STRESS FRACTURES AND ACUTE FRACTURES OF THE FOOT AND LOWER LEG

DEFINITION

A stress fracture can be defined as a partial or complete fracture of bone as a result of repetitive sub-maximal loading. A stress fracture will occur if the loading frequency is high enough such that the rate of bone resorption exceeds the rate of bone formation during the remodeling process (e.g. excessive running volume and inadequate recovery time), which can result in weakening of the bone and, eventually, fracture of the bone can occur (Zadpoor and Nikooyan, 2011). This is in contrast to an acute fracture, which is usually characterized by a single, severe impact. A stress fracture is most likely to occur during an early phase of training (i.e. during the first 40 days) or when training volume is significantly increased (Magness et al, 2011).

INCIDENCE

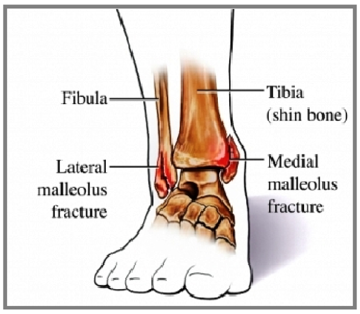
Stress Fractures

Stress fractures are among the most prevalent sports injuries, particularly in sports involving running and jumping (Popp et al, 2009), and account for approximately 10% of all overuse injuries (McBryde, 1985). In sports such as soccer, basketball, and track and field, stress fractures are common in the tibial shaft and the metatarsals (Iwamoto and Takeda, 2003), while stress fractures in runners are concentrated in the tibia, navicular, and metatarsals (Weist et al, 2004). Lower extremity stress fractures have been reported to account for 61.2% to 97% of all stress fractures in athletes (Orava et al, 1978; Matheson et al, 1987; Iwamoto and Takeda, 2003). The tibia is reported to be the most common fracture site in the body, accounting for 33-55% of the total number of stress fracture incidences (Taunton et al., 1981; Giladi et al., 1987; Matheson et al., 1987; Pester and Smith, 1992; Brukner et al., 1996), while metatarsal stress fractures, which are most common amongst dancers (Romani et al, 2002), have been reported to account for up to 25% of all incidences of stress fractures (Queen and Nunley, 2009). Stress fractures have been reported to occur in every bone of the foot and ankle, except the lesser toes (Brockwell et al, 2009).

In any given year, more than one in five runners will sustain a stress fracture (Bennell et al, 1996b). In the U.S. alone, this equates to nearly 2 million stress fractures annually (Crowell et al, 2010). Given the high incidence of lower extremity stress fractures in runners, with recovery typically taking up to 8 weeks (Beck, 1998), training and competition schedules can be greatly disrupted (Magness et al, 2011). In addition to the high incidence of injury, recurrence rates of 36% have been documented (Magness et al, 2011).

Acute Fractures

Acute ankle fractures (i.e. fractures of the distal end of the tibia or fibula) (image #1) are the most common type of fracture treated by orthopedic surgeons in the United States (Michelson, 1995). An ankle fracture can occur when the joint is forced beyond its normal range of motion or when there is a direct impact to the bone itself. Running or jumping on uneven surfaces can lead to ankle fractures, while high impact sports such as football or rugby have a high incidence of ankle fractures (Walker, 2007).



1. Source: Nucleus Medical Media

2. Source: Manchester Orthopaedic Group

Approximately 10% of all acute fractures occur in the bones of the foot (Silbergleit, 2012) (image #2), with fractures to the bones of the forefoot (metatarsals and phalanges (toes)) being the most common (Hatch and Hacking, 2003). The metatarsal bones play a major role in propulsion and support. For propulsion, they act like a rigid lever to transmit forces to the ground, and for support they act like a flexible structure that assists with balance. Acute fractures to the metatarsal bones are typically caused by direct trauma or excessive rotational forces. Metatarsal fractures are relatively common in running and jumping sports or activities involving change of direction such as football, soccer (most common), rugby, basketball and ballet (Shuen et al, 2009).

The midfoot, which consists of the tarsal bones (navicular, cuboid, and medial, middle, and lateral cuneiforms) (image #2), has little mobility due to dense ligamentous connections, and therefore provides a rigid mechanical link between the hindfoot and the forefoot to allow for force transmission during rotational movements, such as inversion and eversion, and to provide stability during weight-bearing (Early, 2006). Fractures of the navicular and cuboid are the most common of the tarsal bones, and can greatly impair foot function due to their roles in force transmission and stability of the arch of the foot (Early, 2006).

