

# Consequences of Ankle Inversion Trauma: A Novel Recognition and Treatment Paradigm

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## 1. Introduction

Diseases associated with physical inactivity (i.e. hypokinetic diseases) include, but are not limited to: cardiopulmonary disease, hypertension, obesity, metabolic disorders, non-smoking related cancers, and osteoporosis.(Admirall et al., 2011; CDC, 2009; Liu et al., 2008; Sesso, Paffenbarger, & Lee, 2000; Steanovv, Vekova, Kurktschiev, & Temelkova-Kurktschiev, 2011; Weiderpass, 2010) Physical inactivity remains one of the most important public health concerns as objective measures demonstrate that less than 5% of Americans participate in the recommended amount of physical activity necessary for health benefits.(Troiano et al., 2008) Additionally, physical inactivity is currently identified as the second leading actual cause of death, implicated in more deaths than the next seven causes of death combined.(Mokdad, Marks, Stroup, & Gerberding, 2004) Further, injury associated with sport, exercise, and recreation is a leading cause for the cessation of regular physical activity.(Koplan, Powell, Sikes, & Campbell, 1982; Pate, Pratt, Blair, & al., 1995) With lateral ankle sprains (LAS) being the most commonly occurring orthopedic pathology (Fernandez, Yard, & Comstock.R.D., 2007; Hootman, Dick, & Agel, 2007), and with such a high percentage of disability occurring after the initial injury(McKay, 2001; Verhagen, de Keizer, & Van Dijk, 1995) its role in potentially limiting physical activity is significant.(Verhagen et al., 1995) Despite the obvious public health problem that ankle sprains represent, no significant inroads have been made at preventing the injury and/or treating the associated sequelae using traditional treatment paradigms. Thus the evidence regarding the presentation and treatment of the consequences associated with LAS will be described within the context of a new recognition and treatment paradigm known as the PCL(McKeon PO, Medina McKeon JM, Mattacola CG, Lattermann C. Finding, 2011) (patient-, clinician-, laboratory-oriented) model which addresses the sequelae of lateral ankle sprains from a holistic perspective. Further, this model will be situated within the dynamic systems theory to provide the framework for understanding how all of the individual post-injury adaptations create a singular pathology that predisposed an individual to fall into a continuum of disability that will affect them for the remainder of their lives.

## 2. Ankle sprain epidemiology

### 2.1 Observation and description of the clinical phenomenon

Lateral ankle sprains are the most common injuries associated with physical activity and athletic participation. (Fernandez et al., 2007; Hootman et al., 2007) Forceful plantar flexion and inversion is the most common mechanism of injury causing damage to the passive lateral ligamentous structures of the ankle. (Baumhauer, Alosa, Renstrom, Trevino, & Beynnon, 1995) Specifically, the anterior talofibular ligament (ATFL), reported to be the weakest, is the first ligament injured. (Brostrom, 1964) Rupture to the ATFL is followed by damage to the calcaneofibular ligament (CFL) and finally to the posterior talofibular ligament (PTFL). (Brostrom, 1964) Isolated injury to the ATFL occurs in 66% of LAS while ATFL and CFL ruptures occur concurrently in another 20%. (Brostrom, 1964) The PTFL is not commonly injured because of the large amount of dorsiflexion needed to strain the ligament places the ankle in a closed packed and thus more stable position. The current literature suggests it takes over 6 weeks for ligament damage to heal, (Avci & Sayh, 1998; Brostrom, 1966; Cetti, Christensen, & Corfitzen, 1984; Freeman, 1965b; Konradsen, Holmer, & Sondergaard, 1991; Munk, Holm-Christensen, & Lind, 1995) however, studies have also documented joint laxity 6 months after injury. (Brostrom, 1966; Cetti et al., 1984) In addition to the lateral ligamentous structures of the talocrural joint, the subtalar ligaments can also be injured. However, injury to the subtalar joint often occurs in combination with injury to the lateral ankle ligaments as evidenced by the estimated 75 to 80% incidence of subtalar instability in those with CAI. (Hertel, Denegar, Monroe, & Stokes, 1999; Meyer, Garcia, Hoffmeyer, & Fritschy, 1986) Damage to the ligaments of the ankle can lead to the development of an unstable or hypermobile ankle joint which ultimately leads to an increase in the accessory motion available at a joint. Increased accessory motion places further strain on the injured ligaments and it is hypothesized that increased mobility of the talus, due to hypermobility, may lead to the axis of rotation becoming more anterior or posterior in the frontal plane.

With injury to ligaments, mechanoreceptors may also be damaged. If damaged, the afferent (i.e. sensory) input from ligamentous mechanoreceptors may be altered and further disrupt the axis of joint rotation causing the injured individual to compensate in an effort to maintain proper function. (Konradsen & Magnusson, 2000) However, there is a lack of consistent empirical data to confirm that alterations in function are due to the loss and/or disruption of afferent input from ligament mechanoreceptors. (Hubbard & Hertel, 2006a) Despite the inconsistency of the literature, evidence does exist to suggest that a loss of afferent information from the lateral ligaments can have both local and global consequences on sensorimotor function in both asymptomatic individuals (Myers, Riemann, Hwang, Fu, & Lephart, 2003; McKeon, Booi, Branam, Johnson, & Mattacola, 2010) and those with CAI.

In addition to ligamentous mechanoreceptors, musculotendinous mechanoreceptors may also become altered with ankle instability. (Freeman, 1965a) Increased mobility of the talus stresses the joint capsule (Wilkerson & Nitz, 1994) which then negatively affects (via the gamma motorneurons) the activation threshold of the muscle spindles in muscles and tendons that cross the ankle joint. Further, the gamma motor neurons may also increase co-contraction levels (Wilkerson et al., 1994) resulting in altered afferent signals being sent to the central nervous system. Evidence of these altered afferent signals are the early recruitment of proximal muscles such as the gluteals to help provide stability (i.e. the development of a hip strategy). (Beckman & Buchanan, 1995; Bullock-Saxton, Janda, &

Bullock, 1994) A vicious and continuous cycle is thus put into motion when proper healing and joint alignment are not restored due to inappropriate treatment.(Hubbard et al., 2006a) Unfortunately, inappropriate or totally absent treatment occurs far too often for lateral ankle sprains. Indeed, LAS are often erroneously considered to be an inconsequential injury with no lasting consequences. However, LAS account for approximately 60% of all injuries during interscholastic and intercollegiate sports in the United States.(Fernandez, Yard, & Comstock, 2007; Hootman et al., 2007) Further, more than 23,000 LAS are estimated to occur per day in the United States which equates to approximately one sprain per 10,000 people daily.(Kannus & Renstrom, 1991) In addition, health care costs for acute LAS have been estimated to be over \$4 billion dollars annually in the United States alone when accounting for inflation in 2011.(Soboroff, Pappius, & Komaroff, 1984) Another consequence of societal insignificance assigned to LAS is the high percentage of people (~55%) who sprain their ankle and do not seek treatment from a health care professional.(McKay, 2001) As a result, the true incidence of injury may be much greater than what has been previously reported.

