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Review Article

Review of Medial Tibial Stress Syndrome: A Comparison of *In Vivo* and Computational Methods

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Abstract

Medial Tibial Stress Syndrome (MTSS) also referred to as Shin Splints (SS), is the most frequent overuse injury in the lower leg in endurance running athletes and soldiers. MTSS could be defined as pain as evidenced by palpation along the posteromedial border of the tibia. While MTSS may not be considered a serious injury, microfractures that occur in the medial tibia as a result of MTSS, can lead to stress fractures over time. Until recently, effective strategies for the prevention of MTSS have been lacking. In order to prevent MTSS, knowledge of the biomechanical risk factors associated with the onset of MTSS is crucial. This article reviews the background of MTSS and assesses the current literature with regard to the biomechanics of MTSS.

Keywords: Shin splints; Stress fracture; Exercise; Risk factors; Biomechanics; Military; MTSS

Introduction

Medial Tibial Stress Syndrome (MTSS) is one of the most common injuries experienced by running and jumping athletes. As a condition it is often labeled as "Shin Splints" (SS) a term that dates back over 40 years, and describes leg pain which occurred in athletes with MTSS [1]. MTSS however, specifically refers to pain on the posteromedial tibial border occurring during exercise. The terms are not interchangeable as "Shin Splints" can refer to a general sensation of pain proximal to the shin. Exams have reported pain on palpation of the tibia over a length of at least 5 cm. Many studies have attempted to clarify the origins of this condition. While there is disagreement about ongoing studies, researchers do agree that MTSS is caused by bony resorption outpacing bone formation in the tibial cortex as evident in several studies describing MTSS findings on bone scan, magnetic resonance imaging (MRI), high-resolution computed tomography (CT) scan and dual energy x-ray absorptiometry [2]. The time lag between scientific understanding and practical application appears to be pronounced in the area of tibial stress injuries. While this may reflect the non–life-threatening nature of the injury, the belated dissemination of more progressive management techniques implies that rest from weight-bearing activity is an acceptable treatment. However, not only can tibial stress injuries be highly disruptive to a regular fitness regimen, these injuries end careers of competitive athletes and military personnel. Furthermore, in a world that is becoming increasingly focused on 'sport as business', in which readiness to participate is an economic consideration. Prolonged periods of recovery from injury have additional negative repercussions for athletes [3]. This paper will review the significance, physiology, current issues with diagnosis, and biomechanical research methods of MTSS and SS.

Significance

The incidence of MTSS is reported between 4% and 35% in military personnel and athletes [2]. Medial tibial stress syndrome accounts for about 10% to 15% of all running injuries. It has also been found that up to 60% of all conditions that cause leg pain in athletes have been attributed to SS. SS, referring to pain and discomfort in the leg from repetitive running on hard surfaces or forcible excessive use of foot flexors, accounts for 6% to 16% of all running injuries and is responsible for as much as 50% of all lower leg injuries reported in select populations [4]. Recent studies report up to a 35% incidence of MTSS in actively training military recruits and 13% in civilian runners [5]. MTSS accounts for 17.3% of all injuries in runners and accounts for 22% of all injuries in aerobic dancers [6]. In spite of such significant numbers, little data is available on the economic impact of these conditions.

Anatomy and physiology

The term "shin splints" is an encompassing term for general shin pain, whereas this paper is focused on the medial section of the tibia. MTSS is a common diagnosis given when someone is suffering from pain in the front of their legs or more specifically the medial portion of the tibia and is often associated with running. Alternative terms to SS have been proposed over the years. Mubarak et al. popularized the term *medial tibial stress syndrome*, a condition that leads to pain in the posteromedial aspect of the distal two thirds of the tibia [7]. Figure 1 shows a CT scan of a runner experiencing MTSS. Figure 2 (a-c) is a CT scan of a runner with a chronic case of MTSS.

