Finding the line: A radiological approach to stress fractures of the lower limb

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Learning objectives

In this educational exhibit, we discuss the physiopathology of stress-related bone injuries and present selected examples of stress reactions, stress and insufficiency fractures from a multimodality point of view with emphasis in skeletal scintigraphy, computed tomography (CT) and magnetic resonance imaging (MRI).
Background

Stress-related bone injuries also known as chronic repetitive stress injury of bone involve a myriad of bone lesions extending from mild stress "reactions" with pain, soft tissue and periosteal oedema to complete and displaced stress or insufficiency fractures. Stress fractures are not the result of one specific load. Instead, they arise as the result of repeated trauma with a force that is lower than that required to fracture the bone in a single load cycle. When an abnormal bone, with deficiency in mineral or collagen content is under physiological stress sometimes fails and develops an insufficiency fracture.

Bone suffers a stress on any occasion a force is loaded on it. These forces may be originated from the traction of a muscle or the impact of a weight-bearing extremity contacting the ground. These low-energy forces cause bone to deform, which is known as strain. Depending on the load's direction and intensity, the bone's geometry, microarchitecture, and density there will be a different response. If the applied forces exceed the elastic resistance of the bone and reach the plastic range there is a real risk of permanent damage.

During the normal load the forces applied are essential to the development and maintenance of the bone structure, not only during the growing period of the human development, but along his whole life through a delicate balance between bone formation (the main function of the osteoblasts), the maintenance of the bone mass (as a consequence of the actions of the osteocytes) and bone resorption (the main function of the osteoclasts).

The histological characteristics of the bone and its plastic abilities allows this unique structure to effectively endure compression, tension, bending, torsion, and shear forces.

Histologically mature bone is composed of a peripheral area of cortical bone comprised between two layers of connective tissue (periostium and endostium) and a central area of cancellous bone. These architectural features provides it with a relatively light but extremely resistant structure. (fig 1)

Cortical bone is a dense, hierarchically organized tissue which is composed of collagen fibres arranged in sheets known as lamellae. These lamellae are arranged in concentric rings known as osteons or Haversian systems. The osteons are surrounded by interstitial lamellae, which are areas of relative weakness where stress fractures can propagate. (fig 2)

Cortical bone endures compression forces better than tensional ones. Trabecular bone is an irregularly shaped web and withstands compression stress according to the alignment of this fiber matrix. There are large areas of cancellous bone at the metaphyseal and epiphyseal areas and in the central portion of the shaft of the long bones. Short and flat bones are also specially rich in trabecular bone.
Repetitive loads applied to normal bone initiate the process of accelerated remodeling and eventually may produce cumulative microdamage. In base of the Wolff’s law, compression forces stimulate osteoblast activity while shear forces lead to increased osteoclast activity. Under normal circumstances there is a balance between formation and resorption which contributes to maintain the normal strength of the bone and is also involved in homeostatic processes such as the maintenance of the normal blood levels of Calcium.

The total bone mass of an adult individual depends on the conjoined action of the processes of resorption and bone formation.

This physiological response to the physiological loads locally alters the microarchitectural configuration of the bone to better deal with an altered environment. When this process is disturbed and there is a disbalance between the osteoclastic and osteoblastic activity, the bone is weakened and becomes increasingly susceptible to injury.

The process of bone remodeling is different with compression and shear forces. Under shear forces bone remodeling is initiated with vascular congestion, thrombosis and osteoclastic resorption. This chain of events is promoted by the activation, proliferation and differentiation of monocytes and macrophages in osteoclasts.

In contrast, under compression forces there is an activation of the osteoblasts with thickening of the cortex and physiological strengthening of the bone.

Osteoclasts create tunnels following a parallel direction to the long axis of the bone (resorption channels). This process ends when an inversion zone is created with development of a new consolidation line formed by the osteoblasts with aposition of new bone. In an adult the basic multicellular unit is responsible of this process of bone remodelation which it takes up to five weeks to be completed. (fig 3).

If these cyclic loads are continuously applied there is an increased rate of osteoclastic activity which may overpass the normal deposition of bone and form a cluster of resorbed cavities with further development of microfractures with extension to the cortex. This causes progressive weakening of the cortex and if the load is frequently applied, exceeding bone’s adaptation capacity, microcracks can coalesce into macroscopic fissures and a stress fracture may eventually result as the end of the process. Because this process is described as a pathology continuum, the clinical features also exist along a sequential process from mild (stress reaction) to severe injuries (complete/displaced stress fractures) (fig 4).

