yet been widely established in foot and ankle surgery because the range of procedure codes used in complex

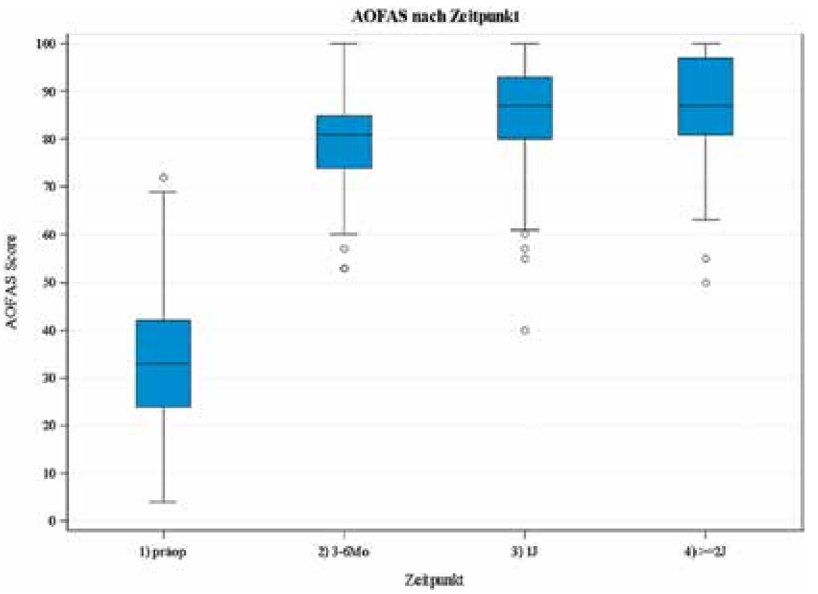


**Figure 1.** Outcome data from German foot and ankle societies' total ankle replacement register: AOFAS-score—follow-up of 2 years completed (n = 144 patients, medians and interquartile ranges (IQR) are given; circles = outlier >1.5 IQR.

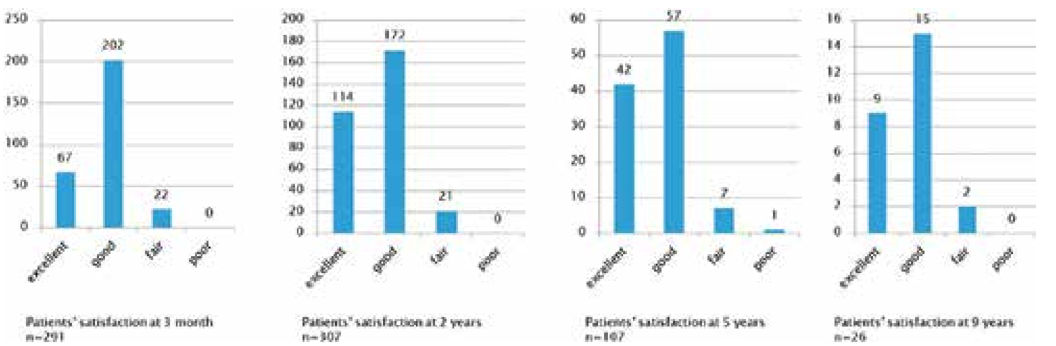


**Figure 2.** Data from the German Total ankle replacement registry showing patient satisfaction from 3 months to 9 years.

foot surgery makes it problematic to assign a single foot operation, especially in countries where different insurance providers pay for the treatments.

## 3. Personal certification of surgeons

Parallel to the establishment of registries, in the last 5–10 years, personal certification of surgeons has become more prevalent. These personal certifications require that surgeons participate in a number of standardized courses with lectures, as well as hands-on workshops, either on sawbones or on cadaver specimens. Some of these certifications also require that one provides verification of having performed a number of predetermined surgical procedures. For example, the German foot and ankle Society's (deutsche Assoziation für Fuß und Sprunggelenk e.V.)

certification is based on having attended eight courses with lectures and hands-on workshops on cadaver specimens. These cover all the main topics in foot and ankle surgery, such as anatomy, surgery on tendons, osteotomies of fore- and hindfoot, foot disorders in children, arthrodesis, arthroscopy, rheumatic diseases, and diabetic foot syndrome. To receive certification, candidates are not required to perform a predetermined number of surgical procedures; however, they must take part in all eight of these courses [13]. In contrast, the master certificate from the society for foot surgery in Germany (Gesellschaft für Fußchirurgie) is based on a credit point system, requiring that one participate in lectures and hands-on workshops using cadaver specimens, seminars on different foot and ankle surgery related topics, and the option to get credit points for participating in a choice of other topics. In addition, a predetermined number of surgical procedures are required [14]. There is no oral exam necessary in either of these two certification systems.

Beyond these national personal certificates, the European foot and ankle society (EFAS) has established the European certification in trauma and orthopedic foot and ankle surgery with the stated goal "to promote the highest standard of practice in our field of expertise to benefit patients" [15]. To receive the EFAS certificate, candidates must provide evidence of 5 years of practice in the specialty, with a certified logbook. Additional criteria include meeting attendance, publications, and fellowships. Candidates must sit for an examination, consisting of a multiple choice questionnaire (MCQ) and viva [15].

## 4. Centers of excellence

Establishing centers of excellence requires focusing on the fact that it is not solely the surgeon who is involved in patient care. In order to provide a good quality of total inpatient treatment, processes and structures must be optimally coordinated. This can be achieved, for instance, by means of ISO 9001—a worldwide accepted standard defining requirements for effective quality management used widely in the industry. Using this methodology, structure quality and process quality are measured directly, while quality in results and outcomes must be recorded and analyzed using the so-called "quality indicators" as surrogate parameters. One example for such a quality initiative in foot and ankle surgery is the German FussCert© initiative [5, 6].

In this system, besides following legal verification, standard operation procedures for treatment and after treatment, as well as the management of complications, have to be recorded. Qualification of the lead surgeon, as well as all the associated surgeons, is required and the so-called "main surgeons" ("Hauptoperateure") are defined. All elective surgery has to be done or assisted by one main surgeon. Management of institutionalized meetings must be established, and education and training must be standardized. Throughout the year, further educational activities for the entire team as well as for the individual surgeon must be planned prospectively and carried out. All elective surgery has to be done by or assisted by a so-called "main surgeon," who has to verify s/he has performed a minimum volume of foot procedures in the past 2 years. In addition, verification must be provided indicating that a minimum volume of procedures are performed in the entire center each year. Cooperation with professions involved in inpatient treatment must be regulated and confirmed in a written agreement. The so-called quality circles, meetings with participating surgeons, and cooperating partners are obligatory, where results, problems, and other important topics are discussed. Satisfaction surveys of referring physicians and patients have to be done and analyzed regularly. Clinical results, such as frequency of complications, correction angles, and so on, must be recorded and analyzed. An annual management review has to be provided to make the results transparent.

These centers are established in three different ways: centers for maximum providers, standard centers, and centers performing foot surgery in an outpatient setting. Each of these centers has different demands as it relates to volume, both of the centers and the individual main surgeon.

After passing the certification process, consisting of a formal control and control of the content of all application forms, an onsite visit (certification audit) by two experts is conducted. To date, hospitals do not have official quality management certification. An expert in quality management as well as a yearly monitoring audit will take place over the next 2 years. A new cycle with a complete certification process follows every 3 years to ensure that all these demands continue to be met.

The demands upon these centers will be regularly updated in the context of revisions of ISO 9001 quality standards and FussCert® system certification [16].

## 5. Conclusion

Standardized mandatory surveys and compulsory quality reports are well known in different procedures in health care, but are uncommon in foot and ankle surgery. This may be due to the variety of different foot and ankle disorders, as well as the great variety of the treatment options available in individual disorders.

Registries are a common and trusted system used in outcome research in foot and ankle surgery, where a high level of representation and coverage can be assumed. The latter can become problematic in countries with a voluntary registry without linkage to public health data. Nevertheless, despite providing a broad overview of patients' outcomes and having proven to improve clinical results, registries cannot account for causal relationships in most of the cases [17].

For those countries with difficulties establishing registry with a high level of representation and coverage (due to a voluntary system, a decentralized health care system and/or missing linkage to public health data), certification of individual surgeons as well as entire centers can be a viable and transparent system to analyze and improve quality in patient care.

Nevertheless, data from all of these initiatives have to be validated in order to provide reliable results from which to draw conclusions.

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Section 4

# Innovations in Foot and Ankle Surgery and Pathology

Chapter 7

# Third-Generation Percutaneous Forefoot Surgery

Jorge Javier Del Vecchio, Miky Dalmau-Pastor and
Mauricio Esteban Ghioldi

Additional information is available at the end of the chapter

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**Abstract**

Hallux valgus is one of the most common diseases that affects the foot. The primary symptom of this disease is usually pain. Although non-operative treatment should be attempted, some patients eventually need surgical treatment. There are numerous surgical procedures for correction of HV deformities. Some of these surgeries may be performed through open or percutaneous surgery (MIS). Distal metatarsal chevron osteotomy is an excellent treatment option in mild-to-moderate deformities, providing good results in the correction of deformities and symptoms. This technique can also be done by percutaneous or MIS surgeries; the set of these surgeries are called Third generation procedures. They have been showed to be useful, effective and (maybe) easier than open procedures.