The hindfoot consists of the calcaneus (heel bone) and talus (image #2). The talus forms the ankle joint with the distal ends of the tibia and fibula, while the joint between the talus and calcaneus (sub-talar joint) allows for movements of inversion and eversion. The hindfoot bears and distributes body weight across the foot during weight bearing activity. Fractures of the hindfoot are less common sports-related injuries due to the greater relative strength of these bones, and are usually associated with high-impact collisions such as those that occur during motor vehicle accidents or a fall from a significant height. However, fractures of the talus are becoming more common in sports such as snowboarding (Valderrabano et al, 2005), where there is a potential for high-impact collisions with the ground after jumping and landing from a significant height. If the impact with the ground occurs such that the foot is axially loaded in dorsiflexion and inversion, significant compressive force is applied to the lateral process of the talus, which can cause it to fracture (Mukherjee et al, 1974). Langer and DiGiovanni (2008) reported that fractures to the lateral process of the talus account for approximately 15% of all ankle injuries in snowboarding.

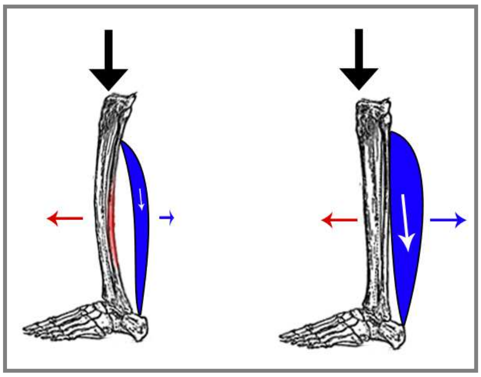
Risk Factors for Stress Fractures

- an abrupt increase in training load or intensity (Scully, 1982; Beck, 1998);
- inadequate recovery time (Magness et al, 2011);
- running volume in excess of 20 miles (32 km) per week (Magness et al, 2011);
- previous history of stress fractures (Kelsey et al, 2007);
- leg length discrepancy (Bennell et al, 1996a; Korpelainen et al, 2001);
- low bone density in females (Bennell et al, 1996a);
- menstrual irregularity associated with disordered eating (Duckham et al, 2012);
- low-fat diet in females (Bennell et al, 1996a);
- bending forces (see below for more details) (Bennell et al, 1999; Popp et al, 2009);
- inadequate muscle strength (see below) (Ferris et al, 1995; Burne et al, 2004);

- inadequate muscle endurance (see below) (Yoshikawa et al, 1994);
- heel-strike foot impact during running (see below) (O'Leary et al, 2008; Magness et al, 2011; Zadpoor and Nikooyan, 2011);
- lack of cushioned insoles for heel-strike runners (O'Leary et al, 2008).

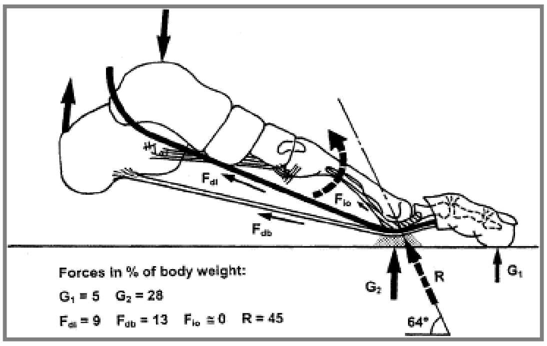
Bending Forces

In a study on 39 competitive female distance runners, Popp et al (2009) reported that tibial loading during running compresses and bends the distal portion of the tibia backward throughout most of the stance phase, leading to the greatest stresses in the posterior side of the tibia, which is the most common site of fracture. The authors calculated that the combination of the ground reaction force (GRF) and plantarflexor muscle force acted to compress the tibia during the stance phase, with these forces combining to increase the compressive force on the distal tibia to a magnitude that surpassed the peak compressive force at foot impact. Even though the tibial compressive force increased, the plantarflexor muscle force generated a shear force component that acted in an opposing direction to that of the shear force produced by the GRF (image # 3 – exaggerated bending to illustrate shear force effects), which effectively reduced the net shear force on, and bending of, the tibia. Therefore, although larger muscle forces could potentially cause larger tibial compressive forces, they may reduce the net shear force. The authors reported that tibial mid-shaft muscle cross-sectional area was lower in runners with a history of stress fractures compared to those without, which implies that stress fractures of the posterior tibia may be due to repetitive shear forces.



3. Source: Davis (2012)

Similarly, repetitive bending forces can cause stress fractures in the metatarsals of the feet (Ferris et al, 1995). Jacob (2001) reported that the force on the 1st and 2nd metatarsal heads was recorded to be 119% and 45% of body weight, respectively, during normal gait, resulting in high bending moments around the metatarsal shafts (image #4).