Even more troubling is the fact that about 30% of those who suffer a first time LAS develop CAI; however this number has been reported as high as 75%.(Anandacoomarasamy & Barnsley, 2005; Peters, Trevino, & Renstrom, 1991; Smith & Reischl, 1986) This translates to at least 1 out of every 3 individuals who sprain their ankle will go on to suffer residual symptoms (i.e. CAI) indefinitely. Indeed, the residual symptoms that define CAI significantly alter an individual's health and function by causing them to become less active over their life span.(Verhagen et al., 1995) Further, a clear link has been established between CAI and post-traumatic ankle osteoarthritis (OA). Post-traumatic ankle OA is the most common cause, accounting for more than 70% of all ankle OA cases (Valderrabano, Hintermann, Horisberger, & Fung, 2006a) and both ankle joint fractures (Horisberger, Valderrabano, & Hintermann, 2009b) and ligament lesions associated with CAI (Hirose, Murakami, Minowa, Kura, & Yamashita, 2004; Valderrabano et al., 2006a) are a significant cause of post-traumatic ankle OA. Indeed, a high percentage (66-78%) of patients with CAI go on to develop post-traumatic ankle OA.(Hirose et al., 2004; Valderrabano et al., 2006a)

### **3. Pathophysiology: Perspectives of the patient, clinician, and laboratory scientist**

#### **3.1 Acute ankle sprains**

##### **3.1.1 Patient-oriented evidence**

Anyone who has ever suffered a lateral ankle sprains knows that it is a painful and disabling injury. The published literature also supports this belief across a wide range of self-report questionnaires/scales.(de Vries, Kingma, Blakevoort, & van Dijk, 2010; Evans, Hertel, & Sebastianelli, 2004) For example, Brostrom (Brostrom, 1966) reported 20% of patients reported their ankle feeling unstable a year after an initial ankle sprain. Further, a prospective investigation performed by Evans et al.(Evans et al., 2004) indicated that self-assessed disability (as measured by two independent scales) did not return to baseline (i.e. pre-injury) levels until twenty-one days post injury.

##### **3.1.2 Clinician-oriented evidence**

The hypermobility associated with acute LAS can be assessed qualitatively and empirically using various clinical techniques such as manual stress tests, instrumented arthrometry and stress radiographs. Manual stress tests are one of the most common means to assess laxity

after an ankle sprain. To date, evidence indicates that 30% of patients have had a positive anterior drawer 2-weeks post injury and 11% had a positive anterior drawer 6-weeks post injury.(Avci et al., 1998) Additionally, 12% have been shown to have a positive anterior drawer at 8-weeks post injury. (Cetti et al., 1984) Similarly, significantly more anterior displacement and inversion rotation was shown via an ankle arthrometer 8-weeks after an acute LAS.(Hubbard & Cordova, 2009a) Another study showed that 42% and 33% of subjects from separate treatment groups had an increased talar tilt compared to their uninjured healthy ankle at 3-months post injury using stress radiography. (Freeman, 1965b) At 1-year post injury, ~30% of patients had a positive anterior drawer. (Brostrom, 1966) Using a more objective outcome, 5% of patients presented with pathologic stress radiography values 3-months post injury.(Konradsen et al., 1991) Further, over 50% of patients who sprained their ankle between 9-13 years prior, had mechanical laxity on stress radiographs.(Munk et al., 1995)

In addition to hypermobility, LAS can also cause hypomobility. Hubbard and Hertel (Hubbard & Hertel, 2008), using simple lateral radiographs of the ankle, found that the distal fibula has been pulled anteriorly, relative to the tibia, from a 'normal' position seen in healthy uninjured adults (i.e. a positional fault had occurred). Similarly, a decreased posterior talar glide (Denegar, Hertel, & Fonseca, 2002) has been observed in those with acute LAS suggesting that a talar positional fault may also be present. Since normal osteokinematic motion cannot occur without proper arthrokinematics, these studies support the commonly observed limitations in ankle range of motion (ROM) following acute LAS.(Aiken, Pelland, Brison, Pickett, & Brouwer, 2008; Youdas, McLean, Krause, & Hollman, 2009) These studies have shown that: 1) active dorsiflexion ROM returns to 'normal' values between 4- and 6-weeks post injury (Youdas et al., 2009) and that clinical measures of ROM are not as sensitive as laboratory measures (e.g. isokinetic dynamometer).(Aiken et al., 2008)

### 3.1.3 Laboratory-oriented evidence

There have been numerous investigations that have quantified deficits in sensorimotor function in those with LAS using laboratory-oriented evidence. In short, grade II or III acute LAS have been reported to cause deficits in ankle inversion joint position sense for up to 12-weeks post injury when compared to the uninjured limb.(Konradsen, Olesen, & Hansen, 1998) In addition, isometric strength deficits have been reported, in multiple planes of motion, as long as 6-weeks post injury.(Holme et al., 1999; Koralewicz & Engh, 2000) The most commonly studied sensorimotor outcome is postural control. Recent systematic reviews demonstrated that postural control is impaired on the involved limb (McKeon & Hertel, 2008a; Wikstrom, Naik, Lodha, & Cauraugh, 2009) and uninjured limb following acute LAS.(Wikstrom, Naik, Lodha, & Cauraugh, 2010c) These findings are supported by prospective data indicating that balance deficits on the uninjured limb resolve in about 7-days while balance deficits on the involved limb take about 21-28 days to fully resolve.(Evans et al., 2004) Given the above mentioned impairments, as well as the obvious pain and dysfunction associated with LAS, it is not surprising that both the temporal and spatial parameters of gait are also impaired.(Crosbie, Green, & Refshauge, 1999)