Stress fractures are common in professional or recreational athletes and in military personnel. These injuries account for up to 10% of all lesions seen in sports medicine clinics. The lower extremities are more frequently involved (up to 95%) than the upper extremities. Although stress fractures are significant for all patients they are a well recognized cause of impairment in elite athletes and also cause extended periods of absence from training and notorious economic losses in professional armies. Different
locations are described as a consequence of the involved physical activity. Runners are among the most frequent patients with stress related bone injuries. They may develop stress fractures of the tibia, distal end of the fibula, calcaneus, metatarsals, and sesamoid bones. Classical ballet dancers, gymnasts and jump athletes mainly present stress fractures in the talus, navicular and sesamoid bones while for football players the metatarsals (specially the fifth metatarsal) and fibula fractures are the more common locations.

On the contrary, there is another type of stress related bone injury which develops when a weakened bone failures under normal or physiological stress. Insufficiency fractures usually occur on elderly patients with abnormal mineral content or with diminished elasticity of bone and are frequent in osteoporosis. These fractures are becoming increasingly important by the progressive aging of the population with a higher prevalence of osteoporosis. The most frequent locations for insufficiency fractures are the pelvic girdle, femur, tibia, and foot bones. (fig 5)

Insufficiency fractures may complicate other pathological conditions affecting the bone, including Paget’s disease, Cushing’s disease, rheumatoid arthritis, diabetes mellitus, hyperparathyroidism, radiation-induced changes in bone and others.
Fig. 1: Figure 1. Longitudinal section of the femur showing its internal macroscopic architecture from the epiphysis to the beginning of the diaphysis. (1) Synovial joint; (2) internal zone of mature or laminar trabecular bone; (3) external zone of compact cortical bone.

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Fig. 2: Tridimensional structure of laminar (mature) bone. Axial view of the diaphyseal region of a long bone. (1) External circumferential system (Cortical bone); (2) Osteon or haversian system; (3) Interstitial systems; (4) Periostium; (5) Bone lamellae (longitudinal view); (6) Lacuna containing osteocytes; (7) Mature trabecular bone; (8) Longitudinal view of Haversian channel; (9) Völkmann’s canals; (10) Blood vessel; (11) Medular cavity.

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Fig. 3: The basic multicellular unit responsible of bone remodelling. Longitudinal view (left) and four different axial slices on different levels (right). A: Central vessel; B: Osteoclast precursors. C: Osteoclasts inside Howship. D: Monocytes. E: Trails of osteoblasts filling the defects left by the osteoclasts. F: Osteoblastic lining cells over the Haversian’s systems. G: Haversian system. Osteoclasts progress from cranial to caudal and radially in the cutting cone (1) creating a resorption lacuna (2). Finally the cutting zone is shown (3)

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Fig. 4: Physiopathology of stress-related bone injuries. Stress fractures are the final result of the microdamage caused by repeated low-energy loading overpassing the physiological abilities for bone remodeling.

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**Fig. 5:** Frequent locations of insufficiency fractures of the bony pelvis. The most common sites of insufficiency fractures around the pelvic girdle are sacrum and pubic rami.

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Findings and procedure details

We performed a retrospective search in our teaching file of all stress-related bone injuries. We collected imaging studies of sixty-three patients with stress-related bone injuries in the lower extremities. The age of the study population ranged from 14 to 73 years. Of the sixty-three patients studied, 33 were men and 30 were women. We found 6 mild stress reaction, 23 insufficiency fractures and 34 stress fractures. Clinically the patients with stress fractures presented with localized pain related to a change in their usual physical activity or preceded by an effort to which they were not accustomed. The pain subsided with rest and increased when resuming the sport activity. Location is an important factor in the diagnosis of stress fractures. Different sports activities lead to location specific injuries. This information allows the clinician to classify the fractures in the high or low risk categories. This classification is important as high-risk fractures are subsidiary of aggressive and prompt treatment. (fig 6)

In contrast, patients with insufficient fractures had previous pathological conditions which suggested this diagnosis. Most of the insufficiency fractures around the pelvic girdle were related to previous radiotherapy or steroid treatments (fig 7), whereas, on the other hand, fractures of the proximal and distal femoral region, fractures of the knee and feet were more frequently related to osteoporosis. In order to evaluate the lesions, both bone injuries and pathological findings on the adjacent soft tissues were taken into account.