A sudden increase in running mileage, and/or the beginning of a new running activity may also cause SS, which worsen when running downhill. The pain associated with MTSS, as opposed to posterior tibial stress syndrome or lateral tibial stress syndrome, is a deeper, achy pain, which can lead to a slapping foot while running. Once an athlete stops running, the pain may remain for 15 minutes. If pain continues, it may be associated with Exertional Compartment syndrome, which is described as feeling pressure pushing towards the lateral side of the lower leg [9]. The cause of the pain in this scenario, is an increase in pressure in the anterior compartment of the leg. The affected compartment is between the tibia and fibula (the two bones in the lower leg) and a thick layer of fascia around the posterior tibialis

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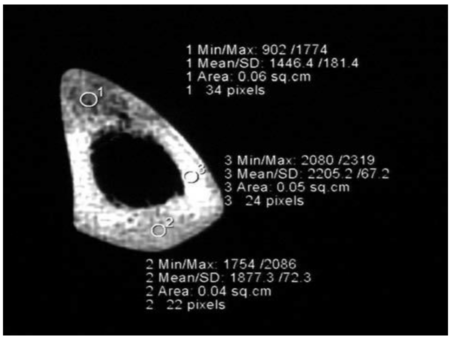

Figure 1: Example of a 20-year-old male runner with medial tibial stress syndrome. CT measurements demonstrate normal medial cortex and osteopoenic anterior and posterior cortices [8].

muscle. Within this compartment lies the tibialis anterior muscle as well as the muscles that extend your toes. When running, these muscles help to lift (dorsiflex) one's foot and toes allowing for ground clearance during the swing phase. These muscles also lower one's foot and toes to the ground after heel strike at the beginning of the stance phase of running. Muscle contraction increases the need for blood in the area. This increased blood supply to the muscle in turn increases the size of the muscle. This process is normal and usually goes unnoticed, however if the size or volume of the muscle increases too much, especially when the muscle is held tight like in the anterior compartment, it results in an increase in pressure causing pain. The pressure in the anterior compartment can get high enough that it affects the muscles ability to function often causing foot slapping while running. During this condition, the aforementioned muscles can no longer control the lowering of the foot to the ground after heel contact, so the foot slaps uncontrollably. If the pressure continues to increase, it can even disable the sensory nerve contribution to the skin between the first two toes [9].

Mechanism of injury

Once the soleus muscle gets tight and/or overworked from sudden increases in running mileage or when starting a new activity, the muscle begins to tug at the attachment along the medial border of the tibia. This tugging causes the pain on the inside of the shin. The body responds by creating scar tissue along the attachment for reinforcement. This reaction only causes the muscle to become tighter and places even more stress along the attachment at the shin. This vicious cycle of pain and tightening will continue until one seeks treatment, stops the activity, or modifies the activity to provide time for proper healing [10]. The pain is sharp and decreases significantly once running stops, and after 15 minutes is almost gone. Shins are tender or painful to the touch along the middle third of the inside of the tibia [11]. If the pressure continues to increase, it can even disable the sensory nerve contribution to the skin between the first two toes [9]. MTSS usually begins with the onset of a new running activity and/or a sudden or rapid increase in mileage. An increase in body weight and running on hard surfaces has also been known to lead to this type of shin pain. The pain is caused by the soleus muscle that attaches to the tibia along its inside border [11]. Hubbard et al. concluded that the cause of MTSS is not attributed to a single internal or external factor [12]. For example, as much as 70% of runners overpronate, however between 40 and 50% of excessive pronators do not have

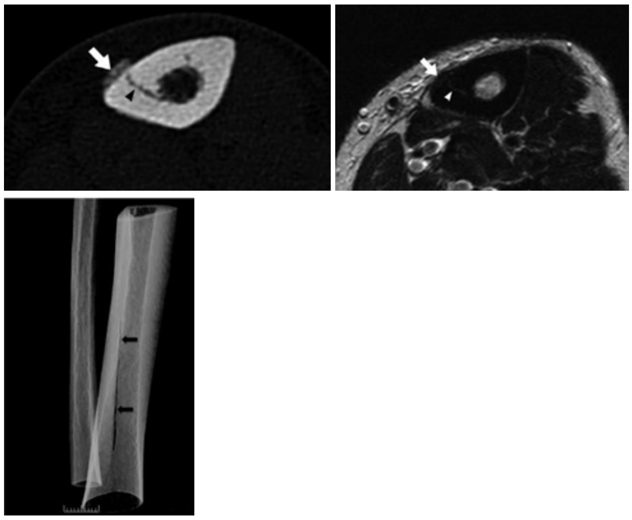

Figure 2: Thirty four-year-old male runner with medial tibial stress syndrome lasting six months and 1-month onset of intractable pain [8].