### 3.2 Chronic ankle instability

Based on the above presented information, it is clear that there are numerous consequences of acute LAS and that those consequences are multi-factorial in nature. While the exact

physiological mechanism of CAI remains unknown, evidence suggests that it is multi-factorial in nature. Therefore, while ankle ligamentous damage is the most obvious result of a LAS, the laxity itself is not likely to be the sole cause of CAI. Rather, the true mechanism is most likely linked to a number of adaptations and impairments which cause a cascade of events that ultimately leads to CAI (Figure 1). (Hertel, 2008) One consequence that has been, for the most part, ignored is the loss of relevant sensory (i.e. afferent) information from those damaged ligaments, and surrounding tissue, that is associated with the continuum of disability. (McKeon, 2010; McKeon et al., 2010) As mentioned above, the deafferentation theory (Freeman, 1965a), has been refuted in the literature because of inconsistent support and because the link between local mechanical instability and global functional disability in those with CAI has not been clearly established. One factor that remains clear however, is that those with CAI have a decreased ability to cope with changes in task and environmental demands. This inability to effectively cope is thought to be most commonly manifested in episodes of giving way.

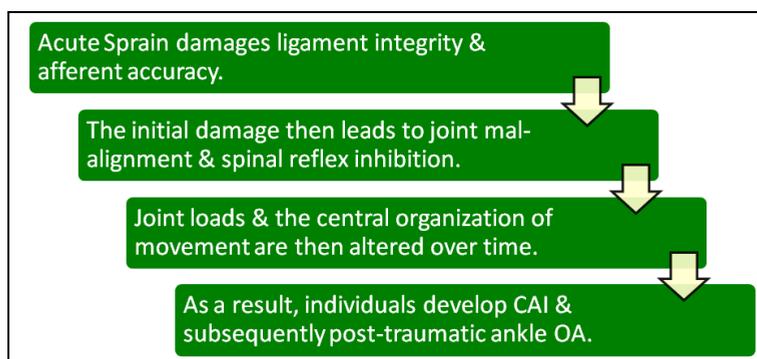


Fig. 1. Hypothetical cascade of events that causes the development of CAI and post-traumatic ankle OA based on the available evidence.

### 3.2.1 Patient-oriented evidence

The most commonly reported symptom across the continuum of disability associated with CAI is decreased functional performance due to repeated episodes of 'giving way'. (Hertel, 2002; 2008) It is crucially important to assess how impaired sensorimotor control due to CAI, often measured with laboratory-oriented outcomes, manifests into patient-reported activity limitations and participation restrictions. In other words, how does the instability a patient experiences at the ankle move from a local ankle instability to a global disability in function? Gaining the patient's perception of disability is very important in developing a thorough understanding of the impact of CAI on quality of life. These patient-oriented tools can be used to both assess the impact of CAI and the effects of rehabilitation strategies on function. Overall, patient-oriented measures of function provide the opportunity to gain insight into how the patient experiences disability due to ankle injuries.

Numerous scales/questionnaires have been developed in the sport injury literature to quantify the impact of CAI on patient-oriented function. Each scale assesses functional ability differently and has unique grading/weighting systems but all scales contain questions related to an individual's ability to complete both activities of daily living and

sport. The Ankle Joint Functional Assessment Tool (AJFAT), Cumberland Ankle Instability Tool (CAIT), Foot and Ankle Outcome Score (FAOS), the Foot and Ankle Disability Instrument (FADI), and the Foot and Ankle Ability Measure (FAAM) are some of the more commonly reported scales in the literature. In 2007, Eechaute et al. (Eechaute, Vaes, Van Aerschot, Asman, & Duquet, 2007) performed a systematic review of the clinimetric qualities of these scales and found that the FADI and the FAAM are the most appropriate scales to use for the assessment of function in those with CAI. Further, a self-reported loss of at least 10% of function during activities of daily living and at least a 20% loss of function during sport-related activities are the current recommendations for classifying those with CAI when using the FADI and/or FAAM. (Hale & Hertel, 2005)

### 3.2.2 Clinician-oriented evidence

Capturing the deficits that patients report associated with CAI in measurable clinical tests is crucial for the development of objective outcomes for diagnosis, prognosis, and rehabilitation. Several clinical tests have been developed to assess the effects of CAI across a wide range of outcomes and some of the more commonly reported will be discussed below. There have been numerous studies which have reported mechanical instability in those with CAI. Tropp et al. (Tropp, Odenrick, & Gillquist, 1985) reported 42% of subjects with CAI had a positive manual anterior drawer test. More recently, Hertel et al. (Hertel et al., 1999) illustrated ankles with CAI demonstrated significantly greater laxity during an anterior drawer test and greater talar tilt angles upon supination stress than did uninjured ankles. Significantly greater talar tilt values have also been shown in those with CAI compared with a healthy reference group. (Lentell et al., 1995; Louwerens, Ginai, Van Linge, & Snijders, 1995) Similar results have also been reported using an instrumented ankle arthrometer (i.e. more anterior translation and inversion stress in those with CAI relative to uninjured ankles). (Hubbard, Kramer, Denegar, & Hertel, 2007) Further, those with CAI, relative to uninjured controls, have been shown to have an anterior positional fault of the distal fibula (Hubbard, Hertel, & Sherbondy, 2006b) and talus. (Wikstrom & Hubbard, 2010b) These results using different techniques demonstrate that mechanical instability and structural adaptations are present in patients with CAI and similar to those reported following a LAS.

The weight-bearing lunge test (WBLT) is a clinical measure of the amount of dorsiflexion available in a weight-bearing environment. (Hoch & McKeon, 2011) It has been demonstrated that those with CAI have a dorsiflexion deficit on their affected limb during functional activities. (Drewes, McKeon, Kerrigan, & Hertel, 2009) The WBLT and the anterior reach of the Star Excursion Balance Test (SEBT) are highly correlated in healthy people, but not correlated as highly in those with CAI suggesting that those with CAI adopt a new movement strategy to complete the test. The SEBT has been the most extensively studied clinical measure of balance. (Gribble, Hertel, & Denegar, 2007; Hertel, 2008; Hertel, Braham, Hale, & Olmsted-Kramer, 2006; Olmsted, Olmsted, Carcia, Hertel, & Shultz, 2002) It has been consistently shown that those with CAI have a reduced ability to maintain balance on their injured leg and maximally reach with the opposite limb in different directions. Currently, it is recommended that the anterior, posteromedial, and posterolateral directions be used because each present a unique contribution to the assessment of dynamic postural control deficits and because these directions can elucidate postural control deficits associated with CAI. (Hertel, 2008; Hertel et al., 2006) Another test for the assessment of balance in those with CAI is the Balance Error Scoring System (BESS) (Docherty, McLeod, & Shultz, 2006). The premise of the

