Forefoot Injuries in Sports

Sean HS Lai¹, Camelia QY Tang², Gowreeson Thevendran³

ABSTRACT

Forefoot injuries are common injuries in high-impact sports. The forefoot experiences a large amount of stress during the late stance phase of the gait cycle. Repetitive load applied to the forefoot without adequate rest can lead to tissue breakdown, resulting in injury. Forefoot sporting injuries can deteriorate gait function, sporting performance, and quality of life. In this article, we review the typical presentation, approach, and treatment modalities of the commonest forefoot sporting injuries. These include metatarsal stress fractures, second metatarsophalangeal joint (MTPJ) instability, turf toe injury, sesamoid pathologies, as well as hallux valgus and rigidus. Metatarsal stress fractures are frequent overuse injuries. They can be managed conservatively with activity modification and protected weight-bearing or surgically with open internal fixation. Second MTPJ instability typically involves disruption of the second MTPJ ligamentous joint capsule. Management of this condition includes customized orthotics, physiotherapy, hydrocortisone and lignocaine (H&L) injections, osseous procedures for phalangeal alignment, and plantar plate repairs. Turf toe injury refers to a hyperextension injury of the plantar capsuloligamentous structure of the hallux MTPJ. Plantar plate repairs are typically indicated in grade III injuries or when conservative treatment has failed. Sesamoid injuries include stress fractures, infections, degenerative disease, and osteochondral lesions. Customized orthotics limiting flexion across MTPJ while providing sesamoid stress relief is helpful, while surgical treatment involves fixation with possible bone grafting or partial sometimes complete sesamoidectomy. While hallux valgus and rigidus are not specific to sportsmen, treatment should take into account the patient's athletic demand. These conditions are typically treated surgically with realignment osteotomies if refractory to conservative treatments such as foot orthoses and physiotherapy.

Keywords: Foot, Foot ankle surgery, Foot injury, Metatarsal, Sesamoid, Sports.

Journal of Foot and Ankle Surgery (Asia Pacific) (2020): 10.5005/jp-journals-10040-1124

INTRODUCTION

Forefoot injuries are common in sportsmen who participate in high-impact activities involving significant amount of running and jumping. Poor management of forefoot injuries can prolong time return to sports and the preinjury level of sporting activities. For the purpose of this review, we define forefoot as the structures in the foot extending from the tarsal-metatarsal joint to the toes. Common forefoot sporting injuries include metatarsal stress fracture, second metatarsophalangeal joint (MTPJ) instability, turf toe injury, and sesamoid pathologies. Other common pathologies include hallux valgus and hallux rigidus. In this article, we will review the diagnosis and management of these forefoot sporting injuries.

ANATOMY AND BIOMECHANICS OF THE FOREFOOT

The forefoot comprises of structures in the foot extending from the tarsal-metatarsal joints to the tip of the toes, namely the 5 metatarsals, 14 phalanges, and 2 sesamoid bones. The first MTPJ is surrounded by a capsular ligamentous complex that contributes significantly to the stability of the first MTPJ. It consists of the medial and lateral collateral ligaments, plantar plate, adductor hallucis, abductor hallucis, and flexor hallucis brevis. The sesamoid bones arise within the tendons of the flexor hallucis brevis and articulate with the plantar aspect of the first metatarsal head. They act as pulleys to transmit forces from the flexor hallucis brevis through the plantar plate to the first proximal phalanx base and elevate the first metatarsal head, thereby providing a moment arm that augments plantar flexion of the first MTPJ.¹⁻⁴

The foot experiences a high amount of stress during locomotion. Biomechanical studies have shown that the peak vertical forces on the foot can increase up to 120% of body weight during walking, and up to 220% of body weight during running.⁵

¹Department of Infectious Disease, Tan Tock Seng Hospital, Singapore

²Department of Orthopedic Surgery, Tan Tock Seng Hospital, Singapore

³Department of Orthopedic Surgery, Mount Elizabeth Hospital, Novena, Singapore

Corresponding Author: Sean HS Lai, Department of Infectious Disease, Tan Tock Seng Hospital, Singapore, Phone: +65 82996706, e-mail: sean.lai.sg@gmail.com

How to cite this article: Lai SHS, Tang CQY, Thevendran G. Forefoot Injuries in Sports. *J Foot Ankle Surg (Asia Pacific)* 2020;7(2):50-56.

Source of support: Nil

Conflict of interest: None

The center of pressure is shifted under the forefoot during the late stance phase with the first to third metatarsal heads bearing the highest concentration of pressure.⁵⁻⁸ Repetitive load applied to the forefoot in sporting activities without adequate interim period of rest could hence lead to tissue breakdown with concomitant discomfort and time off sports.