4. Source: Jacob (2001)

Muscle Strength

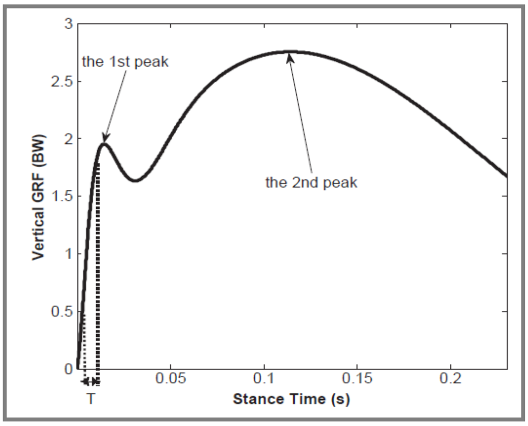
Though rarely considered, muscle strength plays an important role in the prevention of stress fractures (Michaud, 2012). For example, Burne et al (2004) reported that a 10-mm (0.4 inch) reduction in calf circumference resulted in a fourfold increase in the incidence of tibial stress fractures in males and females. This finding is consistent with research that demonstrates that lower extremity muscles such as tibialis anterior and triceps surae can prevent tibial fractures by pre-tensing prior to heel strike to dampen bony oscillations (Wakeling and Nigg, 2001; Wakeling et al, 2003). In addition to dampening bony oscillations following heel strike, certain muscles play a key role in creating compressive forces that allow various bones to resist bending strains present during the gait cycle. For example, if the contraction of the triceps surae muscle group is strong enough, it can oppose the bending forces on the tibia during running (Popp et al, 2009) (image #3), while sufficient contraction of the toe flexor muscles can create a strong enough compressive force along the plantar metatarsal shafts to significantly reduce bending forces (Ferris et al, 1995).

Muscle Fatigue

If the muscles of the lower leg and foot become fatigued, they can lose their ability to absorb shock and resist bending forces, resulting in an increased risk for stress fractures. For example, Milgrom et al (2007) reported that fatigue of the gastrocnemius and soleus muscles of 4 subjects, following a 2 km run, resulted in significant increases in tibial tension strain and strain rates, and compression strain rates, as recorded by strain gauges that were inserted in the medial aspect of their mid-tibial diaphyses. Mizrahi et al (2000) reported that fatigue of the anterior tibialis muscle of 14 male recreational runners, following a maximally exhaustive anaerobic treadmill run, resulted in an increase in tibial impact acceleration. The authors suggested that an imbalance in muscle activity between the triceps surae and anterior tibialis may result in the development of excessive tibial bending stresses and higher risk of stress fracture. Weist et al (2004) reported that fatigue of the gastrocnemius and soleus muscles of 30 experienced runners, following a maximally exhaustive anaerobic treadmill run, resulted in significant increases in maximal force, peak pressure, and impulse under the second and third metatarsal heads, and under the medial midfoot, which would increase the risk of stress fractures in the second and third metatarsals, and the navicular, respectively. The increased forefoot and medial midfoot loading patterns observed after the fatiguing run are consistent with increased pronation of the foot, which could be related to the decreased ability of the triceps surae and tibialis posterior (EMG of tibialis posterior not recorded in this study due to the need for indwelling electrodes) to eccentrically decelerate the foot during pronation. Based on the results of these studies, it is clear that muscular endurance is an important factor in reducing the risk of stress fractures.

Type of Foot Strike

In a systematic review of the literature that was conducted on the relationship between the history of tibial stress fractures and the magnitude of the ground reaction force (GRF) and loading rate during running, Zadpoor and Nikooyan (2011) found that the magnitude of the ground reaction force was not related to risk for tibial stress fractures, but the vertical loading rate was (vertical loading rate is defined as the slope of the initial part of the vertical GRF-time curve (between foot strike and the vertical impact peak) during the time period within which the force-time curve is most linear (i.e. time period 'T' in image #5)) (Note: image #5 displays a force-time curve for a heel-striking shod runner). In mechanical fatigue testing of bone samples, it has been found that the fatigue strength of bone is significantly less when the load is applied at a higher strain rate (Schaffler et al, 1989); these results are consistent



5. Source: Bennell et al (2004)

with the finding that the vertical loading rate during running is related to increased risk for stress fracture.

The vertical impact peak force seen in image #5 is typically present in heel-striking runners, though its magnitude tends to be smaller and the vertical impact loading rate tends to be reduced in runners wearing shoes with a cushioned insole compared to barefoot heel-strikers (Dickinson et al, 1985; De Wit et al, 2000; Lieberman et al, 2010). O'Leary et al (2008) reported that vertical ground reaction force peak impact and loading rate, as well as peak tibial acceleration, decreased significantly with the use of cushioned insoles compared to standard running shoes without cushioned insoles. Magness et al (2011) reported that runners who over-stride typically have an increased heel-strike impact and loading rate.