overuse injuries, such as MTSS [13,14]. Literature has also noted that "experts do not agree upon the cause of MTSS", making it difficult to prevent [15,17-22,73]. In spite of the complexities associated with the onset of MTSS researchers and physicians have agreed upon a general set of possible causative factors including but not limited to: A: Tibialis Posterior Separation from the Bone – Pain is caused by traction of the tibialis posterior muscle origin on the interosseus membrane and tibia [23,24]. This is one of the original theories regarding causes for MTSS, however, researchers have been skeptical of the tibialis posterior's involvement as the location of the muscle origin is quite a distance away from the location of pain [25].

B: Periostitis – This refers to inflammation of the layer of connective tissue that surrounds the tibial bone (the periosteum). Recently research has shown increased bone stress or musculotendinous breakdown before MTSS [26]. Many believe the main cause of MTSS involves underlying periostitis of the tibia due to tibial strain when under a load. However, new evidence indicates that a spectrum of tibial stress injuries is likely involved in MTSS, including tendinopathy, periostitis, periosteal remodeling, and stress reaction of the tibia. Dysfunction of the tibialis posterior, tibialis anterior, and soleus muscles are also commonly implicated. These various tibial stress injuries appear to be caused by alterations in tibial loading, as chronic, repetitive loads cause abnormal strain and bending of the tibia. Although sometimes composed of different etiologies, MTSS and tibial stress fractures may be considered on a continuum of bone–stress reactions [27].

C: Traction of the Deep Crural Fascia – A fairly recent theory on the causation associated with MTSS is traction, or pulling, of the deep crural fascia within the lower leg. Fascia is connective tissue involved with multiple structures within the body, and sometimes fuses with the bony structures [28]. Traction-induced injury, related to muscles of the superficial and deep posterior compartments, has been implicated as the cause of medial tibial stress syndrome (MTSS) with symptoms commonly occurring in the distal third of the posteromedial tibia. Research into the anatomical arrangement of these structures has been inconclusive. The deep crural fascia (DCF) has been implicated as a cause of traction-induced injury in MTSS but not fully researched [17].

Diagnosis

MTSS is diagnosed primarily based on physical examination with CT and MRI [9]. MTSS is often associated with the muscles surrounding the tibia, but there is also a risk of stress microfractures developing in the tibia. The association of MTSS with microfractures is under investigation but has not been confirmed due to the lack of radiologic findings. MRI can reveal stress microfractures in the bone [9]. When attempting to diagnose a tibia stress fracture through MRI and CT, the lack of a fracture leads to the assumption of MTSS. It offers the most accurate description of the involved anatomy and presumed pathophysiology of this most common form of tibial stress injury. The hallmark of the physical examination in MTSS is palpable tenderness over a 4 to 6 cm area at the posteromedial margin of the middle to distal third of the tibia. Passive stretch of the soleus, heel rises, and unilateral hopping may reproduce pain [7].

Treatment options

Non-surgical: In clinical practice, graded running, as well as strengthening and stretching exercises for the calf muscles are frequently prescribed for MTSS [30,31]. Waldorff et al. concluded that graded running in itself could strengthen the tibial cortex by increasing the remodeling of the tibia and increased resorption of micro-damage [32-34]. While very few studies have been published on the effect of stretching for MTSS, research has shown that stretching may help in the recovery stage; there is no fast cure to medial tibial stress syndrome. A doctor or physical therapist will often recommend a stretching regimen, icing of the affected area, and wrapping the lower leg with an Ace bandage to reduce inflammation [35-38].