**Keywords:** percutaneous, minimal invasive surgery, forefoot, third generation

## 1. Introduction

### 1.1. Definition and incidence

Hallux valgus is one of the most common disease that affects the foot (**Figure 1**) [1, 2]. It has been estimated that this condition affects around 3% of the population [3]. It takes place when the hallux has a lateral deviation, and the first metatarsal (1MT) deviates medially [4]. This condition has a clear predominance in women. According to different series, this entity is around nine times more frequent in women than in men [4–6].

Different causes have been proposed as etiological factors of this deformity: genetic predisposition and intrinsic and extrinsic causes. While some studies have indicated [7, 8] that intrinsic

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**Figure 1.** Hallux valgus deformity.

factors (pes planus) play a major role in the etiology, others suggested that this plays a minor role in the development. The most important extrinsic cause is constricting footwear; it has been suggested that this pathology almost exclusively affects shoe-wearing societies [9–11]. Genetic predisposition has been implicated as a cause of hallux valgus in adults [12, 13].

### 1.2. Symptoms and physical examination

The primary symptom of hallux valgus is pain. It is often located in medial eminence because of bursal inflammation or skin irritation. Pressure from footwear is the most frequent cause of this discomfort.

Physical examination should be performed with the patient standing and sitting. The deformity is often accentuated when the patient is standing bearing weight. The magnitude of the deformity should be recognized, as is any pronation of the hallux is present. The range of

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**Figure 2.** AP X-ray. Moderate hallux valgus.

motion (passive and active) of the metatarsophalangeal joint should be noted [14]. If pain and crepitus are present when evaluating the metatarsophalangeal joint, it often indicates that degenerative injuries are present, and this could change the choice of the surgical technique. Some authors have stated that around 5% of the patients have hypermobility of the metatarsocuneiform joint (mobility of more than 9 mm), and this should be assessed as well as the neurovascular status [15, 16]. Lesser toe deformities are often associated and could be a cause of discomfort, and this should be evaluated.

### 1.3. Radiological examination

Plain radiographs (AP and lateral) should be taken with the patient bearing weight (**Figure 2**). Angular measurement includes assessing of the hallux valgus angle (HVA), the first-second intermetatarsal angle (IMA), the distal metatarsal articular angle (DMAA), and the proximal phalangeal articular angle. The presence of osteoarthritis, joint congruity, and the amount of sesamoid subluxation are examined. All angular measurements should be made according to the guidelines set by the AOFAS Ad Hoc Committee on Angular Measurements [17]. The severity of the deformity can be classified as mild, moderate, or severe deformity [13].

## 2. Treatment

### 2.1. Conservative

Non-operative treatment should be attempted. Symptoms are often relieved by reducing friction over the prominent medial eminence. Recommendations about patient's footwear could be helpful; sometimes, a simple change in the type of shoes or size may reduce symptoms substantially [18]. Despite non-operative measures, some patients eventually need surgical treatment.

### 2.2. Operative correction

There are numerous surgical procedures for correction of HV deformities, which indicates that there is not only one procedure that is universally applicable for all patients. Usually, the choice of the procedure depends upon how rigorous the deformity is and where it is located. Options include proximal, shaft, or distal metatarsal osteotomies (associated or not to lateral release). Osteotomies of the cuneiform, arthrodesis of the metatarsophalangeal joint, and excisional arthroplasty have also been described. Some of the aforementioned surgeries may be performed through open or percutaneous surgery (MIS).

#### *2.2.1. Chevron osteotomy: open surgery*

Distal metatarsal chevron osteotomy is an excellent treatment option in mild-to-moderate deformities, providing good results in the correction of deformity and symptoms [19–21]. The radiographic indications are hallux valgus angle less than 40° and first-second intermetatarsal angle less than 20°. With this procedure, a resection of the medial eminence, a distal metatarsal osteotomy, and a medial capsuloplasty are used to realign the great toe. Johnson et al. [22] and others [23–25] have reported good to excellent results with this procedure. After this osteotomy, the average correction of the HVA has been reported to be 12–13°, and the average correction of the IMA has been 4–5° [26].

This type of metatarsal osteotomy has some advantages: is stable, has a wide contact surface, has the ability to allow corrections of the DMAA, and admits weight bearing immediately after surgery [27]. However, it has some weakness due to a small power of deformity correction. To overcome this issue, an Akin phalangeal osteotomy and lateral soft tissue release can be added to augment angular correction [28, 29].

Lateral soft tissue release can be achieved through different procedures (open or MIS, through a medial or dorsal approach). The goals of this surgical gesture are to eradicate the lateral deforming forces and allow a better realignment of the first metatarsophalangeal joint by cutting the latero-plantar capsule, the transverse metatarsal ligament, the adductor tendon, and the lateral metatarsosesamoid ligament [27].

Several complications have been described with the chevron osteotomy: undercorrection and recurrence of the deformity are the most frequent ones. Recurrence could happen when the surgical indications are not respected in terms of angular values, and more severe deformities are treated. Undercorrection can be caused by a secondary displacement at the osteotomy site. This was more frequent when no internal fixation was used, as the original technique described by Austin and Leventen [30]. Nowadays, internal fixation has shown to reduce the rate of loss of correction [22, 25].

Shortening is another complication to consider, and it may occur when too much bone had been removed. Postoperative transfer metatarsalgia has been reported as a result of this complication [31].

The most critical complication after a chevron osteotomy is an avascular necrosis (AVN) of the 1MT head. Some reports have shown an increased risk of AVN when lateral soft tissue release is combined with a distal chevron osteotomy [32, 33], although other studies state that this is a rare complication [34, 35]. The reported incidence of avascular necrosis (AVN) ranges between 0 and 20% [36, 37].

## 3. Percutaneous or minimally invasive surgery (MIS) of the forefoot

### 3.1. Definition

Percutaneous surgery of the foot, also known as minimal incision surgery or *minimally invasive surgery* (MIS), allows interventions to be carried out through extremely small incisions without direct exposure of deep tissues, thus causing minimal injury [38]. This is done with the help of tactile sensation combined with radioscopy.

### 3.2. History and generations

The applications of percutaneous surgery in hallux valgus correction were first introduced in the 1970s and 1980s [39]. It has since evolved into endoscopic, minimum-incision, and percutaneous techniques. In the last 10 years, there has been a growing interest in percutaneous techniques for HV correction especially in Italy and Spain, at the beginning. First-generation percutaneous technique was described by Isham [39] in which no internal fixation was needed. The second-generation technique was a distal transverse osteotomy of the 1MT stabilized with an axial wire [40, 41]. Recently, some comparative studies evaluating these procedures received a degree of recommendation C (poor-quality evidence for or against recommending intervention), although these results are being reviewed due to the omission of relevant studies [41–44]. The third-generation (TG) MIS involves procedures based on the design of chevron osteotomies with the need of screw fixation that has added extra stability and minor complications [45, 46].

### 3.3. Current situation and indications

Forefoot MIS has experienced a vertiginous and sustained growth especially in the last decade. Clinical series and comparative studies have been published [47–50]. Additionally, cadaveric results [51, 52], technique reports [53], and radiological validations [54, 55] have been described. Despite the fact that for some authors percutaneous surgery of the forefoot lacks scientific support [56–58], recently two systematic reviews published support its indication in hallux valgus surgery [43–59].

## 4. Third-generation forefoot MIS

Considering the indications and potential advantages of percutaneous surgery, some authors experienced with osteotomies similar to the open chevron, although with conceptual differences. They can be divided into intra- or extra-articular osteotomies.

Some examples of those performed proximal to the joint capsule (extracapsular) are as follows:

- **MICA** *(minimally invasive chevron Akin*) is performed at the neck of the first metatarsal (extra-articular) and requires two screws for the stabilization of the osteotomy associated with an Akin osteotomy. According to the authors, the development of this fixation (MICA) allows it to be used in severe HV deformity (maximum displacement of 100%) and truly marries the perceived advantages of an extracapsular first metatarsal osteotomy in which the soft tissue envelope is preserved with rigid internal fixation. As a result of evidenced movement of the osteotomy in some cases, the fixation technique was modified (tricortical fixation with proximal screw) to successfully avoid this problem. In 50–60% of cases, a percutaneous Akin osteotomy of the hallux proximal phalanx is also performed with percutaneous screw fixation. It showed good to excellent results, and around 90% of patients are satisfied or very satisfied with the results. The authors mentioned that the outcomes thus far suggest that the MICA technique may be associated with a lower risk of infection, less stiffness, and less pain. No reports exist of osteonecrosis with the MICA technique (**Figure 3**) [60–63].


**Figure 3.** (A) AP view. Incongruous moderate hallux valgus. (B) MICA technique. (C) Intraoperative radioscopy. (D) Final lateral X-ray (courtesy of Dr. Vernois, Joel).