BESS is that individuals attempt to maintain balance under a series of postural challenges and the clinician counts the number of errors committed during the test. Further, the BESS provides a clinical assessment which utilizes the manipulation of different postural control tasks and environments to explore the sensorimotor system's ability to cope with changing demands. Out of the six conditions of the BESS, it has been found that the single limb stance on a firm surface and a foam surface provide the most relevant information associated with clinically relevant postural control deficits in those with CAI.(Docherty et al., 2006)

### **3.2.3 Laboratory-oriented evidence**

Ankle instability has been shown to result in a host of functional impairments. These impairments have included local effects thought to be a direct consequence of the joint damage described above including deficits in ankle joint position sense and movement detection, evertor muscle strength, peroneal and soleus motor neuron pool excitability, and peroneal muscle reaction time in response to perturbation (see Hertel, 2008) for further review). In addition to local effects around the joint, CAI has also been associated with global deficits in sensorimotor function, specifically alterations in proximal muscle and joint control as well as alterations in stereotypical movement patterns. For example, those with CAI have decreased hip extension and abduction strength.(Hubbard et al., 2007) and have diminished levels of alpha motorneuron pool excitability at the knee.(Sedory, McVey, Cross, Ingersoll, & Hertel, 2007) The use of motion analysis systems has also identified an increased use of knee flexion ROM while landing from a jump (Caulfield & Garrett, 2002) and altered hip biomechanics during the SEBT in those with CAI.(Gribble, Hertel, & Denegar, 2007) Differences have also been seen in stereotypical movement patterns which are now believed to be the result of a constrained sensorimotor system. For example, those with CAI have altered movement patterns during the swing phase of walking gait (Delahunt, Monaghan, & Caulfield, 2006; Monaghan, Dean, & Caulfield, 2006) and throughout the entire running gait cycle.(Drewes et al., 2009) More recently neuromuscular and biomechanical control alterations have been seen during gait initiation (Hass, Bishop, Doidge, & Wikstrom, 2010) and gait termination.(Wikstrom, Bishop, Inamdar, & Hass, 2010a) These most recent investigations clearly demonstrate that the global deficits associated with CAI negatively affect the central nervous system as both gait initiation and termination are mediated via supraspinal motor control mechanisms.(Wang et al., 2009). Cumulatively, these deficits and/or alterations in proximal muscles and joint control as well as stereotypical movement patterns indicate global deficits in sensorimotor function. However, the link between local and global impairments in sensorimotor control is poorly understood at this time and this link must be a focus of future investigations if more effective treatments are to be developed.

### **3.3 Post-traumatic ankle OA**

Only recently has there been an impetus to investigate the impairments associated with post-traumatic ankle OA because the diagnosis of ankle OA is becoming more common (Saltzman et al., 2005) and because ankle replacement procedures are anticipated to increase at a rate of about 5% a year.(Jeng, 2006) However, there is a limited amount of information available regarding patient-, clinician-, and laboratory-oriented evidence for those with ankle OA at this time. The vast majority of post-traumatic ankle OA research has been focused on patient-oriented evidence and the results consistently show, regardless of the

scale used, that those with post-traumatic ankle OA have greater levels of self-reported disability relative to age matched controls.(Horisberger, Hintermann, & Valderrabano, 2009a; Hubbard, Hicks-Little, & Cordova, 2009b; Khazzam, Long, Marks, & Harris, 2006; Messenger, Anderson, & Wikstrom, 2011; Valderrabano et al., 2007; Valderrabano et al., 2006b) Clinical-oriented evidence shows similar impairments as those associated with acute LAS and CAI. Specifically, decreases in ankle muscle strength and increased mechanical stiffness have been observed relative to age matched controls.(Hubbard et al., 2009b) Laboratory-oriented evidence is also similar to the impairments associated with acute LAS and CAI. For example, static postural control (i.e. plantar pressure distributions and COP displacements) have been reported to be altered and/or increased (Horisberger et al., 2009a; Hubbard et al., 2009b; Messenger et al., 2011) and walking gait velocity, cadence, and stride length are all reduced in those with ankle OA.(Khazzam et al., 2006; Valderrabano et al., 2007) Most recently, Messenger et al.(Messenger et al., 2011) illustrated that post-traumatic ankle OA alters gait initiation relative to uninjured age-matched controls. This evidence further illustrates that the long term sequela of LAS are global in nature and can negatively influence the central nervous system.

#### **4. Finding context**

Based on the information provided above from the PCL model, those with acute LAS, CAI, and post-traumatic ankle OA report significant and similar limitations in patient-, clinician-, and laboratory-oriented outcome measures. By examining all 3 sources of evidence, it is clear that an ankle sprain is more than just a peripheral musculoskeletal pathology with only local consequences. Further, examining the interaction of specific deficits on global function will help elucidate the cascade of events that leads to the development of CAI (Figure 1) and more importantly identify effective evidence-based treatment protocols that can address not only the isolated impairments but also the complex interactions among them. By developing context through the PCL model, a more thorough understanding of the consequences of injury and rehabilitation can be gained. What remains needed is a working theoretical construct to link these sources of evidence in a meaningful way. In the next section, we provide the theoretical construct that we believe will allow a more thorough understanding to be obtained.

#### **5. Ankle instability and impaired sensorimotor control**

The human body is a system composed of many interacting parts which can be organized in a variety of ways to accomplish movement goals.(Davids & Glazier, 2010) The hallmark of this system is its ability to adapt to changing demands both internally and externally. The sensorimotor control theory that captures the dynamic nature of this system is known as the dynamic systems theory of motor control.(Davids, Glazier, Araujo, & Bartlett, 2003) According to dynamic systems theory, the organization of the sensorimotor system is constrained, or shaped, by the interaction of 1) the health of the person (organismic constraint), 2) the task being performed (task constraint), and 3) the environment in which a movement goal is executed (environmental constraint) (Hoch & McKeon, 2010b; McKeon & Hertel, 2006) (Figure 2). Rather than having preprogrammed pathways to accomplish a movement goal, the dynamic systems theory states that the sensorimotor system is free to develop and change strategies based on its current state as it interacts with the

environment.(Davids et al., 2010) For example, an individual will use different gait strategies when walking on a sidewalk compared to walking in soft sand on a beach because the individual is interacting with different environments. In this way, coordination within the sensorimotor system changes based on the constraints related to the movement goal. Because of this freedom of spontaneous (goal-oriented) self-organization, a healthy sensorimotor system can accomplish a movement goal in a variety of ways based on the interaction with the tasks performed and the environmental cues received.(Hoch et al., 2010b) If there are changes in the task or environment, the sensorimotor system can reorganize to adopt a new strategy to achieve the movement goal. More strategies translate to an enhanced ability to successfully accomplish the movement goal and cope with change. This has been referred to as invariant results through variant means, also known as functional variability.(Latash, Scholz, & Schoner, 2002)