In-shoe foot orthotic devices are designed to support foot structures and limit abnormal and potentially harmful motions that may lead to lower extremity pain and dysfunction. Orthotic inserts or arch taping are thought to correct pes planus and limit pronation, thereby reducing the incidence of, preventing exacerbation of, and sometimes assisting in the recovery from tibial overuse injuries. Pes planus has been associated with an increased incidence of shin injury and tibial stress fracture. Similar to hyperpronation, the effect is likely to be one resulting from excessive medial tibial torsion following exaggerated internal rotation during the stance phase of a stride [3]. This is important because excessive bone strain and strain rates are associated with microdamage and stress fracture of bone. Hence, orthotics may be an effective prevention and treatment strategy for strain injuries [39]. Sports compression stockings are used frequently in the Netherlands to treat MTSS [40]. A sports compression stocking provides direct compression of the tibia and via the surrounding soft tissues, especially during intermittent loading. Compression of bony tissue has been shown to promote the expression of bone remodeling genes, accelerating the healing process [41].

Treatment options: Excessive pronation of the foot while standing and female sex were found to be intrinsic risk factors in multiple prospective studies [42]. Other intrinsic risk factors found in single prospective studies are higher body mass index, greater internal and external ranges of hip motion, and calf girth. A previous history of MTSS is considered to be an extrinsic risk factor [29].

It is well understood that individuals with MTSS also show a reduced bone density in the tibia, which returns to normal with recovery [31]. Also it has been noted that both the soleus and tibialis anterior muscles have reduced activity in the lower leg, prior to injury, suggesting that strength of these muscles are likely affected when running [44]. An in depth investigation of the following biomechanical factors: pronation, range of motion, and foot strike, follows.

Pronation: The diagnosis of MTSS has been associated with a greater degree of foot pronation [45]. Foot pronation is a complex triplanar movement. Visually, it is characterized by a flattening of the Medial Longitudinal Arch (MLA) and an abduction of the calcaneus. Bouche et al. hypothesized that large foot pronation induces tension on the tibial fascia at its insertion into the medial tibial crest and this could be one of the causes of MTSS [46].

Excessive navicular drop has been reported to predispose individuals to shin and MTSS [11,47-49]. Navicular Drop Test (NDT) is a test which quantifies the amount of foot pronation in runners [50]. It is intended to represent the sagittal plane displacement of the navicular tuberosity from a neutral position to a relaxed position in standing [51]. A navicular drop greater than 10 mm has a high risk of leading to MTSS [47,52].

Range of motion: Clinical measurement of range of motion is a fundamental evaluation procedure with ubiquitous application in physical therapy. Objective measurements of ROM and correct interpretation of the measurement results can have a substantial impact on the development of the scientific basis of therapeutic interventions [53]. Moen et al. (2012*)* reported after multivariate regression analysis, increased ankle plantar flexion, decreased internal hip range of motion and a positive navicular drop test were significantly associated with MTSS and defined as risk factors [11]. A higher BMI was shown to be a prognostic indicator for a longer time to full recovery. All other prognostic indicators such as a previous duration of symptoms, functional activity score, the symptom-free running distance at baseline, increased ankle plantar flexion, decreased internal range of hip motion and positive navicular drop test were not associated with time to recovery. A decreased range of hip internal rotation was found to be associated with MTSS in this study. The mechanism through which hip ranges of motion affect loading of the tibia is unclear. "Burne et al. speculated that increased internal hip range of motion caused a specific pattern of running, which could lead to increased loading of the posteromedial tibia [11]." Possibly, both increased and decreased internal hip range of motion influence running in such a way that the posteromedial tibia is loaded excessively [11].

Foot strike: Because a runner's kinematics affects how external and internal forces are generated and withstood by the body, one should consider how differences in general running form may influence overall injury rates. Although running form has many components the impact of foot strike pattern is of special interest, on injury rates has not been previously studied is of special interest. Foot strikes vary, and there is no consensus on how to define and measure these patterns. For this review, three categories of strike types that are prevalent among distance runners are defined: rearfoot strikes (RFS), in which the heel contacts the ground first (heel–toe running);

forefoot strikes (FFS), in which the ball of the foot contacts the ground before the heel (toe–heel–toe running); and midfoot strikes (MFS), in which the heel and ball of the foot contact the ground simultaneously [54].