- **PERC** (*percutaneous, extra-articular reverse-L chevron osteotomy*): that is also performed on the metaphysis of the first metatarsal (1MT), and the main difference with other techniques is that the osteotomy is stabilized with a dorsal-to-plantar screw. In a case series (38 patients, 45 procedures), this technique showed an improvement of the AOFAS score of 62.5 (30–80) preoperatively to 97.1 (75–100) postoperatively. A total of 37 patients (97%) were satisfied. At the last follow-up, there was a statistically significant decrease in the HVA, the IMA, and the proximal articular set angle. The range of movement of the first metatarsophalangeal joint improved significantly. An additional percutaneous Akin osteotomy was performed in 82%, and percutaneous lateral capsular release was performed in 48%. According to the authors, this technique is reliable and reproducible and maintains an excellent range of movement (**Figures 4–6**) [46].
- **PECA** (*percutaneous chevron/akin*): technically, this is identical to MICA that showed comparable outcomes of the new technique (equated to open Scarf/Akin). Surgeries were done by a non-developer group (MICA). Regarding patient satisfaction, this technique showed excellent (84%) and good (16%) results in a comparative series. The PECA showed statistically significant superiority regarding the pain level in the early postoperative phase compared to open Scarf. There were no wound complications, and 24% of patients required removal of the screws because of prominence under the skin (**Figure 7**) [49].
- **Third-generation MIS technique**: described by Brogan et al., it needs one screw and K-wire to provide stability. In the initial series (45 ft), there was a statistically significant improvement in all three domains of the MOXFQ, proper correction of angular values (HVA and IMA), and overall toe length decreased by only 2 mm (range −11 to 13 mm). It showed no avascular necrosis (AVN), infection, hallux varus, nonunion, dorsal malunion of the distal fragment, metatarsalgia and/or incidence of recurrence. Other infrequent complications were described: screw backout, prominent metalwork, etc. [45]. In a comparative study (chevron MIS and open chevron), there were no significant differences. Clinical and radiologic postoperative scores in all domains were substantially improved in both groups. There were no significant differences in complications between the two groups. The third-generation MIS technique proved that it is a safe procedure (MIS) with good clinical outcomes for symptomatic mild-to-moderate hallux valgus at midterm results [64].

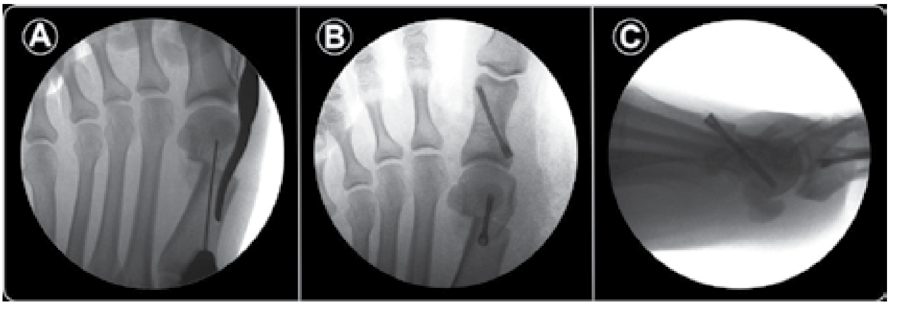


**Figure 4.** (A) Upon completion of the osteotomy, a designed 'pry bar' is introduced into the proximal canal via the site of the osteotomy to translate the metatarsal head in a lateral and plantar direction. (B) AP view. Final correction and fixation of the PERC and percutaneous Akin osteotomy. (C) Lateral radioscopic view. Obliquity of the fixation and MTT position (courtesy of Dr. Laffenêtre, Olivier).


**Figure 5.** (A and B) AP view. Mild-to-moderate HV. Correction achieved. (C and D) Clinical images. Pre and postop (courtesy of Dr. Laffenêtre, Olivier).

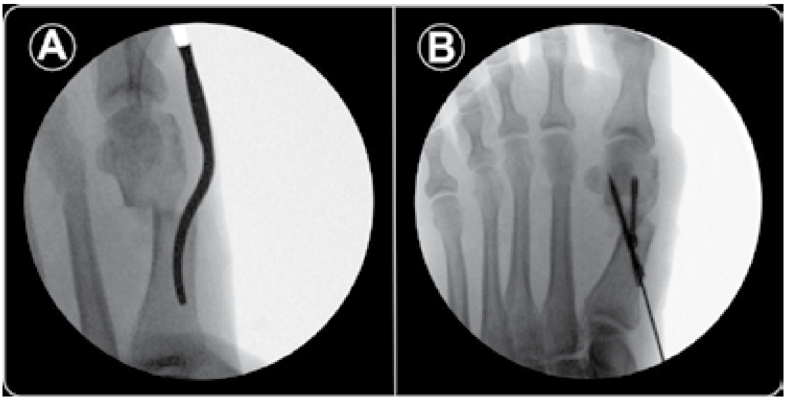


**Figure 6.** (A) Displacement of the metatarsal head. (B) Fixation with two screws; new technique and unpublished data (authorization of Dr. Laffenêtre, Olivier).

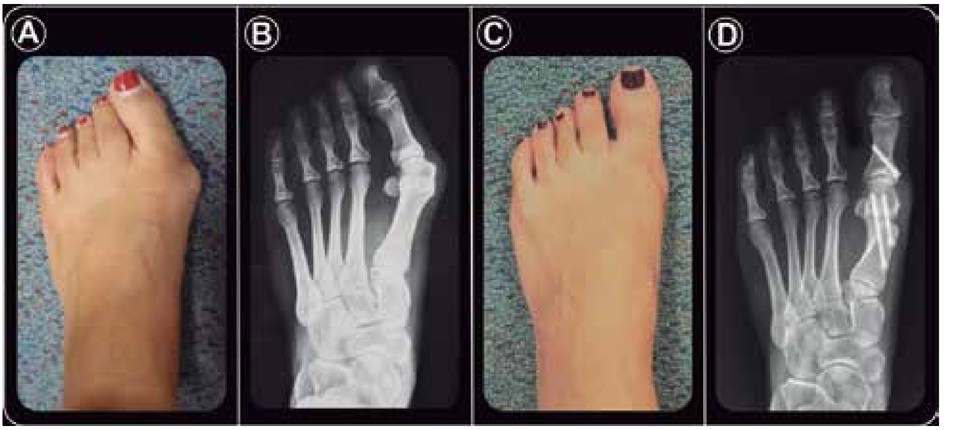


**Figure 7.** (A and B) Moderate HV. (C and D) Correction achieved with the PECA technique (courtesy of Lam, Peter).

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An intra-articular technique has recently been described:

- **PICO** (*percutaneous, intra-articular, chevron osteotomy*): the authors evaluated the radiological outcomes of 21 patients (24 ft) in a population of moderate hallux valgus. It showed a mean preoperative IMA of 12.46° (range 11–15°) and a postoperatively (POP) of 8.13° (range 5–10°; SD 1.16), with an average angular correction of 4.33°. The mean HVA was 33.96° (20–40°) before surgery, and the average POP was 8.16° (range 3–15°), thus obtaining an average improvement of 25.86°. No metatarsal shortening or recurrence was observed (**Figures 8–10**) [54]. PICO offers theoretical advantages over other TG techniques described since it does not need fixation with two screws (only one is enough) and/or additional K-wire, which results in a shorter surgical time and complication rate, and also decrease costs. In addition, as it is done on the head of the 1MT, it offers greater stability and involves fewer surgical steps. Nevertheless, this novel

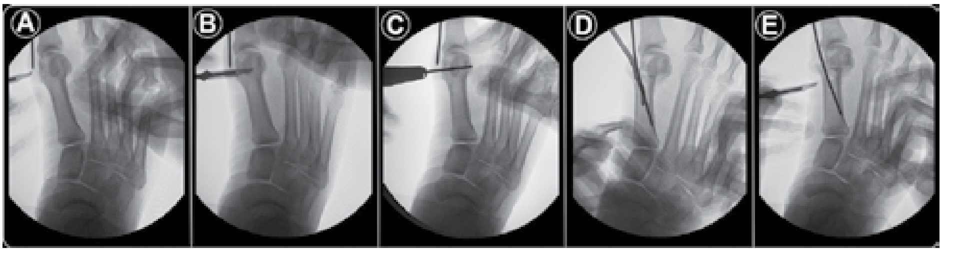


**Figure 8.** (A) Medial portal (P1). (B) Dorsal partial capsular detachment. (C) Entry point and perpendicular orientation of the Shannon burr. (D) Displacement of the metatarsal head using the 'Bosch method'. (E) Location of P2.

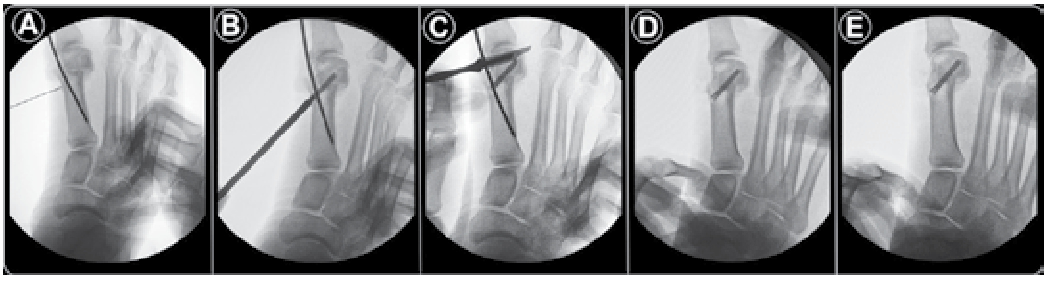


**Figure 9.** (A) Orientation of K-wire. (B) 3.0 mm conic screw insertion. (C) Lateral release portal (P3). (D and E) Remnant medial exostosis and its resection.