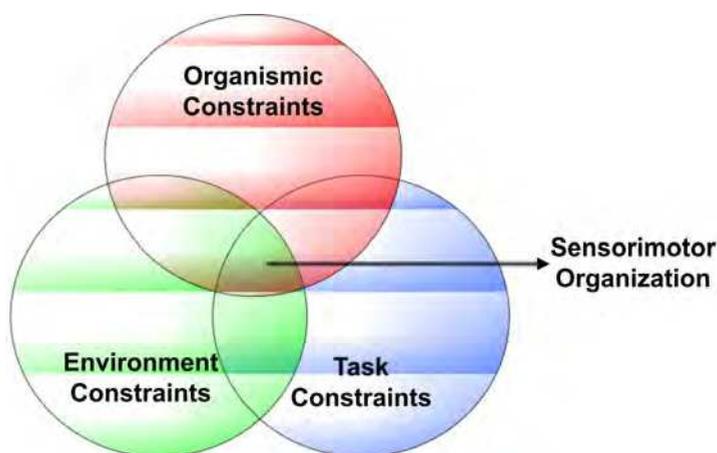


Fig. 2. Sensorimotor organization based on the interaction of constraints as described by the Dynamic Systems Theory

Ankle injury, which introduces organismic constraints, can significantly hinder the sensorimotor system in its ability to accomplish movement goals.(Hoch et al., 2010b) Ankle injuries result in mechanical and functional alterations within a component part of the sensorimotor system.(Hertel, 2002) Consequently, injured parts of the system cannot be used in movement solution development. This then reduces the functional variability of the sensorimotor system—in other words; it is constrained in its ability to cope with change. The result of this decrease in sensorimotor control is a reduction in functional performance. Ankle injury epidemiological evidence supports this framework in that the primary risk factor for an ankle sprain is a previous history of one. (Beynon, Renstrom, Alosa, Baumhauer, & Vacek, 2001) Based on this information, it is apparent that there is the potential for a continuum of disability associated with CAI (McKeon, 2010) (Figure 3). Poor control may predispose a person to injury and injury significantly constrains sensorimotor control. To gain understanding into this continuum as it relates to CAI, we will discuss management strategies that address different points along the continuum and present recommendations to help improve treatment options that may attenuate the effects of organismic constraints on sensorimotor control.

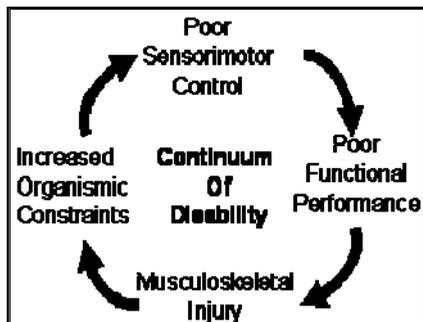


Fig. 3. Continuum of Disability

## 6. Management strategies through the continuum

Acute LAS management typically involves rest, ice, compression, elevation (RICE) and functional rehabilitation (i.e. early mobilization with support). (Mattacola & Dwyer, 2002) In more severe cases, LAS are treated with crutches and are typically immobilized for a short period of time. (Mattacola et al., 2002) To date, numerous investigations have assessed the efficacy of rehabilitation techniques on short-term patient-oriented outcomes including: pain, ROM, and return to work/activity. However, the high percentage of re-injury occurrence (up to 70%) and development of CAI (up to 75%) (Anandacoomarasamy et al., 2005; Peters et al., 1991; Smith et al., 1986) after an LAS, suggests that further research of both short and long-term outcomes following rehabilitation is needed to investigate not only specific mechanical and/or sensorimotor impairments but the interactions among them by examining patient-, clinician-, and laboratory-oriented evidence.

### 6.1 Acute care/immobilization – Overcoming the constraints of a damaged joint

Immediately after a LAS the primary goals are to manage pain, control inflammation and protect the joint. In the acute phase of healing, the most important structures to protect are the lateral ligaments of the ankle because the traumatic mechanism has caused increased laxity. In the past, the majority of the literature has focused on functional rehabilitation (i.e. early mobilization with support) but the high recurrence rates of LAS and development of CAI suggest that functional rehabilitation may not allow adequate time for the ligaments of the ankle to heal and stability to be restored. Indeed, increased laxity has been reported using both patient- (ankle giving way, or feelings of instability) and clinician-oriented (manual stress tests, radiographs) outcomes. (Hertel et al., 1999; Hubbard et al., 2007; Lentell et al., 1995; Louwerens et al., 1995) Unfortunately, ankle laxity often persists despite treatment as positive anterior drawer tests were still present in 3%-31% of subjects 6-months after injury (Cetti et al., 1984; Konradsen et al., 1991) and feelings of instability were present in 7%-42% of subjects up to 1-year after injury. (Brostrom, 1966; Munk et al., 1995) Cumulatively, these studies provide strong evidence that better and longer protection of the ankle joint after an acute LAS is needed to help restore mechanical stability. If mechanical stability is not restored, increased laxity could lead to further mechanical adaptations, deficits in sensorimotor control, recurrent injury and decreases in global function as a maladaptive compensation of the changes in joint laxity and/or sensorimotor control.

To help examine the effects of immobilization, a multi-center prospective randomized control trial was conducted examining three different mechanical supports (Aircast brace, Bledsoe boot, and 10-day below the knee cast) compared with that of a double-layer tubular compression bandage (current standard of care) in promoting recovery after severe LAS. (Lamb, Marsh, Nakash, & Cooke, 2009) A total of 584 patients with LAS were followed over nine months with the primary outcome being the quality of ankle function measured using the Foot and Ankle Score (i.e. a patient-oriented outcome). The below-knee cast caused a more rapid recovery than the tubular compression bandage with clinically important benefits in quality of ankle function at 3-months post injury. (Lamb et al., 2009) Based on the data, a short period of immobilization in a below-knee cast or Aircast ankle brace (2<sup>nd</sup> best results) may result in faster recovery than the current standard of care. Additionally, the authors recommended the below-knee cast because it showed the widest range of benefit. However, future research is needed to determine if similar benefits will be found in clinical and laboratory measures such as ligament laxity and postural control.