METATARSAL STRESS FRACTURE

Presentation

Metatarsal stress fractures are frequent overuse injuries that occur in athletes. They typically present with an insidious onset of pain that occurs during periods of activity and is relieved by rest. The second and third metatarsal bone accounts for 80-90% of metatarsal stress fractures.⁹⁻¹² Due to the plantar-oriented forces that occur during weight-bearing, the most common area where fractures occur is over the metatarsal neck.^{13,14} However, notable exceptions are dancer's fracture (proximal second metatarsal fracture) and Jones fracture (proximal fifth metatarsal fracture).¹⁵ Biomechanical alterations that result in repetitive stress over the metatarsals such as gastrocnemius tightness, cavovarus foot, pes

planus, or other altered foot biomechanics have been implicated in the predisposition to metatarsal stress fractures.^{16–18}

Imaging

Stress fractures can be detected via radiographs when bone reaction such as callus formation has begun (Fig. 1).^{19,20} In view of its accuracy, earlier diagnosis, and prognostic value, MRI is the modality of choice when working up for metatarsal stress fracture.^{21,22} When MRI examinations are inconclusive, bone scintigraphy has been recommended by some to aid in the assessment of a stress fracture.²³ In patients with multiple stress fractures, laboratory tests are useful in evaluating for any underlying metabolic or endocrine cause.²⁴

Management

Conservative treatment of metatarsal stress fracture comprises of activity modification with protected weight-bearing.²⁵ This involves the use of customized orthotics for shock absorption, cast, or Velcro walking boots.^{26,27} Return to sports should be started at low-intensity level with gradual increments.^{28,29} Such delayed return to sports, coupled with high nonunion rates, makes operative treatment a preferred option for athletes whose priority is an early return to sports.^{18,30}

Operative treatment typically involves open surgery with fracture site curettage with or without reaming of the medullary canal and plate stabilization augmented by the autogenous or allogenic bone graft.^{31–33} Underlying structural abnormalities should also be addressed, for instance, corrective osteotomies for dorsiflexed first ray or cavus foot and gastrocnemius recession for gastrocnemius tightness.^{34–36} Adjunct treatments to improve bone healing in stress fractures, such as low-intensity pulsed ultrasound (LIPUS) and extracorporeal shockwave therapy (ESWT), have been proposed, though their efficacy still remains a subject of controversy.^{37–39}

SECOND METATARSOPHALANGEAL JOINT INSTABILITY

Presentation

The proposed pathogenesis of second MTPJ instability is varied in the current literature but generally involves lateral capsule and collateral ligament disruption together with plantar plate

rupture.^{40–42} Patients typically complain of tenderness over the plantar aspect of MTPJ, tender plantar hyperkeratotic lesions, and toe deformities.^{40,43} First ray pathologies, such as hallux valgus, excessive second metatarsal length, trauma, improper footwear, tight Achilles tendon, and inflammatory arthropathy, have been implicated second MPTJ instability.^{44–48} A dorsal drawer test, or Lachman's test, where increased mobility of the second MTPJ is observed, indicates plantar plate insufficiency.

Imaging

Radiographs and MRI are commonly used in the assessment of second MTPJ instability (Fig. 2). Anteroposterior radiographs of the foot allow for evaluation of the forefoot cascade and shape of the second metatarsal head, while lateral views allow for evaluation of the shape of the foot and relative orientation of the metatarsal heads.⁴⁹

The MRI is useful in evaluating the integrity of the second MTPJ plantar plate. Signs suggestive of a torn plantar plate include discontinuity of the plantar plate with fluid interposition, presence of pericapsular fibrosis extending from the proximal phalanx base into the intermetatarsal space (pseudoneuroma sign), and increased plantar plate-proximal phalanx distance.⁵⁰ Yamada et al.⁵¹ found that a plantar plate to proximal phalanx distance of greater than 0.275 cm has a sensitivity of 65% and specificity of 90% in diagnosing plantar plate tears.

When imaging investigations are inconclusive, lesser MTPJ arthroscopy is an emerging diagnostic and therapeutic tool for synovectomy, direct plantar plate repair, and loose body removal.^{50,52,53}

Management

Conservative management of second MTPJ instability includes customized orthotics, shoe wear modifications, and physiotherapy for calf stretches.^{54,55} Pharmacological treatment such as nonsteroidal anti-inflammatory drugs and hydrocortisone and lignocaine (H&L) injections aid in symptom relief, although multiple corticosteroid injections risk compromising MTPJ stability.^{50,56}

Surgical management of second MPTJ instability mainly involves osseous procedures for phalangeal alignment and soft-tissue repairs. Osseous procedures for phalangeal alignment

Figs 1A and B: Radiograph of right second metatarsal stress fracture in a dancer²⁰

Figs 2A to C: Radiograph of forefoot (A) and MRI Forefoot coronal view (B) showing fourth metatarsal head widening and flattening suggestive of dysplasia, secondary to chronic instability. Sagittal view of MRI (C) also show dorsal spurs and cyst formation

include a Weil's recession osteotomy for excessively long second metatarsal, MTPJ synovitis, and Morton's neuroma, as well as a dorsiflexion osteotomy for Freiberg's infraction.^{57,58} Increasingly, there has been a focus on soft-tissue procedures, which include plantar plate reconstruction, collateral ligament repair, and tendon transfers (extensor digitorum brevis, extensor digitorum longus, flexor tendon). Plantar plate reconstruction is an increasingly popular procedure, with direct repair of plantar plate back onto the base of the proximal phalanx of the toe with nonabsorbable sutures or suture anchor devices.^{42,59} No standard postsurgical rehabilitation program has been established but a postoperative anti-extension splint with a forefoot off-loading orthotic for 4 weeks is recommended.