Plain Radiography

The first imaging test on the majority of the studied cases was plain radiography. Its initial sensitivity is lower than 10 percent but it increases reaching 30 to 70 percent after three weeks. As in most of the cases the initial radiography is negative (fig 8), a sequential radiography may be repeated after three weeks if there is persistence of the symptoms. Common described features of stress fractures on plain radiography are a subtle lucency (fig 9) or faint sclerosis (fig 10) with more obvious signs appearing over the weeks: more obvious sclerosis (fig 11) with periosteal thickening (fig 12) and, finally, callus formation (fig 13). These late findings are highly specific for stress fractures and can confirm the diagnosis.

Bone scintigraphy

Bone scanning with Tc-99m-MDP is highly sensitive (74-84%) but nonspecific for stress fractures. Bone scintigraphy had been for many years the gold standard for the diagnosis of stress-related injuries. Unfortunately there are many causes for false positives in situations with increased bone metabolism such as stress reactions, infections and
tumors. An abnormal uptake may be seen within 6 to 72 hours of the development of a stress fracture. (fig 14 and 15). The main advantage of bone scanning is its ability to obtain a whole bone scan with a relatively low cost and time of examination. (fig 16)

CT

Computed tomography allows to study the bone in great detail and is useful in difficult cases, particularly in the case of stress fractures of the pelvic girdle or the foot and for demonstrating lineal stress fractures following the long axis of the tibia, sometimes a troublesome diagnosis with other imaging modalities. (fig 17)

MRI

MRI is recognised as the most sensitive and specific imaging technique for the diagnosis of stress related bone injuries. Early MRI findings in patients with stress related bone injuries is an area of intermediate intensity signal on T1-weighted images with high signal intensity on T2-weighted and fluid sensitive sequences. These MRI findings are consistent with the presence of bone marrow edema. Marrow edema can have multiple etiologies and may raise differential diagnosis with shin splints (fig 18), tumors (specially osteoid osteoma and Ewing’s sarcoma) (fig 19) or osteomyelitis among other pathological conditions. In these difficult cases the ability to detect a fracture line is primordial. A multimodality aproach to these conditions allows the radiologist to correctly diagnose most of these complex cases. Sometimes however final diagnosis is made after biopsy. The finding of a fracture line is the most specific feature that makes the diagnosis of stress fracture as highly probable. Fracture lines are frequently visible both on T1 and T2-weighted images. (fig 20) It is finally important to take note that the signal changes in stress fractures may persist during 5 to 6 months after the onset of the symptoms on the follow-up.
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<th>Anatomic Region</th>
<th>High-risk locations</th>
<th>Low-risk locations</th>
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<td>Femoral neck</td>
<td>Pelvis and femoral shaft</td>
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<td>Patella</td>
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<td>Anterior cortex tibia</td>
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<td>Tarsal bones</td>
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**Fig. 6:** Low and high risk stress fracture classification Modified from Dobrindt et al. BMC Musculoskeletal Disorders 2012; 13:139. Estimation of return-to-sports-time for athletes with stress fracture - an approach combining risk level of fracture site with severity based on imaging

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Fig. 7: 69-year-old woman with rheumatoid arthritis (RA) with lon-term glucocorticoid treatment. Patient complained of insidious bilateral groin pain. She denied a history of previous traumatic event. CT scan with mutiplanar and volume rendering 3D reconstructions showed multiple bilateral fractures of pubic rami, sacrum and iliac bones.

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Fig. 8: 32-year old man with pain in his right knee. The pain had started steadily after two weeks of trekking holidays. The initial x-ray was reported as normal, but on MRI (T1-
weighted and T2-weighted with fat suppression) examination of the knee there were bone marrow edema and incomplete fracture in the proximal tibia indicating the presence of a stress fracture. Follow-up examination showed complete resolution of these findings. (images not shown)

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Fig. 9: 42 year-old patient with heel pain for weeks, no history of trauma. Hypointense line surrounded by T1-hypointense and T2-hyperintense bone marrow haematoma. No fragment displacement. On plain radiography a faint lucent line is noticed (arrows). Grade IV calcaneus stress fracture.

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**Fig. 10:** 31 year-old patient complained of right groin pain during sports activity. AP radiography of the right femur showed a subtle sclerosis (white circle). MRI with coronal T2 weighted image with fat suppression showed endosteal edema in keeping with stress reaction involving the inferior aspect of the right femoral neck.