**Figure 10.** (A) Symptomatic mild hallux valgus. (B) PICO technique. One week postoperative (POP). (C) POP bandage correction. (D and E) Week 8 POP. AP and Lateral view.

technique needs a clinical and functional validation to be accepted as a valid and reproducible procedure, and this is what the other procedures have shown so far.

## 5. Possible concerns

The 'third-generation' (TG) chevron techniques reliably mimics the open chevron procedure with all its known virtues while it does not reproduce its disadvantages and complications. There is no doubt that this group of techniques reflects the future of percutaneous hallux valgus surgery. In relation to the results shown, we can mention that TG techniques are useful, effective, and (maybe) easier than open procedures. We emphasize that percutaneous surgery has an extensive learning curve, and therefore it may be difficult to imitate the results shown on already-published data.

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Chapter 8

# Diabetes Ground Control: A Novel System for Correcting Anomalous Stride in Diabetic Patients

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Additional information is available at the end of the chapter

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**Abstract**

Diabetes mellitus is a chronic disease characterized by several complications, including diabetic foot, a serious problem induced by increased foot plantar pressure during gaiting. This misbehavior intensifies the risk of ulceration, which may lead to minor and major amputations. This study proposes the inclusion of a passive element to correct diabetic stride, namely the Diabetes Ground Control (DGC), a customized latex-based insole designed to perform load redistribution along the entire foot length, and by so minimizing overload and pressure levels on the foot sole of diabetic patients. A mathematical model in state space for the DGC system is proposed and dynamically characterized using polynomial chaos analysis. The inclusion of the DGC element reduced considerably the amplitude of foot pressure oscillations during walking. Hence, the DGC, which can be customized according to the patient's physical characteristics and weight, is a potential instrument for controlling the tensions on the diabetic foot.

**Keywords:** diabetic foot, bond graph, polynomial chaos, biomechanics, organic control, latex

## 1. Introduction

Diabetic foot is a pathophysiological state associated with the appearance of ulcers, infections, and/or destruction of deep tissues, observable in patients with diabetes mellitus (DM). These symptoms occur as a consequence of neuropathy, peripheral vascular disease, or deformities in lower limbs [1–4].

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The diabetic foot is a very debilitating complication of the DM, which often leads to ulcerations that can evolve to minor or major amputations [5]. The injuries can appear in different places such as in the toes, due to high external pressures caused by muscle atrophy, in interdigital skin, as a result of fissures and small cuts that favor the colonization by skin fungus, in distal parts of the foot, where the prominences of the metatarsus, when ulcerated, can originate infection outbreaks that can penetrate phalangeal articulations and thus leading to infections, and in the middle portion of the foot, where callosities and injuries can be developed since this is the area responsible for body support [2, 6–9]. According to El-Hilaly et al. [5], each patient should receive personalized treatment, since there are always individual differences in pressure values, pressure distribution, foot deformities, and soft tissue thickness and integrity. Usually, there is a decrease in the accuracy of gait movement due to variations on pelvic angles, reduced speed of muscle activation, reduced gait speed, reduced movement capability, smaller step amplitude, and greater impact absorption by the foot [4, 10–12].

The vast majority of design strategies and selection criteria for suitable insoles for diabetics rely mainly on experience and intuition of the shoemakers rather than on design techniques based of scientific principles. A shoe design must protect the foot in locations that are at risk of developing lesions, by reducing pressure to values below specific thresholds, to avoid ulcerations. Some authors have used insoles with pressure sensors for indicating and correcting plantar pressure distribution, through adjustments in footwear and commercial insoles. These insoles have hexagonal-shaped plugs, with the possibility of removing pieces to promote plantar pressure relief in a region such as the metatarsal point [13, 14]. This system, known to be the most personalized gadget available in the market for the correction of the diabetic gait, still does not consider all the evidences of muscular deficit and corresponding cinematic decreases in the prevention and treatment of diabetic foot.

The main reason for the absence of general design criteria for therapeutic shoes is the wide range of patient characteristics and the high number of design variables. Therefore, presenting a mathematical model for the diabetic gait is essential for understanding the mechanical parameters, for the analysis of pressure data, and for gaiting control through the usage of customized insoles. Specifically, we believe that characterizing the influence of a damper on the distribution and dynamics of the foot sole allows a clearer understanding of the diabetic stride, by clarifying its interference in the distribution of pressure and its role in reducing impacts during the process of walking.

Based on the mechanical etiology of the problem, this chapter proposes the inclusion of an external element, namely the Diabetes Ground Control (DGC) insole, to change the forces of contact between ground and foot, aiming to minimize overload and pressure levels in the patients' foot sole. This controlled interaction between the diabetic foot and the device is what the authors claim as the concept of Organic Control. Specifically, the passive controller actively modifies the system response through the redistribution of the load along the entire length of the foot. The sensibility/robustness of the system is then analyzed by the method of polynomial chaos. It will be used to evaluate the poles dispersion by the introduction of the DGC.

## 2. Material and methods

### 2.1. Data collection and analysis procedures

One female individual (age: 33 years, height: *** cm, mass: ** kg) volunteered for this investigation and gave her informed written consent. The volunteer has Diabetes Type 1 (diagnosed 24 years ago), has communication and locomotion capabilities, and uses insulin pumps. The research protocol was approved by the Research Ethics Committee from the Federal District's Health Department (SES/DF) under the following protocol number: 428/11.

Before the data collection, the volunteer answered a structured questionnaire with close-ended questions (birth date, gender, date of diagnosis, type of medication, type of DM, and others) and the questionnaire provided by the Michigan Neuropathy Screening Instrument (instrument that evaluates the symptoms related to the diabetic neuropathy). After that, we carried out an interview to collect data regarding the characterization of the patient's gait conditions, taking into consideration a possible difficulty to walk. We measured her height, weight, basal temporal dose, heartbeat, oxygen saturation, anthropomorphic dimensions of the foot (with a caliper), and glycemic index—with the Accu-Chek® Active lancing device (Hoffmann-La Roche, Basel Switzerland). Then, the patient was asked to answer a questionnaire destined to assess her quality of life and her motor skills (e.g. walking, climbing stairs, driving a car, performing household chores), as well as aspects related to financial considerations, medication side effects, and lifestyle (general dimensions). The participant was advised not to consume alcohol or any kind of medication 24 h prior to the commencement of the experiment. The participant was also advised about the experiment and given a trial run before the readings were taken.

Since the method includes the use of a custom-made insole with sensors, some measurements were performed to collect data that would allow the optimization of the insole. To determine where the sensors would be placed, we performed a pedographic analysis using the Emed® n50 Novel platform (Novel, Munich, Germany), which allows for the collection of plantar pressure distribution data, which consists of sensors and circuits for data collection as well as control software. The patient, barefoot and with her eyes open, was asked to remain for 30 s in an orthostatic position and to distribute her body weight evenly between both feet. Afterwards, we attached, to one of the patient's feet, a system designed to capture and record the signal generated by four strength sensors. The system was controlled by the EZ430-F2013 development kit by Texas Instruments, which is equipped with the MSP430 controller and with a Wi-Fi module for data transmission. The system's sampling rate is 40 Hz. The circuit that conditions the pressure outputs are connected to the A/D converter embedded in the microcontroller, which sends the data to the computer via Wi-Fi. Software was developed to control the data acquisition from the insole, to send and receive messages containing these data, to allow for the reading of the elements by MatLab and, finally, to present the information obtained. Four FlexiForce® sensors by Tekscan, model HT 201 (Tekscan, South Boston, USA), were used. The sensors were attached to the insole with a tape so that they could not move during the tests. With the insole attached to the patient's foot, we began the collection of the data. In the experimental procedure, the volunteer stood still for 10 s, walked for about 50 s, and then stopped again for 30 s. Another similar collection was carried out to generate validation data. The insole, made of natural latex (biomaterial), is, differently from other insoles with plantar pressure measurement systems, fabricated to be completely individualized and customized, following the anatomy and the characteristics of the patient's feet. Because of this, in order to capture the plantar pressure values, the sensors were placed in specific parts of the foot. **Figure 1a** shows the plantar distribution of the sensors and **Figure 1b** shows the acquisition system, consisting of FlexiForce® sensors connected to a data acquisition board with a buffer, and a gain stage connected to the microcontroller Msp430f2274 (rf2500), and the natural latex insole. We highlight that the alterations in the trajectory of the center of pressure (COP) in the medial-lateral direction, in neuropathic individuals, as shown in **Figure 1a**, is an important factor when using a customized insole.

### 2.2. Manufacturing of the insole

Most diabetic insoles available on the market are composed of silicon, polyurethane, ethylene-vinyl acetate (EVA), or memory foam. We, nevertheless, chose to work with latex. This biomaterial, which is a milky sap and a living organism before vulcanization, is obtained from a tree called *Hevea brasiliensis*, represents a durable, low-cost and high-quality raw material with physical and chemical characteristics that are biocompatible. It is also known for its antigenicity, hypoallergenicity, impermeability, elasticity, softness, flexibility, and resistance. Latex has been utilized in the past for the manufacturing of esophageal prosthesis, bio-membranes and modules for the control of esophageal flow, as described by Rosa and Altoé [15] and Andrade [16].