Turf Toe Injury

Presentation

Turf toe injury is recognized as a hyperextension injury to the plantar capsuloligamentous structure of the hallux MTPJ. It was first described in 1976 by Bowers and Martin⁶⁰ at the University of West Virginia who documented 5.4 cases of such injuries per season in football players at the university. They attributed the injury to a combination of hard artificial turf and flexible footwear, which were recently introduced to football at that time. Turf toe injury has since been found not to be exclusive to football and has been seen in a number of other sports such as basketball, baseball, soccer, Taekwondo, and sprinting.⁶¹ The classical mechanism of injury involves a combination of a hard artificial turf, flexible footwear, and an axial loading foot in equinus causing hallux hyperextension.⁶²

Apart from metatarsalgia, signs of turf toe injury include ecchymosis and tenderness over the hallux MTPJ, weakness with plantarflexion, and a positive dorsoplantar drawer test. Turf toe injury is graded according to the extent of plantar capsule disruption. A common grading system proposed by Anderson⁶³ classifies turf toe injury into three different grades, ranging from stretching of and partial tears of the plantar complex to complete tears, each with their commonly associated signs and symptoms (Table 1).

Imaging

Radiological evaluations are part of the workup for hyperextension injuries of the toe. Initial investigation includes an AP foot X-ray as well as a forced dorsiflexion lateral foot X-ray. In complete plantar

complex tears, proximal retraction of the sesamoid bones can be appreciated on the lateral foot radiographs with the hallux in dorsiflexion.⁶⁴ Comparison with the contralateral foot radiographs would aid with detecting this difference.

MRI remains the imaging modality of choice when evaluating plantar plate injuries. Sprains and partial thickness tear would appear as either thinning or thickening with indistinctness of the plantar plate, while full-thickness tears would appear as focal discontinuity of the plantar plate with retraction and a fluid gap.⁶⁵ Nonetheless, plantar plate recesses at the proximal phalangeal attachments can be a normal variant, and caution must be taken to not overcall partial tears.⁶⁶ Acute injuries usually demonstrate soft tissue edema, which is absent in chronic injuries. Chronic injury might lead to development of osteophytes at the first metatarsal head, leading to hallux rigidus.⁶⁷

Management

Treatment of turf toe injuries depends on the degree of plantar complex injury. Most turf toe injuries can be treated conservatively with rest, ice, compression, and elevation (RICE) and orthotics.^{68,69} Anti-inflammatories and analgesics can help decrease pain and swelling. A short period in a walking boot or a toe spica extension is beneficial (Fig. 3).⁷⁰ Taping the hallux helps to decrease movement at the MTPJ while providing compression. The patient should be kept on a weight-bearing as tolerated regimen.

Surgical interventions are typically indicated only for grade III injuries or when conservative treatment has failed. Typical indications for surgery include large capsular tear with joint instability, sesamoid diastasis, traumatic hallux, loose bodies, or chondral injuries.⁷¹ Reconstruction of turf toe injury classically involves a medial "J" incision, whereby the incision extends along the hallux MTPJ flexion crease.⁷² Surgical repair of the plantar plate involves repair with nonabsorbable sutures placed in an interrupted fashion, suture anchors, or a drill hole technique followed by medial capsular imbrication. Alternatively, particularly when there are complete plantar plate ruptures, a dual-incision technique with incisions along the medial and lateral border of the hallux MTPJ can be used to gain access to both the medial and lateral aspects of the plantar capsular ligamentous complex.⁷³ Postoperatively, the patient is kept nonweight-bearing in a removable toe spica splint, with gradual return to full weight-bearing from the 4th week onward.

Table 1: Classification of turf toe injury

Grade	Description
I	Stretching of plantar complex Localized tenderness, minimal swelling and no ecchymosis over the first MTPJ
II	Partial tears Diffuse tenderness, moderate swelling, ecchymosis and restricted movement with pain.
III	Frank tears Severe tenderness, marked swelling and ecchymosis, limited movement with pain, and positive dorso-plantar test

Clinical classification of turf toe injury as adapted from Anderson RB. Turf toe injuries of the hallux metatarsophalangeal joint. *Techniques in Foot & Ankle Surgery* 2002;1(2):102–111

Fig. 3: Toe spica taping⁷⁰

SESAMOID PATHOLOGIES

Presentation

Comprising of 9% of foot and ankle injuries and 1.2% of running injuries, sesamoid pathologies are a significant etiology that should be given due consideration during the workup of forefoot pain.⁷⁴ Given their location within the tendons of the flexors, sesamoids aid in transmission of force during gait and are predisposed to repeated stress and trauma, making them susceptible to a range of acute and chronic injuries.⁷⁵ These includes sesamoid stress injuries or sesamoiditis that are due to repetitive trauma, sesamoid fractures, infections, degenerative diseases, and osteochondral lesions (Fig. 4).^{3,76,77} Structural variations such as pes cavus, significantly plantarflexed first ray, ankle equinus, abnormal sesamoid size or rotations, and absence of metatarsal crista have been implicated as predisposing factors to sesamoid pathologies.^{3,74,78,79} Sesamoid pain is classically described as an activity-related pain with localized discomfort on the compression test.⁸⁰