An earlier study (Beynnon, Renstrom, Haugh, Uh, & Barker, 2006) also examined the type of immobilization that had the best outcomes. The authors stratified acute LAS based on the grade (I, II, or III) and randomized patients to undergo functional treatment with different types of ankle immobilization. They compared an elastic wrap (current standard of care), Air-Stirrup ankle brace, Air-Stirrup ankle brace with an elastic wrap and fiberglass walking cast. They reported treatment of grade I and II ankle sprains with Air-Stirrup brace combined with elastic wrap allowed patients return to pre-injury function, as measured by both patient- and clinical-oriented evidence, quicker than the other immobilizers. (Beynnon et al., 2006) For grade III sprains, there were no differences between the Air-Stirrup brace and the fiberglass walking cast. The subjects in the Lamb et al. (Lamb et al., 2009) study were considered to have severe ankle sprains, which may be why the below-knee cast was more favorable.

Based on the research available to best treat acute LAS, some form of immobilization needs to be used to help protect the joint and allow ligament healing to occur. Thus, elastic or tubular wraps are not recommended because research suggests that they do not provide adequate protection to allow restoration of function. An Air-Stirrup brace with elastic wraps for grade I and grade II, and below-knee casts for grade III appear to be the best treatment strategy based on the current literature. After a period of controlled immobilization functional exercises are necessary to rehabilitate the joint and two of the more commonly used adjunctive therapies are discussed below.

## 6.2 Joint mobilizations

To date manipulative therapy techniques; including Maitland's mobilizations, (Maitland, 1985) Mulligan's mobilizations with movement, (Mulligan, 2004) and High-Velocity Low-Amplitude (HVLA) thrusts, (Bleakley, McDonough, & MacAuley, 2008; van der Wees et al., 2006) have all been postulated to be effective treatments for acute LAS. Indeed, manipulative therapy techniques are theorized to reduce pain (patient-oriented), improve function and increase ROM via the restoration of arthrokinematic motions (i.e. roll, glide, spin) (clinician-oriented), (Maitland, 1985) and improve spatiotemporal postural control in single limb stance (laboratory-oriented); thus recommendations to use these techniques make intuitive sense.

Patient-oriented outcome measures have improved following manipulative therapy. For example, multiple manipulative therapy treatment sessions result in improvements in self-report levels of pain and function. (Coetzer, Brantingham, & Nook, 2001; Green, Refshauge,

Crosbie, & Adams, 2001; Pellow & Brantingham, 2001; Whitman et al., 2009) Further, a single treatment session, involving multiple osteopathic and manipulative techniques, immediately reduced self-reported pain in patients with acute LAS.(Eisenhart, Gaeta, & Yens, 2003) Based on this evidence, it appears that multiple treatment sessions are needed to consistently see improvements in a variety of patient-oriented outcomes, regardless of the specific manipulative therapy technique used, in patients with acute LAS. However, the exact number of treatments and dosage within each treatment session remains unknown.

The available literature also indicates that both active and passive ROM (clinician-oriented evidence) are improved following the delivery of multiple treatment sessions.(Green et al., 2001; Pellow et al., 2001) Additionally, significant improvement in non-weight bearing range of motion (ROM) was reported after the delivery of a variety of manipulative therapy techniques over a 2-week intervention.(Coetzer et al., 2001) Thus, the cumulative data suggest that multiple treatment sessions are needed to see ROM improvements in patients with acute LAS. However, significant improvements in dorsiflexion ROM have been reported after just a single treatment session of Maitland's (AP talocrural) mobilizations in patients who underwent a prolonged period of ankle immobilization for a variety of pathological conditions.(Landrum, Kellen, Parente, Ingersoll, & Hertel, 2009) Thus, it appears that even if acute LAS patients are immobilized (i.e. casted) following injury, ankle joint mobilizations could be used to help restore ROM.

Similarly, a single treatment session consisting of two manipulative therapy techniques lead to an immediate redistribution of foot loading patterns (laboratory-evidence) during static stance relative to a placebo laying of hands procedure in patients with acute grade II LAS.(Lopez-Rodriguez, Fernandez de-las-Penas, Albuquerque-Sendin, Rodriguez-Blanco, & Palomeque-del-Cerro, 2007) There is also evidence to suggest that a single bout of anterior-to-posterior talocrural joint mobilizations (Maitland Grade 3 oscillations) improves ROM measured by the WBLT (clinician-oriented evidence) and spatiotemporal measures of postural control (laboratory-oriented evidence) in those with CAI.(Hoch & McKeon, 2010a; c) By combining these results with the patient-oriented evidence above, there appears to be strong indications that joint mobilization has the potential to be an excellent rehabilitation intervention for those with acute LAS and CAI. However, no investigation has directly compared the effectiveness of different manipulative therapy techniques on any outcome measures in patients with acute LAS or those with CAI. Thus direct comparisons of manipulative therapy techniques should be the focus of future research endeavors.

### **6.3 Balance exercises**

One of the most commonly examined sensorimotor outcome measures following a LAS is single leg postural control and recent systematic reviews have demonstrated that postural control is impaired on both the involved limb (Arnold, De La Motte, Linens, & Ross, 2009; McKeon et al., 2008a; Wikstrom et al., 2010c) and the uninvolved limb (Wikstrom et al., 2010c) relative to an uninjured control group within six weeks of a LAS. The presence of bilateral balance impairments (Wikstrom et al., 2010c) suggest that global impairments as a result of a peripheral injury have occurred. Further, impaired postural control is associated with an increased risk of ankle injury (McGuine, Greene, Best, & Levenson, 2000; McKeon et al., 2008a) and because of this strong association, balance training is a common component of therapeutic intervention programs used by allied health care practitioners to treat acute LAS. Fortunately, balance training is effective at improving postural control scores in

subjects with acute LAS (McKeon & Hertel, 2008b; Wikstrom et al., 2009) and at reducing the risk of recurrent LAS.(McKeon et al., 2008b; McKeon & Mattacola, 2008d) The effectiveness of balance training is hypothesized to be due to the modality's ability to restore and/or correct feed-forward and feedback neuromuscular control alterations that have occurred as a result of a LAS. Indeed, neural adaptations occur at multiple sites within the central nervous system as a result of balance training intervention programs.(Beck et al., 2007; Taube et al., 2007) In other words, balance training capitalizes on the incredible plasticity of the central nervous system and enhances a patient's ability to react to both internal and external perturbations.