The abovementioned characteristics, which diabetic insole materials must present, are in accordance with the latest scientific studies and aim to provide patients with a more comfortable

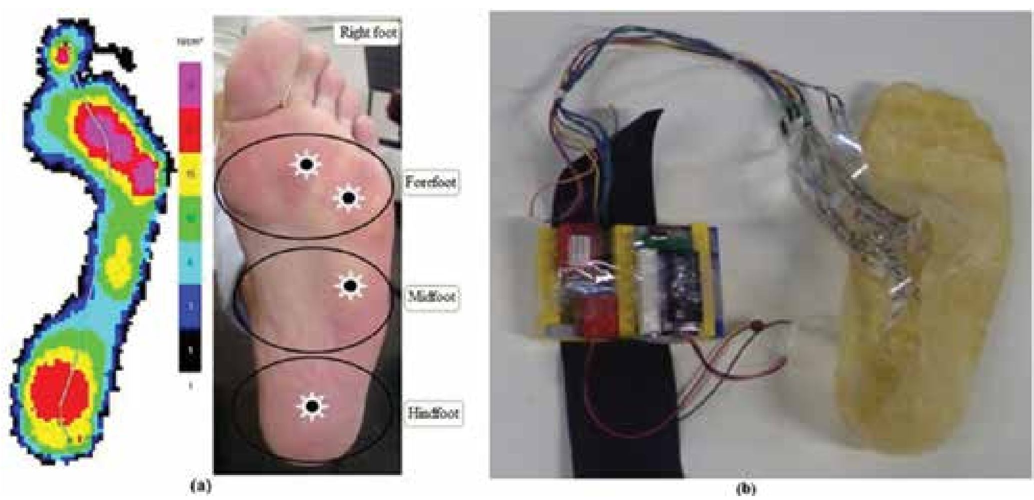


**Figure 1.** Distribution of the sensors for the capture of data in the identification of the model. (a) Image from the pedographic essay that shows the plantar pressure (N/cm$^2$), the color map and the center of pressure trajectory composed by innumerous displacements in the sagittal plane; (b) disposition of the sensors on the patient's foot.

experience, including concerns with the feet temperature control and the reduction of allergy risks. Therefore, latex will be the constituent of the dampers on the insole with its mechanical properties changed according to the foot temperature. This interaction between the foot and the latex insole occurs as a symbiotic relationship and will be the foundation of the bioinspired system under study.

In the manufacturing process of the insole, the technique of successive immersion baths was applied, in which the mold is slowly plunged, on a perpendicular position, into the final latex compound, and then heated in a thermostatically controlled kiln. The first step consists of washing the mold with water and soap. Then, the mold has to be dried with hot air, sterilized in an autoclave (heated in the kiln at a temperature of 50°C), removed, and, then, plunged into the latex, where it should remain for 1 min. This step represents the beginning of the polymerization that determines the final manufacturing of the product. After this phase, the molds will be slowly and gradually removed from the latex compound and put into the kiln (subject to heating for vulcanization at a temperature of 70°C) for 10 min. After this, the mold is kept for 20 more min out of the kiln. We highlight that the bathing and heating steps will be repeated until we can obtain a thickness of approximately 3 mm for the insole. By the end of the process, we place the insole under running water to remove it from its mold. According to the literature, by diluting latex—at a temperature of 25°C—in double-distilled water we obtain at 30% an $\eta$ (25°C) = 15 centipoise or 0.02 N s/m$^2$. The $\tau$ on the front portion of the foot corresponds to the ratio between the weight force and the rectangle's area (0.05 m × 0.032 cm), that is, $\tau$ = 42.875103 N/m$^2$. The shear rate is given by 21.43106 m$^2$/s of how much the latex layers in the shock absorber 'slide' over each other. It was based on this value that we determined the percentage of water required to alter the viscosity of the latex. Because viscosity is considered non-constant and must be altered for each patient, we could not obtain a flow curve.

### 2.3. Modeling by bond graph

The *Bond Graph* (BG), which is an alternative method to the classical existing modeling practices, has been used for obtaining a mathematical model for the presented system. As usual in BG modeling, some assumptions were made in the mathematical modeling, in order to avoid high and unnecessary complexity. These are (1) The developed models are only approximate representations, and there is no single model of the system, but rather a family of models with varying features and performances; (2) The static (damping) force of Coulomb friction is considered to be negligible; (3) The effect of the Lagrange equation ($\delta$qi) is considered to be a non-infinitesimal virtual displacement; (4) The displacement of elements (deflection) is referred to by $\delta$ in steady state; (5) The surface where the subject walks is fixed, that is, it will be considered to have no misalignments (holes and steps) and an angle will be assigned for situations with ascending or descending movement; (6) There will be no rotation around the axes, only the translational movement will be worked on; (7) The system is considered to be symmetric, and only the right leg is modeled; (8) The model is of the concentrated parameters type.

The BG models proposed for the system were constructed using the 20-sim simulation software. The purpose of the system is to represent the reductions in kinematic variables, such as displacement, velocity, acceleration, and linear momentum. Mass (M1), the frontal part of foot, is connected in series with a spring (K1) and a damper (B1), parameter of the foot/leg, representing the greater impact that body weight has in the frontal part of foot during passive diabetic stride. For representing the lag in the activation of the muscles that directly influence the COP, we use a damper (B1), accounting for the angle (ankle-joint) reduction and a low torque. Finally, at the heel region, responsible for propelling the movement, a spring (K2) was used to demonstrate the deformation of the movement. In both cases, in the compression of the spring and in its movement back to its equilibrium length, the force is always in the opposite direction of the movement, and was proportional to the displacement in this study.

One of the symptoms of the diabetes mellitus is the gradual change in the patient's normal stride. These deviations or distortions (± δ) can appear in several mechanical elements of the model. We incorporated these distortions into masses (M0 and M1), springs (K1 and K2) and damper (B1). The distortion is like an imperfect coupling of impedance (impedance mismatch) that generates a loss of signal strength (or amplitude) at the angle of the ankle joint, stride height, and muscle strength (B1 and M1). It is also responsible for the shock on the frontal part of the foot (M1) and the low amplitude of its velocity. Therefore, these variables change their reference from point to surface, which implies the deflection that generates the delay displayed on the mathematical formulation of the system.

Diabetic person's foot in descent/ascent movement can be modeled by changing its spatial position, here represented by an inclined plane. The influence of the force decomposed into rectangular coordinates generates a dependency that is directly proportional to inclined plane angle β. Furthermore, delays in the stride are recurring, and the person needs to make small stops and then resume walking. In this analysis, we also incorporated in the control system a saturating element (hysteresis) to account for this behavior. **Figure 2** presents the system with its ideal physical model and the complete BG model without simplification.

The corresponding state space representation is given by the following equations:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{pmatrix} = \begin{pmatrix} -\frac{A}{M_0} & -K_2\cos^2\beta & -K_1\cos^2\beta & \frac{A}{\mathrm{M}_1} \\ \beta & 0 & 0 & 0 \\ \beta & 0 & 0 & -\beta \\ \frac{A}{M_0} & 0 & K_1\cos^2\beta & -\frac{A}{\mathrm{M}_1} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{1}$$

$$y = \begin{pmatrix} 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \tag{2}$$

$$A = \frac{(1 - e^{-\alpha v})^{-1}(b\,v + 1) * \mathrm{sen}\beta}{\frac{1}{12} r^2\,\mathrm{gsen}\beta} \tag{3}$$

$$B = \frac{1}{\frac{1}{12} M_0.r^2\,\mathrm{gsen}\beta} \tag{4}$$

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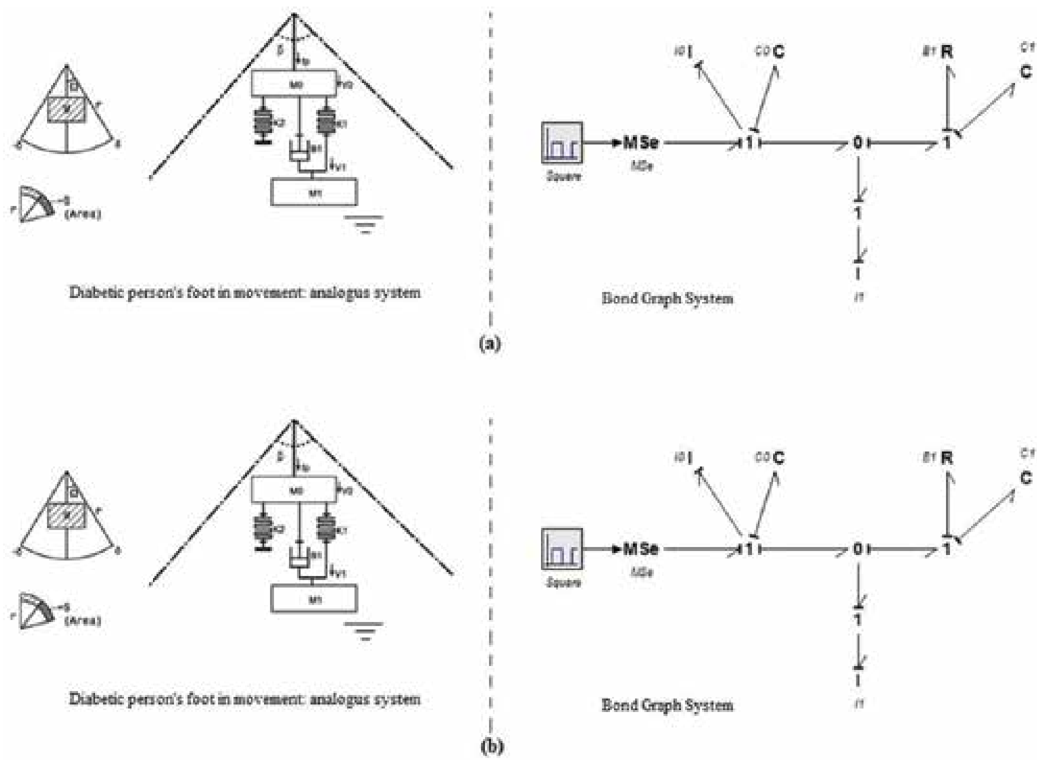