Imaging

While MRI is diagnostic for sesamoid pathologies (Fig. 5), radiographs remain a useful modality in evaluating sesamoid injury.⁸¹ Standard radiographs comparing contralateral foot X-rays are useful, while an additional axial sesamoid view taken for a tangential view of the sesamoids and less metatarsal heads can be very informative (direct beam at forefoot in a tangential manner with forefoot in

a dorsiflexed position) (Fig. 6).⁸² The existing literature has also suggested a role for CT and image-guided injections targeting a symptomatic sesamoid.^{76,81,83}

Management

Nonoperative treatment of sesamoid injury includes period of immobilization or enforced rest in walking boots followed by customized orthotics, such as those limiting flexion across MTPJ or providing sesamoid stress relief.^{84,85} However, symptomatic nonunion may persist after nonoperative treatments.⁸⁶

Operative treatment consists of options of surgical fixation with possible bone grafting, as well as partial or complete sesamoidectomy.^{4,87-89} If surgical fixation is indicated, screws need to be placed perpendicular to the fracture line to prevent fracture displacement and achieve compression, thereby necessitating higher technical expertise. Sesamoidectomy is often advocated as a good alternative, with a recent systematic review by Shimozone et al.,⁷⁷ demonstrating that sesamoidectomy for hallux sesamoid disorders yielded good clinical outcomes with high rate of return to sports.^{87,89} The surgical approach for sesamoidectomy would depend on the sesamoid to be removed and involves meticulous repair of the plantar capsule and flexor hallucis brevis tendon.^{90,91} Potential complications of sesamoidectomy include cock-up hallux, loss of push-off strength, neuritis or scar sensitivity, and hallux varus or valgus.⁹² As a result, a dedicated postoperative rehabilitation program is often required.⁹³

Fig. 4: Sesamoid chondral degeneration (Courtesy: G Thevendran)

OTHERS

Other common forefoot conditions affecting sportsmen include hallux valgus and hallux rigidus. While they are not specific to sportsmen, treatment for symptomatic hallux valgus and hallux rigidus should take into consideration the patients' athletic demands.⁹⁴ Hallux rigidus is commonly seen in runners and is generally perceived to be secondary to chronic repetitive trauma to the first MTPJ (Fig. 7) and typically presents with pain during the toe-off phase of the gait cycle.⁹⁵ If the condition is refractory to conservative treatment with foot orthoses or taping and physiotherapy, surgical treatment with dorsal first metatarsal cheilectomy may be considered.^{94,96,97} The Valenti procedure is also advocated as it allows increased postoperative dorsiflexion and range of motion, thereby quicker return to sport.⁹⁷ First MTPJ fusion offers good pain relief but should be offered judiciously as it will alter the forefoot loading patterns and the gait of an athlete.

Figs 5A and B: Magnetic resonance imaging of fibula sesamoid stress fracture: (A) Axial view; (B) Lateral view (Courtesy: G Thevendran)

Fig. 6: Radiograph shows fibula sesamoid fragmentation in sesamoid view (Courtesy: G Thevendran)

Akin to hallux rigidus, symptomatic hallux valgus should be treated conservatively.⁹⁸ Failure of conservative treatment may warrant a corrective osteotomy with debulking and tightening of medial capsule.⁹⁸ In the scenario where pain is isolated to a prominent medial eminence with only mild deformity parameters, a minimally invasive hallux valgus correction may be considered.

CONCLUSION

There is a spectrum of forefoot sporting injuries. A careful history, meticulous physical examination, and right imaging modality are key to identifying the underlying pathology. While counseling on the course of treatment, it is critical to touch on time taken to return to sport and the preinjury level of activity. While the role of biologics and treatment adjuncts are being popularized, better training regimes, footwear, and minimally invasive surgical techniques will likely polarize our management of forefoot sports injuries in the future.

REFERENCES

1. Aper RL, Saltzman CL, Brown TD. The effect of hallux sesamoid resection on the effective moment of the flexor hallucis brevis. *Foot Ankle Int* 1994;15(9):462–470. DOI: 10.1177/107110079401500902.
2. Cohen BE. Hallux sesamoid disorders. *Foot Ankle Clin* 2009;14(1):91–104. DOI: 10.1016/j.fcl.2008.11.003.
3. Dedmond BT, Cory JW, McBryde Jr A. The hallucal sesamoid complex. *J Am Acad Orthop Surg* 2006;14(13):745–753. DOI: 10.5435/00124635-200612000-00006.
4. Richardson EG. Injuries to the hallucal sesamoids in the athlete. *Foot Ankle*. 1987;7(4):229–244. DOI: 10.1177/107110078700700405.
5. Cavanagh PR. The biomechanics of lower extremity action in distance running. *Foot Ankle* 1987;7(4):197–217. DOI: 10.1177/107110078700700402.
6. Czerwiecki JM. Foot and ankle biomechanics in walking and running. A review. *Am J Phys Med Rehabil* 1988;67(6):246–252.
7. Nagel A, Fernholz F, Kibele C, et al. Long distance running increases plantar pressures beneath the metatarsal heads: a barefoot walking investigation of 200 marathon runners. *Gait Posture* 2008;27(1):152–155. DOI: 10.1016/j.gaitpost.2006.12.012.
8. Dhillon S, Dhillon M, Arumugam S, et al. Foot biomechanics and relation to the gait cycle. *J Foot Ankle Surg* 2018;5:68–72.
9. Iwamoto J, Takeda T. Stress fractures in athletes: Review of 196 cases. *J Orthop Sci* 2003;8(3):273–278. DOI: 10.1007/s10776-002-0632-5.