There are three major reasons to consider the biomechanics of foot strike pattern as it relates to MTSS/SS. First, how the foot strikes the ground involves disparate kinematics of the lower extremity. During a rearfoot strike, a runner usually lands with the foot in front of the knee and hip, with a relatively extended knee, and with a dorsiflexed, slightly inverted and abducted ankle; the runner then plantarflexes rapidly as the ankle everts just after impact. In contrast, a forefoot striking runner lands with a more flexed knee and plantarflexed ankle, usually making ground contact below the fourth or fifth metatarsal heads; the runner then simultaneously everts and dorsiflexes the foot during the brief period of impact, usually with more ankle and knee compliance. MFS landings are highly variable, but generally intermediate in terms of kinematics [54]. Second, different strike patterns generate contrasting kinetics, especially at impact. Midfoot striking can cause a broad range of impact peaks, from high to low, depending on ankle and knee compliance. Strike pattern also affects lower extremity joint moments, with forefoot strike landings causing higher net moments around the ankle in the sagittal plane and lower net moments around the knee and hip in both the sagittal and transverse planes. A final reason to study the relationship between foot strike pattern and injury rates is the growing popularity of running either barefoot or in minimal shoes that lack an elevated heel, contain no arch support, and have a thin, flexible sole [54]. All humans ran either barefoot or in minimal shoes before the invention of the modern running shoe in the 1970s [55]. Habitual shod runners, when asked to run barefoot, instinctively land more toward the ball of the foot [56]. These and other sources of information, such as old coaching manuals, lead to the hypothesis that forefoot strike running may have been more common for most of human evolution. This hypothesis is relevant to the issue of running injury because if the foot evolved via natural selection to cope primarily with movements and forces generated during mostly forefoot rather than rearfoot strikes, then it follows that the body may be better adapted to forefoot strike running [57].

Faulty biomechanics can be very detrimental to the running athlete and result in pain. Biomechanics in the lower extremity hinge on the principle of the kinematic chain. The kinematic chain principle models extremities as composed of successively linked joint segments, which transfer forces and motions to the neighboring joints in a predictable pattern. In theory, when dysfunction occurs at a specific joint, the dysfunction will transfer to the following joint in sequence. When decreased motion occurs at the ankle during weight-bearing activity, both the knee and hip will feel the effects of the dysfunction and attempt to balance out the lost motion by increasing their ranges of motion. Attempts to compensate for the faulty mechanics of the ankle will cause the knee and hip to function in a new pattern. This transfer of faulty forces and movement can lead to injuries. This principle holds true for any joint in the chain during weight-bearing; therefore pelvic and hip range of motion are possible contributors to injury in the lower extremity [58].

Current Methods in Determining Risk Factors

In Vivo methods

In vivo methods to determine risk factors are popular due to readily available and reliable kinematic data. An often cited weakness is the neglect of strain placed on the medial tibia which cannot be observed through traditional means. In epidemiology and in this review, a risk factor is a variable associated with the increased risk of developing an injury or illness. Therefore the risk factors discussed, are believed to increase the risk of developing MTSS.

Moen et al. (2012) conducted a randomized multi-center study with three groups. The study population was comprised of athletes with a history of overuse injury. Each participant was randomly assigned to receive a specific intervention. Clinically trained sports physicians examined the athlete for complaints of MTSS during exercise and for suitability for inclusion. Moen used the exclusion criteria described by Edwards et al. in their recent review were used to identify stress fractures of the tibia and chronic exertional compartment syndrome (CECS). The athletes had to be involved in sport at least once a week. No significant differences between the intervention groups were found. Therefore, if MTSS is treated with a running program, no large additional effect of the two interventions can be expected. It should however, be noted that a graded running program has not been compared with a control group that rested in any study. It can only be assumed that graded running programs improve the density and strength of the tibia, and that rest does not have this effect [43]. Studies like the work of Moen et al. require a large number of subjects, researchers, and physicians. The time necessary to perform such project is much greater than for a project incorporating in silico methods. Challenges include coordinating tests around the athletes' and physicians' schedules, participant attrition due to pain, which has an increasingly high probability as the duration of the study increases. As participants drop from a study like this, the opportunity to determine damage location in the tibia, cause of this damage, and whether it is damage muscle or bone tissue, is lost.