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![Image of Fig. 10](image)

**Fig. 11:** Stress Fracture of the Calcaneus. Plain radiography (lateral view) of calcaneus shows vertically-oriented dense band of sclerosis (arrow), perpendicular to the orientation of the trabeculae. STIR and T1-weighted MRI images show a stress fracture of the calcaneus (arrow) and the surrounding marrow edema

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![Image of Fig. 11](image)
Fig. 12: A 13 year-old female patient with right leg pain. AP radiograph of the leg shows cortical thickening in the medial aspect of tibial shaft. Axial CT image demonstrates the cortical thickening. Axial T2-weighted with fat suppression and coronal T1-weighted MRI examination demonstrates periosteal reaction with soft tissue and bone marrow edema. Grade III stress fracture

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Fig. 13: A 46 year-old woman presenting with left foot pain without previous history of trauma. An initial diagnosis of tenosynovitis was made based on the clinical findings and examination. Initial radiography (not shown) was unremarkable. An MRI was performed (long axis T1-weighted and T2 weighted with fat suppression sequences showed) suggesting the diagnosis of stress fracture of the base of the third metatarsal. After 6 months a sequential radiography was obtained showing a fracture callus on the referred location. (white circle)

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Fig. 14: MRI examination of a 14 y.o patient with pain on his right leg. A. Coronal T1-weighted. B. Coronal T2 weighted with fat supression. C. Axial T1-weighted. D. Axial T2-weighted with fat supression. A visible fracture line is visible both on T1-weighted and T2-weighted sequences. There is an established periosteal reaction. Grade IV tibial stress fracture.

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**Fig. 15:** Transverse, sagittal, and coronal slices of single photon emission computed tomography (SPECT) images of the same patient from figure showing increased tracer uptake along the medial aspect of the proximal right tibia with associated sclerosis and hyperostosis on the corresponding CT images.

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**Fig. 16:** Stress fracture in a 56 year-old female patient with metastastic breast cancer on quimiotherapy. Multiple bone metastases were been controlled with consecutive bone scans. There is a new focal area of uptake on the medial tibial malleolus (black arrow). Patient was complaining of pain on this location. Plain radiograph demonstrates a subtle fracture line on the medial malleolus (white arrow). CT scan on reformated coronal view shows clearly the stress fracture.

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**Fig. 17:** 27 year-old patient with pain on his right leg without previous history of direct trauma. Axial and sagittal reformated computed tomographic images through the right tibia showed linear area of low attenuation along the long axis of the tibial shaft with fracture line in the posterior cortex associated with marrow edema visible on T1-weighted and T2 fat suppressed MRI images. Radiography was unremarkable. Exercise-related longitudinal tibial stress fracture.

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**Fig. 18:** 45 year-old patient with sharp pain over the anterior medial aspect of the left leg after running a half-marathon. Axial fat-suppressed MRI sequences showed a linear abnormally high signal along the medial anterior surface of the tibia (A). Follow-up examination showed partial resolution of this edema. No marrow edema was noticed on both examinations. Shin splints.

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![Image](image1.png)

**Fig. 19:** A 23 year-old woman presenting with left groin pain for months without previous history of trauma. Clinical condition worsened and CT examination, single photon emission computed tomography (SPECT) and MRI were performed. On CT (A) a fracture line was identified but abnormal bone density raised suspicion for malignancy. On MRI a high intensity area of abnormal signal on T2-weighted sequence with fat suppression was noted (B). SPECT (C) showed increased tracer uptake along the left ischiopubic ramus. A bone biopsy was performed with the final diagnosis of Ewing´s sarcoma.

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**Fig. 20:** 41 year-old male patient with previous ankle sprain. On initial examination no fracture was noticed. The patient was under vigorous phisyotherapy when started complains about ankle pain. On MRI examination with fat suppressed sequences soft tissue, periosteal and marrow edema was noticed, together with a clear fracture line. Grade IV stress fracture of the distal tibia.

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Conclusion

Diagnostic imaging plays an important role in the specific diagnosis of stress related bone injuries and provides valuable information about the location and severity of stress fractures by classifying them into low and high risk fractures. In the absence of a clear correlation between repeated stress and pain in an active individual the clinical diagnosis of a stress-related bone injury may be troublesome and a possible delayment may cause worsening of this condition and further impairment to a professional athlete. Also in some patients there are indeterminate findings that may suggest stress related bone injury but subsequent imaging techniques or biopsy provide a final diagnosis of inflammation or tumor. The use of CT, bone scan and MRI is of a great importance for early diagnosis and allows the radiologist to exclude another causes of bone lesions that may lead to confusion in the differential diagnosis of a patient with pain and non-specific abnormalities on plain radiography and/or Nuclear Medicine bone scans. The classical imaging findings of stress fractures may be of a great aid for the clinician specially in these complex situations.
References