Fig. 7: First metatarsal head osteochondral lesion (Courtesy: G Thevendran)

10. Fetzter GB, Wright RW. Metatarsal shaft fractures and fractures of the proximal fifth metatarsal. *Clin Sports Med* 2006;25(1):139–150. DOI: 10.1016/j.csm.2005.08.014.
11. Saunier J, Chapurlat R. Stress fracture in athletes. *Joint Bone Spine* 2018;85(3):307–310. DOI: 10.1016/j.jbspin.2017.04.013.
12. Weinfeld SB, Haddad SL, Myerson MS. Metatarsal stress fractures. *Clin Sports Med* 1997;16(2):319–338. DOI: 10.1016/s0278-5919(05)70025-9.
13. Anderson LD. Injuries of the forefoot. *Clin Orthop Relat Res* 1977;122(122):18–27. DOI: 10.1097/00003086-197701000-00004.
14. Gross TS, Bunch RP. A mechanical model of metatarsal stress fracture during distance running. *Am J Sports Med* 1989;17(5):669–674. DOI: 10.1177/036354658901700514.
15. Welck MJ, Hayes T, Pastides P, et al. Stress fractures of the foot and ankle. *Injury* 2017;48(8):1722–1726. DOI: 10.1016/j.injury.2015.06.015.
16. Chen WM, Park J, Park SB, et al. Role of gastrocnemius-soleus muscle in forefoot force transmission at heel rise - A 3D finite element analysis. *J Biomech* 2012;45(10):1783–1789. DOI: 10.1016/j.jbiomech.2012.04.024.
17. Krahenbuhl N, Weinberg MW. Anatomy and biomechanics of cavovarus deformity. *Foot Ankle Clin* 2019;24(2):173–181. DOI: 10.1016/j.fcl.2019.02.001.
18. Brockwell J, Yeung Y, Griffith JF. Stress fractures of the foot and ankle. *Sports Med Arthrosc Rev* 2009;17(3):149–159. DOI: 10.1097/JSA.0b013e3181b12727.
19. Greaney RB, Gerber FH, Laughlin RL, et al. Distribution and natural history of stress fractures in U.S. Marine recruits. *Radiology* 1983;146(2):339–346. DOI: 10.1148/radiology.146.2.6217486.
20. Watson HI, O'Donnell B, Hopper GP, et al. Proximal base stress fracture of the second metatarsal in a highland dancer. *BMJ Case Rep* 2013;2013:bcr2013010284. DOI: 10.1136/bcr-2013-010284.
21. Matcuk Jr GR, Mahanty SR, Skalski MR, et al. Stress fractures: pathophysiology, clinical presentation, imaging features, and treatment options. *Emerg Radiol* 2016;23(4):365–375. DOI: 10.1007/s10140-016-1390-5.
22. Fredericson M, Jennings F, Beaulieu C, et al. Stress fractures in athletes. *Top Magn Reson Imaging* 2006;17(5):309–325. DOI: 10.1097/RMR.0b013e3180421c8c.
23. Dobrindt O, Hoffmeyer B, Ruf J, et al. MRI versus bone scintigraphy. *Evaluat Diagn Grad Stress Injur Nuklearmed* 2012;51(3):88–94. DOI: 10.3413/Nukmed-0448-11-12.
24. Ramponi DR, Hedderick V, Maloney SC. Metatarsal stress fractures. *Adv Emerg Nurs J* 2017;39(3):168–175. DOI: 10.1097/TME.0000000000000154.
25. Greaser MC. Foot and ankle stress fractures in athletes. *Orthop Clin North Am* 2016;47(4):809–822. DOI: 10.1016/j.ocl.2016.05.016.