**Figure 2.** The right foot in the passive diabetic stride. The frontal part of the foot is the dashed line. It is considered that, in (a), the situation is the foot of a person with diabetes in descendent/ascendant movement with deflection (± δ), highlighting the visualization area and (b) complete BG model.

where x1(t) $x_1(t)$ represents the velocity of mass M0, x2(t) corresponds to the displacement of spring K1, x3(t) to the displacement of spring K2, and x4(t) the velocity of mass M1.

We then derived a second model that includes the customized insole made of latex, the DGC element. It was modeled using two additional shock absorbers B2 and B3 in series with M1 and the corresponding mass of the customized insole (M2). **Figure 3** shows the mechanical analog and complete BG model for the DGC system.

The resulting state space representation for the DGC system is given by Eqs. (5) and (6):

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{pmatrix} = \begin{pmatrix} -\frac{B_1}{M_0} & -K_1 & -K_2 & \frac{B_2}{M_1} & 0 \\ \frac{1}{M_0} & 0 & 0 & -\frac{1}{M_1} & 0 \\ \frac{1}{M_0} & 0 & 0 & -\frac{1}{M_1} & 0 \\ \frac{B_1}{M_0} & K_1 & K_2 & -\frac{B_2}{M_1} - \frac{B_2 B_3}{(B_2+B_3) M_2} & \frac{B_2 B_3}{(B_2+B_3) M_2} \\ 0 & 0 & 0 & \frac{B_2 B_3}{(B_2+B_3) M_1} & -\frac{B_2 B_3}{(B_2+B_3) M_2} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} Mse \tag{5}$$

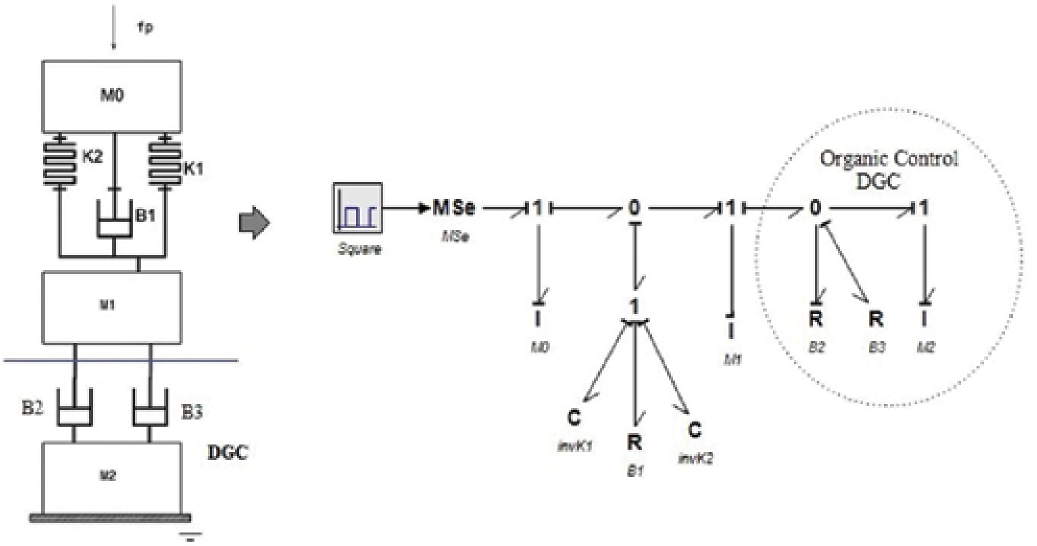


**Figure 3.** DGC mechanical representation and complete BG model.

$$y = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} \tag{6}$$

where Mse is the weigh force and x5(t) represents the velocity of mass M2.

Since the DGC is made of latex, it is possible to control the pressure distribution on the foot sole by changing the shock absorbers density during manufacturing, that is, we can alter the dampers B2 and B3's internal dynamic viscosity based on the patient's physical characteristics and weight, which directly affect the relation between the shear stress and shear rate during gaiting (varying the Bi constants changes the position of the system's poles in the spaces, and consequently its response).

### 2.4. Polynomial chaos

Polynomial chaos is a method to solve stochastic differential systems of the form [17]:

$$\dot{X}_t = F(X_t, W_t, \theta, c, t) \tag{7}$$

where $\theta$ is a vector of random parameters in the probability space $(\Omega, F, P)$, generally independent and identically distributed; $W_t$ is a stochastic process that represents an input to the system, also in $(\Omega, F, P)$; c is a vector of initial conditions, that can also be a vector of random variables. The solution of Eq. (3) is a stochastic process $(X_t, t \in T)$, which is an uncountable collection of random variables in the same probability space $(\Omega, F, P)$, where T is the set of time instants. Another way to see the solution (or any other stochastic process) is through an application

$X: T \times \Omega \rightarrow R^p$, that is, a function of two variables $X(t, \omega)$, where $\omega \in \Omega$ and is a particular result of the experiment. For each $\omega$, there is a time function called a trajectory. Normally, the regularity of $X$ is only measurable in both variables. Supposing that $X_t$ belongs to $L_2(\Omega, F, P)$, the Hilbert space of finite variance random variables, the method of polynomial chaos consists in expanding the solution of Eq. (3) into an orthogonal basis of this space. It was shown, in [18], that this expansion can be done for Gaussian processes by using Hermite polynomials, and, in [19], the method was extended to other standard probability distributions by using other polynomial basis (the Wiener-Askey scheme of polynomials). If there is only one independent random variable in Eq. (3), say $\theta \in L_2(\Omega, F, P)$, then all other functions of this random variable can be expanded as a Fourier series of the form.

$$f(\theta) = \sum_{i=0}^{+\infty} f_i \phi_i(\theta) \tag{8}$$

where $\{\phi_i(\theta)\}$ is the orthogonal basis. It is known that in $L_2(\Omega, F, P)$, the internal product is given by:

$$E(fg) = \int p(\theta(\omega)) f(\theta(\omega)) g(\theta(\omega)) dP(\omega) \tag{9}$$

where $p(\theta)$ is the weight function (probability density function) and $E(\phi_i(\theta)\phi_j(\theta)) = a_j \delta_{ij}$ and $a_j$ are constants. The solution of Eq. (3) can then be expanded as

$$X(t, \omega) = \sum_{i=0}^{+\infty} X_i(t)\, \phi_i(\theta(\omega)) \tag{10}$$

where the coefficients $X_i(t)$ are nonrandom time functions.

The system in Eq. (3) is then transformed into an infinite set of deterministic ordinary differential equations (one for each orthogonal polynomial). For numerical solutions, the series in Eq. (6) must be truncated, and the coefficients $X_i(t)$ must be calculated by Galerkin projection [20]. So, the stochastic system in Eq. (3) can be approximated by a set of $np$ ordinary differential equations, where $n$ is the order of the stochastic system and $p$ is the number of the polynomials in the Galerkin expansion. For systems with a set of random parameters $\{\theta_i\}$, with $i = 1,\ldots,n$ (independent of each other), multivariable polynomials can be used, which are also orthogonal and can be constructed by products of the single variable polynomials.

In this chapter, we analyze the case where only one system parameter is a variable, expressly the mass of the front region of the foot sole ($M_1$). We assumed it is a random variable with uniform distribution and that the orthogonal polynomials for its weight function $p(M_1)$ are the Legendre Polynomials $L_i$ that satisfy

$$\int_{-1}^{1} L_i(\theta)\, L_j(\theta) d\theta = \frac{2}{2j+1} \delta_{ij} \tag{11}$$

and can be calculated by the recursive formula found in [19], that is meaning standard probability distributions. Ten Legendre polynomials will be used, which means that the extended system of differential equations will have 50 equations. As the stochastic system in Eq. (3) is linear, the extended deterministic system will also be linear allowing us to analyze its eigenvalues/poles and zeros.

## 3. Results

### 3.1. Bond graph modeling

The input data to solve the systems is represented by Eqs. (1) and (2) was obtained through the Emed n50 Novel platform's static test. **Figure 4** shows the measurement apparatus as well as the mechanical model and pressure distribution on the fabricated latex-based insole. Two sensors were included in the forefoot—one to gather and the other to validate experimental data—since this is the area that experiences highest peak pressure values.