In contrast to heel-strikers, the vertical impact peak is often absent in forefoot-striking runners (and sometimes in mid-foot strikers) regardless of footwear condition, and loading rates are comparable to or sometimes even lower than those observed in heel-striking runners wearing cushioned shoes (Cavanagh and Lafortune, 1980; Nilsson and Thorstensson, 1989; Lieberman et al, 2010). Lieberman et al (2010) reported that, in the majority of barefoot runners, rates of loading were approximately half those of shod heel-strike runners. The hypothesized reason for these differences is that, instead of absorbing impact through a collision between the heel of the foot and the ground, barefoot runners typically strike the ground with their forefoot, and therefore absorb the impact through alternate mechanisms such as: 1) deformation of the medial longitudinal arch of the foot, 2) eccentric contraction of the triceps surae, and 3) stretch of the Achilles tendon (Laughton et al, 2003).

A forefoot strike is therefore advantageous for minimizing stress on the tibia; however, when transitioning from shod to minimalist or barefoot running, it is recommended that toe flexor muscle strength and endurance be enhanced to minimize shock and reduce bending forces on the metatarsals, to reduce the risk of metatarsal stress fractures.

PREVENTION OF STRESS FRACTURES

1. High-intensity resistance training (low repetitions, heavy weight) to increase bone mineral density – include exercises such as squats, leg presses, calf raises;
2. Females should supplement a well-balanced diet with vitamin D (Sonneville et al, 2012);
3. Heel-strikers should wear cushioned or shock-absorbing insoles;
4. Over-striding heel-strikers can reduce stride length with a higher stride frequency to minimize stress on the tibia (Magness et al, 2011);
5. Limit weekly increases in training volume to no more than 10% per week (Magness et al, 2011);
6. Every 4th week, reduce training volume to allow for recovery (Magness et al, 2011);
7. Avoid running more than 20 miles (32 km) per week (Magness et al, 2011);
8. Employ a forefoot or mid-foot foot strike; if transitioning from shod to minimalist or barefoot running, it is recommended that toe flexor muscle strength and endurance be enhanced;
9. Increase muscle strength and endurance of the following muscles:
    a. Toe flexors – eccentric strengthening to optimize shock absorption upon ground contact, which can help to minimize skeletal impact forces upward along the kinetic chain, and to reduce bending forces on the metatarsals;
    b. Triceps surae (calf muscles) and anterior tibialis – eccentric and balanced strengthening to minimize stress on the tibia;
    c. Tibialis posterior (sub-talar inverter) – eccentric strengthening.

Risk Factors for Acute Fractures

- Osteoporosis (low bone density), which can be caused by any of the following modifiable factors:
  - » smoking (Drake et al, 2012);
  - » excessive alcohol use (Drake et al, 2012);
  - » chronic corticosteroid use (Drake et al, 2012);
  - » reduced muscle strength (Russo, 2009);
  - » calcium and vitamin D deficiencies (Cashman, 2007).
- Lack of protective equipment

Prevention of Acute Fractures

1. Avoid smoking, excessive alcohol and corticosteroid use;
2. High-intensity resistance training (low repetitions, heavy weight) to increase bone mineral density – include exercises such as squats, leg presses, calf raises;
3. Increase strength in all muscles of the lower legs and feet;
4. Ensure adequate amounts of calcium (minimum 1000 mg daily) and vitamin D (minimum 600 IU daily);
5. Wear appropriate sport or activity-related protective equipment.

How AFX Helps to Prevent and Treat Stress Fractures and Acute Fractures

- Engages the toe flexors through a full range of motion (image #6), and allows for eccentric strengthening (image #7);
- Allows for strengthening of the Triceps surae (calf muscles) (images #6 to 7) and anterior tibialis (images #8 to 9), including eccentric strengthening to minimize stress on the tibia;
- Enables full range of motion strengthening in a non-weight bearing position (images #6 to 11);
- Full range of motion stretching and mobility exercises in a non-weight bearing position (images #12 to 15);
- All exercises can be performed from one comfortable seated position, so you are not required to continually reposition the athlete or re-tie elastic bands;
- AFX's foot support doesn't slide or slip-off, thereby ensuring that the resistance stays in consistent alignment, and reduces frustration for both the patient & practitioner.

Eccentric loading of toe flexors and plantar flexors

6. Plantar flexion and toe flexion

7. Increase resistance by pulling back on handles and resist movement with foot

Eccentric loading of anterior tibialis

8. Dorsiflexion – start

9. Eccentric dorsiflexion – increase resistance by pulling back on knee as foot is lowered to start position

Inversion and Eversion

10. Inversion

11. Eversion

Stretching

12. Dorsiflexor stretch

13. Evertor stretch

Mobility exercises

14. Foot circles

15. Alphabet

~ Rick Hall, M.Sc.

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