26. Yates J, Feeley I, Sasikumar S, et al. Jones fracture of the fifth metatarsal: Is operative intervention justified? A systematic review of the literature and meta-analysis of results. *Foot (Edinb)* 2015;25(4):251–257. DOI: 10.1016/j.foot.2015.08.001.
27. Kerkhoffs GM, Versteegh VE, Siersevelt IN, et al. Treatment of proximal metatarsal V fractures in athletes and non-athletes. *Br J Sports Med* 2012;46(9):644–648. DOI: 10.1136/bjsports-2011-090389.
28. Pegrum J, Dixit V, Padhiar N, et al. The pathophysiology, diagnosis, and management of foot stress fractures. *Phys Sportsmed* 2014;42(4):87–99. DOI: 10.3810/psm.2014.11.2095.
29. Robertson GA, Wood AM. Lower limb stress fractures in sport: optimising their management and outcome. *World J Orthop* 2017;8(3):242–255. DOI: 10.5312/wjo.v8.i3.242.
30. O'Malley M, DeSandis B, Allen A, et al. Operative treatment of fifth metatarsal Jones fractures (zones II and III) in the NBA. *Foot Ankle Int* 2016;37(5):488–500. DOI: 10.1177/1071100715625290.
31. Rammelt S, Heineck J, Zwipp H. Metatarsal fractures. *Injury* 2004;35(2):SB77–SB86. DOI: 10.1016/j.injury.2004.07.016.
32. Bowes J, Buckley R. Fifth metatarsal fractures and current treatment. *World J Orthop* 2016;7(12):793–800. DOI: 10.5312/wjo.v7.i12.793.
33. Glasgow MT, Naranja Jr RJ, Glasgow SG, et al. Analysis of failed surgical management of fractures of the base of the fifth metatarsal distal to the tuberosity: the Jones fracture. *Foot Ankle Int* 1996;17(8):449–457. DOI: 10.1177/107110079601700803.
34. Fernandez-Seguín LM, Díaz Mancha JA, Sánchez Rodríguez R, et al. Comparison of plantar pressures and contact area between normal and cavus foot. *Gait Posture* 2014;39(2):789–792. DOI: 10.1016/j.gaitpost.2013.10.018.
35. Telfer S, Kindig MW, Sangeorzan BJ, et al. Metatarsal shape and foot type: a geometric morphometric analysis. *J Biomech Eng* 2017;139(3). DOI: 10.1115/1.4035077.
36. Bowers AL, Castro MD. The mechanics behind the image: Foot and ankle pathology associated with gastrocnemius contracture. *Semin Musculoskelet Radiol* 2007;11(1):83–90. DOI: 10.1055/s-2007-984418.
37. Schandelmaier S, Kaushal A, Lytvyn L, et al. Low intensity pulsed ultrasound for bone healing: systematic review of randomized controlled trials. *BMJ* 2017;356:j656. DOI: 10.1136/bmj.j656.
38. Leal C, D'Agostino C, Gomez Garcia S, et al. Current concepts of shockwave therapy in stress fractures. *Int J Surg* 2015;24(Pt B):195–200. DOI: 10.1016/j.ijsu.2015.07.723.
39. Victoria G, Petrisor B, Drew B, et al. Bone stimulation for fracture healing: what's all the fuss? *Indian J Orthop* 2009;43(2):117–120. DOI: 10.4103/0019-5413.50844.
40. Bergeron MC, Ferland J, Malay DS, et al. Use of metatarsophalangeal joint dorsal subluxation in the diagnosis of plantar plate rupture. *J Foot Ankle Surg* 2019;58(1):27–33. DOI: 10.1053/j.jfas.2018.06.007.
41. Klein EE, Weil L, Jr, Weil LS, Sr, et al. Clinical examination of plantar plate abnormality: a diagnostic perspective. *Foot Ankle Int* 2013;34(6):800–804. DOI: 10.1177/1071100712471825.
42. Flint WW, Macias DM, Jastifer JR, et al. Plantar plate repair for lesser metatarsophalangeal joint instability. *Foot Ankle Int* 2017;38(3):234–242. DOI: 10.1177/1071100716679110.
43. Coughlin MJ, Baumfeld DS, Nery C. Second MTP joint instability: grading of the deformity and description of surgical repair of capsular insufficiency. *Phys Sportsmed* 2011;39(3):132–141. DOI: 10.3810/psm.2011.09.1929.
44. Coughlin MJ. Crossover second toe deformity. *Foot Ankle* 1987;8(1):29–39. DOI: 10.1177/107110078700800108.
45. Mann RA, Mizel MS. Monarticular nontraumatic synovitis of the metatarsophalangeal joint: a new diagnosis? *Foot Ankle* 1985;6(1):18–21. DOI: 10.1177/107110078500600104.
46. Coughlin M. When to suspect crossover second toe deformity. *J Musculoskelet Med* 1987;4(1):39–48.
47. Coughlin MJ. Second metatarsophalangeal joint instability in the athlete. *Foot Ankle* 1993;14(6):309–319. DOI: 10.1177/107110079301400601.