Balance training programs have been shown to improve self-reported function (patient-oriented), enhance the performance on the SEBT (clinician-oriented), and improve center of pressure and spatiotemporal measures of postural control (laboratory-oriented).(Hale, Hertel, & Olmsted-Kramer, 2007; McKeon et al., 2008c) While balance training improves postural control, the exact treatment dosage needed to cause balance improvements and reduce the risk of recurrent injury remains unknown. However, the generally accepted timeframe for improvements to be observed is 4-6 weeks of balance training.(McKeon et al., 2008b; McKeon et al., 2008d). Bahr et al. (Bahr, Lian, & Bahr, 1997) reported that the longer a balance training program is implemented the greater preventative effects accrue from the program. To date, published balance training investigations primarily use prospective cohort designs where the baseline measures represent postural control prior to the intervention but not pre-injury postural control values. So while the literature indicates that balance training improves postural control, it is not clear if balance training restores postural control to pre-injury balance values.

When designing a balance training program, it is important to consider the dynamic systems theory of motor control (Figure 2). Specifically, this chapter has focused on the organismic constraints as defined by both mechanical adaptations and sensorimotor dysfunction associated with LAS, CAI, and post-traumatic ankle OA. In order to overcome the effects of these constraints on the sensorimotor system, a systematic process of purposefully manipulating task and environmental constraints must be employed.

### **6.3.1 Cultivating functional variability**

In rehabilitation, it becomes imperative that the clinician is very specific when identifying the desired movement goal for the patient.(McKeon, 2009) Rather than focusing on the task to be performed (task-oriented rehabilitation), the functional activities should be associated with the quality of the movement goal execution (goal-oriented rehabilitation). The most important elements for the development of functional variability are to incorporate: 1) a systematic progression through the exercises, 2) a logical manipulation of task and environmental constraints at each level of the progression, 3) specific outcomes that capture improvements and help the clinician determine when patient progression is appropriate, 4) an ability to reduce the outcomes into a decision as to whether the patient has overcome the continuum of disability, and 5) ensure that the process is replicable by documenting the systematic, logical, empirical, and reductive elements.

In order to present the systematic and logical process of program development, we have included examples of a published balance training protocol used for patients with CAI.(McKeon et al., 2008c) Further information associated with this program, including the full description of activities, progressions, outcomes used, and results can be found in the published manuscript.

### 6.3.2 Task constraints in balance training

Changing the demands of the balance training task results in changes within the component parts of the sensorimotor system to accomplish the movement goal.(McKeon, 2009) The complexity of the task will govern the variability of movement solutions the sensorimotor system can use. An example of this is balancing in single limb stance. In order to accomplish this movement goal (i.e. maintain single limb stance), the sensorimotor system can develop several movement solutions from its many component parts (e.g. ankle muscles, knee muscles, hip muscles, etc.) and is readily afforded the freedom to correct for any errors introduced in executing the movement goal. However, when a person lands from a jump on one leg and attempts to regain balance there are fewer solutions available to accomplish the movement goal, because of the increased task demands (e.g. increased 3-dimensional forces, momentum acting on the body, etc.). As a result, there is an increased likelihood of errors being committed. If an error in postural control is introduced during physical activity and/or athletic event, it can potentially have severe consequences, such as an ankle injury. As stated above, an ankle injury would result in increased organismic constraints and subsequently increase the likelihood of errors in the future, starting a vicious cycle. However, the introduction of errors in a controlled training environment gives the sensorimotor system time to develop either 1) more/new movement solutions or 2) enhance the efficacy of existing movement solutions so that the likelihood of committing errors and the consequences of those errors can be diminished over time.

### 6.3.3 Purposeful manipulation of task constraints

When progressing an individual through a balance training program, it becomes essential for the movement goals to be meaningful to the individual.(McKeon, 2009) Balance training has been shown to be beneficial at improving functional outcomes associated with CAI.(Holmes & Delahunt, 2009; McKeon et al., 2008b; McKeon et al., 2008d) From the dynamic systems perspective, the most important consideration in functional rehabilitation program development is the clarity of the movement goal.(McKeon, 2009) The task constraints then can be structured to challenge the sensorimotor system as it spontaneously organizes (i.e. develops new solutions) to accomplish the movement goal.

An example of the strategic manipulation of task constraints in the referenced balance training program is the "Hop to Stabilization" activity compared to the "Hop to Stabilization and Reach" activity (McKeon et al., 2008c). For both activities, the movement goal was to regain single limb stance as fast and effectively as possible after landing from a hop. In the first activity, subjects performed single limb hops to a target, stabilized single limb stance, and then hopped back to their starting position. In the "Hop to Stabilization and Reach" activity, subjects hopped to the target, stabilized, and reached back to the starting position with their opposite leg. Although the movement goal was the same, the tasks resulted in the development of different solutions for goal achievement. In order to keep patients on the cusp of failure (i.e. continuously challenge the sensorimotor system), the task constraints were increased when each patient could perform 10 error-free repetitions in the current task constraints. An important note is that each patient in the program progressed to higher levels based on their ability to execute the movement goals. This was done by increasing the distance of the hop target. To add additional task constraints for each activity, the patients hopped in eight different directions. Each direction presented unique task constraints that challenged the sensorimotor system to develop

movement solutions to accomplish the movement goal and ultimately make the patient more adaptable to unexpected perturbations (e.g. a mid-air collision with another player) that occur during athletic events.

#### **6.3.4 Environmental constraints in rehabilitation**

Environmental constraints (or cues) are essential components for the organization of the sensorimotor system.(McKeon, 2009) Rather than viewing the environment as such things as grass versus sidewalk, the cues from the environment should be considered for the predictability they offer to the sensorimotor system.(McKeon, 2009) More predictable environmental cues allow for greater freedom for the development of strategies to accomplish movement goals. Less predictable environment cues constrain the sensorimotor system's ability to develop movement goal strategies. An example of this is performing sport-specific activities in a rehabilitation environment compared to sport-specific activities during actual participation in athletic events. In the rehabilitation environment, environmental cues are based on the room, the performance of the activities, and the interaction with the therapist, and are much more predictable compared to real life performance. Once the patient returns to participation in athletics, the interaction with the playing surface, teammates, and opponents provide significantly more unpredictable environmental cues. This is one of the reasons that an athlete might pass a functional screen performed by a health care provider, but still struggle upon their return to actual competition.