**Table 1** summarizes the data collected from each region of the subject's right foot. The greatest variation of data occurred in the middle of the foot, indicating that the alteration in the COP and in the pressure distribution is caused by the neuropathy.

We used a Wiso W601 Digital 150 kg weighting scale to determine the center of mass, the weight, and the mass of the subject's right foot. The measurements were taken using a double-support board, as suggested in [21]. The results were as follows: height = 1.72 m; weighting scale's reading point in the board for the first measurement, Ta = 28.04 ± 0.2 m; weighting

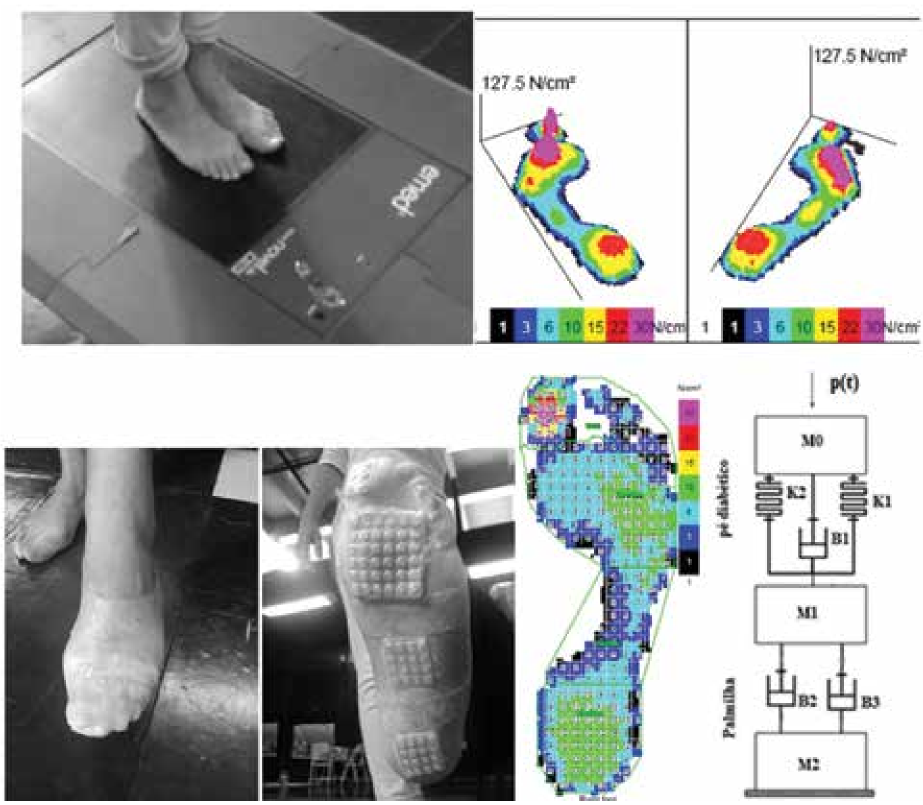


**Figure 4.** Insole prototype: Front side of insole's shock absorbers—Right foot; cushioning system.

| Parameters | Total | Hindfoot | Midfoot | Forefoot |
|---|---|---|---|---|
| Maximum force (N) | 774.5 ± 28.8 | 465.0 ± 28.4 | 215.9 ± 18.6[1] | 682.1 ± 14.5 |
| Peak pressure (N/cm$^2$) | 66.3 ± 18.2 | 30.9 ± 2.3 | 22.1 ± 5.8[2] | 65.8 ± 18.7 |
| Contact time (%) | 100.0 ± 0.0 | 58.0 ± 3.7 | 69.6 ± 2.6 | 84.3 ± 1.4 |
| Contact area (cm$^2$) | 121.65 ± 2.74 | 33.65 ± 1.25 | 29.15 ± 0.40 | 49.05 ± 1.15 |
| Comparative data: Right foot | | | | |
| Maximum force (N) | 768.5 ± 15.2 | 493.3 ± 12.5 | 121.7 ± 7.9 | 609.8 ± 13.9 |
| Peak pressure (N/cm$^2$) | 54.0 ± 3.0 | 32.3 ± 1.0 | 11.6 ± 0.7 | 44.7 ± 2.5 |
| Contact time (%) | 100.0 ± 0.0 | 61.4 ± 1.0 | 61.0 ± 1.2 | 82.1 ± 0.7 |
| Contact area (cm$^2$) | 135.03 ± 2.23 | 34.37 ± 0.59 | 27.13 ± 0.56 | 50.79 ± 0.84 |

[1]Higher measures than those from the comparative data.
[2]Higher measures than those from the comparative data.

**Table 1.** Experimental results of the static test obtained through the Emed n50 novel platform.

scale's reading point in the board for the second measurement, T′a = 27.0 ± 0.2 m; leg length, ℓ = 0.65 m; distance between the two supports, d = 1.61; weight = 70 kg; center of mass (CM) position along the foot length direction member in relation to the nearest extremity, $x_{CM}$ = 0.43 cm; and calculated foot weight of M0= 7.6 ± 1.2 kg.

The parameters and constants used to solve the systems described by Eqs. (1) and (2) are listed in **Table 2**. Dynamic changes resulting from the introduction of the DGC were observed in the state space matrices of the system with DGC when compared with the one without DGC. It is noticed that the introduction of the DGC element alters the characteristic equation of the system, introducing phase lag and causing a damped system response when excited by a single step. This lag is a result of the reduction of the interaction of the foot with the surface.

Comparing the data captured by sensors S1 (identification) and S2 (validation), we tried to make a prediction of 10 future samples using the system model of Eq. (2). **Figure 5** shows, on its left, the prediction for 10 future samples, comparing between the estimated and the validation data. On the right, the image was zoomed and the original signal was introduced. We can observe that including the DCG element has provided a better behavioral pattern to represent the system of the diabetic gait.

Furthermore, **Figure 6a** and **b** shows the systems' responses for an impulse and a step input, respectively. We can clearly see a reduction in amplitude and oscillation in the DGC system's output signal when compared to the system without DGC.

### 3.2. Polynomial chaos analysis

All system parameters were assumed constant, except for the mass M1, considered to be a uniformly distributed random variable with average value of 1.47 and standard deviation of 0.20 kg, conforming to **Table 1**. **Figure 7a** illustrates the resulting extended system

| System's constants | Description of the variable | Obtainment | Value in SI and (CGS) |
|---|---|---|---|
| *V* | Displacement velocity of the shock absorber of the analogous system | It is considered to be the body velocity of the radial displacement (mm) of a diabetic barefoot person, obtained from the pressure platform and calculated with regard to the person's right foot. | 0.01 [m] (1 cm) |
| *α* | Constant that characterizes the decay of the static friction due to the viscosity of the latex | Adopted based on the inclination of the coagulation line of a slow particle. | $2.06\ 10^{-7}$ [s/m] ($2.06\ 10^{-9}$ s/cm) |
| $B_1$ | Coefficient of friction | The coefficient of friction corresponds to the ratio between the maximum friction force (weight force) and the intensity of the vertical force N (↑) of the ground against the shoe's sole. | 0.2 [N·s/m] (200 dyn·s/cm) |
| B | Negative and positive angles of inclination | Angle of inclination of the platform used to simulate the movement of going up or down steep regions. | 8° (±2°) (0.14 radians) |
| Cosine and sine | Indicates the relationship between the distance and the covered path. | Calculation of the cosine of the platform's angle of inclination. | ------ |
| $M_0$ | Mechanical stress concentrations in deep tissues of the plantar pad of the foot, may lead to foot ulceration, mass of foot | Ratio CM/length of the member in relation to the nearest extremity [21]. | 7.6 kg (7600 g) |
| R | The radius between the generated surface and the deflection (+/−δ), as shown in **Figure 2**. | Obtained with a normal gait surface, under the Axis of the Gait—19° in relation to the axis of the gait for a diabetic patient and a surface of S = 0.0002 $m^2$. | 0.02 m (2 cm) |
| G | Gravitational acceleration | — | 9.8 $m/s^2$ (9800 $cm/s^2$) |
| $K_1$ | The elasticity of the human skin in the front region of the foot corresponds to the spring constant | Typical deformation curve, obtained by a Cutometer—Ua/Uv [22], which, for this region, is of 0.633 mm, with the application of a weight force of 686 N. | $10.8\ 10^{-5}$ N/m (0.1080 dyn/cm) |
| $K_2$ | Elasticity of the human skin in the region of the heel. | Typical deformation curve, obtained by a Cutometer—Ua/Uv [22], which, for this region, is of 0.315 mm, with the application of a weight force of 686 N. | $22.1\ 10^{-5}$ N/m (0.2210 dyn/cm) |
| $M_1$ | Mass of the front region of the plantar surface of the right foot bearing the body weight. The mass is obtained by the engraving of the foot's image on carbon paper. | Approximately oval area considered as an ellipsoid with a = 4.8 cm, b = 3.5 cm, and c = 3.0 cm (thickness of the foot). The volume obtained for the density of the skin was of 7 g/ $cm^2$. | 1.47 ± 0.2 kg (1470 g) |
| Mse = fp | Weight force | Measured by the force platform, Emed n50 Novel, with the patient standing in a double support static position. | 686 N (680,000 dyn) |
| $B_2$ | Coefficient of friction of the structural (or hysteretic) shock absorber, based on Eqs. (1) and (2). Damping is the process through which high pressure is removed from the system of the diabetic foot. | We measured it and multiplied it by the area of the shock absorber ($\tau = \mu.(v/t)$), being v = 54.9 m/min (±12.0), the diabetic patient's displacement velocity for a period of 2 min. | $6.4\ 10^{-7}$[N·s/m] ($6.4\ 10^{-4}$ dyn·s/cm) |

| System's constants | Description of the variable | Obtainment | Value in SI and (CGS) |
|---|---|---|---|
| $B_3$ | | | $12.8\ 10^{-7}$[N·s/m]<br>($12.8\ 10^{-4}$ dyn·s/cm) |
| $M_2$ | Mass of the natural latex insole, including the shock absorbers. | Made of natural latex. Weighted with a digital weighting scale containing a high-precision sensor that identifies weight variations above 1 g. | 0.007 kg<br>(7 g) |

**Table 2.** Parameters and constants for systems in **Figures 2** and **3**. The values in parenthesis were assumed to be uniformly distributed with 15% deviation from their nominal values. The simulation units are in the centimeter-gram-second (CGS) unit system.