48. Bhutta MA, Chauhan D, Zubairy AI, et al. Second metatarsophalangeal joint instability and second metatarsal length association depends on the method of measurement. *Foot Ankle Int* 2010;31(6):486–491. DOI: 10.3113/FAI.2010.0486.
49. Kaz AJ, Coughlin MJ. Crossover second toe: demographics, etiology, and radiographic assessment. *Foot Ankle Int* 2007;28(12):1223–1237. DOI: 10.3113/FAI.2007.1223.
50. Reddy SC. State of the art in lesser metatarsophalangeal instability. *Foot Ankle Clin* 2019;24(4):627–640. DOI: 10.1016/j.fcl.2019.08.007.
51. Yamada AF, Crema MD, Nery C, et al. Second and third metatarsophalangeal plantar plate tears: Diagnostic performance of direct and indirect MRI features using surgical findings as the reference standard. *Am J Roentgenol* 2017;209(2):W100–W108. DOI: 10.2214/AJR.16.17276.
52. Nery C, Coughlin MJ, Baumfeld D, et al. MRI evaluation of the MTP plantar plates compared with arthroscopic findings: a prospective study. *Foot Ankle Int* 2013;34(3):315–322. DOI: 10.1177/1071100712470918.
53. Nery C, Coughlin MJ, Baumfeld D, et al. Lesser metatarsal phalangeal joint arthroscopy: anatomic description and comparative dissection. *Arthroscopy* 2014;30(8):971–979. DOI: 10.1016/j.arthro.2014.03.018.
54. Peck CN, Macleod A, Barrie J. Lesser metatarsophalangeal instability: presentation, management, and outcomes. *Foot Ankle Int* 2012;33(7):565–570. DOI: 10.3113/FAI.2012.0565.
55. Maas NM, van der Grinten M, Bramer WM, et al. Metatarsophalangeal joint stability: a systematic review on the plantar plate of the lesser toes. *J Foot Ankle Res* 2016;9(1):32. DOI: 10.1186/s13047-016-0165-2.
56. Trepman E, Yeo SJ. Nonoperative treatment of metatarsophalangeal joint synovitis. *Foot Ankle Int* 1995;16(12):771–777. DOI: 10.1177/107110079501601206.
57. Watson TS, Reid DY, Frerichs TL. Dorsal approach for plantar plate repair with weill osteotomy: operative technique. *Foot Ankle Int* 2014;35(7):730–739. DOI: 10.1177/1071100714536540.
58. Georgiannos D, Tsikopoulos K, Kitridis D, et al. Osteochondral autologous transplantation versus dorsal closing wedge metatarsal osteotomy for the treatment of Freiberg infraction in athletes: a randomized controlled study with 3-year follow-up. *Am J Sports Med* 2019;47(10):2367–2373. DOI: 10.1177/0363546519859549.
59. Elmajee M, Shen Z, A'Court J, et al. A systematic review of plantar plate repair in the management of lesser metatarsophalangeal joint instability. *J Foot Ankle Surg* 2017;56(6):1244–1248. DOI: 10.1053/j.jfas.2017.05.039.
60. Bowers Jr KD, Martin RB. Turf-toe: a shoe-surface related football injury. *Med Sci Sports* 1976;8(2):81–83. DOI: 10.1249/00005768-197600820-00012.
61. Vopat ML, Hassan M, Poppe T, et al. Return to sport after turf toe injuries: a systematic review and meta-analysis. *Orthop J Sports Med* 2019;7(10):2325967119875133. DOI: 10.1177/2325967119875133.
62. George E, Harris AH, Dragoo JL, et al. Incidence and risk factors for turf toe injuries in intercollegiate football: data from the national collegiate athletic association injury surveillance system. *Foot Ankle Int* 2014;35(2):108–115. DOI: 10.1177/1071100713514038.
63. Anderson RB. Turf toe injuries of the hallux metatarsophalangeal joint. *Techniq Foot Ankle Surg* 2002;1(2):102–111. DOI: 10.1097/00132587-200212000-00004.
64. Waldrop 3rd NE, Zirker CA, Wijdicks CA, et al. Radiographic evaluation of plantar plate injury: an in vitro biomechanical study. *Foot Ankle Int* 2013;34(3):403–408. DOI: 10.1177/1071100712464953.
65. Schein AJ, Skalski MR, Patel DB, et al. Turf toe and sesamoiditis: what the radiologist needs to know. *Clin Imaging*. 2015;39(3):380–389. DOI: 10.1016/j.clinimag.2014.11.011.
66. Theumann NH, Pfirrmann CW, Mohana Borges AV, et al. Metatarsophalangeal joint of the great toe: normal MR, MR arthrographic, and MR bursographic findings in cadavers. *J Comput Assist Tomogr* 2002;26(5):829–838. DOI: 10.1097/00004728-200209000-00029.
67. Rodeo SA, O'Brien S, Warren RF, et al. Turf-toe: an analysis of metatarsophalangeal joint sprains in professional football players. *Am J Sports Med* 1990;18(3):280–285. DOI: 10.1177/036354659001800311.