King J. (2013) analyzed data collected from The Runners and Injury Longitudinal Study (TRAILS), a large observational trial that examined the biomechanical, behavioral, physiologic, psychological, and clinical risk factors for runners who sustain an anterior knee pain overuse running injury. A secondary purpose was to determine the shared risk factors among runners who sustained any of the common overuse running injuries: anterior knee pain, iliotibial band friction syndrome, medial tibial stress syndrome, Achilles tendinitis, or plantar fasciitis. For this study, baseline kinematic, kinetic, anthropometric, and strength data, and data on injury status were used to compare selected biomechanical, physiological, and behavioral variables of runners. These runners were selected based on current injury, lack of injury, or had had a history of overuse injury [59]. 184 distance runners between the ages of 18 and 60 years old were recruited to TRAILS during a 6-month period. Male and female runners were enrolled who have been running injury free for the past 6 months. For this analysis, 159 TRAILS participants, whose gait, strength, and anthropometric data were available, were split into a "Never Injured" (N=49), "Occasionally Injured" (N=36), and "Frequently Injured" group (N=74). The Never Injured group had not experienced an overuse running injury prior to the study and had remained injury free over the course of the study. The Occasionally Injured group had either 1) been injured prior to the study but not during the study, or 2) had been injured during the study, but not prior to the study. The Frequently Injured group had been injured prior to the study and during the study. Motion and force data were analyzed to determine lower extremity and motion parameters, and used as input into a musculoskeletal model to calculate knee joint forces [59].

The authors examined rearfoot biomechanics and knee-joint loads. Subjects ran in their normal training shoes at their average training speed on a 22.5 m runway while motion and force data was captured. Outcome variables included rearfoot motion parameters, tibial medial/lateral rotation, knee flexion/extension, timing between lower extremity segments, and vertical and anteroposterior ground-reaction forces [59]. This method collects a large amount of kinematic data to recreate a musculoskeletal model. The study was statistically justified out of the 184 research subjects, 25 were dropped from the study, roughly 14% of the subjects.

Computational methods

Olesen et al. [60] built a musculoskeletal model of the lower extremity the Any Body Modeling System [60]. The model was based on cadaver data and included 38 muscles that were divided into 316 muscle fascicles, based on the line-of-action. A Hill-type muscle model with passive elasticity and force-length-velocity relationships was used. The model was driven through a gait cycle with kinematic and kinetic data from a gait experiment on a healthy male. The right foot was artificially rotated about an axis going from the calcaneus and through the 2^{nd} metatarsal bone to simulate different degrees of pronation. The rotation went from 20° pronation to -5° supination, mimicking foot postures from highly pronated to slightly supinated. The simulations were run with increments of 5°. For each foot posture the muscle recruitment problem was solved and the passive force of the muscles in the deep flexor compartment was estimated. These results correspond well with the tibial traction theory, which suggests MTSS is caused by excessive traction to the tibial fascia at its insertion 2-8 cm above the medial malleolus. The results showed excessive foot pronation caused increased forces to be transmitted to passive elastic fibers of the deep flexor compartment (tibialis posterior, flexor digitorum longus and flexor halluces longus) [60].