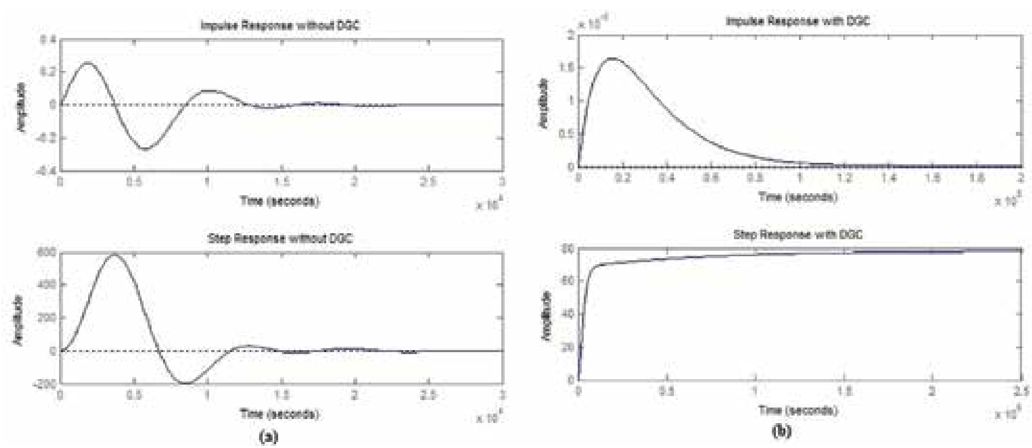


**Figure 5.** (a) Step response for both systems. (b) Impulse response for both systems.

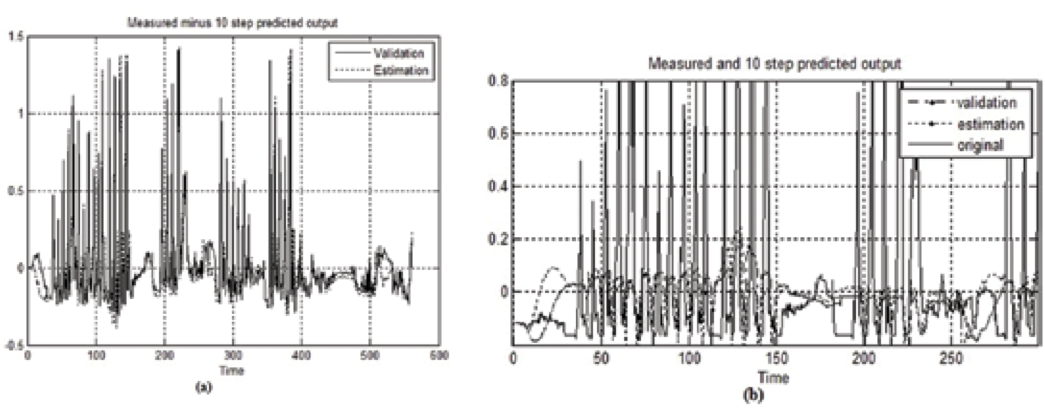


**Figure 6.** The plot shows an agreement between the different model structures and the data measured for validation. The unit of the Y-axis is in volts.

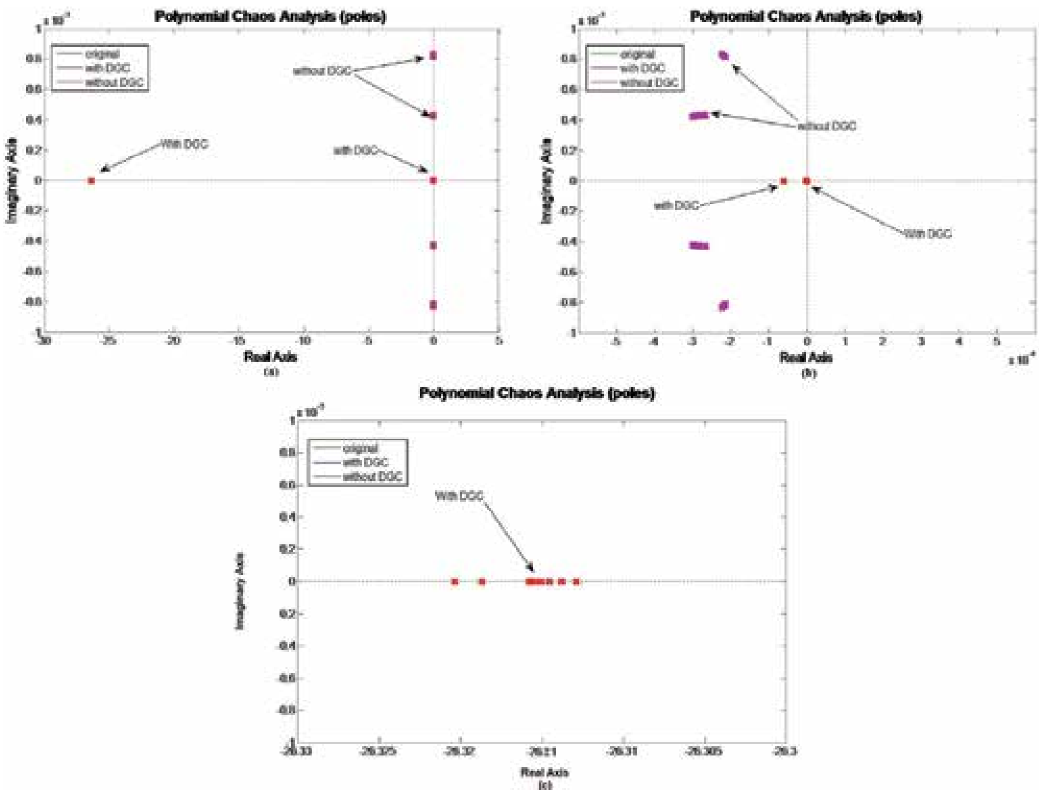


**Figure 7.** (a) Poles and zeros representation for the systems in Eqs. (1) and (2) using polynomial chaos analysis. (b) Zoomed portion of graph presented in **Figure 7a**. (c) Further zoom of the graph presented in **Figure 7b**.

poles (with and without DGC). This pole dispersion pattern represents the random of M1 for different feet (different people). From **Figure 7b**, we can conclude that the poles' variation was reduced in the presence of the DGC controller. Moreover, in **Figure 7c** and the zoomed version of **Figure 7b**, we can clearly see that the addition of DGC showed to be a good solution for the cancelation of the oscillatory behavior, besides making the system poles real. Finally, in **Figure 6a**, we can also see that an additional real pole appeared in −23.6, which was not present in the situation without DGC, which helps stabilize the system response. Therefore, the inclusion of the DGC in the system provides a more robust solution, with potential to benefit different kinds of feet (represented by differences in the mass M1).

## 4. Discussion and conclusion

This chapter proposes the inclusion of an external element called *Diabetes Ground Control* (DGC), a personalized latex-based insole, aiming to correct the diabetic stride through the redistribution of the load on the foot. A mathematical model of the foot based on bond graph modeling was proposed with and without the inclusion of the DGC insole. The resulting DGC system was able to successfully predict the gaiting pattern for 10 future samples. In particular, the proposed system reduced considerably the amplitude of foot pressure oscillations in foot sole during walking. In addition, a polynomial chaos analysis showed that the inclusion of the DGC element augmented the sensibility/robustness of the system. Hence, the DGC presents itself as a potential instrument to help controlling the tensions on the diabetic foot. Moreover, since the insole's shock absorbers can be fabricated with different dynamical viscosity values, the DGC element can be customized according to the patient's physical characteristics and weight, so everyone can receive the most efficient treatment based on his own gaiting pattern. The authors, after this result, will analyze the uncertainty of this mass of variables related to the patient, using quantifying uncertainty. Thus, the following result can provide a characterization of the eigenvalues of the problem solution in the presence of this uncertainty.

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With this book, you'll be able to update your knowledge in the field of foot and ankle surgery and pathology.

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This book is a useful tool in your practice armamentarium.

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