68. Clanton TO, Butler JE, Eggert A. Injuries to the metatarsophalangeal joints in athletes. *Foot Ankle* 1986;7(3):162–176. DOI: 10.1177/107110078600700306.
69. Coker TP, Arnold JA, Weber DL. Traumatic lesions of the metatarsophalangeal joint of the great toe in athletes. *Am J Sports Med* 1978;6(6):326–334. DOI: 10.1177/036354657800600604.
70. VanPelt MD, Saxena A, Allen MA. Turf toe injuries. *Int Adv Foot Ankle Surg*. London: Springer; 2012. pp. 219–228.
71. Smith K, Waldrop N. Operative outcomes of grade 3 turf toe injuries in competitive football players. *Foot Ankle Int* 2018;39(9):1076–1081. DOI: 10.1177/1071100718775967.
72. McCormick JJ, Anderson RB. Turf toe: anatomy, diagnosis, and treatment. *Sports Health* 2010;2(6):487–494. DOI: 10.1177/1941738110386681.
73. McCormick JJ, Anderson RB. The great toe: failed turf toe, chronic turf toe, and complicated sesamoid injuries. *Foot Ankle Clin* 2009;14(2):135–150. DOI: 10.1016/j.fcl.2009.01.001.
74. Boike A, Schnirring-Judge M, McMillin S. Sesamoid disorders of the first metatarsophalangeal joint. *Clin Podiatr Med Surg* 2011;28(2):269–285. DOI: 10.1016/j.cpm.2011.03.006.
75. Kadakia AR, Molloy A. Current concepts review: traumatic disorders of the first metatarsophalangeal joint and sesamoid complex. *Foot Ankle Int* 2011;32(8):834–839. DOI: 10.3113/FAI.2011.0834.
76. Biedert R, Hintermann B. Stress fractures of the medial great toe sesamoids in athletes. *Foot Ankle Int* 2003;24(2):137–141. DOI: 10.1177/107110070302400207.
77. Shimozono Y, Hurley ET, Brown AJ, et al. Sesamoidectomy for hallux sesamoid disorders: a systematic review. *J Foot Ankle Surg* 2018;57(6):1186–1190. DOI: 10.1053/j.jfas.2018.03.044.
78. Taylor JA, Sartoris DJ, Huang GS, et al. Painful conditions affecting the first metatarsal sesamoid bones. *Radiographics* 1993;13(4):817–830. DOI: 10.1148/radiographics.13.4.8356270.
79. Resnick D, Niwayama G, Feingold ML. The sesamoid bones of the hands and feet: participants in arthritis. *Radiology* 1977;123(1):57–62. DOI: 10.1148/123.1.57.
80. Allen MA, Casillas MM. The passive axial compression (PAC) test: a new adjunctive provocative maneuver for the clinical diagnosis of hallux sesamoiditis. *Foot Ankle Int* 2001;22(4):345–346. DOI: 10.1177/107110070102200414.
81. Sanders TG, Rathur SK. Imaging of painful conditions of the hallux sesamoid complex and plantar capsular structures of the first metatarsophalangeal joint. *Radiol Clin North Am* 2008;46(6):1079–1092. DOI: 10.1016/j.rcl.2008.09.001.
82. Grace DL. Sesamoid problems. *Foot Ankle Clin* 2000;5(3):609–627.
83. Chan BY, Markhardt BK, Williams KL, et al. Os conundrum: identifying symptomatic sesamoids and accessory ossicles of the foot. *Am J Roentgenol* 2019;213(2):417–426. DOI: 10.2214/AJR.18.20761.
84. Hulkko A, Orava S, Pellinen P, et al. Stress fractures of the sesamoid bones of the first metatarsophalangeal joint in athletes. *Arch Orthop Trauma Surg* 1985;104(2):113–117. DOI: 10.1007/BF00454250.
85. Axe MJ, Ray RL. Orthotic treatment of sesamoid pain. *Am J Sports Med* 1988;16(4):411–416. DOI: 10.1177/036354658801600419.
86. Robertson GAJ, Goffin JS, Wood AM. Return to sport following stress fractures of the great toe sesamoids: a systematic review. *Br Med Bull* 2017;122(1):135–149. DOI: 10.1093/bmb/ldx010.
87. Bichara DA, Henn RF 3rd, Theodore GH. Sesamoidectomy for hallux sesamoid fractures. *Foot Ankle Int* 2012;33(9):704–706. DOI: 10.3113/FAI.2012.0704.
88. Anderson RB, McBryde Jr AM. Autogenous bone grafting of hallux sesamoid nonunions. *Foot Ankle Int* 1997;18(5):293–296. DOI: 10.1177/107110079701800509.
89. Blundell CM, Nicholson P, Blackney MW. Percutaneous screw fixation for fractures of the sesamoid bones of the hallux. *J Bone Joint Surg Br* 2002;84(8):1138–1141. DOI: 10.1302/0301-620x.84b8.13064.
90. Saxena A, Krisdakumtorn T. Return to activity after sesamoidectomy in athletically active individuals. *Foot Ankle Int* 2003;24(5):415–419. DOI: 10.1177/107110070302400507.
91. Rodrigues Pinto R, Muras J. Medial approach to the fibular sesamoid. *Foot Ankle Int* 2010;31(10):916–919. DOI: 10.3113/FAI.2010.0916.
92. Taylor CF, Butler M, Parsons SW. Problems associated with the excision of the hallux sesamoids. *Foot Ankle Clin* 2014;19(3):425–436. DOI: 10.1016/j.fcl.2014.06.014.
93. Coetzee JC, Stone RM, Fritz JE, et al. Functional outcome of sesamoid excision in athletes. *Orthop J Sports Med* 2016;4(3 suppl 3). DOI: 10.1177/2325967116S00065.
94. Nihal A, Trepman E, Nag D. First ray disorders in athletes. *Sports Med Arthrosc Rev* 2009;17(3):160–166. DOI: 10.1097/JSA.0b013e3181a5cb1f.
95. Tregouet P. An assessment of hallux limitus in university basketball players compared with noncompetitive individuals. *J Am Podiatr Med Assoc* 2014;104(5):468–472. DOI: 10.7547/0003-0538-104.5.468.
96. Mulier T, Steenwerckx A, Thienpont E, et al. Results after cheilectomy in athletes with hallux rigidus. *Foot Ankle Int* 1999;20(4):232–237. DOI: 10.1177/107110079902000405.
97. Saxena A, Valerio DL, Behan SA, et al. Modified valenti arthroplasty in running and jumping athletes with hallux limitus/rigidus: analysis of one hundred procedures. *J Foot Ankle Surg* 2019;58(4):609–616. DOI: 10.1053/j.jfas.2018.07.009.
98. Fournier M, Saxena A, Maffulli N. Hallux valgus surgery in the athlete: current evidence. *J Foot Ankle Surg* 2019;58(4):641–643. DOI: 10.1053/j.jfas.2018.04.003.