With increased exposure to task and environmental constraints, the sensorimotor system can develop new strategies to accomplish movement goals and cope with change over time. Therefore, to maximize the efficacy of the sensorimotor system in those with ankle inversion trauma, it is essential to adjust the environmental and task constraints to keep the patient on the cusp of failure (i.e. continually manipulate the constraints so that patients have to provide near maximum physical and psychological effort to complete the assigned activities) throughout the rehabilitation program. When challenged in this way, the sensorimotor system develops greater flexibility in achieving its motor goals, and this translates into better outcomes of the movement goal and potentially a decreased risk of injury.(McKeon, 2009; McKeon et al., 2008c)

#### **6.3.5 Purposeful manipulation of environmental constraints**

The environmental constraints used in balance training should also be associated with specific movement goals.(McKeon, 2009) Initially, a predictable environment allows the sensorimotor system the freedom to explore a variety of strategies to accomplish a specified movement goal. The more unpredictable the environment becomes, the less free the sensorimotor system becomes to explore strategies. Consequently, a valuable balance training activity has a systematic progression from hopping to a predictable target, as described above, to an unpredictable one. In the example above of the hopping activities, patients started by hopping to a predictable target. The environmental constraints were then manipulated by having the subjects perform the same types of hops in an unpredictable environment in the "Unanticipated Hop to Stabilization" activity. In the Unanticipated Hop to Stabilization, patients were presented with a random sequence of numbers on a grid set up like a large phone pad that represented the order of targets to which they would hop and

stabilize in single limb stance. For each number sequence, the subjects had a specified amount of time to get the next target before the next number in the sequence was shown to them and the sequence changed each time they performed this activity. As performance improved and subjects began to make their target times, the environmental constraints were increased by decreasing the amount of time allotted to complete the task. From the dynamic systems perspective, this change in the number sequence is a form of environmental constraint. The cues subjects received from the environment (the number in the hopping sequence) shaped the strategies that the sensorimotor system needed to use to accomplish the movement goal. The reduction in time challenged the sensorimotor system to adapt to the unpredictable environment in which the movement goal was being executed.

It is important to note that with the systematic and logical progression, each patient progresses through the balance training program at their own rate based on their individual ability to accomplish the movement goal in each activity. Upon completion of the program, patients reported significant improvements in their ability to engage other task and environmental constraints in activities such as running, cutting, and participating in their desired activities.(McKeon et al., 2008c) The goal of balance training and functional rehabilitation from the dynamic systems perspective is to restore the sensorimotor system's ability to cope with change during the execution of movement goals, thus improving sensorimotor control and functional performance. Once a movement/rehabilitation goal can be accomplished without error, the constraints can again be systematically increased. Purposeful and logical manipulation of task and environmental constraints include the logical progression from single limb balance activities to more functional activities such as hopping, landing, rapidly changing direction, etc. In order to accomplish more advanced movement goals effectively, more degrees of freedom (i.e. using more joints, muscles, etc.) are necessary to correct for errors introduced during goal execution. By freeing more degrees of freedom to correct errors, the Continuum of Disability (Figure 3) can be broken. The clinician can utilize the principles of the purposeful manipulation of task and environmental constraints to guide the progression of rehabilitation. By doing so, it is possible to tailor a program to a patient's ability to achieve movement goals and restore sensorimotor system freedom.

Lastly, it is imperative to utilize outcome tools that have been shown to capture patient-oriented, clinician-oriented, and laboratory-oriented aspects of changes within the sensorimotor system. In the study referenced in this section, (McKeon et al., 2008c) those in the balance training group experienced significant improvements in self-reported function (patient-oriented evidence), dynamic postural control as assessed through the SEBT (clinician-oriented evidence), and spatiotemporal postural control (laboratory-oriented evidence). By assessing self-reported function through the FADI or FAAM, dynamic balance through the BESS or SEBT, and potentially instrumented measures of postural control and/or gait when available, it is possible to determine if a rehabilitation program has an impact on taking a patient out of the Continuum of Disability.

## 7. Summary

When evaluating patients with ankle inversion trauma and/or instability, clinicians should consider the Continuum of Disability rather than simply local instability. Buchanan et al.

(Buchanan, Docherty, & Schrader, 2008) has provided the best example of why the PCL model is more appropriate than the examination of deficits in isolation to date. The authors had individuals with CAI and healthy controls complete clinical measures of functional performance (i.e. hop tasks) and asked the subjects if their ankle “felt” unstable during the tasks. The initial results indicated no group differences in performance but a secondary analysis compared those with CAI that “felt” unstable to those with CAI that “felt” stable and healthy controls. This secondary analysis, that combined patient- and clinical-oriented outcomes, revealed that the CAI subjects who “felt” unstable during the tasks had performance deficits relative to the other groups. This investigation demonstrates how the combination of a patient- and clinician-oriented outcomes are more revealing than either outcome in isolation. We recommend using the constraints-led approach to guide decisions about comprehensive sensorimotor system evaluation, the development of rehabilitation progressions, and safe return to participation. Most importantly, as presented throughout this chapter, an ankle sprain is not simply a local joint injury; it results in a constrained sensorimotor system that leads to a continuum of disability and life-long consequences such as high injury recurrence and decreased quality of life.

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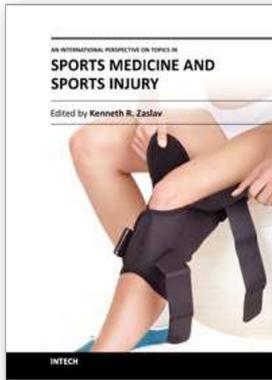
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For the past two decades, Sports Medicine has been a burgeoning science in the USA and Western Europe. Great strides have been made in understanding the basic physiology of exercise, energy consumption and the mechanisms of sports injury. Additionally, through advances in minimally invasive surgical treatment and physical rehabilitation, athletes have been returning to sports quicker and at higher levels after injury. This book contains new information from basic scientists on the physiology of exercise and sports performance, updates on medical diseases treated in athletes and excellent summaries of treatment options for common sports-related injuries to the skeletal system.

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