Al Nazer et al. [61] constructed a generic lower body musculoskeletal model using BRG. LifeMODE 2007.0.0 in order to study the stresses and strains which develop MTSS [61]. A computer model was built on the kinematics of a single subject, a healthy Caucasion man (25 years, height 184cm, mass 89kg) to study the tibial strains when walking. The subject was asked to perform a walking test on a level surface at constant speed. In order to track the human body motion, visual markers were placed on various locations of the subject. A motion capture system tracked segment trajectories during the walking performance. The trajectories were then used to drive the model in the inverse dynamics simulation where the desired muscles shortening/lengthening patterns were calculated [61]. The skeletal lower body model was generated from an anthropometric database. The multibody simulation approach with the floating frame of reference formulation was used to estimate tibial deformations during walking. In the floating frame of reference approach, large reference motions were described using a reference frame and the deformations of the tibia are described relative to the reference frame. This approach allows coupling of deformations and large reference motions in the inertia description of the tibia. The deformations of the tibia were described using the finite element approach. Due to the complex geometry of the tibia, the finite element model consisted of a large number of nodal degrees of freedom, which makes it computationally expensive to define the deformations in the time domain analyses. This computational problem was alleviated using the component mode synthesis. In the component mode synthesis, the deformations of the tibia were assumed to be linear with respect to the reference frame. The assumption made it possible to use modal coordinates instead of nodal coordinates in the description of tibial deformations. In this study, the modes denote vibration modes of the tibia obtained from an eigenvalue analysis of the tibial finite element model. The use of modal coordinates allowed a number of variables that describe the deformation to be reduced. This, in turn, reduced the computational effort drastically without a significant loss of accuracy. The vibration modes were calculated by employing the Craig–Bampton method with the orthonormalization procedure. In the Craig–Bampton method, the vector of nodal coordinates of the finite element model was divided into boundary and interior nodal coordinates. The Craig–Bampton method results in two sets of modes, which are non-orthogonal constraint modes and orthogonal fixed interface normal modes. The constraint modes describe deformation due to unit displacements of boundary nodal coordinates, while the fixed interface normal modes describe vibration modes when fixed boundary conditions are applied at all the boundary nodal coordinates. The orthonormalization procedure was applied to the Craig–Bampton modes in order to enforce the deformation modes as orthogonal. In the finite element model of the tibia, nodes at the knee and ankle joints were selected as boundary nodal coordinates. The boundary nodes were connected via massless rigid beams to the nodes at the surface of the tibial metaphyses. The flexible tibia was used in forward dynamic analysis to calculate deformation due to dynamic loading. The strains during the walking exercises were obtained using the modal strain matrix that defines the relationship between the modal coordinates and strains of finite elements. The finite element model of the tibia was described in the ANSYS 8.1 software using shell elements. The thickness of each element was assumed to be equal to the average cortical wall thickness of the subject's tibial mid-shaft, which was 6.3mm as obtained from a peripheral quantitative computer tomographic (CT) scan. Young's modulus and the shear elastic modulus of the cortex bone were assumed to be 17 and 10 GPa, respectively, in the longitudinal direction along the bone, while they were assumed to be transversely isotropic with values of 5 and 3.5 GPa, respectively. The total number of nodal degrees of freedom of the tibial finite element model was 61,872. The software ANSYS 8.1 was used to calculate the number of Craig–Bampton modes needed in the floating frame of reference formulation [61].

The methods used by Olesen et al [60] and Nazer et al. [61] are similar in the regard to in silico experimentation. Both methods incorporate a single person's kinematic data with a 3-D model based on the research subject in order to perform the experimentation and analysis. However, Nazer et al. [61] is a much more inclusive study, using multiple computational biomechanics programs. This method of determining stresses and strains in the musculoskeletal frame is what is needed to drive future biomechanics research.

Future direction

The future direction of biomechanical research should include *in vivo* and *in silico* experimentation and data collection methods. The integration of methods will lead to an increase in information as to how risk factors interact and which risk factors play key roles in the development in medial tibial stress syndrome. *In vivo* experimentation requires more time, subjects, and funds when compared to *in silico* experimentation; however, *in silico* experimentation will lack accuracy and require more assumptions to create the biomechanical models and simulations. Kinematic data and imaging can be obtained and used to create 3-dimensional dynamic simulations, which then can be used to determine forces experienced by the tibia and surrounding muscles through finite element analysis.

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